MEDDELELSER OM GRØNLAND
UDGIVNE AF
KOMMISSIONEN FOR VIDENSKABELIGE UNDERSØGELSER I GRØNLAND
BD. **195** · NR. **3**

PETROLOGY OF THE PUKLEN SYENITE–ALKALI GRANITE COMPLEX, NUNARSSUIT, SOUTH GREENLAND

BY

IAN PARSONS

WITH 23 FIGURES AND 6 TABLES IN THE TEXT,
AND 1 PLATE

KØBENHAVN
C. A. REITZELS FORLAG
BIANCO LUNOS BOGTRYKKERI A/S
1972

Abstract

The Puklen complex (Pulvertaft, 1963) has been studied with a view to comparison with the larger adjacent Nunarssuit syenite. It comprises augite syenites, quartz syenites, often pegmatitic in type, a transition group of quartzose syenites and quartz-poor granites, a relatively large alkali granite body, and cross-cutting microgranites. Modal quartz increases continuously from syenite to soda granite. A sodic vapour phase was entrapped in the drusy quartz syenites; their textures contrast with the even textured transition group syenites which grade into soda granite. Mineral layering is seen in the transition group.

Pyroxenes in the quartz syenites are strongly zoned aegirine-augites; in the transition group they are less strongly zoned but have similar bulk compositions. The transition to granite is marked by appearance of riebeckite-arfvedsonite as the dominant mafic mineral, by late crystallizing acmitic pyroxene, and by astrophyllite, aenigmatite and biotite.

The potassium-rich phase in the microperthitic alkali feldspars varies from dominant orthoclase in the coarse augite syenites, orthoclase + microcline in the quartz syenites and transition group, and microcline alone in the soda granites and microgranites. The variation is attributed to the increasing peralkalinity of the magma.

The rocks plot near thermal minima in the Ab-Or-Qz system. The effect of anorthite, peralkalinity and acmite on this system are discussed. The granites crystallized at $P_{H_2O} < 1$ Kbar and at temperatures $> 780°$ C. Quartz-feldspar textures are discussed and the granophyric intergrowths (mainly in the microgranites but also in certain layered rocks) are ascribed to a pressure reduction. The intrusion involved two main magmatic pulses; a slightly oversaturated syenite and a soda granite lying in the feldspar field in the Ab-Or-Qz system. Both have fractionated to some extent *in situ*.

ISBN 87 421 0066 6

CONTENTS

INTRODUCTION

The Puklen intrusion is a member of the Gardar suite of alkaline intrusions in South Greenland. It was named and described by PULVERTAFT (1961), who showed that the small oval mass, some four kilometres long by two kilometres wide, is comprised of augite syenite, quartz syenite, soda granite and granophyre. It lies on the eastern side of the island of Nunarssuit, some three kilometres outside the much larger syenite-soda granite complex of Nunarssuit-Alángorssuaq (HARRY & PULVERTAFT, 1963). The location of Puklen is shown in fig. 1. PULVERTAFT's account of the Puklen mass was based on short visits during 1958 and 1959. The present description is based on specimens collected by the writer during a three day visit to Puklen in 1966 together with P. B. GREENWOOD. Our collection was based on the map given by PULVERTAFT (1961), and this is reproduced, with trivial modifications (to be discussed later), and a little additional information, as fig. 2. In this short visit we were not able to visit the eastern and north-eastern parts of the intrusion, but our specimen coverage includes all the rock types described by PULVERTAFT and also areas showing different types of contact between them.

The Puklen body seemed to merit more detailed study for several reasons. Firstly, its nearness to the Nunarssuit intrusion and superficial similarities between the rock types suggest that the two bodies may be closely related, but the Puklen intrusion has, within its own intrusive outline, distinct augite syenite and soda granite phases, intimately related to each other and quite certainly part of the one intrusive complex. The Nunarssuit intrusion contains only minor soda granite bodies within its boundaries and is not seen in contact with the large soda granite intrusion at Malenefjeld, although it is separated from it only by a narrow strip of Julianehåb granite (fig. 1). Consideration of the Puklen sequence could indicate whether the Malenefjeld granite is closely related to the Nunarssuit syenite, and might offer an insight into the processes of derivation of the Nunarssuit soda granites.

Secondly, the Puklen complex includes the only extensive bodies of thoroughgoing granophyre described from the Gardar series, and although subordinate masses of soda granite are commonly associated with the augite syenites of south Greenland (*e.g.* Kûngnât (UPTON, 1960) and

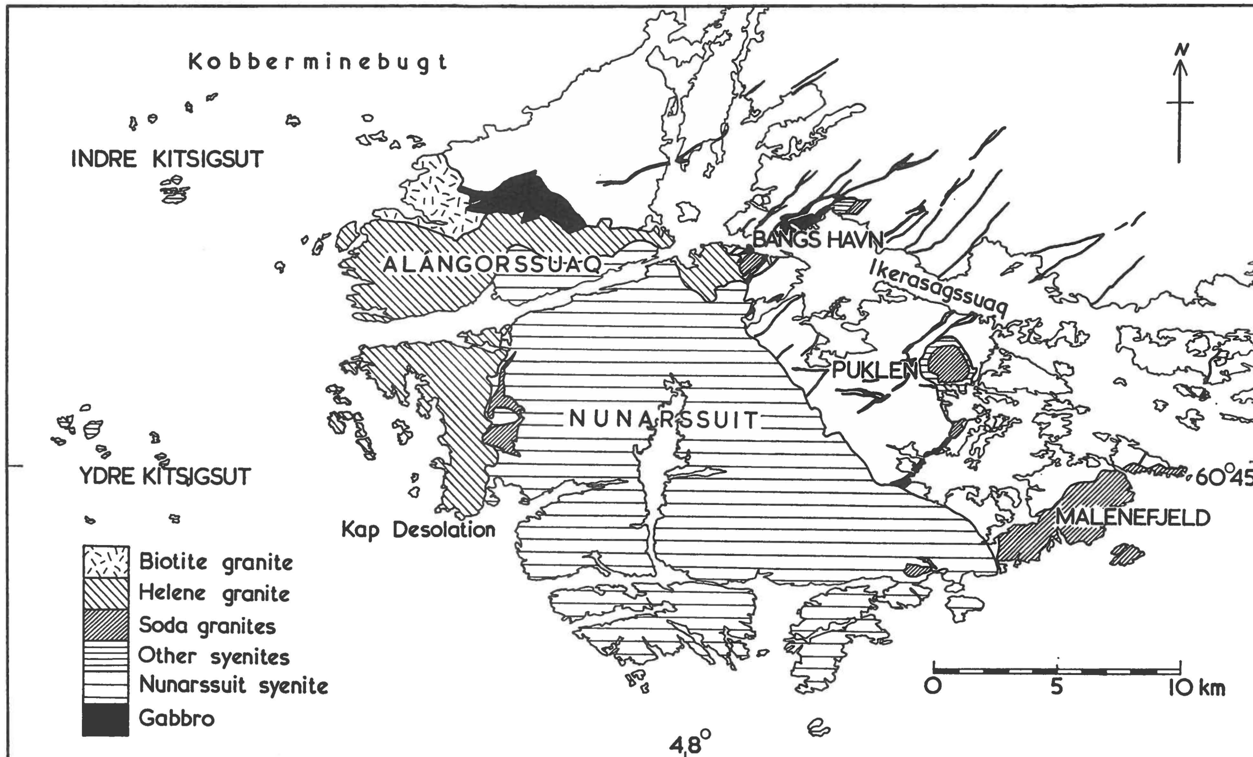

Fig. 1. Geological map of Nunarssuit-Alángorssuaq, showing the relationship of the Puklen mass to other Gardar intrusives in the area (after Harry & Pulvertaft, 1963).

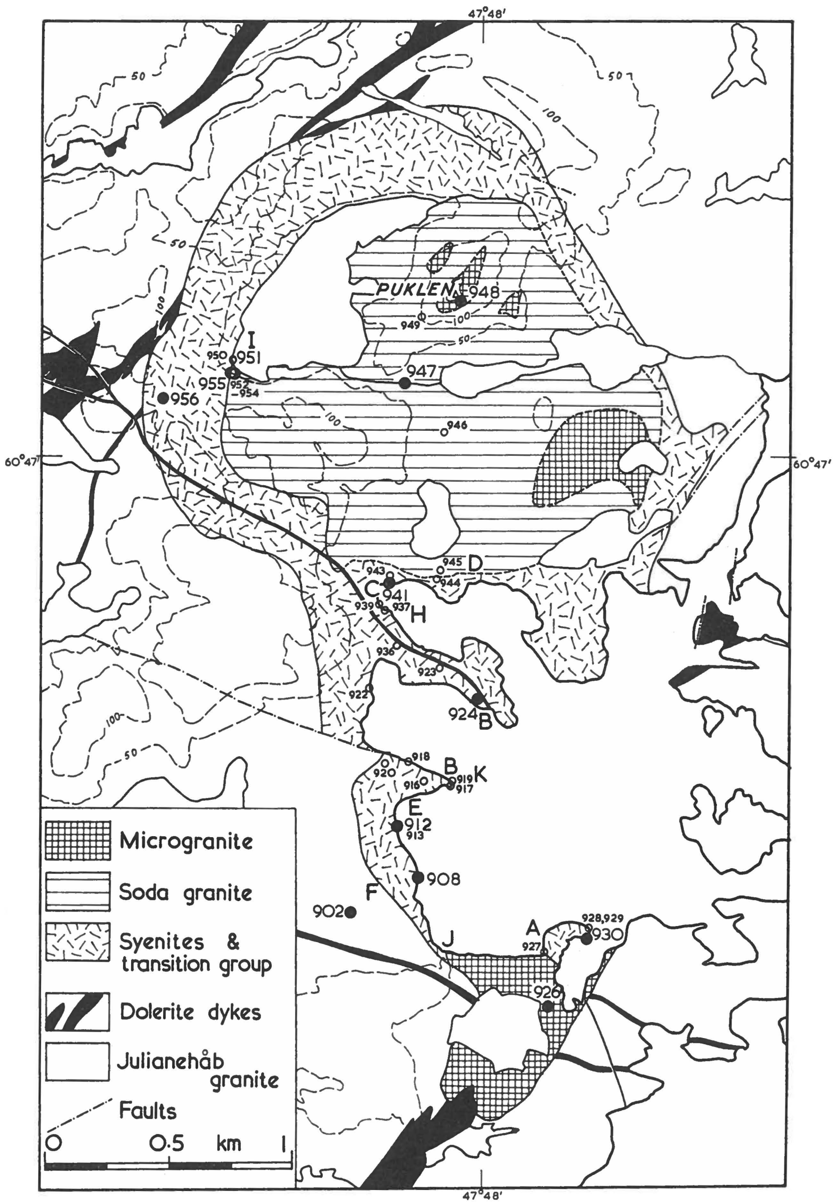

Fig. 2. Geological map of the Puklen complex, based on that of PULVERTAFT (1961) with certain modifications (see text). Numbers refer to samples described in the text, the letters to localities described in detail in the text. Large figures are analyzed samples.

Nunarssuit (HARRY & PULVERTAFT, 1963), the relative proportion, in terms of areal extent, of soda granite at Puklen is much larger. The processes of generation of the soda granite, and the conditions leading to the crystallization of granophyre, are therefore particularly worthy of investigation in the Puklen body.

Thirdly, early in this work it became apparent that the rock types within the Puklen intrusion constitute a continuous gradation from syenite to soda granite with widespread development of intermediate types. Clearly the mechanism of development of this range of rock types is of application to other Gardar intrusives in which such intermediates are not common (see SØRENSEN, 1966).

It is not the purpose of this paper to repeat the observations of PULVERTAFT (1961) and the latter paper should be consulted for an account of many aspects of the intrusion not covered in the present study. Only where they are needed for a full understanding of a line of reasoning will PULVERTAFT's observations be repeated.

DISTRIBUTION OF ROCK TYPES WITHIN THE COMPLEX

Subdivision of rock types

PULVERTAFT (1961) recognized the existence of quartz-free syenites (augite syenites), quartz syenites, coarse soda granites, and fine-grained acid varieties which he called granophyre. The distribution of these four types was shown on his map, although he mentions that the subdivisions are to a great extent gradational and that all intermediates may be found. The writers impression of the overlap between augite syenites and quartz syenites, both in terms of hand specimen appearance and in terms of petrography, is that any subdivision of the syenite areas, like that shown by PULVERTAFT (his fig. 1), is unrealistic. On the present map, therefore (fig. 2), quartz syenite and augite syenite are classified only as syenite. This grouping is supported by chemical data on samples of quartz-bearing and quartz-free syenites from PULVERTAFT's augite syenite and quartz syenite areas respectively. The quartz content of the syenites is very variable, often over short distances. Very detailed mapping would be needed to establish whether any systematic element existed in the distribution of the quartz-rich areas, and in the time available we made no attempt to map in detail the distribution of the four subdivisions of the syenites described below. The syenites margining the northern soda granite are dominantly quartz-bearing (as indicated on PULVERTAFT's map) but even here quartz-free rocks may be found. Conversely, within the areas named as syenite on the present map, variants may be found which on the criterion of quartz content would be classified as granites. The rocks falling in this latter category are refered to as the transitional group. Sharp boundaries may be seen between these variants at certain localities, but in general, the varieties grade into one another.

The most notable field criterion for the subdivision of the complex into granitic and syenite members is the distinctive reddish colouration of the feldspar of the granites in contrast to the pale pinks, browns and greys of the syenites. Members of the transitional group of intermediate appearance (and often, as noted above, high quartz content) occur along the margins of the granite bodies, within the areas shown as syenite on the map (fig. 2).

PULVERTAFT (1961) refers to the fine-grained varieties of the granitic types as 'granophyre' and his mapping of these subdivisions is shown in the present fig. 2. In fact the micrographic or granophyric texture (which seems to be a prerequisite of classification as a granophyre) proves to be lacking in many of these finer types, while some of the coarse soda granites do exhibit this intergrowth, as does interstitial material in certain quartz syenites. The writer, therefore, has used the term 'microgranite' on the map, fig. 2.

The soda granites, microgranites and granophyres can, like the augite syenites and quartz syenites, be considered together when describing their petrography. Sharp contacts are sometimes seen between the fine and coarse granites, the former cross cutting the latter, often as narrow veins. However there are areas where coarse granite grades into finer material. The areas taken from PULVERTAFT's (1961) map (fig. 2) should be regarded only as particularly conspicuous areas of microgranite rather than defining all the fine grained bodies. The southern granite body also shows substantial gradational change in grain size.

A detailed modification of PULVERTAFT's map is that the present writer shows the small promontory to the north of the southern soda granite to be syenite (Locality A, fig. 2). The sections available to the writer show the rock here to be a medium grained quartz syenite. This perhaps indicates that the southern microgranite has only limited northward extension.

Variation within the syenites

A number of variants within the augite syenites and quartz syenites may be recognised in the field. To view these variants as distinct phases of intrusion is probably erroneous but some sharp contacts are seen. The locations at which examples of these variants may be seen or contact relationships established are shown on fig. 2. Three types can, somewhat arbitrarily, be recognized.

(a) Coarse brown syenites

This variant is of limited extent and occurs towards the submerged centre of the mass (locality B, fig. 2), so it is possible that the type is more extensive than the present exposure would suggest. The coarse syenites would be more easily eroded leading to the embayment by the sea in this part of the intrusion. The rock in hand specimen is strongly reminiscent of the coarse brown-weathering syenite which forms the bulk of the large Nunarssuit syenite, and like the latter, may be greenish-grey when found fresh. The tabular feldspars may be 1 cm in length. Quartz is not found and the pyroxene, the most conspicuous mafic constituent, is deep green or black in colour. This extreme variety is of even grain size, and lacks the pegmatitic patches common in the more abundant variable type (b) syenites, into which it grades.

(b) Heterogeneous quartz syenites

The bulk of the syenite area is made up of rocks falling into this category, and they grade into the coarse brown variety. Feldspar size may range from about 1 cm for certain coarse pink-coloured rocks, but they are more typically 0.25–0.5 cm in length. There does not seem to be any systematic difference in the nature of the constituent minerals of the pink and brown varieties (except for the colouration of the feldspars) and they may or may not be quartz bearing. The amount of quartz varies greatly over the area concerned, quartz-free rocks giving way to varieties with conspicuous quartz, over short distances. Some, but not all, of the quartz is associated with pegmatitic patches. These occur particularly in the southern part of the syenites, where there is a tendency for the pink varieties to be rather inhomogeneous in texture. Euhedral feldspars in excess of 2 cm length are associated with sheaves of deep blue amphibole and interstitial quartz, and small cavities are commonly found at the centre of the patches. Perhaps the pink colouration is a late effect of the coexisting vapour phase which is presumably indicated by the drusy nature of these syenites. In contrast, the syenites of the transition group, although more quartzose, are not drusy and are texturally homogeneous.

(c) Porphyritic syenites

Some syenites exhibit a distinctive porphyritic texture with subhedral feldspar phenocrysts set in a fine-grained matrix. The areas where the syenite shows this texture have generally irregular, ill-defined margins and grade into normal pink or brown (type (a) or (b)) syenite on their flanks. There are some localities at which coarse pink syenite forms distinct veins in the porphyritic variety. The porphyritic feldspars in these varieties may be up to 1 cm long (like the enclosing syenite) but the matrix is fine grained and individual minerals are barely discernible to the naked eye. The examples sectioned prove to be quartz free or to contain only trivial amounts of quartz. This porphyritic type occurs sporadically throughout the outcrop of the augite syenites in the southern part of the mass, and although the type shows evidence of thermal reworking (see Pulvertaft (1961) and below) there seems no direct relationship between their distribution and the present outcrop of the later granite intrusions.

The porphyritic varieties grade into the pink syenite with pegmatitic patches and into the brown even-grained syenites. In an intermediate type the even coarse grain of the normal syenite is lost and occasional coarse (1 cm) feldspars are set in a matrix of feldspars of variable grain size, perhaps of the order of 1 mm across. The field name 'granulated' seems appropriate for this type.

The transitional group

A suite of rather fine-grained, characteristically grey or bluish, or more rarely pale pink variants, invariably quartz bearing, and often so quartzose as to be strictly granites, occur in a number of field settings in the areas visited by the writer. At the head of the northernmost inlet of the sea in the main syenite area (locality C, fig. 2) a homogeneous green variety of syenite is seen below a pale brown (type (b)) syenite with pegmatitic patches, and in knife sharp contact with it. The contact is irregular, the brown syenite sending veins into the green variety. In general the green variety is finer grained than the brown, and there are numerous patches of a fine-grained type strongly similar in appearance to quartz syenite dykes seen cutting the coarse syenites to the south. Northwards (locality D, fig. 2) the fine-grained green syenite grades into coarser pink syenite which, in turn, grades into soda granite. It is a medium-grained member of this sequence which exhibits the layering described below.

A rather similar setting for the grey quartz syenite, at the margins of a granite body, is seen in the small promontory north-east of the southern granite mass (locality A, fig. 2). At the south-west contact of this small syenite outlier the grey-brown syenite is fine grained (feldspars 0.2 cm) and, over the width of a small gully gives way to pink microgranite. Towards the north-east the syenite becomes coarser (feldspars 0.5 cm) and tends towards the brown and coarse reddish varieties in colour. The coarser red quartz syenites at this locality prove, in thin section, to contain quartz-feldspar intergrowths of the 'granophyric' type, also well developed in the nearby microgranite. There are narrow (5 cm) grey granitic veins cutting the quartz syenites at this locality.

Grey quartz syenite dykes cut the coarse, largely quartz-poor syenites at various localities in the southern part of the syenite area. These may be as much as 1 m wide (locality E, fig. 2), with sharp margins, or sometimes they exhibit diffuse margins. A fine facies of quartz syenite of similar appearance is found at the contact between the syenites and Julianehåb granite in the southern part of the mass (locality F, fig. 2).

The quartz syenites of the transition group are a diverse group in number of field settings, considered together because of hand specimen similarity. However, as will be described subsequently, there are textural and mineralogical similarities between the rocks within this group. Although all transitional group specimens are quartz bearing, this is not an easily applied criterion for distinquishing them from type (b) syenites, because the quartz contents may overlap. Grain size, colour, and inhomogeneity of texture are the most distinctive features of the type (b) syenites. Similarly, colour is the only field feature which distinguishes the quartz rich transitional group members from the granite suite.

The widespread examples of transitional group dykes cutting types (a) and (b) would suggest that the type was, in general, intruded later than the types (a), (b) and (c) syenites. At one locality (C, fig. 2) there is evidence for mobility of the type (b) syenite when the transitional group syenite was intruded. At other localities a gradational relationship has been shown. However, the existence of dykes of transitional group rocks as well as of some large areas of transitional group rocks with at least one sharp margin (locality C, fig. 2) does suggest that the group represents a distinct magmatic stage, and not merely a suite of hybrids produced by purely mechanical mixing of early syenite with later granite.

Mineral layering in the transitional group

Pulvertaft (1961) reported irregular banding in quartz syenites near the north-east sea channel, describing wisps and lenses up to 1 m long of augite and ore in a zone near to, and running parallel with, the outer contact of the intrusion. A similar, but rather more coherent development of banding, was found by the writer in rather fine-grained quartz syenites of the transitional group at sea level on the southern shore of the inlet of the sea that borders the southern margin of the northern granite (locality H, fig. 2). Fig. 3 shows the most extensive banding found. The mafic layers extend for at least 3 m before dipping westward beneath the sea, and consist of lenticular bands of augite and hornblende in the region of 10 cm thick, separated by narrow bands of pink quartz syenite like that forming the bulk of the unbanded rock in adjacent parts of the intrusion. The bands have an overall trough-like form and there is a discordance in the banding at the outcrop figured (fig. 3, to left and behind hammer). The banded rocks do not exhibit parallelism of the constituent minerals. The total thickness of the trough of banded rock is about 60 cm. Similar banding is shown at various points in the Nunarssuit syenites (Harry & Pulvertaft, 1963) and these authors figure very similar structures in the Helene granite (p. 93). The Puklen rock is rather finer grained than the Nunarssuit examples, the majority of feldspar grains being about 2 mm in largest dimension, occasionally 5 mm.

Narrower, less extensive banding is found at other points in the vicinity of the outcrop described above. Mafic bands 1–2 cm in thickness

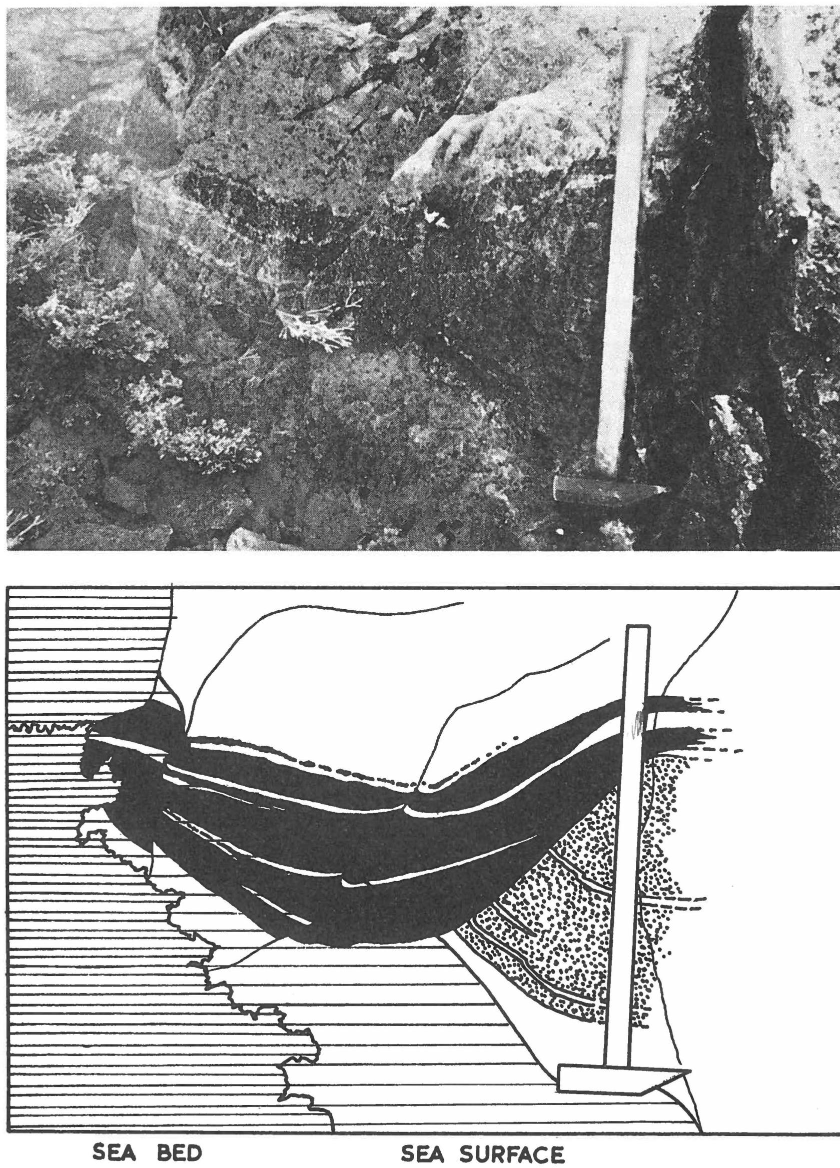

Fig. 3. Trough-shaped bedded structure in transition group quartz synenites and granites at locality H of fig. 2. The main structure dips beneath the sea to the left of the photograph, whilst it wedges ot to the right, and truncates the bedding of another structure running off the right of the photograph. Explanatory sketch below.

pinch out and exhibit folding. One example shows two narrow mafic bands, about 3 cm apart and roughly parallel, which show rudimentary grading, the lower surfaces of the mafic bands being sharper than the upper which grade into normal syenite. North of this locality the transitional group rocks grade into soda granite.

In common with other Gardar syenites, it is hard to escape the view that structures like those figured (fig. 3) were produced in the same manner as analogous structures in sedimentary rocks, namely by the settling of crystals and their sorting by magmatic flow. The folding and pinching out of the layered structures presumably indicates disturbance of the crystal mush by later magmatic movements. It will be shown below that the Puklen layered quartz syenites are perhaps unique in possessing intercumulus quartz-feldspar material exhibiting the granophyric intergrowth.

Variation within the granites

Apart from variation in grain size the granites show great consistency in appearance, being universally reddish pink in colour with only a slight tendency for the coarse rocks to be paler pink. No porphyritic varieties are found. The feldspar size ranges from about 0.5–1 cm for the coarsest examples of the northern soda granite, down to the finest microgranites, which are fine grained, almost flinty rocks in which the largest crystals are barely visible to the naked eye. The coarsest example for the southern soda granite body contains feldspar up to 2 mm in length, but the granite in this part of the intrusion is typically finer.

There is visible variation in the nature of the mafic constituents, which may be pale green pyroxene, sometimes as coarse single crystals up to 3 mm long, or in radiating fibrous sheaves. In other rocks the only mafic constituent may be needles of deep blue amphibole up to 5 mm long, but in many examples both mafic minerals may be present. No systematic element in the distribution of these mafic constituents was noted, and their relative abundance could be seen to change over short distances.

As Pulvertaft (1961) describes, the fine-grained granites are often demonstrably later than the coarse granites at many localities. Equally, however, a gradational relationship may elsewhere be demonstrated.

Granite veins occur in the syenites at various localities; these are pink in colour, sometimes coarse-grained (feldspars up to 3 mm long) although the veins themselves may be only 15 cm in width. These veins may be found at localities throughout the southern augite syenite area.

The Puklen granites are quite different in appearance to the soda granites found within the Nunarssuit syenite, which contain predominantly white feldspar with conspicuous black amphibole needles and prisms. These latter rocks are frequently pegmatitic attaining extremes of crystal size. The late soda granites are most similar in appearance to the soda granite of Malenefjeld which similarly has a marginal syenite facies, although of relatively limited extent (HARRY & PULVERTAFT, 1963).

Contacts between the granites and syenites may be completely gradational, as they are along the eastern and south-eastern margins of the northern granite (locality D, fig. 2), and at the western margin of the southern granite, or they may be gradational over a short distance (locality I, fig. 2). Here and elsewhere along the north-west margin of the northern granite, the granite gives way to syenite over a distance of about 10 m, with a slight change in feldspar colour the only indication of a change in the rock type other than a change in quartz content. The contact is strongly brought out by weathering, however, particularly by the curving western shore of the large lake to the west of Puklen itself.

Conclusions from field relations

The extreme types of the variants within the quartz syenites and augite syenites are distinguishable and may have sharp contacts with other variants. At other localities variants may grade into one another. A similar variable relationship exists between syenites and granites and between coarse and fine soda granites. There is clear evidence that different phases of intrusion were involved in the evolution of the mass. These magmas were in a position to mix with earlier rocks at the level we now see them, giving rise to gradational contacts, or they could, at other localities, exhibit sharp relations with them. It is not clear from the field relations whether we should regard these gradational contacts as places where physical mixing of early crystalline material with later magma is occurring, where partly liquid magmas are mixing, or where essentially metasomatic interchange is occurring between adjacent rocks. This aspect of the petrology will be discussed later.

Taking into account only the contacts which show reasonably clear age relations, the intrusive sequence arrived at by PULVERTAFT (1961) can be derived. Using the present writer's nomenclature this becomes as follows.

The quartz-free augite syenites (type a) are cut by veins of transitional group rocks, and by granite. Elsewhere type (a) syenites grade into type (b) syenites, sometimes quartz-bearing, and this variety can be seen grading into the transitional group. There is an ambiguous relationship at one locality (locality C, fig. 2) where brown syenite (type b) veins a grey-green transitional group syenite which elsewhere cuts across the brown syenite. Evidence exists, therefore, of contemporary mobility of at least two syenite types. The early type (a) is affected by recrystallization (the use of this term will be justified below, and see PULVERTAFT, 1961) which gives rise to porphyritic varieties. These are not obviously related to the contacts of later phases. The soda granites are certainly younger than the quartz syenites and many microgranite bodies are demonstrably younger still. Again, however, gradational relationships can be demonstrated and there is no certainty that the fine and coarse granites represent two distinct phases of intrusion.

The layered structures, which may be ascribed to gravitational sorting of crystals in the magma, are sporadic at best and often pinch out or exhibit folding. Disturbance of a mush of settled crystals is implied, but the best example of banded quartz syenite found preserves, "sedimentary" structures and quite delicate banding showing grading. Whilst it is not impossible to envisage these layered portions being carried wholesale as solid masses from depth, they do not show any sharp breaks in nature from the surrounding rocks, and it seems reasonable to presume that the layering formed essentially *in situ* and that the disruption of the layered structures was caused by later magmatic movements acting on unconsolidated parts of the layered rocks.

Pulvertaft (1961) discusses in some detail the contact relationships between the Puklen rocks and the surrounding Julianehåb granite. He presents clear evidence (p. 42) that the Julianehåb granite has been mobilized by the syenite. This observation must be considered in any discussion of the genesis of the acid rocks in the Puklen sequence.

PETROGRAPHY

General outline of chemical and modal variation

Twelve rocks were analyzed for major elements by X-ray fluorescence analysis. Duplicate lithium metaborate fusion beads were crushed and compressed as pellets for analysis. Various wet-analyzed rocks were used as standards. The departures from 100 % totals shown by some of these analyses are probably due to lack of really suitable standards over this compositional range. FeO was determined by the ammonium metavanadate method of Wilson (1955) and CO_2 and H_2O by the method of Riley (1958).

The analyses are listed in Table 1. The brief descriptive notes are expanded, where appropriate, in the petrographic descriptions which fol-

Table 1. *Chemical analyses of Puklen syenites and granites, with one analysis of Julianehåb granite.*

Localities are shown on fig. 2.

Specimen Nos:	951	948	926	947	930	955	941	908	956	912	924	902
SiO_2	72.51	72.11	71.78	71.43	65.13	63.58	62.59	59.41	59.31	59.31	58.33	61.00
TiO_2	0.28	0.24	0.30	0.27	0.57	0.60	0.62	0.88	0.96	0.94	0.97	0.74
Al_2O_3	11.88	12.93	13.41	12.97	13.36	13.34	13.78	13.40	14.94	14.59	14.96	17.20
Fe_2O_3	1.84	0.96	1.64	2.31	2.55	2.02	3.73	2.16	2.90	0.83	2.49	0.84
FeO	2.09	1.54	1.41	1.61	4.36	5.25	4.22	6.57	4.04	7.49	5.55	3.81
MnO	0.07	0.04	0.07	0.08	0.16	0.15	0.14	0.19	0.17	0.18	0.17	0.10
MgO	0.12	0.15	0.19	0.09	0.08	0.09	0.15	0.17	0.53	0.58	0.61	1.56
CaO	0.34	0.60	0.38	0.28	1.02	1.54	1.44	2.18	2.92	2.50	2.73	3.48
Na_2O	4.66	3.87	4.49	4.35	5.62	5.61	5.07	5.73	5.58	5.90	5.68	5.58
K_2O	4.76	4.88	5.27	5.14	5.27	4.98	5.46	4.98	5.75	4.81	5.24	4.04
P_2O_5	0.06	0.07	0.07	0.05	0.09	0.11	0.10	0.14	0.27	0.26	0.27	0.25
CO_2	0.15	0.12	0.12	0.14	0.16	0.08	0.27	0.26	0.08	0.14	0.11	0.04
H_2O^+	0.25	0.56	0.35	0.31	0.42	0.47	0.51	0.82	0.60	0.71	0.86	0.62
H_2O^-	0.05	0.12	0.17	0.05	0.11	0.15	0.17	0.22	0.07	0.08	0.13	0.09
Total	99.06	98.19	99.65	98.18	98.90	97.97	98.24	97.11	98.12	98.32	98.25	99.35

951 Northern granite
948 Northern microgranite
926 Southern granophyre
947 Northern granite
930 Heterogeneous quartz syenite (type b)
955 Heterogeneous quartz syenite (type b)
941 Transition group quartz syenite
908 Quartz-poor syenite (type b)
956 Quartz-poor syenite (type b)
912 Porphyritic syenite (type c)
924 Quartz-free syenite (type a)
902 Julianehåb granite

low. Perusal of the analyses and the localities from which they come (shown on fig. 2) shows the justification for the simple two-fold subdivision of rock types used on the present map, and also points to the great variability of the rocks classed within the syenite areas.

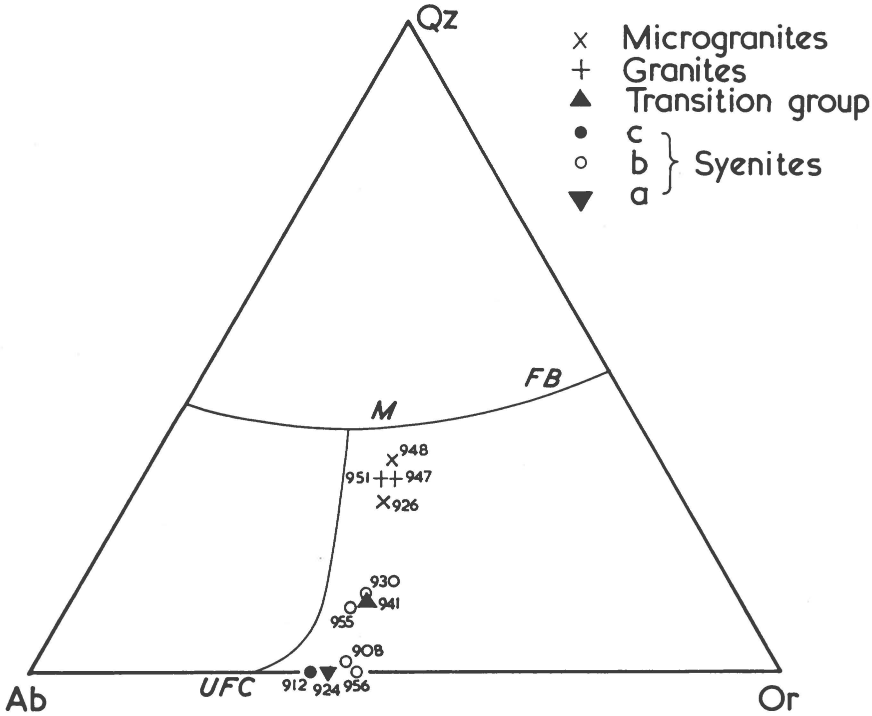

Fig. 4. Normative *ab-or-Q* for the eleven analyzed Puklen rocks plotted on a diagram showing the field boundary and unique fractionation curve in Ab-Or-Qz at 1000 kg/cm^2 (Tuttle & Bowen, 1958). M is the thermal minimum. Specimen numbers are shown.

Tables 2 and 3 show modal mineralogy of the analyzed rocks and some additional rocks. These modal estimates were made by point-counting at least 2000 points on a single randomly orientated thin section of each rock, and must be considered very approximate, particularly in the case of the coarse-grained syenites. In addition, many rocks of this suite are notably inhomogeneous, and the thin sections inevitably tend to avoid the pegmatitic patches in which some concentration of quartz may occur. Despite this, there is good agreement between modes and the CIPW norms of the analyzed rocks given in Table 4.

The analyses are most instructively plotted in terms of normative *ab-or-Q* (fig. 4).[1] The threefold grouping of analyses on this diagram is

[1] Throughout this paper conventional symbols such as *ab-or-an-Q* refer to normative minerals. Ab-Or-An-Qz, for example, refer to the ideal end-member molecules such as $NaAlSi_3O_8$, etc.

Table 2. *Modal analyses of chemically analyzed Puklen rocks.*
Volume %, by point counting single thin sections.

Specimen Nos:	951	948	926	947	930	955	941	908	956	912	924
Quartz	32.4	27.0	23.8	26.1	10.7	7.9	8.8	1.5	0.3	–	–
Alkali feldspar	55.8	71.7	75.3	68.4	75.8	71.9	84.3	77.8	85.2	81.3	84.5
Augite: aegirine-augite	–	–	–	–	8.6	10.9	3.0	8.8	9.3	6.7	6.3
Acmite	4.3	–	–	2.2	–	–	–	–	–	–	–
Amphibole	7.0	0.7	0.6	3.0	2.7	5.5	0.3	9.0	0.8	8.2	4.1
Ores	0.5	0.7	0.7	0.3	1.0	2.7	3.5	2.9	3.9 c	3.9	5.1c
Fayalite	–	–	–	–	–	0.9	–	tr.c	c	c	c
Others	tr.d,h	tr.a	–	tr.d,h	0.2f	–	0.1 h	–	0.5 b	tr.b	tr.b
Interstitial albite	tr.	–	–	tr.	1.0	0.2	–	–	–	–	tr.
Granophyric intergrowth, total	tr.	–	52.2	–	9.2	–	tr.	–	–	–	–
Quartz in intergrowth	tr.	–	38.8	–	50.2	–	tr.	–	–	–	–
Feldspar in intergrowth	tr.	–	61.2	–	49.8	–	tr.	–	–	–	–

a = biotite
b = apatite
c = includes fayalite pseudomorphs
d = astrophyllite
e = sphene
f = unidentified red alteration products
g = aenigmatite
h = zircon
tr. = present but not counted
– = not found

Table 3. *Modal analyses of various Puklen rocks with quartz contents transitional between syenites and granites.*

Specimen Nos:	937	939	941	943	945	919	929	927
Quartz	19.4	21.9	8.8	14.6	31.1	11.5	29.3	11.8
Alkali feldspar	64.0	69.4	84.3	74.0	64.5	77.6	63.2	72.5
Pyroxene (aegirine-augite)	7.8	1.7	3.0	0.6	0.6	0.3	–	3.8
Amphibole	8.3	5.6	0.3	10.1	2.5	8.5	7.5	8.7
Ores	0.3	0.5	3.5	0.3	0.7	tr.	tr.	2.8
Others	0.2e	0.8a,f	0.1 h	0.4e	0.7a	1.7a,f	tr.f	0.1e
Interstitial albite	–	tr.	–	tr.	tr.	0.3	–	0.2
Granophyric intergrowth, total	5.8	6.0	tr.	tr.	–	–	–	–
Quartz in intergrowth	60	51	tr.	tr.	–	–	–	–
Feldspar in intergrowth	40	49	tr.	tr.	–	–	–	–

Localities are shown on fig. 2. Symbols are as used in Table 2.

937 Horizon with mafic bands in transition group.
939 Unlayered rock in vicinity of 937
941, 943, 945 Traverse from south to north across gradational southern boundary of northern granite
919 Pink vein of granitic aspect in syenite
929 Grey vein in 927
927 Transition group syenite from near margin of southern microgranite

Table 4. *CIPW norms of analyzed Puklen rocks, together with calculated feldspar compositions (ab + or + an = 100 %) and pyroxene as (ac/ac + di + hy + wo) × 100.*

	951	948	926	947	930	955	941	908	956	912	924	902
Q......	26.3	29.2	24.6	26.3	9.6	7.8	8.8	1.3	–	–	–	2.6
C......	–	0.5	–	–	–	–	–	–	–	–	–	–
or	28.4	28.9	31.1	30.6	31.1	29.5	32.3	29.5	33.9	28.4	31.1	23.9
ab.....	34.1	32.5	37.7	33.0	39.3	40.9	40.4	40.9	44.0	48.2	47.2	47.2
an	–	2.2	0.9	–	–	–	–	–	–	–	–	10.0
ne	–	–	–	–	–	–	–	–	0.3	–	0.6	–
ac	4.6	–	–	3.2	7.4	5.5	2.3	6.5	2.3	1.4	0.5	–
di	0.7	–	0.2	0.5	4.0	6.9	6.4	9.6	11.0	10.2	8.7	6.0
wo.....	–	–	–	–	–	–	–	–	0.7	–	–	–
hy.....	3.7	1.9	1.2	1.5	5.9	5.7	1.4	6.3	–	–	–	6.0
ol	–	–	–	–	–	–	–	–	–	6.6	2.7	–
mt.....	0.5	1.4	2.3	1.6	–	0.2	4.2	–	3.0	0.5	3.5	1.2
il......	0.6	0.6	0.6	0.5	1.1	1.2	1.2	1.7	1.8	1.8	1.8	1.4
ap	–	–	–	–	–	–	–	–	–	–	0.7	–
cc	0.3	0.3	0.3	0.3	0.4	–	–	–	–	0.3	0.3	–
					Total feldspar to %							
or	45.4	45.4	44.6	47.9	44.2	41.9	44.4	41.9	43.5	37.1	39.7	29.4
ab.....	54.5	51.1	54.1	51.9	55.8	58.1	55.6	58.1	56.5	62.9	60.3	58.2
an	0	3.5	1.3	0	0	0	0	0	0	0	0	12.3
					Pyroxene as (ac/ac + di + hy + wo) × 100:							
ac %...	51	no ac	no ac	62	43	31	23	29	16	12	5	no ac

fortuitous, and rocks may be found which show every gradation in quartz content from quartz-free syenite to 30 % or more quartz in the alkali granites. This spectrum of quartz contents is shown in Table 5, in which modal quartz is recalculated as (Qz/Qz + Fsp) × 100. The table also shows that within the subdivisions of rock types erected on the basis of field work, considerable overlap occurs; many rocks in the transitional group (shown as syenite on fig. 2) have high quartz contents and would clearly be classed as granites. Conversely some members of the granite group have low quartz contents, although other criteria, discussed below, support their grouping with the granites. For this reason the field grouping seems more appropriate than a classification based on the variable quartz contents, but in reading the descriptions which follow it must be born in mind that the terms 'syenite' and 'granite' are not always being applied in a strict sense.

Fig. 4 shows that the general trend of the analyses, when plotted in terms of *ab-or-Q* is clearly parallel to the unique fractionation curve (or 'thermal valley') in the system Ab-Or Qz as determined at P_{H_2O} =

1000 Kg/cm² by TUTTLE & BOWEN (1958), although slightly offset towards the Or apex. Possible reasons for this offset, and the justification for discussing the analyses in terms of the simplified Ab-Or-Qz system, will be given later. Fig. 4 shows, however, that a scheme of continuous fractionation is a possibility for the Puklen rocks. Detailed consideration of the chemical data and of the mineralogical changes which might be expected to parallel such a process of fractionation, together with other possible reasons for the gradation exhibited, will be considered after the petrographic descriptions which follow.

Petrography of the syenites

(a) Quartz-poor syenites

The coarse brown syenites (which are similar in appearance to the main Nunarssuit syenite) fall into this category, but in thin section these prove to be texturally and mineralogically identical with quartz-free

Fig. 5. Interstitial and marginal albite in augite syenite. Boundaries between perthite crystals (stipple) are usually irregular, but euhedral surfaces sometimes develop against albitic patches. The albite may be structurally continuous with perthitic crystals (note albite-pericline twinned patches in lower crystal) or, more rarely, discrete grains may be found (right centre). Crossed nicols, diameter of field 2 mm. Specimen 924.

patches within the heterogeneous (type b) syenites. In tables 1, 2 and 4 rocks 924 and 956 are representative of the quartz-free and quartz-poor types. Only seven out of thirty-five thin sections of syenite were devoid of quartz, and in one of these quartz is visible in pegmatitic patches in the hand specimen.

Microperthitic alkali feldspar forms the bulk of the rock. Rarely, it may be accompanied by some albite in interstitial grains (fig. 5), which are distinct from the clear albite rims which occur occasionally on the well-formed patch-perthite crystals which make up the great bulk of the

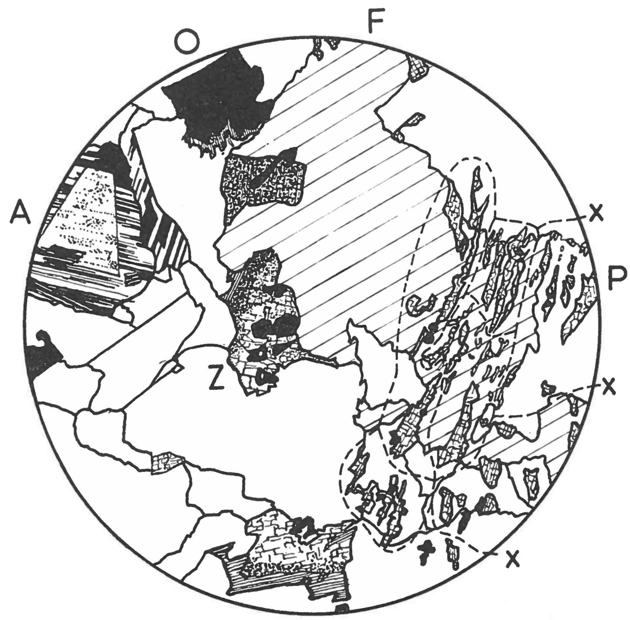

Fig. 6. Textures in coarse quartz-poor syenite. (Very low power, diameter of field = 12 mm). Z = colourless augite, intergrown with ore. The top left of this grain grades into green pyroxene, and is margined by deep green amphibole. Note that the coloured portion of the pyroxene is not a continuous rim. O = ore grain, with blue amphibole fringe. P = colourless augite intergrown with alkali feldspar (cross-hatching and no ornamentation). The broken lines (X) outline areas of pyroxene in optical continuity. These optically continuous areas cross boundaries between feldspars. The cross-hatched feldspar (F) is one grain. Boundaries of the unornamented feldspars are also shown. A = euhedral alkali feldspar surrounded by clear albite rims (twinning represented as for crossed nicols; remainder ordinary light). Specimen 916.

rock. The late albite is rare in the quartz-free syenites, but much more common in the quartz-bearing varieties (see (b), below).

The pyroxenes in the quartz-free syenites are almost wholly colourless or faintly purplish augites, with large extinction angles, $\alpha \wedge Z = 40°$. Sometimes faintly green rims are developed grading into the colourless pyroxene which at their most extensive development show smaller extinction angles, with $\alpha \wedge Z$ as low as 10°. These green rims (fig. 6) are irregular in development, sometimes appearing only in certain parts of a single thin section, and often extending only around parts of the margins of crystals, or along cleavages into the interior of the crystal. This irregular type of colour variation possibly suggests that the green aegirine-augite rims are due to late addition of sodium from percolating late-stage solutions, rather than colour zoning produced during magmatic crystallization. Usually the pyroxenes are rounded, rarely subhedral. Feldspar

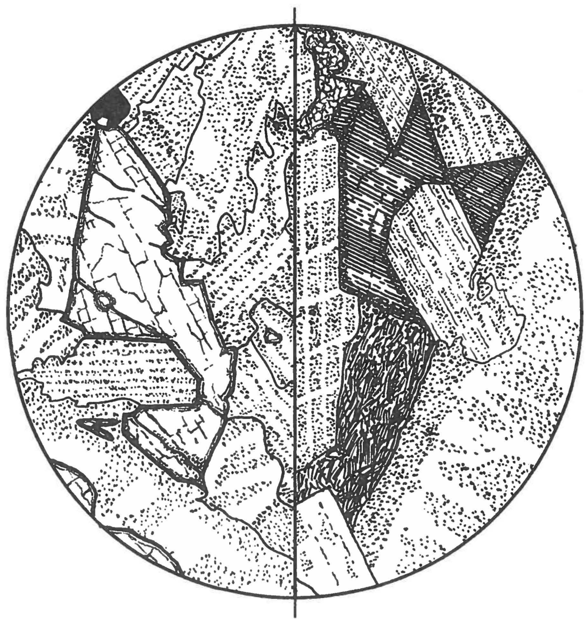

Fig. 7. Relations between feldspar and mafic constituents in augite syenites. Left: colourless augite moulded on euhedral feldspar, (stipple). This is a less common relationship than that shown in fig. 8. Specimen 918.
Right: green-brown amphibole, centre top, moulded on euhedral feldspar. Fibrous alteration products fill the interstice below the amphibole; against this material the feldspar has outgrown, around the amphibole, and shows a clear albite (?) rim in places. Specimen 913. Both ordinary light. Diameter of field 4.5 mm.

normally encloses pyroxene, but there are instances where pyroxene fills interstices between euhedral feldspar grains (fig. 7, left). There are also instances of intergrowths of alkali feldspar and pyroxene (fig. 6) in which rods or droplets of pyroxene, of roughly circular cross-section, occur in groups with parallel optical properties, enclosed in the much-larger feldspar crystals. This type of texture is suggestive of simultaneous crystallization (or recrystallization), and also occurs in the porphyritic (type c) syenites.

Amphibole is invariably present; its scheme of pleochroism is variable even within a single thin section. Varieties with straw yellow to deep blue pleochroism may give way in the same section to amphiboles with olive green to brown pleochroism. The blue variety often margins the green amphibole or frequently surrounds ore grains (fig. 6). Both types of amphibole may be present in large crystals filling interstices between well-formed feldspar grains and this post-feldspar development of amphibole is its characteristic mode development (fig. 7, right). In the example shown however, there is textural evidence for the further growth of feldspar around the boundary of the amphibole into an interstice occupied by a fine-grained, fibrous, colourless mineral (amphibole?), and fibrous orange alteration products. The proportion of amphible to pyroxene in the sections is variable, and some contain amphibole exclusively.

Fresh fayalite is extremely rare; only a few grains were discovered in the thirty syenites and quartz syenites sectioned. Pseudomorphs of orange iddingsite and ore are present in the majority of the quartz-free syenites. In the modal analyses (Table 2) this ore has been grouped with primary opaque minerals because it is difficult to distinguish with certainty original ore and ores replacing olivine. Obvious pseudomorphs after fayalite may be abundant in some quartz-poor rocks, reaching 4 % in one instance, but normally only a few pseudomorphs occur in any one thin section.

Opaque material is abundant in many sections, sometimes as well-formed grains enclosed by feldspar or pyroxene, but also as irregular masses between feldspar grains, and sometimes extending into cracks in the feldspar crystals. Examples of this relation occur which are quite certainly not fayalite pseudomorphs, but demonstrate the late crystallization of ore minerals. Apatite is a universal and often abundant accessory.

(b) Heterogeneous quartz syenites

The analyzed rocks 908, 955, 930 (Table 1) fall into this category, as do the majority of rocks from the areas mapped as syenite (fig. 2). The heterogeneous quartz syenites grade from the quartz-poor syenites (type a) and are a variable group both in quartz content, mafic mineralogy, and textures.

Quartz normally appears in the interstices between well-formed microperthitic alkali feldspar crystals. When found in juxtaposition with fayalite, aegirine-augite, amphibole or ore a fringe of radiating pale blue amphibole needles develops (see figs. 9 and 16 for examples of this texture). In some of the more quartz-rich varieties (up to 11 % quartz, by volume, may be present) patches are developed in which a rather open structure of euhedral feldspar crystals is developed with quartz in the interstices. Fig. 8 shows this texture; much of the remainder of the thin section is made up of coarse feldspars with a little interstitial quartz like those shown at bottom and top right of the sketch. The remainder of the field of view is made up of smaller euhedral feldspars, set in a quartz matrix large parts of which are in optical continuity. Other quartz syenites show a quite different relationship between quartz and feldspar, in which curved interfaces are developed between quartz and feldspar. The latter type is shown in fig. 9; quartz and feldspar are here intergrown to form a coarse micrographic texture, with intricate intergrowths having

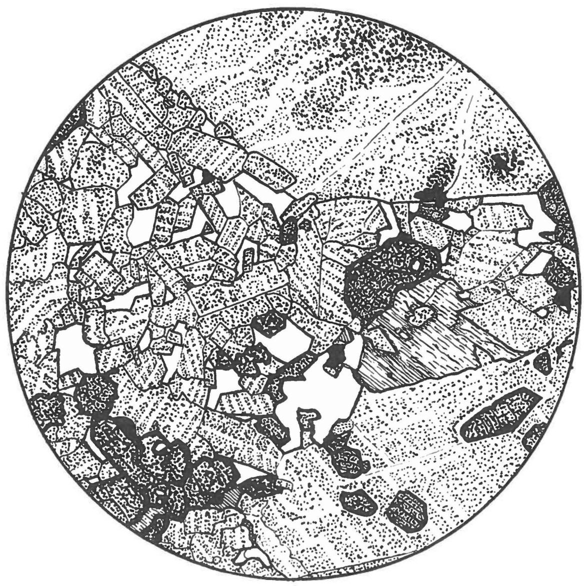

Fig. 8. Texture of a heterogeneous quartz syenite (type b). Microperthitic alkali feldspar stippled; quartz clear; pyroxenes, showing cleavage, have pale green cores and dark green rims; hornblende, partly moulded on feldspar, showing one cleavage. Specimen 923. Ordinary light. Diameter of field 4.5 mm.

curved, feathery interfaces. Whereas, in the 'euhedral feldspar' type (fig. 8) areas of quartz, but not feldspar, are in optical continuity, in the 'micrographic' type (fig. 9) large, optically continuous areas of quartz are intergrown with feldspar which is also optically continuous. It is particularly interesting that quartz syenites showing the 'micrographic' intergrowth have been found only in syenites near the margins of the two alkali granite bodies, together with one example from close to the contact with the Julianehåb granite. Elsewhere, away from the contacts, feldspars do not show intricate boundaries against quartz, and normally show euhedral outlines.

Fig. 8 also shows the textural variability of the heterogeneous quartz syenites. The rock shows great variability in grain size, comparitively fine-grained patches alternating with much coarser areas. Two large alkali feldspar crystals are shown in the drawing; these are not phenocrysts, but are the edges of irregular areas in which all the feldspars are comparitively coarse, and the rock is similar in thin section to the quartz-poor type (a) syenites. This variability of grain size extends to include rocks of extreme coarse-grained pegmatite type, the pegmatite patches having drusy cavities at their centres, lined by inward growing quartz, alkali feldspar, and alkali amphibole. This variability of grain size, and

Fig. 9. Quartz-feldspar intergrowth, of 'micrographic' type, between subhedral feldspars in heterogeneous quartz syenite. Feldspar, fine stippled; quartz, clear; aegirine-augite, heavy stipple; fringes of blue amphibole needles occur at some, but not all, contacts between quartz and pyroxene. Specimen 930. Ordinary light. Diameter of field 4.5 mm.

the presence of drusy cavities, is the most striking and distinctive feature of the heterogeneous quartz syenite suite; it contrasts strongly with the coarse, but even textured, brown quartz-poor syenites, and with the finer grained and even textured rocks which make up the more quartzose members of the Puklen sequence. The texture is distinct from the porphyritic syenites (type (c), below), which show evidence of recrystallization (Pulvertaft, 1961).

A striking difference between the quartzose syenites and the quartz-free syenites is the appearance of brilliant green pyroxenes in many rocks. Some quartz syenites do contain dominantly colourless augite with only faintly green rims, but in the majority of rocks the pyroxenes are distinctly green in colour and strongly zoned. Brilliant green aegirine-augite is the only pyroxene in some rocks, with small maximum extinction angles, $\alpha \wedge Z$, of 10°. There is much variability, however, and pyroxenes at one end of a single thin section may be green whilst those elsewhere in the section may be almost colourless.

The most strongly coloured pyroxenes come from rocks with conspicuous pegmatitic patches. As shown in fig. 8 the pyroxenes are usually subhedral and enclosed by feldspar. Sometimes euhedral prismatic pyroxenes occur; the best development of these is in the rock 930 (fig. 9) which comes from near to the margins of the southern granite mass. These pyroxenes are very intense green, with small extinction angles (about 5°) in outer zones, and much replacement by blue alkali amphibole. Another rock with very sodic pyroxene (944) comes from the southern margin of the northern granite body. The irregular development of sodic pyroxenes with variation within the range of a thin section, the irregularity of colour zoning in individual cystals, the association of most sodic pyroxenes with drusy pegmatitic patches, and proximity to the soda granite bodies, all point to the activity of a sodic residual vapour phase within this suite of rocks, alkali pyroxene being produced at least in part by metasomatic interchange with initially augitic pyroxenes.

The amphibole in the quartzose syenites is usually moulded on the euhedral feldspars (fig. 8). It is normally olive green in colour, strongly pleochroic to yellow-brown. Blue, sodic amphibole occurs as fringes of needles particularly where green amphibole or fayalite abuts against quartz (fig. 9), or as rims to green amphibole into which the blue amphibole grades. Very occasionally entire grains of blue amphibole are present. Such grains often abut on fayalite crystals. Pleochroism may be pale yellow to deep purple, but the colour variation, both within thin section or even within individual grains, is extreme. Some amphiboles show rudimentary zoning, with yellow-green cores and blue-green margins, but often the colour variation is patchily developed. There does not seem to be a simple relationship between the development of sodic amphiboles and the identity of the pyroxene. Rocks in which the bulk of the amphibole is riebeckite-arfvedsonite may contain almost colourless augitic pyroxene; however rocks with sodic pyroxenes normally contain a sodic amphibole. The relative proportion of amphibole to pyroxene is also variable; some indication of this can be obtained from Table 2.

Fayalite is sporadically developed and almost always pseudomorphed. The modes tabulated (Table 2) are not wholly representative of the fayalite content of these rocks. Often the pseudomorphs after fayalite are easily recognized, and they may make up to 4 $^0/_0$ of a thin section. Ores, often present in little clusters of euhedral grains, are usually present, often associated with clumps of amphibole. As much as 4 $^0/_0$ of opaque material occurs in certain rocks.

(c) Porphyritic syenites.

This group of syenites, usually quartz free but sometimes with a trace of quartz, have a peculiar porphyritic texture ascribed by PULVERTAFT (1961) to recrystallization, a view shared by the writer. Mineralogically they are similar to the quartz-poor, type (a) syenites, into which they often grade via an intermediate variety to which the field name 'granulated' could be applied. This gradation can take place over short distances, and textures may change within one thin section.

The distinctive texture is shown in fig. 10. Large clear 'phenocrysts' of feldspar are set in a matrix of cloudy alkali feldspar, occasional quartz and many small, ragged grains of amphibole and pyroxene, often of drop-like form. The clear feldspar phenocrysts show neither fine-scale twinning nor perthitic intergrowth (except around the margins) but X-ray diffraction (see feldspar section) shows them to be cryptoperthites, of roughly the same bulk composition ($Ab_{60}Or_{40}$) as the microperthitic feldspars of the normal syenites. The matrix feldspars, smaller in size and with very intricate, ill-defined boundaries, are microperthitic. The clear 'phenocrysts' have narrow cloudy microperthitic rims, often, but not always, containing a regular line of drop-like colourless augite crystals, or sometimes amphibole needles, along the boundary between clear and cloudy feldspar (crystal F, fig. 10). The clear feldspars often occur in groups (part of such a group is shown in fig. 10) with the normal type of boundary seen in the non-porphyritic syenites between them. Within the groups pyroxene droplets are sometimes present along the crystal boundaries (a minor development of this relationship is seen in fig. 10, slightly to the top of right centre). Normally, it is the boundaries of 'phenocryst' against matrix which show the pyroxene fringes, and these regular lines of pyroxenes can extend some distance into the matrix from the phenocryst which elsewhere they margin, (along the line X, fig. 10). The droplike pyroxenes are scattered throughout the matrix of the rock, and sometimes groups of them show parallel optical properties. Fig. 10 shows a group (left of centre) which exhibits a rudimentary radiating structure. Feldspar-pyroxene intergrowths of similar type are sometimes encountered in otherwise normal quartz-poor syenites (fig. 6), without porphyritic texture, but are not then extensively developed. The matrix in the porphyritic syenites also contains green skeletal hornblende; often quite large areas show amphibole in optical parallelism. A trace of quartz is sometimes present, often with a partial rim of pyroxene 'droplets' (Q, fig. 10). Better formed amphibole and pyroxene grains, the former sometimes moulded on well-shaped alkali feldspar crystals, are sometimes present (A and P, fig. 10), and the rock may revert towards normal syenite textures even within the length of a thin section.

Texturally these porphyritic rocks are distinctive within the Puklen suite. Other rocks, in the heterogeneous quartz syenites, show variation in feldspar size (fig. 8), but these more quartzose rocks have euhedral feldspars in the fine-grained material and the drop-like pyroxenes are absent. Chemically (Table 1) the porphyritic varieties are not distinct from the quartz-poor, type (a) syenites. PULVERTAFT (1961) suggested

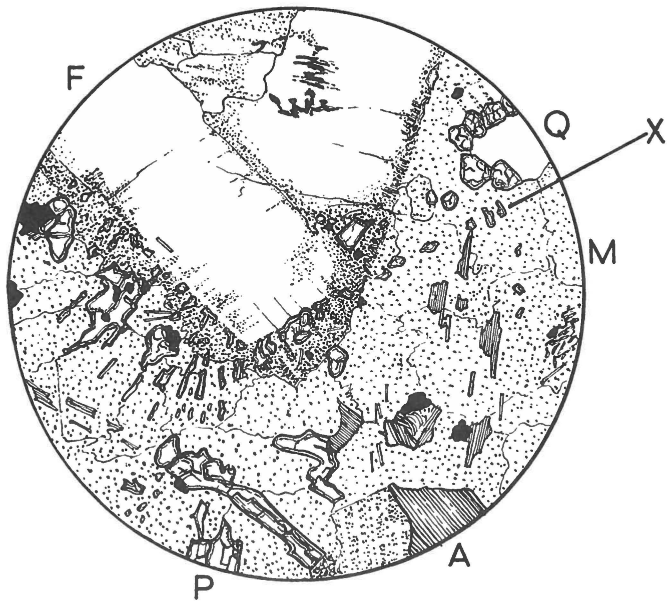

Fig. 10. Porphyritic syenite. Large clear cryptoperthitic alkali feldspars (F) are set in a matrix of interlocking microperthitic alkali feldspars (M), and occasional quartz (Q). Ragged hornblende (A) and colourless augite (P) occur as groups in optical parallelism. Pyroxenes are sometimes aligned parallel to feldspar "phenocryst" boundaries, both as droplets within the phenocryst and as continuations into the matrix (along the line X). Specimen 922, diameter of field 2.5 mm, ordinary light.

that their textures were the result of recrystallization so that the large feldspars are not true phenocrysts. This view will be upheld in discussions of petrogenesis which follow.

Petrography of the transition group

As Tables 4 and 5 show, there is overlap, in terms of normative mineralogy, between quartzose syenites (type b) and the transition group rocks. There is a striking textural difference between the two groups, however, the heterogeneous, often pegmatitic texture of the type (b) syenites contrasting with the finer, even grain size of the transition group

Table 5. *Relationship between rock type, modal quartz contents and nature of the K-feldspar in the Puklen rocks.*

Specimen No.	Classification on field criteria	Total modal Fsp + Qz (vol %)	Modal Qz % (Fsp + Qz = 100 %)	K-feldspar 131 Reflection type X	Specimen No.	Classification on field criteria	Total modal Fsp + Qz (vol %)	Modal Qz % (Fsp + Qz = 100 %)	K-feldspar 131 Reflection type X
951	G	88.2	36.7	4	919	GV	89.1	12.9	4
945	G	95.6	32.5	4	930	Sb	86.5	12.4	3a
929	GV	92.5	31.7	4	955	Sb	79.8	9.9	3b
935	GV	–	–	4	950	Sb	–	–	4*
947	G	94.5	27.6	4	941	T	93.1	9.5	3a
948	GP	98.7	27.4	4	908	Sb	79.3	1.9	3a
926	GP	99.1	24.0	4	956	Sb	85.5	0.4	3a
952	G	–	(30)	4	936	Sb	–	tr.	3a
953	G	–	(30)	4	922	Sc	–	tr.	3a
939	T	91.3	24.0	3a	920	Sa	–	tr.	2a
937	TL	83.4	23.0	–	918	Sb	–	tr.	3a
943	T	88.6	16.5	3b	912	Sc	81.3	0	3a
927	T	84.3	14.0	3a	924	Sa	84.5	0	2a
928	T	–	–	3a	917	Sa	–	0	3a
954	G	–	(15)	4					

X = Symbols of Parsons & Boyd (1971)
* = See text – = not estimated tr. = trace present
G = Granite GV = Granite vein in syenite
GP = Granophyre or microgranite T = Transition group
L = Layered rock Sa, Sb, Sc = syenite types

rocks. Within the transition group occur a number of rocks which, while mapping outside the granite areas (fig. 2), have high quartz contents which would strictly make the term granite appropriate for them (Table 5). As will be apparent from the following description, these rocks have mineralogical affinities with the syenite group in respects other than quartz content. Rock 941, Table 1, is the only analyzed representative of the transition group rocks. In terms of areal extent they are certainly a subordinate member of the complex, but detailed mapping would be needed to establish their actual extent. In the field the rocks fall into two groups, both in rather similar field settings. The more northerly group was found around localities C, H and D (fig. 2). In the south of the intrusion fine transition group syenites make up the south-western end of the promontory (at A, fig. 2) and occur as dykes in heterogeneous syenites to the north-west. Both settings are therefore in the vicinity of the granite bodies, although not restricted to the contacts. A development of fine quartz syenite also occurs at locality F (fig. 2), close to the contact with the Julianehåb granite. The northern outcrops exhibit layering in places, described in the following section.

As stated above the transition group rocks are generally finer grained than the heterogeneous quartz syenites, and, moreover are even grained and not patchily pegmatitic. Usually quartz is interstitial to well-formed

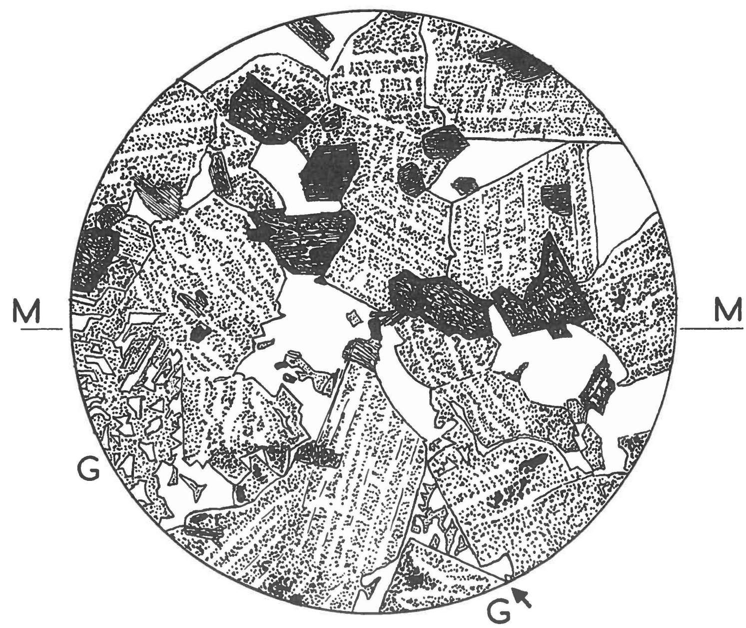

Fig. 11. Layered rock from the transition group. The line M–M indicates the approximate base of a band of concentration of aegirine-augite and hornblende. Alkali feldspar (stippled) is usually well formed, but shows evidence of intercumulus growth (top right). Interstitial material may be quartz (no ornamentation) or quartz-feldspar intergrowths of micrographic type (G). Specimen 937, diameter of field 4.5 mm, ordinary light.

feldspars (the 'euhedral feldspar' texture, shown in fig. 8) but some of the coarser examples show patches of micrographic intergrowth centred on euhedral feldspars in the way shown in figs 9 and 11. The feldspars are microperthites and are not systematically different from those of the heterogeneous quartz syenites, but marginal albite is only rarely developed, and not to the same extent as in the former group.

The main mafic constituents are light green pyroxenes, usually only slightly zoned, with large extinction angles, together with olive green hornblende. Although generally more quartzose than the heterogeneous quartz syenites, the transition group rocks lack the strongly zoned aegirine-augite and sodic hornblendes of the former group. The pyroxenes of the transition group rocks are often somewhat rounded, and although in some examples (such as the analysed rock, 941) they may be quite strongly coloured, maximum extinction angles $\alpha \wedge Z$ are nonetheless large (about 30°). The colour of the pyroxene varies considerably from one section to the next of the transition group, but the grains are not patchily coloured like the quartz syenite pyroxenes. The most intensely coloured examples come from transition group rocks margining the northern granite body.

Green hornblende occurs as ragged laths, usually enclosed by feldspar: the conspicuous interstitial amphiboles of the variable syenites are lacking.

The fine transition group rocks from close to the southern granophyre are texturally similar to the northern examples, but all show deep green pyroxenes and blue amphibole as well as green. A medium-grained example from near the contact with the Julianehåb granite (locality F, fig. 2) shows an intergrowth of rounded blebs of quartz in feldspar, a form of micrographic intergrowth which is different to the angular intergrowths of the granophyric type. Many dykes of transition group type exhibit the 'euhedral feldspar' texture, but one dyke of grey syenite (at locality E, fig. 2) shows ragged elongate alkali feldspars with a rough parallelism.

Petrography of the layered rocks

A rock showing two narrow, crudely graded, mafic layers (937) was collected in the vicinity of the layered outcrop shown in fig. 3. A sketch of a thin section through one of these layers is given as fig. 11. The rock is part of the largest area of transition group rocks (at locality H, fig. 2) and the thin section shows 19 $^0/_0$ (by volume) of quartz (a modal analysis of the large section appears in Table 4). The quartz is rather unevenly distributed throughout the section. The mafic bands are less conspicuous in thin section than in hand specimen (M–M, fig. 11), and consist of concentrations of pale green, weakly colour zoned, rather equidimensional subhedral pyroxenes and olive green to pale green amphibole in discrete plates or as broad rims on pyroxene cores. These mafic constituents are enclosed apparently at random in both alkali felspar and quartz. No preferred orientation is visible. Sphene is also abundant in the thin section, but is moulded on feldspar in several instances.

Quartz and feldspar show variable relationships throughout the section. In places (top of fig. 11) quartz alone is interstitial to well-shaped feldspars, but elsewhere there are pronounced curving interfaces between the two minerals. At other points in the section (G, fig. 11) the interstices between feldspars are filled by quartz and feldspar in the distinctive granophyric intergrowth.

Since the rock is banded it seems reasonable to interpret these textures in the terms of igneous cumulates and the textures are compatible with this origin. The cumulus augites and hornblendes must have achieved only localized and partial concentration before being entrapped in feldspar and quartz, which apparently crystallized simultaneously for the most part, although the sometimes euhedral feldspars were the first leucocratic phase to appear. The section as a whole shows 15 % modal mafics, about twice that of other transition group rocks from adjacent parts of the intrusion, and the more mafic bands reach perhaps 25 % by volume of mafics. Whether feldspar accumulation occurred is not clear, although it is certainly possible to interpret the subhedral outlines of many feldspars (top right and bottom, fig. 11) as being compatible with a cumulate origin modified by intercumulus growth. UPTON (1961) illustrates similar textures for the layered rocks of Kûngnât, undoubted cumulates, but in the following section a granite vein from Puklen is illustrated (fig. 16) which shows exceptionally good examples of such textures, usually associated with cumulates, in a setting in which accumulation cannot have occurred.

Undoubtedly the most interesting feature of the Puklen layered rocks is the presence in them of interstitial material showing granophyric intergrowths, a relationship discussed subsequently.

Petrography of the Granites

(a) Coarse soda granites

Rocks mapped as granite on the basis of their reddish hand specimen appearance occur in two distinct bodies within the outline of the Puklen intrusion, but no particular chemical or petrographic differences can be discerned between them, although the coarsest varieties, which make up the bulk of the larger northern body, are lacking in the south. The alkali feldspars in the coarse granites tend to be more coarsely perthitic than those in the syenites, and albite twinning is usually visible in the sodium-rich phase of the perthites. Rims of albite or discrete small grains of albite are much more common than in the syenites, and relationships like those shown in fig. 5 are frequently observed. Particularly against quartz patches this albite often has very broad twin lamellae. Despite this apparent abundance of albite it should be noted that the bulk feldspar compositions (calculated as norms) are actually more potassic than the syenite feldspars, (as the melting relations in Ab-Or-Qz predict), so that the perthitic alkali feldspars in the granites are more Or rich than those of the syenites.

Quartz and feldspar in the soda granites commonly show complex, curving and interdigitating outlines. Fig. 12 illustrates these complex grains, which are in marked contrast to the 'euhedral feldspar' texture of the quartz syenites, and certain quartz-poor granitic veins. These complex boundaries are reminiscent of the granophyric intergrowths of the fine-grained acid rocks, but on a much coarser scale. Superimposed on the outlines of many feldspars in the granites at feldspar-feldspar boundaries, are complex 'swapped rims' (VOLL, 1960), in which the per-

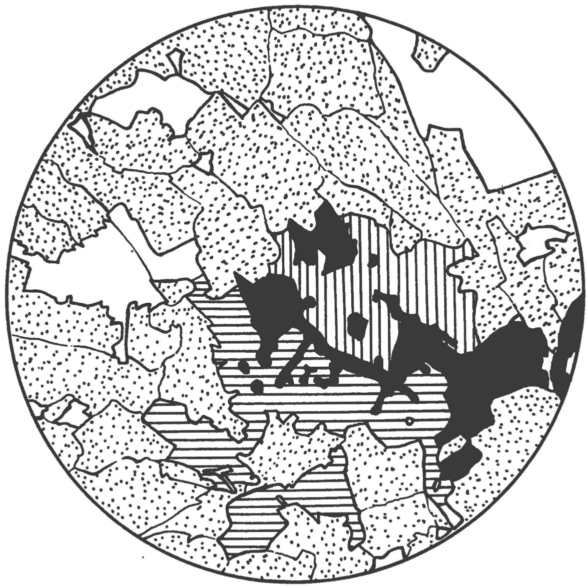

Fig. 12. Textural relationships between quartz and feldspar in a soda granite (945). No ornamentation = quartz; cross-hatching = optically continuous patches of quartz; stipple = feldspar; solid black = single continuous feldspar. Diameter of field 4.5 mm.

thitic lamellae of adjacent grains interdigitate with each other (Fig. 15 at S).

Some granites show clear evidence of the late mobility of quartz, and sections are traversed by minute quartz veinlets which brecciate the feldspars into displaced cleavage fragments. Quartz, together with haematite, elsewhere replaces amphibole (fig. 12). In such cases a few needles of blue riebeckite-arfvedsonite may be the only relics of amphibole otherwise wholly replaced by quartz and deep red haematite, the margins of the patches of the latter being controlled by the cleavages of the preexisting amphibole.

Undoubtedly the most striking and distinctive mineral of the granites is an acmitic pyroxene of small extinction angle $\alpha \wedge Z$ of 3°. This mineral is present in all but one of the granites sectioned, and varies from pale green, to pale yellow or almost colourless in thin section. The high birefringence, almost parallel extinction and extreme relief suggest that this pyroxene is close to acmite in composition. In hand specimen the pyroxene is visible in many rocks as tiny green spherules, and material drilled from spherules in rock 949 gave an X-ray powder diffraction pattern closely similar to an acmite from boiler scale (ASTM card 3-0621) and to the synthetic acmite figured by NOLAN & EDGAR (1963). The pale

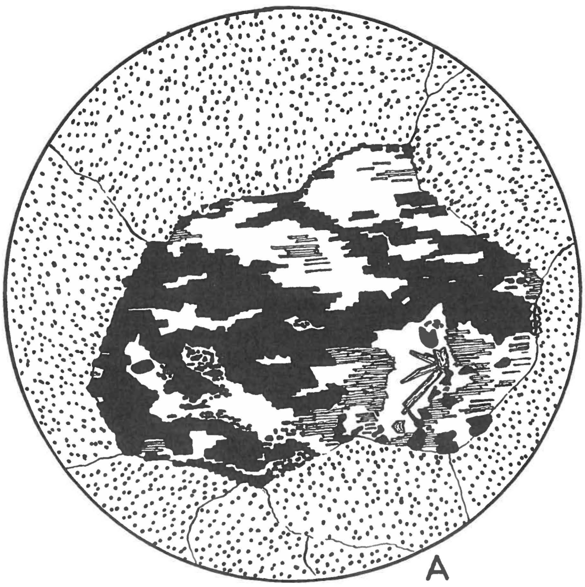

Fig. 13. Riebeckite-arfvedsonite (shown by the fine cleavage) in soda granite, largely replaced by quartz (clear) and haematite (solid black). The group of needles above (A) are of yellowish acmite. Feldspar stippled. Rock 954. Ordinary light. Diameter of field 2.5 mm.

green or even yellowish colour of this material is in marked contrast to the vivid green pyroxene of the most quartzose syenites or of the green pyroxenes of the most quartzose transition group rocks. BAILEY (1969) describes synthetic acmites as being a pale green colour, and TYLER & KING (1967) comment on the pale or yellowish colours of the most acmitic pyroxenes. The pyroxene in the Puklen soda granites has an elongate prismatic or acicular habit, and it seems reasonable to refer to it as acmite, which serves to accentuate the contrast with the aegirine-augites which characterize the rocks outside the granite suite, even though, from extinction angles, the latter approach acmite in composition.

The acmite in the granites is clearly a late-crystallizing mineral. Various textural relationships are exhibited in figs 13, 14 and 15. In some rocks it appears as rims on alkali amphibole, or may invade the inner parts of crystals along the cleavages (fig. 14, left). Large grains of acmite may occur which reflect the broad prismatic outlines of amphiboles elsewhere in the section, and which may replace the amphibole, together with quartz, in a way which outlines the cleavages of the now pseudomorphed amphibole (fig. 14, right). In the example figured fringes of astrophyllite, as bright orange sheaves, occur, and a few opaque grains (magnetite?) are present within the acmite. Figure 13 also shows a little

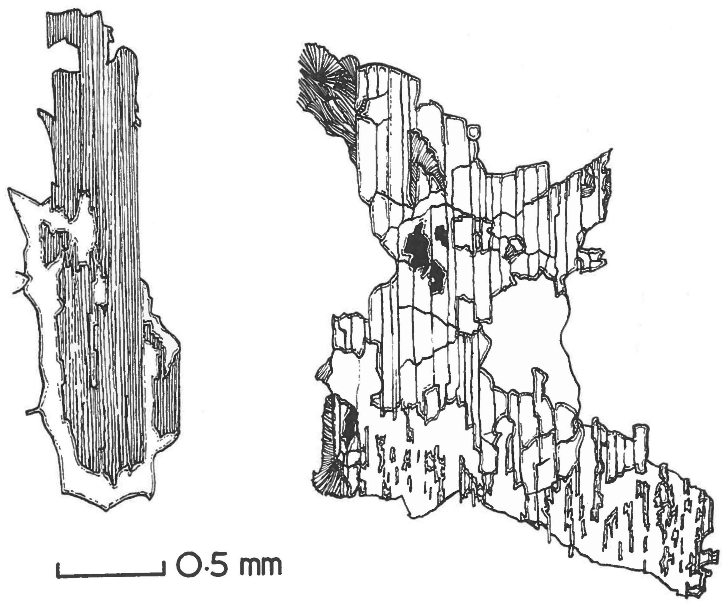

Fig. 14. Textural relationships of acmite in soda granites.
Left: purple riebeckite-arfvedsonite (showing cleavage) rimmed and invaded by acmite. (Rock 949).
Right: amphibole completely pseudomorphed by quartz (clear) and acmite (high relief, broad cleavage). A few patches of ore and sheaves of astrophyllite occur. (Rock 953).

acmite apparently replacing amphibole, but in this case it appears as a few radiating needles not reflecting the amphibole morphology. The third, and most prevalent mode of development of acmite is shown in fig. 15. It occurs as radiating groups of elongate prisms or needles, which give sheaf-life aggregates or may form complete spherules, which in some rocks are visible in hand specimen. The spherulitic structures normally centre within patches of quartz, or at feldspar-quartz boundaries, but, as fig. 15 shows (at F) needles may extend into alkali feldspar grains. The medium-coarse perthite lamellae are undisturbed and continuous with the perthite lamellae of the remainder of the feldspar crystal; this is not an association of acmite with late-crystallizing albite, but suggests that the formation of acmite did overlap at least the final stages of feld spar crystallization (as soda sanidines, see later feldspar section).

The amphibole of the granites is very strongly pleochroic, showing yellow, violet and deep indigo colours. The presence of large, discrete grains of this amphibole further distinguishes the granites from the syenites and transition group rocks. Although blue riebeckite-arfvedsonite does not occur in the most quartzose syenites, it is always subordinate to green varieties of amphibole. There is one example of granite, from

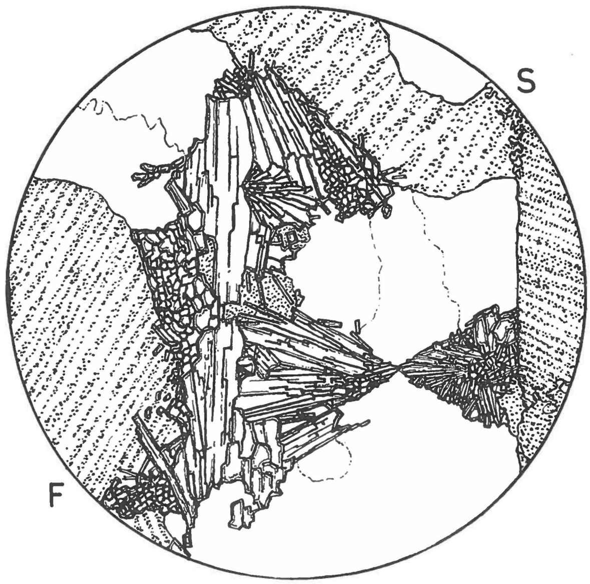

Fig. 15. Rosettes of acmite in soda granite (946). Acmite occurs as radiating aggregates or as larger blades (running up and down the drawing, slightly left on centre). Microperthites are stippled, quartz clear. F = acmite blades enclosed in microperthite; S = swapped rims between microperthites. Ordinary light. Diameter of field 2.5 mm.

near the southern boundary of the northern granite body, which carries an amphibole pleochroic from yellow to deep blue-green, and a granite vein (described in detail below) also carries this type of amphibole.

Biotite is the most abundant mafic constituent in one slice, being deep orange-brown in colour and occurring as ragged plates. Astrophyllite is common as an accessory (often fringing amphibole or acmite after amphibole) and is abundant in one rock from near the western margin. Aenigmatite has been found in one rock from the southern granite body: PULVERTAFT (1961) also reports aenigmatite from this part of the intrusion, so possibly this is a petrographic distinction between the two granite bodies.

Granite veins, pink in color, with obvious quartz, cut the syenites at various points well away from the main granite bodies. One example (919, from locality K, fig. 2) from a 15 cm wide vein cutting coarse type

(a) syenite is shown in fig. 16. On the basis of its pink colour in hand specimen, it was placed with the granite suite, a classification born out by details of its feldspar mineralogy (see later section) and the alkali amphibole which is its dominant mafic constituent. Modal quartz is only some 12 % however. Whatever its affinities, this rock shows interesting textural relationships. Fig. 16 shows a very loosely assembled mass of

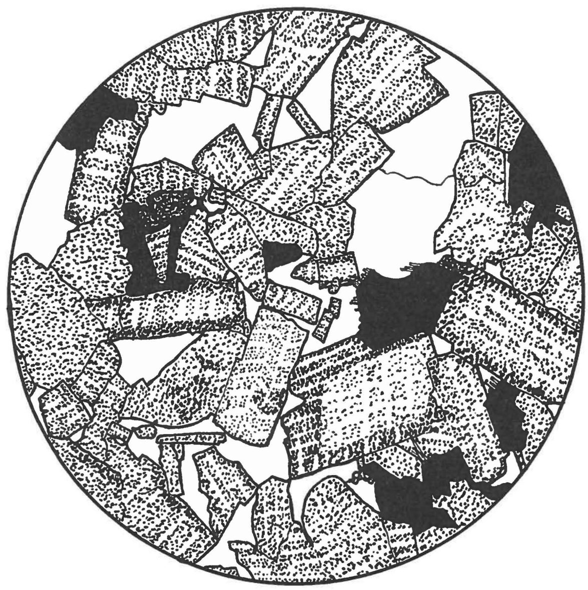

Fig. 16. Euhedral feldspar' texture in a granite dyke. Stipple = alkali feldspar; quartz = clear; black = deep blue-green alkali amphibole; heavy stipple = pyroxene. One amphibole grain (right of centre) has a fringe of light blue amphibole needles. Rock 919. Diameter of field 4.5 mm. Ordinary light.

euhedral microperthite crystals, permeated throughout its interstices by quartz or alkali amphibole. Although quartz is the dominant interstitial mineral in the part of the section drawn, elsewhere in the thin section it is amphibole which fills the interstices in precisely the same manner as the quartz. This textural relationship, of quartz and amphibole crystallizing from a late liquid entrapped in an open mesh of feldspar occurs in members of the syenite group (*e.g.* fig. 8). Remarkably similar textures are figured by Upton (1961), for the banded cumulate rocks of Kûngnât. The narrow, rather sinuous dyke from which the present rock comes could certainly not have been subject to crystal settling, so that the idea that such textures, when seen elsewhere in the Puklen suite necessarily indicate a cumulate origin, must be ruled out.

(b) Microgranites and granophyres

The analyzed rocks (948 and 926) in this group are notably leucocratic, with 98 % by volume of modal quartz and feldspar. Although always fine grained compared to the soda granites, the textural relationships of quartz and feldspar are variable, and two examples are shown in Plate 1. Fig. 1 shows extensive development of granophyric inter-

Fig. 17. Spherulitic structure in microgranite. Stipple = alkali feldspar. Solid black = radiating feldspar structure. The feldspars making up this structure are not optically continuous, but the quartz (unornamented) between them, is in optical continuity. Irregular cross-hatching = biotite. High power, diameter of field = 0.5 mm. Specimen 948. See also Plate 1, fig. 2.

growths filling the interstices between euhedral alkali feldspar nuclei and radiating out from them. The most regular intergrowths show the characteristic rods of quartz, of triangular cross section, but such regular regions do not achieve large size and the coarser grained intergrowths show more curving boundaries between quartz and feldspar. The similarity to the texture in the interstices of some syenites (fig. 9) is obvious.

The finer grained members of the microgranite suite do not all show granophyric textures. Plate 1, fig. 2, shows a network of rather well-formed feldspars, up to 0.5 mm in length with interstitial quartz. Scattered throughout the rock are roughly circular patches up to about 0.5 mm in diameter in which quartz and feldspar show a type of radiating, crudely granophyric intergrowth, so that the impression is of a rock studded with rough spherulitic structures. Fig. 17 shows an explanatory enlargement of one such structure. Although the alternating quartz and feldspar portions do not show the acicular form one associates with spherulitic felsites, they are strongly suggestive of an earlier, spherulitic phase of crystallization.

In the rock figured (948) there are rare, corroded and clouded plagioclase crystals. These may be larger than the normal grain size of the rock, and few such grains were found in thin section. Their cloudy nature precluded an estimate of composition, but they are distinct from the clear late albite which occurs in many of the granites. Specimen 948 is unique amongst the analyzed Puklen rocks in showing appreciable normative anorthite and slight normative corundum. Possibly this is accounted for by these altered plagioclase grains, the origin of which is discussed in a subsequent section.

The rare mafic constituents of these rocks comprise occasional grains of green-blue amphibole and ragged biotites, sometimes in grains as large as the feldspars but more often as wisps, irregular patches of astrophyllite, and dustings of rounded ore grains in groups associated with tiny colourless needles presumed to be amphibole. Pulvertaft (1961) found aenigmatite in the southern microgranites.

Relationships at internal contacts

(a) Granite-syenite relationships at the western margin of the northern granite

Along the western margin of the northern granite body (and, according to Pulvertaft, 1961, along its northern contacts) the granite, distinctively reddish in colour, gives way over a short distance (< 30 m) to more brownish syenite. The sharpness of this contact is sufficient to be brought out on air photographs and to control the western edge of the large lake in the north of the Puklen, but on close inspection it is not knife sharp. At locality I, fig. 2, a series of specimens was collected and sectioned (951–955). Two examples were analyzed, 951, a granite, from 24 m east of 955, a syenite.

The chemical analyses and modal analyses show that both specimens are quite typical of the soda granites and heterogeneous quartz syenites respectively, although the syenite is rich in normative quartz compared with the other analyzed type (b) syenites. No sharp break was found between these two rocks in the field (the intermediate rocks are described below) but the two specimens are completely distinctive. The marginal facies of the granite (951) shows more regular perthitic textures than the syenites, with the developments of conspicuous albite rims and 'swapped rims' between adjacent feldspars. The latter seem better developed than in specimens from the interior of the granite. The syenite feldspars have simple boundaries and are patchily, and sometimes finely perthitic. As will be detailed in the following section, the syenite specimens contain orthoclase as well as microcline in the potassium phase of the perthites, the granite specimen carries microcline only. There is some development of marginal albite in the syenite, but this is also found in heterogeneous syenites elsewhere in the intrusion, away from granite contacts.

The mafic constituents of each rock are also distinctive. The syenite contains the brilliant green colour-zoned aegirine-augites which characterize the type (b) syenites, and brown-green amphibole interstitial to the well-formed feldspars. Radiating outgrowths of blue amphibole occur where green amphibole or largely-altered fayalite crystals abut against quartz. There are no signs whatever of recrystallization of this rock by the presumably later nearby granite, and no suggestion of the recrystallization textures developed in the porphyritic syenites.

In the granite, by contrast, the amphibole is blue-violet riebeckite-arfvedsonite, extensively replaced by quartz and haematite (see fig. 12) or by acmitic pyroxene. The latter is virtually colourless or golden in this rock. Albite rims are extensively developed on the alkali feldspars, together with areas in which numerous small equant albite crystals are intergrown with quartz. Such textures are more strikingly developed in the astrophyllite granites from Kûngnât (UPTON, 1961), with their generally pegmatitic aspect.

Rock 954, from 10 m east of the undoubted syenite 955 (above), is transitional between syenite and granite in quartz content but not in other features. In hand specimen it is an intermediate brownish pink colour, and it contains rather little quartz, about 15 % by volume, very sporadically developed. In other ways the rock is most closely like the granites, possessing deep blue amphibole in large grains, extensively replaced by quartz and acmite as shown in fig. 13. The potassium feldspar of this rock correlates with the granites (see later section), as does the abundant, well-developed marginal albite. The rock is totally distinctive from syenite 955, 10 m to the west, even though a knife-sharp contact was not located in the field.

One syenite, 950, from very close to the contact with granite to the north of the series described above, does show more transitional features than the quite normal syenite (955). Coarser grained than the granites and an undoubted member of the syenites, 950 contains the usual well-formed feldspars with a little interstitial quartz, large green amphibole crystals and zoned pale green augitic pyroxenes. In addition it shows an extreme development of fringes of blue amphibole, and the perthitic textures are, for a member of the syenite suite, unusually coarse. A few finely perthitic cores to crystals remain, despite the relatively abundant marginal albite. This is the only syenite without appreciable monoclinic feldspar in the potassium phase (see later section). This rock appears to have been affected by proximity to the granite to a greater extent than specimen 955, but, nevertheless, the effect of the granite on the syenites is very restricted. There is no sign of the recrystallisation apparent in the porphyritic syenites. Although a feldspar-rich marginal facies of granite is present, the latter is not chilled against syenite, and the fine microgranites are not related to the granite contacts.

(b) Gradational granite-syenite contacts at the southern margin of the northern granite

Along this margin, and (according to PULVERTAFT's (1961) descriptions) along the eastern margin of the northern granite, the change from granite to syenite is very ill defined, and rocks falling in the transition group are extensively developed. Many of these rocks are highly quartzose; modal analyses appear in Table 3. Rocks 941, 943 and 945 represent a south to north transition across this contact, and the layered rock (937) and unlayered members in the vicinity (939) also represent parts of this sequence. The latter rock, although highly quartzose (22 % by volume) has almost colourless to pale green pyroxenes, with large extinction angles, and abundant yellow-green amphibole. The layered member (937) has the same mineralogy. Northwards, there is complete gradation from transition group syenites to soda granite. It is difficult to find any textural or mineralogical criterion with which to fix the granite-syenite boundary. 943, with 15 % by volume of quartz (Table 3) is unusually rich in yellow-green amphibole, with distinctive rhythmic colour zoning with bands of a deep blue-green colour. Specimen 944, nearer the granites, is less quartzose, coarser grained, and contains bright green pleochroic pyroxenes, with small extinction angles. This rock is more like certain members of the heterogeneous type (b) syenites than the typical transition group rock but is very even textured. Rock 945, the southernmost rock with a quartz content (31 %) and hand specimen appearance appropriate for a granite is unique amongst such quartzose specimens in containing pale green, colour zoned augites with large extinction angles, and ragged green hornblende. It contains biotite and astrophyllite however, and the coarse perthites, irregular quartz-feldspar interfaces (fig. 12), and identity of the feldspar potassium phase (microcline) are all features characteristic of the granite suite.

Along their southern boundary, the transition group rocks in this part of the intrusion show some sharp contacts against coarse syenites (locality C, fig. 2). The contact is knife-sharp in thin section, the fine-grained green transition group syenite merely contrasting in grain size and quartz content with the brown type (b) syenite, which is at this locality rather even textured. Feldspars and mafic constituents are alike in both rocks. Neither rock seems to have affected the other, and there is complete lack of breakage of crystals indicating forceful injection of either member. The coarse feldspars merely give way, over their natural boundaries, to the finer material. This seems to support the field evidence of contemporary mobility of the two types, although it seems that the coarse syenite was almost wholly crystalline when the transition group was intruded.

(c) Contacts of the southern microgranite

North-west, this body gives way directly to coarse syenite (at J, fig. 2) but north-east, (at A), a screen of transition group rocks is transposed between granite and syenite (930). The transition group rocks give way rapidly to the south-west to granite but grade north-east into coarse syenite. The relations seen at the southern boundary of the northern granite are here reversed. The coarse syenites at the localities labelled J and 930 are both distinctive in containing areas of quartz and feldspar in a coarse 'granophyric' intergrowth between the coarse subhedral feldspars (fig. 9). Normally, in the quartz syenites, only quartz is interstitial to the feldspars. In other textural aspects these syenites are characteristic coarse type (b) syenites, but 930 contains the extreme of brilliant green aegirine-augite, with small extinction angles ($\alpha \wedge Z = 10°$) and well-developed fringes of blue riebeckite-arfvedsonite. The transition group syenites which occur at A, (between the syenite 930 and the microgranite) do not show granophyric intergrowths, (they have the characteristic 'euhedral feldspar' texture, with interstitial quartz) and contain more augitic green pyroxenes, with large extinction angles. They appear to give way rapidly to microgranite, but the junction is obscured.

Feldspar variation

Feldspars in the Puklen rocks fall broadly into three categories, the microperthites, ubiquitous throughout the mass, late albite, developed in the heterogeneous syenites and best developed in the soda granites, and thirdly the corroded, cloudy plagioclase phenocrysts found in certain microgranites.

(a) Microperthites

Bulk feldspar compositional variation is probably well represented (there are no other potassium-bearing phases) by the normative compositions calculated for Table 4, and plotted on fig. 4. These show a change in bulk feldspar composition from about $Ab_{63}Or_{37}$ in the quartz-free syenites, to $Ab_{55}Or_{45}$ for the soda granites. The effect of the small amounts of discrete late albite on these estimates of composition will be small, and the quoted range of Ab : Or is a good approximation to the bulk composition of the microperthites (strictly antiperthites, although the latter term is perhaps best restricted to unmixed feldspars lying close to the Ab-An join).

The maximum normative *an* content is 2.2 %, and this may certainly be regarded as a maximum for the perthitic alkali feldspars. The highly leucocratic microgranite (948) which gave this high *an* content is unique in containing relics of apparently early plagioclase, which may account for the normative *an*. Other rocks, except the second microgranite, 926, show no normative *an*, and, although the CIPW normative procedure conspires to underestimate *an* (by allocating Al_2O_3 first to K_2O, then to Na_2O), it should be noted that the analyses show no normative corundum and that the amount of SiO_2 is just sufficient to saturate the quartz-free rocks, with negligible development of *ne*. This suggests that the normative method here gives a reasonable estimate of modal mineralogy, and that the analyses are not grossly in error. It is unlikely that the microperthitic feldspars contain more than 3 % *an*, and the absence of *an* from the norms is consistent with generally lower An contents, probably < 2 %.

There is a good deal of variation in the appearance of the microperthites in thin section. The feldspars of the granites are always very cloudy in thin section, their pink colouration in hand specimen being a result of this. The finest scale of perthitic intergrowth is in the 'phenocrysts' in the porphyritic syenites, and occasional cores to grains in the coarse even-textured syenites. These fine microperthites are often clear, unclouded crystals; the scale of the perthitic intergrowth may be below the resolution of the high power of the microscope, although grains usually show visible perthitic lamellae around their margins. The superficially non-perthitic clear cores to some of these phenocrysts show diffuse extinction, and the slightly anomalous faintly blue or orange colours on either side of the extinction position which seem to characterize certain fine perthitic intergrowths. Their finely perthitic nature was confirmed by X-ray diffraction study of material removed by dental drill from the phenocrysts in the analyzed porphyritic rock (912). This showed X-ray reflections for low albite and orthoclase, with relative intensities comparable to the more obviously perthitic feldspars from other syenites. This suggests that the clear phenocrysts have bulk compositions similar to the normal perthitic feldspars of the syenites.

Elsewhere there is great diversity in the coarseness of perthitic textures and in the polysynthetic twinning visible in the two phases of the perthites in thin section. Variation in perthite coarseness commonly occurs within individual thin sections of the syenite suite and in the heterogeneous syenites with pegmatitic patches the perthites are commonly very coarse and clear albite rims develop (fig. 5). In the more even-textured syenites and in the transition group rocks, regular lamellar perthites are developed which, when combined with Carlsbad twinning, give the familiar 'herringbone' pattern. In may rocks however, particularly where the perthite is coarser, the two phases may be patchily and irregularly intergrown. In the coarsely exsolved examples albite and pericline twinning can be seen in the usually clear sodium phase, but the potassium phase is normally cloudy and it is difficult to distinguish twinning. In some rocks, particularly from the granites, the grid twinning of microcline may be discerned under high power, using bright illumination.

The regularity of the perthitic textures, the range of coarseness of intergrowth increasing in a broadly systematic way from early syenites to the late soda granites and the narrow but perfectly systematic variation in bulk composition, all confirm the view that these perthites have unmixed from initially homogeneous high temperature alkali feldspars of essentially the same bulk composition as is indicated by the normative data. This history places a clear restriction on the pressure and temperature range of formation of the Puklen rocks. Following the reasoning put forward in many earlier papers on the feldspars of syenites (*e.g.* UPTON, 1961; PARSONS, 1965), using the latest experimental data of MORSE (1970), and assuming the feldspars to be An-free, the quartz-free Puklen syenites must have crystallized at $P_{H_2O} < 4.2$ Kbars. At this pressure the minimum temperature would be 715° C. At lower water vapour pressures higher temperatures are implied, and An will dramatically raise the minimum temperature (perhaps by 40° C Kbar, using TUTTLE & BOWEN's (1958) data) and lower the maximum possible P_{H_2O}. More detailed discussion of the temperature and pressure range of crystallization of the Puklen rocks is given subsequently; the estimate of crystallization temperatures of 700° C is sufficient for the purposes of the discussion of the feldspar variation given in the present section.

The structural state of alkali feldspars (*i.e.* the degree of Al-Si ordering) can be crudely assessed from the separation of certain lines (in particular 131 and $1\bar{3}1$) on X-ray diffraction patterns. These lines are in particular sensitive to the lattice angles α^* and γ^* which, in microcline, progressively depart from 90° as the degree of Al-Si order increases.

X-ray diffractometer patterns were obtained for twenty-eight crushed whole rocks representative of the Puklen sequence. These were then ranked on the basis of the appearance of certain X-ray reflections in the region 29°–32° 2θ, CuKα radiation. Care must be taken, when using whole rocks, that other minerals do not provide strong reflections in this region. Drawings of diffractometer traces of Puklen feldspars in this 2θ region are given in fig. 18. Similar, indexed patterns for slightly more sodic

Table 6. *Distribution of K-feldspar 131 reflection types in the Puklen rocks types.*

Rock Type	Number of specimens giving each of the reflection types (PARSONS & BOYD, 1971)			
	2a	3a	3b	4
Granite				6
Microgranite				2
Granite veins in syenite				3
Transition group		4	1	
Syenite types b		5	1	1*
Syenite types c		2		
Syenite types a	2	1		

* Rock (950); see text.

perthites have been presented previously by the writer (PARSONS, 1965). When maximum microcline is present its 131 reflection appears at about 29.45° 2θ. The 131 reflection of orthoclase is at 29.8° 2θ. Types with both orthoclase and microcline show diffuse reflections depending on the dominance of orthoclase or microcline, and on the obliquity of the microcline.

When ranked on the basis of the appearance of diffractometer traces the Puklen rocks show a surprising and strikingly systematic variation. The main results of the Puklen study have been summarized and compared to the feldspar variation in other intrusions in another paper (PARSONS & BOYD, 1971. An expansion of the data, together with modal analyses, is given in Table 5, and summarized in Table 6. The four classes into which the reflections are placed, 2a, 3a, 3b and 4, are those used in PARSONS & BOYD, 1971. The sodium phase of the perthites is always close to low albite as judged from the separation of the 131–$1\bar{3}1$ reflections for the albite component.

There is a striking correlation between the classification, on petrographic grounds, of a rock specimen into the granite suite, and the presence of a K-feldspar which is wholly triclinic (type 4 reflection) on the basis of the diffractometer trace (as PARSONS & BOYD, 1971, state, this does not rule out the presence of some material of monoclinic symmetry). All other rocks give diffractometer traces which show the coexistence of monoclinic material (orthoclase, within the definition of PARSONS & BOYD) and microcline of variable obliquity, usually approaching maximum microcline. The examples with the least intense X-ray reflections in the microcline positions (type 2a) both come from quartz-free syenites of type (a). The data show that the relative abundance of microcline at the expense of orthoclase increases with increasing fractionation (in terms of *ab-or-Q*) in the Puklen sequence. PARSONS & BOYD (1971) demonstrate exactly this relationship between rock bulk composition and the nature of the K-feldspar in eleven other intrusive complexes, not all related to the scheme of fractionation to which the Puklen body approximates. In the Gardar province UPTON (1960, 1962) cites optical evidence for increasing abundance of microcline with fractionation in the Kûngnât pluton and the central ring complex on Tugtutôq. At Puklen the rock types are texturally different, and we find the apparently surprising relationship that the fine-grained granophyres and microgranites (rocks of broadly high-level aspect) contain the most highly ordered K-feldspars, whilst the coarse, thoroughly plutonic, even pegmatitic syenites carry less highly ordered K-feldspars.

PARSONS & BOYD (1971) discuss the contradiction apparent in the foregoing relationship, and make some suggestions to explain the apparently very common relationship between rock bulk composition (as it reflects the position of the rock in a scheme of fractionation) and K-feldspar type. In the discussion we stress, in particular, the apparent sharpness of the localization of the particular K-feldspar types to particular lithological units. Some additional local details may be given here, in relation to the details of petrography described previously.

In the Puklen rocks we find that all rocks assigned to the granite suite (on the basis of hand specimen appearance, presence of alkali amphiboles in individual crystals and/or presence of acmite, and high quartz content) gave type 4 (microcline only) diffractometer traces. This applies to granites and microgranites of all grain sizes, and includes narrow dykes of granitic type cutting syenite well outside the main masses of alkali granite (see Table 5). With only one exception (950) all syenites and transition group rocks gave traces indicating the existence of some orthoclase. This includes examples close to the wholly microcline-bearing granite dykes. The exception (950) has been described above; it comes from very close to the contact with the granite, and contains abnormally coarse perthites, much interstitial albite, and a great development of secondary alkali amphibole.

The series of rocks 951–955 from the western contact of the northern granite show clearly the way the type of K-feldspar correlates with rock type. The feldspars of the two analyzed rocks, 951 (coarse granite) and 955 (coarse quartz syenite) were used as examples in fig. 18. These rocks come from only 24 m apart. All the intermediate 'granites' 952–954 (Table 5) gave type 4 traces, so that the appearance of orthoclase takes place within a distance of < 10 m and correlates precisely with the disappearance of acmite, and the change from alkali amphibole to aegirine-augite as the important mafic constituent. Rock 956, is a quartz-poor

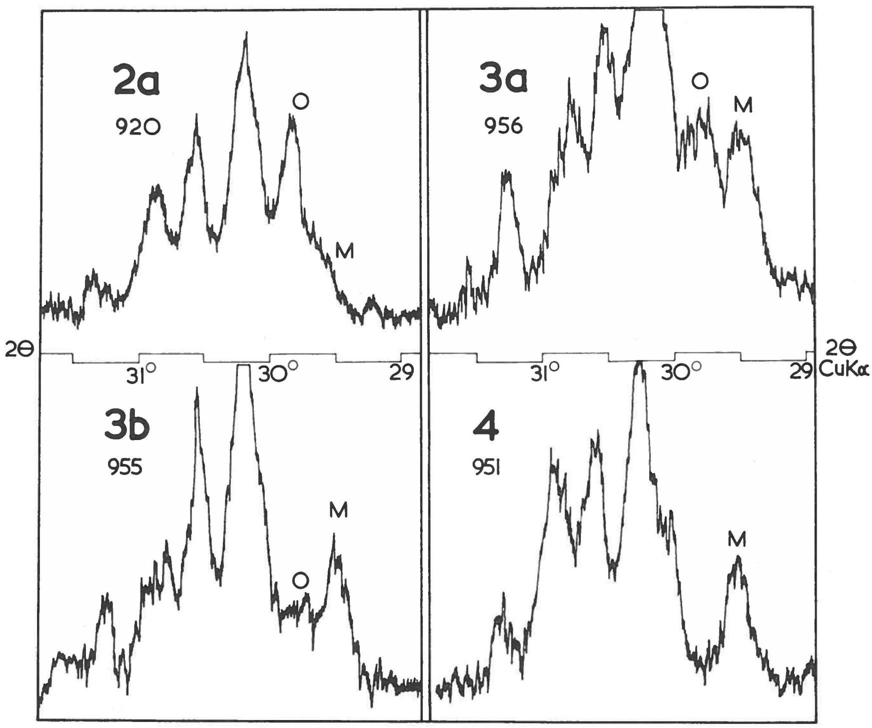

Fig. 18. X-ray diffraction patterns of perthitic alkali feldspars, in the 2θ range 29°–32° (Cu-Kα radiation). Instrument settings: Scanning speed 1/8° /min; chart speed 400 mm/hr; rate meter 4, time constant 8; slits 1°–0.1–1°. Smear mounts. The classification used (2a, 3a, 3b, 4) is that of Parsons & Boyd, 1971. O = orthoclase 131 reflection, M = microcline 131 reflection. Specimen numbers are given.

syenite, 260 m further west; the diffraction pattern of its feldspars (fig. 18) shows that microcline is less developed in this rock than in the more quartzose rocks. In the final example, (920) a quartz-free syenite, with colourless augitic pyroxenes, orthoclase coexists with only minor microcline.

In our discussion of the factors that control the distribution of K-feldspar polymorphs in plutonic rocks Parsons & Boyd (1971) consider three points in particular. Firstly, the development of microcline at the expense of orthoclase parallels the course of fractionation of each rock suite; secondly, the different K-feldspar types are often, as at Puklen, very sharply restricted to particular lithological units; thirdly, all the examples of hypersolvus (the term of Tuttle, 1952) granites and syenites crystallized at temperatures in excess of about 700° C, well above the probable upper temperature limit of stability of microcline which is in the region of 400° C (Barth, 1969, summarizes the data which lead to this conclusion).

PARSONS & BOYD (1971) suggest that the observed distribution can only be explained if a crystal-structural control on late ordering history can be imposed at the time of crystal growth (*i.e.* at magmatic temperatures). Drawing, in particular, on the experimental data of MARTIN (1969) we suggest that crystals grown in a volatile-rich, or perhaps more importantly, peralkaline environment, may develop a degree of order and/or a domain structure which will more readily allow increase in domain size and degree of order to yield eventually the material we recognize as microcline. MARTIN's (1969) experiments showed that low albite would form more readily in an environment with excess Na^+ than from compositions with a 1:1 Na:Al ratio, and that Al excess inhibited ordering. It is therefore particularly interesting that the Puklen rocks which show the highest degree of order are also those with strongly peralkaline affinities — acmitic pyroxene, astrophyllite. Perhaps the apparent contradiction at Puklen, of the most ordered K-feldspars in the finest grained rocks, is explained by the progressive increase in peralkalinity which is expected to parallel fractionation (see discussions of petrogenesis which follow).

In summary, the cooling history of the Puklen microperthites is as follows. The feldspars crystallized as homogeneous sodic sanidines at temperatures in excess of 715° C. As the crystals grew in the magma they may or may not have achieved an equilibrium degree of order appropriate to the temperature of growth, and details of their domain structure varied depending on the amount of peralkaline constituents dissolved in the melt. The feldspars of the granites (which show every sign of having crystallized from a peralkaline magma) achieved a structure which was more readily capable of making the structural readjustments during the cooling of the pluton which led, eventually, to the development of microcline to the exclusion of orthoclase in these rocks. The syenite feldspars were unable to complete this transformation, and orthoclase persists metastably in them. Ordering and unmixing will proceed side by side. Local variation in the coarseness of the perthites, and in the relative abundance of orthoclase and microcline as judged from the diffractometer traces, are accounted for by the availability of volatiles at later stages in the cooling history. That such volatiles were irregularly distributed in the later stages of cooling is illustrated by the patchily pegmatitic nature of the syenite suite. The need for a dominant high temperature magmatic or immediately post-magmatic control of the eventual evolution of microcline is evidenced by the sharp localization of microcline in the granites where they abut against syenite, and in granite veins where they cut syenite. In these field settings both granite and syenite must have cooled into the temperature range of stability of microcline under the same conditions of intergranular volatiles and at the same cooling rate. Although this discussion applies specifically to the case of Puklen, PARSONS & BOYD (1971) show that similar considerations apply in numerous other plutons.

(b) Late albite

Albite rims, and discrete grains of albite, occur with many microperthitic feldspars in the heterogeneous syenites and the coarse soda granites. They rarely appear in the coarse type (a) syenites, in the transition group rocks, or the microgranites. Figs 5 and 6 illustrate the types of relationship which may be observed. In fig. 5 a clear, twinned albite rim occurs on one coarsely perthitic alkali feldspar and in structural continuity with it. The albite outgrowth is interstitial to the subhedral microperthitic feldspars, and to a discrete crystal of albite, not related to any perthitic crystals in the plane of the section. In fig. 6, at A, a perfectly euhedral microperthitic feldspar is totally enclosed by clear twinned albite.

Albite rims may well have formed by unmixing of the microperthite, facilitated by the ease of penetration of volatiles around the margins of the feldspar grains. Possibly the euhedral albite grains could have formed by late recrystallization of initially perthitic feldspars, and the well-known suggestions of TUTTLE (1952) would support this idea. Other writers (for example PULVERTAFT, 1961) have described the albite as original or replacive in potash feldspar.

The writer considers that much, if not all of the albite rimming the microperthites is unmixed from initially homogeneous feldspars, and that only the very clear instances of discrete albite grains can be ascribed to crystallization from a late sodic volatile phase.

Albite rims and discrete grains of albite are largely restricted to the pegmatitic syenites and the acmite bearing granites. If the albite in these rocks was extensively replacive, however, we would have to postulate that the feldspars were originally more potassic and that albite was later added in precisely the proportion needed to bring the bulk *ab*:*or* of the rock onto the comparitively smooth trend shown by the triangular plot of *ab-or-Q* (fig. 4). It is worth noting that the two analyzed rocks showing the most 'late albite' in section (930, 955) are actually more *or* rich than the 'late albite'-poor type (a) and (c) syenites 912 and 924.

(c) Early plagioclase

Two analyzed rocks, both fine-grained members of the granite suite, show normative *an*; of these rock 948, microgranite from the summit of Puklen itself, shows significant *an* (2.2 $^0/_0$). In thin section the rock contains rare, subhedral, very clouded plagioclase phenocrysts. The albite twinning, much broader than the albite twinning common throughout the marginal albite of the mass, is shadowy and obscured by the alteration, which prevented optical estimates of composition. These occasional plagioclase grains presumably account for the normative *an*, since the rock is exceptionally leucocratic, and the analysis (Table 1) is high in CaO (compared to the three other analyzed granites) but comparable in total Fe and MgO. The rock is also unique at Puklen in showing slight normative corundum. Clear, albite rims are sometimes developed on the plagioclases, small crystals of which may also act as nuclei for the crude spherulitic structures shown as fig. 17.

Fractionation in Ab-Or-An-Qz must lead to residual liquids progressively depleted in An; 948 and 926 are therefore atypical of the Puklen rocks, and contrast with the coarse soda granites, which are *an* free. In all other respects (as will be argued later) the normative mineral variation at Puklen is completely in keeping with progressive fractional crystallization.

The presence of the plagioclase phenocrysts (and normative *an*) can perhaps be best explained if they are the result of incorporation of fragments of the country rock. The Julianehåb granite, (an analysis of a 'typical' example from near to the contact is given in Table 1) is calc-alkaline, and strongly anorthite normative (Table 4). PULVERTAFT (1961) offers unequivocal evidence for reactivation of the country granite close to the contacts of the northern syenites. It may be significant that the *an*-rich Puklen rock comes from topographically the highest point in the complex, although the relief is slight.

It is interesting that MACDONALD (1969) shows that the most acid members of the Tugtutôq alkaline dyke suite are also corundum and, in one instance, anorthite normative. He ascribes this effect to late oxidation of amphibole, releasing Na to the wall rock, and generating iron oxides and normative corundum. The Puklen rocks are so leucocratic that this process cannot have been significant, and the observable plagioclase crystals are certainly the most likely source of the normative anorthite, and their alteration the source of the normative corundum, although the latter could well be due to analytical error.

Discussion of petrographic and chemical variation

Mineral variation in the Puklen series is summarized in a highly generalized fashion in fig. 19, and the chemical variation is conveniently represented by the Harker diagrams of fig. 10. Both diagrams may be constructively compared with the similar plots of UPTON (1960) for the Kûngnât western lower layered series syenites and their associated soda granites, and fig. 20 is broadly comparable to the plot of MACDONALD (1969, fig. 3) who uses total $Q + or + ab + ac + ns$ as abcissa, for the Tug-

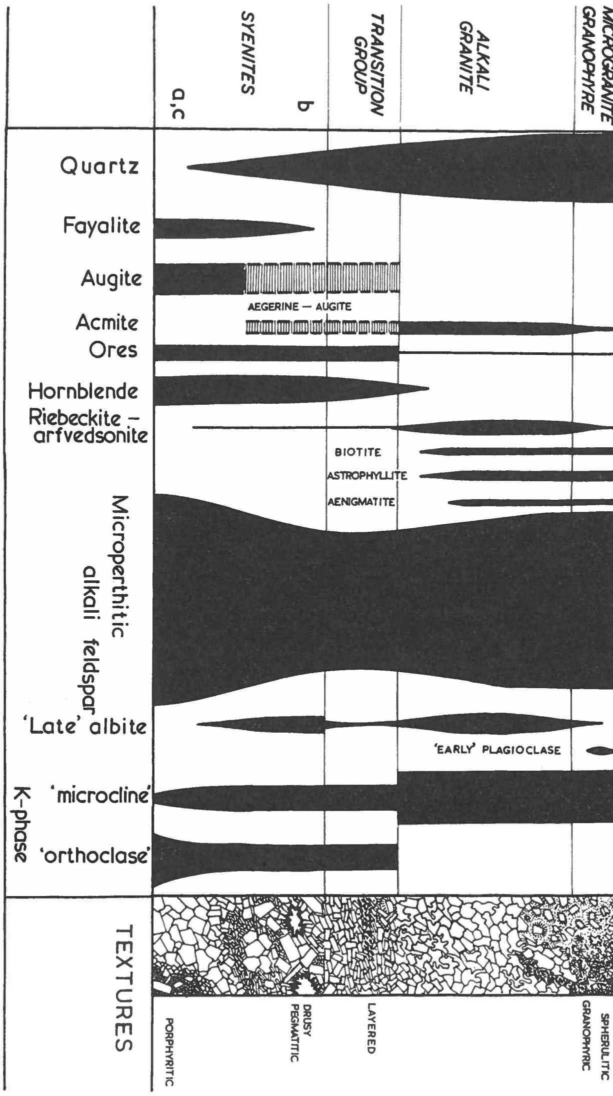

Fig. 19. Diagram summarizing, in highly generalized form, modal mineral variation and textural variation in the Puklen rocks. Vertical width of bands is in rough proportion to modal $^0/_0$ of minerals. Horizontal extent of rock type divisions is roughly proportional to the abundance of each rock type. Special textural features are labelled.

tutôq dyke series. Neither set of analyses provide a complete parallel with Puklen. The Kûngnât suite is chemically similar, but in terms of areal extent, the Kûngnât soda granites are minor bodies, having a pegmatitic aspect, while at Puklen the granites make up nearly half the exposed area and are rocks of regular, medium-grain size or fine-grained types. The Tugtutôq dykes show great variation in $Na_2O/Na_2O + K_2O$, in contrast to the very narrowly defined and systematic Na_2O/Na_2O+K_2O values at Puklen.

Chemically the Puklen rocks present a superficially simple range of variation, quite in keeping with the *in situ* fractionation of a rather quartzose quartz syenite magma. The augite fayalite syenites could be the result of accumulation of early crystals in such a magma, from which the alkali granites would be generated by continuous fractionation. All the mineralogical changes summarized in fig. 19 are in keeping with such a process, and there is every sign of increasing peralkalinity (see following section) as fractionation proceeded. There is field evidence (in the layering) of obe process of crystal fractionation at work. The Harker diagrams (fig. 20) show them to be compatible with a continuous fractionation process, and there seem to be genuine departures from straight line relationships for several elements (MgO, $FeO+Fe_2O_3$, CaO, TiO_2) which suggest that the intermediate types were not produced by mixing the end members.

Superimposed on this simple scheme are a number of textural breaks, associated with mineralogical changes which are not apparent from the analytical data. These breaks seem to suggest that Puklen rocks formed as a result of several pulses of intrusion, and that the pressure-temperature regime at the time of emplacement of these intrusive phases, changed during the intrusive history of the body. These textural breaks are summarized diagramatically on fig. 19. In the quartz syenites there is a striking textural break between the coarse, heterogeneous, patchily pegmatitic and drusy type (b) syenites, and the even-textured transition group syenites. In normative mineralogy both groups overlap, in terms of quartz content, and in their normative pyroxene. Fig. 21 (c) shows the smooth relationship that appears when SiO_2 is plotted against $ac/ac+di+hy+wo$; this reflects accurately the broad changes in the pyroxenes established from the thin sections, colourless augites in the quartz poor syenites giving way to strongly zoned augite-aegerine-augite crystals in the quartz syenites, less strongly zoned aegerine-augites in the transition group, and acmitic pyroxenes in the soda granite. The optical and X-ray data suggest that the late-crystallizing pyroxene in the soda granites is more acmitic than fig. 21 (c) indicates, but the normative procedure groups all mafic constituents into pyroxene, when some will appear in the mode as amphibole. The plot also obscures the differences between the quartz syenites and transition group pyroxenes. In the former the pyroxenes have progressively smaller extinction angles in the outer zones. The zoning may be complete but is frequently patchy; its development in associated with the quartzose pegmatitic patches and with the parallel development of outer zones and fringes of alkali amphibole. While the average composition of the pyroxenes (as represented by fig. 21 (c)) is

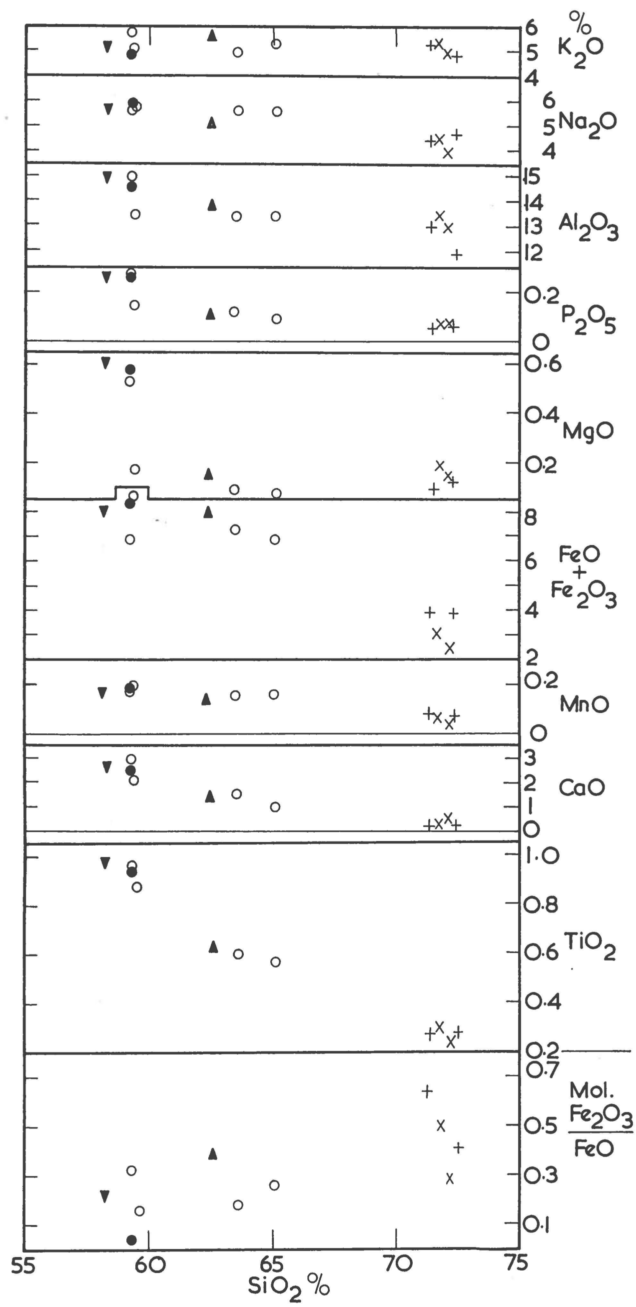

Fig. 20. Harker diagrams of oxide variation for the analyzed Puklen rocks (Table 1). Symbols are as used on fig. 4.

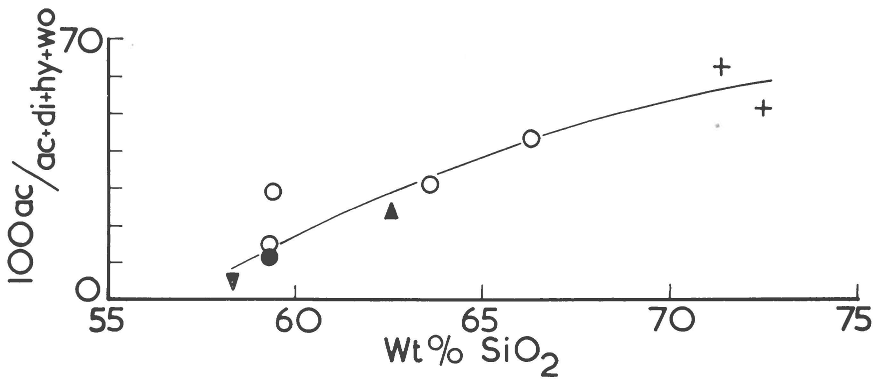

Fig. 21. Plot of estimated pyroxene compositions (normative $[ac/ac+di+hy+wo]\times 100$) against wt. % SiO_2. Symbols are as used on fig. 4. The *ac*-free microgranites do not appear.

similar to those of the transition group, the pyroxenes of the latter are only slightly zoned, usually pale green throughout, with large extinction angles.

The presence of drusy cavities in plutonic rocks is commonly held to indicate the presence of a vapour phase during the final stages of crystallization of the melt which was unable to escape from the crystallizing magma. This vapour phase will concentrate in those parts of the crystallizing body which are last to crystallize, as crystallization of anhydrous minerals from a melt which may or may not be initially water saturated proceeds, and will be subject to very localized structural controls. Experimental work on the composition of the hydrous vapour phase in equilibrium with granite melts by LUTH & TUTTLE (1969) has shown that the anhydrous composition of such a vapour will be similar in composition to the melt but relatively enriched in soda, a finding in accord with widely observed petrological indications, like those at Puklen. Their data also shows that at subsolidus temperatures, the anhydrous composition of the vapour at low pressures is virtually pure silica. This adequately explains the frequently quartzose centres to many of the pegmatitic patches.

The augite syenite-quartz syenite (types (a) and (b)) phase of intrusion at Puklen was accompanied by build up of pressure with the eventual water saturation of the syenite magma under conditions which prohibited the escape of the vapour phase. In contrast, the transition group rocks, although chemically equivalent to the most quartzose syenites, are texturally continuous with the soda granites (and at some localities they seem to be continuously related in the field) and they behave as though they are the precursors of a new phase of intrusive activity which carried on into the granite phase of intrusion. At no stage of this phase of activity was the residual vapour phase entrapped in the rocks. Later, evidence will be given to suggest that the latest stages of emplacement were followed by a comparatively rapid 'pressure quench'. Although the transition group rocks are commonly at the margin of the granites, they do occur as an extensive suite of dykes and thus appear to have existed as a distinct magmatic phase. Although texturally like the granites, they lack the indications of peralkalinity which mark the later intrusive phases (see below) and they are not locally derived syenite-granite hybrids. These intermediate rocks are a minor member of the sequence, in terms of extent, but they provide evidence for the existence of a continuum of magmas in the generation of the Puklen rocks. The possibility that they represent the products of mixing of magmas of syenite and granite composition at depth appears to be unlikely because the syenite phase of intrusion seems to have been distinct, and to have passed through a complete intrusive cycle leading to the development of the pegmatitic rocks, before the transition group were emplaced.

Subsequent to the emplacement of the transition group the main granite bodies were emplaced; the last phase of activity was the development of the fine-grained, leucocratic microgranite suite, which intruded in an irregular fashion the soda granite of which they are the residual members, chemically comparable except for the lack of mafic constituents. An interpretation of the textural variation in these rocks will be given subsequently.

The sporadically developed porphyritic syenites are chemically and mineralogically indistinquishable from the quartz-poor type (a) syenites, but they show very distinctive textures. PULVERTAFT (1961) suggested that these textures could be ascribed to recrystallization. The fringes of drop-like pyroxenes, the radiating groups of pyroxenes, the skeletal amphiboles and intricately interlocking matrix feldspars all support this view. The presence of 'ghost' outlines, made by pyroxenes, of feldspar 'phenocrysts' also suggests that the large feldspars are relics of a much coarser feldspar texture, and the occasional groups of large feldspars, together exhibiting normal syenite relationships, are in keeping with this idea. The recrystallization of pyroxenes must have been previous to the destruction of the large feldspars, before their recrystallization to the interlocking feldspars of the matrix. This is supported by the penetration, in some instances, of pyroxenes along crystal boundaries in the coarse feldspar groups. Outgrowth of feldspar (of cloudy, microperthitic, matrix type) on the coarse feldspar relics has also occurred, because (fig. 10) the pyroxenes commonly occur just within the feldspar boundaries. Recrystallization must have occurred in two cycles; the upward cycle leading to breakdown of the coarse syenite feldspars and migration of pyroxene, and subsequent recrystallization on cooling leading to feldspar outgrowth on the residual 'phenocrysts'.

The remarkable feature of these rocks is that the recrystallization was not accompanied by the invasion of alkalis which so distinguish the heterogeneous quartz syenites. The preservation of the finest microperthitic textures in the feldspar 'phenocrysts' and the lack of alkali amphibole or sodic pyroxene all suggest that the recrystallization took place under comparatively 'dry' conditions. The analyzed example (912, Table 1) has the lowest Fe_2O_3/FeO ratio (fig. 20) of any analyzed rock, which supports this contention. In the field the porphyritic syenites are sporadically developed and they are not restricted to the margin of the granites. It is difficult to suggest a late source of heat which would cause the recrystallization of the earliest syenites (type (a), to which the porphyritic varieties are equivalent) without affecting the quartz syenites (also sporadically developed) which would, in principle, react more readily to heating. More careful fieldwork is needed to provide an answer, but a possible explanation might be that the porphyritic patches are really xenoliths of syenite carried from depth during the earliest syenite phase of intrusion. Recrystallized during this phase of activity, the subsequent crystallization of syenite around the now 'porphyritic' areas might have served to armour the porphyritic areas against the vapour phase so active in the later stage of the syenite intrusive phase.

PETROGENESIS

Peralkalinity

All but two of the analyzed rocks — both microgranites — are slightly peralkaline; that is, they contain more molar $Na_2O + K_2O$ than can be accomodated in feldspar and this shows in the CIPW norms (Table 4) as *ac*, and in the mode, as sodic pyroxenes and amphibole. Fig. 22 shows a plot of peralkalinity (molar $Na_2O + K_2O/Al_2O_3$) against sodicity (molar $Na_2O/Na_2O + K_2O$), a diagram used by Thomson & Mackenzie (1967), and includes the available analyses of Nunarssuit syenites and soda granites compiled by Watt (1966). The Puklen rocks form a tightly packed group, mostly slightly peralkaline, in contrast to the peraluminous Nunarssuit and Kitsigsut syenites (Harry & Pulvertaft, 1963) and the more strongly peralkaline analysed Nunarssuit soda granite. The range of sodicities (which, in these quartz saturated or oversaturated rocks is broadly a reflection of the slope of the 'thermal valley' in Ab-Or-Qz towards increasing Or content with increasing Qz) are similar for both the Puklen and main Nunarssuit rocks.

The experimental work of Bailey & Schairer (1966) and Thompson & Mackenzie (1967) shows that slightly peralkaline liquids must, on fractionation, generate more strongly peralkaline residua. At Puklen, peralkalinity calculated directly as normative *ac* does not increase with fractionation and the two granophyres are peraluminous. However normative *ac* must reflect the presence of modal mafic minerals, and if any process of fractionation is leading to depletion of mafics, the effect will be to suggest decreasing peralkalinity of the magma, which may not actually be occurring. This is the situation at Puklen, where the granophyres are very leucocratic rocks with $< 2\,^0/_0$ modal mafics. Progressive increase in peralkalinity of the magma is better indicated by considering the change in normative pyroxene with fractionation. Fig. 21 plots normative $ac \times 100 / ac + di + hy + wo$ against SiO_2, and this very clearly shows the progressive enrichment in sodium in the mafic constituents. There is direct evidence, therefore, that the Puklen magma was becoming increasingly peralkaline in type with fractionation, even though the analyses do not directly indicate this.

The presence in the soda granites of a pyroxene approximating closely to acmite, which appears as a late crystallizing or replacive con-

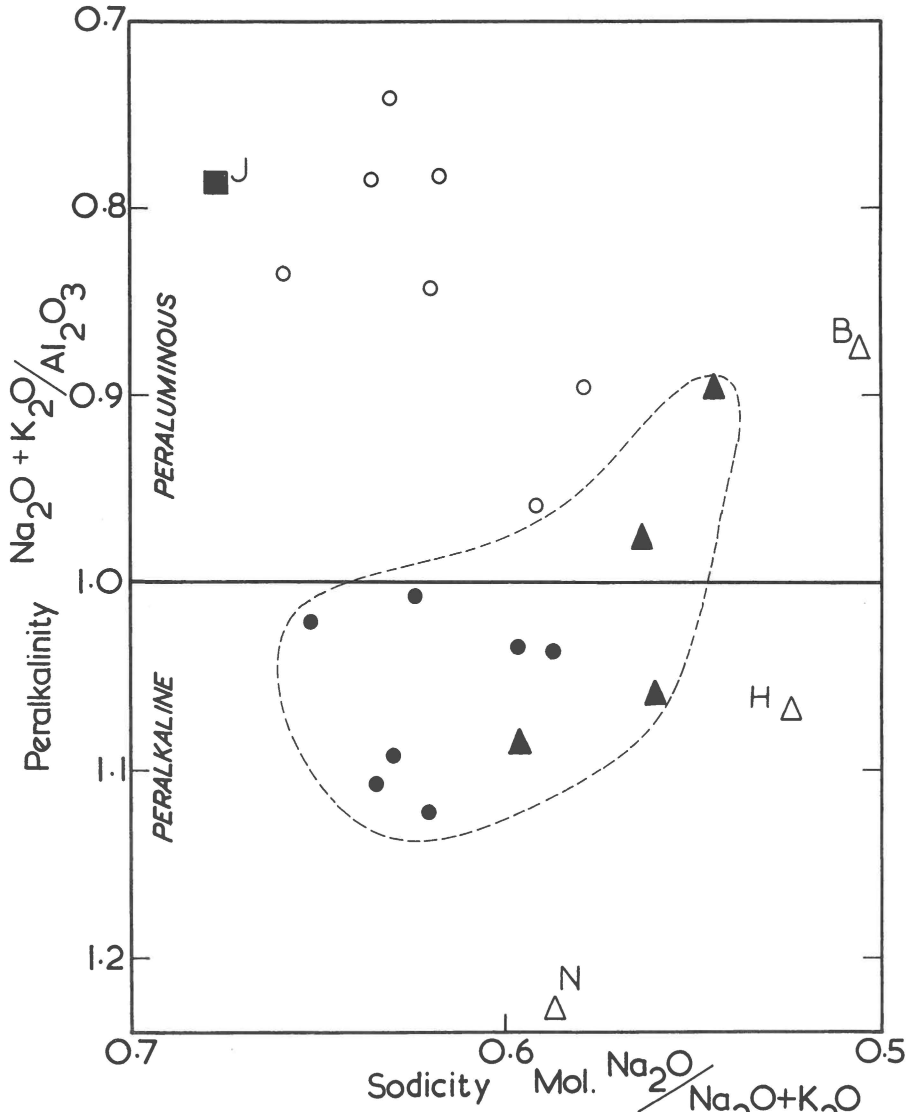

Fig. 22. Plot of peralkalinity (molecular ratio $Na_2O + K_2O/Al_2O_3$) against sodicity (molecular $Na_2O/Na_2O + K_2O$). Analyzes from this paper have solid symbols. Open symbols are other analyzed rocks from the Nunarssuit area, after WATT (1966). Circles = Puklen, Nunarssuit and Kitsigsut syenites. Triangles = various granites. N = Soda granite within Nunarssuit syenite. H = Helene granite. B = Biotite granite (Alángorssuaq). J = Julianehåb granite.

stituent is a clear mineralogical indication of peralkaline conditions, and BAILEY (1969) shows that acmite (pure end-member acmite, that is, to which the Puklen material may only approximate) will crystallize only from liquids containing normative sodium disilicate (*i.e.* containing alkali excess over Al_2O_3 and Fe_2O_3) as distinct from liquids which are merely peralkaline. BAILEY cites the Kûngnât and Tugtutôq suites as showing the disappearance of ore from the mode immediately prior to the appearance of aegerine, and this is broadly true at Puklen, although their is a little early opaque material, often enclosed by amphibole, in the soda granites, (fig. 14). The aegerine-augite bearing transition group are often, by contrast, comparatively rich in early crystallizing iron ores. As BAILEY points out, acmite forms very readily metasomatically, and the replacive nature of the acmite in the soda granites is consistent with its development as an essentially post-magmatic or very late magmatic product. The rosettes of acmite which are widely developed in the soda granite (fig. 15) are strongly reminiscent of the replacive tourmaline 'suns' found in tourmalinized granites, and the replacive quartz (fig. 13) also has a parallel in these rocks. There is evidence for the late addition of albite to the soda granites in particular. There seems to be good evidence for the late existence of a residual liquid probably carrying normative sodium disilicate and capable of crystallizing albite, acmite and quartz.

It is precisely this assemblage which is in equilibrium at the lowest temperature quaternary invariant point in the saturated part of the system Na_2O–Al_2O_3–Fe_2O_3–SiO_2 determined by BAILEY & SCHAIRER (1966). Even in this anhydrous system the assemblage quartz + albite + acmite + disilicate melts at the low temperature of 728° C. BAILEY & SCHAIRER discuss the fate of the disilicate in such assemblages in the plutonic environment (since significant alkali silicate does not appear in the norm of such rocks) and suggest that the largely soluble alkali silicates are lost, together with water, contributing to the alkali metasomatism of the wall rocks. At Puklen there is some evidence of metasomatic introduction of alkalis into wall rock where granites abut sharply against quartz syenite, and the transition group rocks nearest the granite show the most sodic pyroxenes. However much of the activity of late sodic solutions evidenced by the petrography is not related to the granites but to the residual vapour phase which appears to have built up during the syenite intrusive period. It is not easy to disentangle the two possible effects, but there is no doubt that the most extreme development of strongly coloured aegerine-augite, late sodic amphibole and marginal albite is in samples from near the contacts with the granites.

The two analyzed microgranites are anorthite normative, for reasons discussed in the section on feldspars. The analytical result is probably in part a reflection of their very leucocratic nature, rather than an indication of a real chemical difference in the magma at this late stage of evolution because they do exhibit some mineralogical signs of peralkalinity, such as astrophyllite and aenigmatite. The development of maximum microcline in these fine-grained rocks has also been ascribed to their peralkalinity (see section in microperthites).

Effect of anorthite, acmite and alkali silicate on fractionation represented in the system Ab–Or–Qz, and physical conditions during crystallization

Fig. 4 shows the normative composition of the analyzed Puklen rocks plotted in terms of *ab-or-Q* and compared to the synthetic system Ab-Or-Qz (TUTTLE & BOWEN, 1958). The parallelism of the analyses to trend of the unique fractionation curve in the feldspar field of this system is very striking; the trend seems to show a slight flexure towards albite close to the alkali feldspar join, a detail predicted by the synthetic work. As a working hypothesis we proposed that the Puklen rocks were the products of the fractionation of a series of liquids lying in, or very near to, the thermal valley in Ab-Or-Qz. The evidence of increasing peralkalinity, and the mineralogical changes summarized on fig. 19 are all in accord with such a process. The presence of a persodic residuum has been suggested. It is therefore appropriate here to try to deduce, as far as as is possible, the effect that these additional components will have on the melting relations represented in Ab-Or-Qz, and to establish whether the trend of the Puklen results is in any way fortuitous when these other components are considered. Restrictions on the pressure-temperature conditions under which the Puklen rocks crystallized can be deduced.

Anorthite will undoubtedly be present to a limited extent in the Puklen feldspars even though *an* does not occur in the norm. In the feldspar section it was reasoned that 2.0 $^0/_0$ An is probably the maximum contained by the microperthites. The data of JAMES & HAMILTON (1969) on phase relations in the system Ab-Or-An-Qz-H_2O can be applied to take account of this small amount of An. Figure 23 shows the Puklen normative analyses superimposed on their data for the join [Ab-Or-Qz_{97}] An_3 at P_{H_2O} = 1 Kbar. There is remarkable perfection of agreement between normative *ab-or-Q* and the trend of the 'thermal valley' in this join, which coincides with the two-feldspar boundary curve (FQ) as it approaches the quartz-feldspar field boundary. The relations represented by this diagram are not quite appropriate for the Puklen rocks, because they imply that, at P_{H_2O} = 1 Kbar, two feldspars would crystallize from the more acid melts. The soda granites are hypersolvus rocks with one perthitic alkali feldspar (the little interstitial albite is a late addition). Either the Puklen rocks actually do not have 3 $^0/_0$ An, or P_{H_2O} during formation of the quartzose rocks was < 1 Kbar. Lowering the water vapour pressure in the system Ab-Or-Qz moves the isobaric minimum (M of fig. 4) and the thermal valley towards Or; lower An contents move the projected position of the thermal valley towards Ab. The analyses would therefore still plot within a thermal valley in the system Ab-Or-An-Qz, if pressure was somewhat less than 1 Kbar or the An contents less than 3 %. The Puklen rocks are therefore considered to have formed from a series of liquids fractionating along one of the continuum of unique fractionation curves which together represent the extension of the two-feldspar surface (CARMICHAEL, 1963) as it approaches the Ab-Or-Qz plane.

As fractionation proceeded the liquids became progressively more peralkaline. They leave the Ab-Or-Qz plane and trend towards a probable eutectic involving quartz, alkali feldspar and alkali silicates (THOMSON & MACKENZIE, 1967). The existence of residual solutions rich in these components has already been deduced. THOMSON & MACKENZIE have provided liquidus data for a join involving $[\text{Ab-Or-Qz}]_{95}\,[Na_2SiO_3]_5$ at $P_{H_2O} = 1$ Kbar, towards which the later, acid members of the Puklen sequence may be trending. Their data show that the addition of sodium metasilicate has little effect on the projected position of thermal minima in Ab-Or-Qz, or on the disposition of the fractionation curves, but there is a general lowering of liquidus temperatures. In addition they present data for a join containing $[\text{Ab-Or-Qz}]_{95}\,Ac_5$ and show that the latter component too has little effect on the configuration of the liquidus surface.[1] Acmite has a rather smaller effect on the liquidus temperatures than sodium metasilicate. Both components will conspire to further restrict the maximum possible P_{H_2O} if the liquidus is not to intersect the feldspar solvus in Ab-Or-An.

Although, particularly in the earlier members of the Puklen sequence and in some granites (919) there is good evidence for the late crystallization of amphibole, and more rarely, in the quartz-poor syenites, pyroxene, it seems that the presence of these components in the melt does not materially affect the composition of the crystallising feldspars as they project on Ab-Or-Qz. The agreement between the Puklen normative analyses and the disposition of thermal minima in the simplified synthetic systems supports the experimental evidence that mafic constituents and peralkalinity do not greatly affect the course of fractionation when depicted in terms of alkali feldspar and quartz.

The combined effect of the presence of the three components *an*, *ac* and *ns* cannot be precisely calculated, but some attempt to deduce P–T conditions can be made. JAMES & HAMILTON's (1969) data show that the two-feldspar boundary curve appears at the liquidus on the 3 % An join at a temperature as high as 800° C and $P_{H_2O} < 1$ Kbar. Supposing that there is as little as 1 % An in the feldspars of the granites a single alkali feldspar would crystallize throughout the history of the mass only if $P_{H_2O} < 1$ Kbar, at which pressure the liquidus temperature for the

[1] As THOMSON & MACKENZIE point out, this is not a true liquidus because of the incongruent melting of acmite.

Puklen soda granites would be about 780° C. At higher pressures two feldspars would appear. However alkali silicate and acmite would both tend to further lower liquidus temperatures and the presence of these components therefore requires that water vapour pressure during the crystallization of the quartzose rocks must have been below 1 Kbar, and possibly substantially below, if a hypersolvus alkali granite was to crystallize. THOMSON (1969) reports data of JAMES that some liquids with as little as 1 % An will crystallize primary plagioclase at 1 Kbar. It is interesting that the only rock with significant normative *an* at Puklen does contain discrete early plagioclase crystals and is the rock richest in normative quartz. The reason why the rock is anorthite normative may be contamination by the peraluminous country rock granite It is therefore possible that the plagioclase crystals are true xenocrysts, but they could be early crystals of plagioclase crystallizing from a liquid lying on the two feldspar surface. The altered nature of the crystals, their variation in size and corroded nature probably favour the former explanation. Such anorthite-bearing xenocrysts might react only slowly with the granite melt even if P_{H_2O} was sufficiently low for them to eventually dissolve.

The studies in the synthetic systems described above were all carried out under conditions of water vapour saturation, a condition not necessarily fulfilled in nature. At Puklen the drusy character of the heterogeneous syenites suggest coexistence of a gas phase, and in the discussion which follows, a stage of pressure quenching is proposed at the final stage of consolidation of the soda granites. Under these conditions water saturation seems probable.

Textural relationships between quartz and feldspar and the petrogenetic significance of the granophyric intergrowths

VOGT (1928) suggested that granophyric intergrowths of quartz and alkali feldspar could be the result of simultaneous crystallization of these phases from liquids moving along the quartz-feldspar field boundary in Ab-Or-Qz. MEHNERT (1968) reviews evidence to the contrary but concludes that simultaneous crystallization is the most likely mechanism. LEIGHTON (1954) suggested that VOGT's mechanism was wrong because the composition (quartz-feldspar ratio) in the intergrowths was not constant. DUNHAM (1965) showed that the quartz-feldspar ratio of certain granophyric intergrowths (in high level granites) lay close to the quartz-feldspar field boundary and ascribed departures from the boundary curve to the difficulty of distinguishing early, phenocryst quartz from quartz in intergrowth, and to uncertainty in knowing the vapour pressure under which crystallization occurred.

Inherent in these discussion there seems to be the assumption that simultaneous crystallization of quartz and feldspar can only occur in liquids lying on the field boundary on the liquidus. In fact any undercooled liquid in the system is potentially capable of simultaneous crystallization of quartz and feldspar. Granophyric intergrowths will only of necessity have quartz-feldspar ratios lying on the field boundary if the rock has phenocrysts of both quartz and feldspar. That such rocks exist is a demonstration of the importance of undercooling in the derivation of the granophyric texture. Dunham (1965) explains the development of the contrasting granitic and granophyric textures by simultaneous development of quartz and feldspar at different degrees of undercooling. The granitic texture (or the development of obvious phenocrysts) implies limited undercooling into a temperature region where the rate of nucleation is low but the rate of crystal growth high. The granophyric texture implies further undercooling into a temperature region where both rate of nucleation and growth are high. The importance of undercooling is therefore recognized in the evolution of the texture; in the writer's view the undercooling may also imply that strict adherence to the quartz-feldspar field boundary by the intergrowths is not a necessity.

There will be good reasons why the modal composition of granophyric intergrowths will lie close to the field boundary, in magmatic rocks. Many are portions of granitic intrusions which, in any case, lie close to the field boundary. Only in rare instances where a granophyric intergrowth is a member of a fractionated sequence involving feldspar separation from an initially quartz syenitic magma is one likely to encounter residual liquids which depart significantly from the quartz-feldspar field boundary. Even here, strong fractionation of feldspar, will rapidly drive residual liquids towards the field boundary, and this is the case at Puklen.

An attempt was made to establish the quartz-feldspar ratio in the granophyric intergrowths interstitial to feldspar in a number of Puklen rocks. The results are shown in Tables 2 and 3. Only the rock with a large amount of material in granophyric intergrowth, 926, gave a quartz-feldspar ratio lying on the field boundary at $P_{H_2O} = 1$ Kbar. A tie line, drawn on the assumption that the alkali ratio in the feldspars of the intergrowth is the same as that of the rock as a whole, is given on fig. 23. All the other rocks gave quartz contents for their granophyric areas far into the quartz field. This merely means that when quartz started to crystallize, much of the feldspar continued to grow on the existing feldspar crystals, so that when point counting areas showing recognizable quartz-feldspar intergrowths one over-estimates the quartz content which the residual liquid may have had.

Since not all rocks of appropriate composition in the Puklen body show granophyric intergrowths, somewhat special cooling conditions must be needed to explain their development. The intergrowths imply (as DUNHAM, 1965 explains) that the rocks showing them have been quenched more rapidly than adjacent rocks showing normal granitic textures. The main bodies of granophyre at Puklen are not marginal to the granites and are seen both to grade into granite and to cut granite. In the transi-

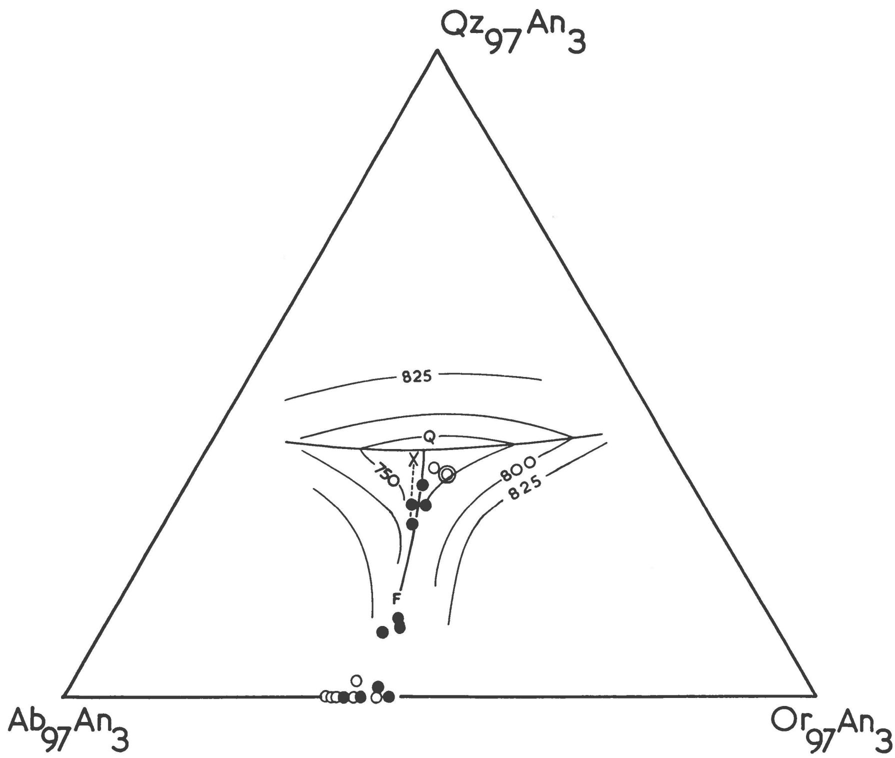

Fig. 23. Normative *ab-or-Q* for the Puklen rocks (solid circles) and other analyzed rocks (open circles) from Nunarssuit-Alángorssuaq (from WATT, 1966) plotted on the isobaric phase diagram for the join [Ab-Or-Qz]$_{97}$ An$_3$ at $P_{H_2O} = 1$ Kbar, of JAMES & HAMILTON, 1969. The cross shows modal quartz content of the granophyric intergrowth in a granophyre joined by a broken tie-line to the whole rock; *ab:or* is assumed to be the same in the intergrowth as in the whole rock. FQ is the two-feldspar boundary curve. Liquidus isotherms in °C.

tion group syenites margining the northern granite, granophyric texture is sporadically developed. The texture is also found in a member of the heterogeneous syenites from close to the southern microgranite. In the northern transition group rocks granophyric intergrowths are found as the intercumulus material in a layered syenite. The latter, although of limited extent, show well-developed banding and at one locality a delicate 'false bedded' structure was found (fig. 3). It semes unlikely that these structures would have survived wholesale emplacement as solid masses, which would offer one method of obtaining a comparatively rapid fall of temperature to account for the interstitial granophyric patches. The observed relations are much better explained if we suggest that crystallization of the Puklen suite terminated in a comparatively sudden reduction in water vapour pressure — a 'pressure quench'. As is well known and explained by TUTTLE & BOWEN, 1958, reduction in P_{H_2O} will cause crystallization of a hydrous granite melt without the necessity of a fall in temperature. A 'pressure quench' mechanism explains the sporadic development of granophyric textures in rocks from several areas. Only where residual liquids persisted until the time of the pressure reduction would the granophyric texture develop. Such patches of late crystallizing interstitial liquid would be subject to local, partly structural controls on cooling rate and water content. On pressure reduction the layered structures, formed essentially *in situ*, would be preserved. The residual quartz-feldspar intercumulus liquid could develop the granophyric intergrowths without the necessity of cooling the rock by emplacement. The field relations of the granophyre and microgranite within the northern granite area, where large bodies of granophyre exist together with a network of microgranite veins cutting the coarse granite mass are structurally in keeping with a pressure reduction, and there are also fine quartz veins cutting sharply through the soda granites. The absence of replacive acmite from the microgranites (they are not *ac* normative) is also consistent with sudden loss of the sodic residual phase which was active in the coarse granites at the end of their period of consolidation.

The coarse soda granites do not show the regular often radiating granophyric intergrowths, but the quartz-feldspar boundaries are often intricate, with curving interfaces (fig. 12). This presumably indicates essentially simultaneous crystallization of quartz and feldspar, but from fewer nuclei, *i.e.* a lower rate of nucleation, expected at a lower degree of undercooling. The bulk composition of the granites implies that quartz crystallization would begin when rather few feldspar crystals were present.

One rather quartz-poor granite vein (fig. 16) and many quartz syenites (fig. 8) exhibit the 'euhedral feldspar' texture in which optically continuous quartz occurs interstitially between very well-formed feldspars. Some rocks, such as the layered rock (fig. 11) show this texture in the same thin section with patches exhibiting the granophyric texture. It seems that during crystallization of the quartz syenites, feldspar crystallization, and crystallization of early amphibole and pyroxene, proceeded to give a rather open, cumulate-like mesh of well-formed feldspar crystals. The composition of the residual liquid would be driven toward the quartz-feldspar field boundary where eventually quartz would begin to crystallize. Growth conditions in the syenites were apparently such that feldspar growth proceeded by overgrowth on the existing feldspar crystals, without interference from the quartz which was presumably crystallizing simultaneously. In the rocks in which the granophyric texture can also be found it seems that the interstitial liquid persisted, in certain patches only, until the time of the proposed pressure quench, when more nuclei, within the interstices, appeared, and the quartz-feldspar intergrowth resulted. It seems likely that emplacement of the granites followed continuously after the emplacement of the transition group, and that crystallization of the interstitial liquids in the latter group was not completed until the final stage of pressure reduction.

Patches showing granophyric intergrowths are also found in certain heterogeneous syenites margining the southern granite body (fig. 9). Since it was argued that these rocks were emplaced during an early, separate phase of intrusion, it seems unlikely that interstitial liquid persisted up to the time of intrusion of the granite body. The patches showing the intergrowth may have been formed by partial remelting at quartz-feldspar boundaries. Although a rock of the bulk composition of the quartz syenite would not be expected to melt completely at any particular P_{H_2O} when the granite was emplaced, there is no reason why partial melting at quartz-feldspar boundaries should not occur. The rocks concerned also show the greatest development of sodic pyroxenes found in the syenite suite, so that it appears that alkali metasomatism may also have affected these rocks. The patches of quartz-feldspathic liquid were still not crystalline at the time of the pressure reduction which produced the granophyric textures in the nearby microgranitic body. The syenites near the western contacts of the northern granite, do not show granophyric intergrowths, but neither do the granites in the vicinity of the contact. Both rocks have here cooled slowly, and consolidated before the 'pressure quench' episode.

Origin of the Puklen magmas and summary of intrusive history

The derivation of the Puklen magmas can hardly be discussed in isolation from the nearby, much larger Nunarssuit syenite and its satellite granite bodies, in particular the superfically rather similar mass of Malenefjeld. Since detailed work on these bodies is in progress by P. B. GREENWOOD it seems best, at this stage to restrict our discussion to conclusions which can be drawn directly from Puklen, and to the possible explanation of some of the features peculiar to the Puklen body.

The mineralogical and chemical data offer a simple picture of continuous fractionation in the Puklen mass generating a continuum of rock types between a subaluminous, just saturated syenite, to peralkaline, strongly oversaturated soda granite. If the present extent of the rock types is representative at all, the parental magma would have to be strongly oversaturated, with perhaps 10–15 % normative quartz. Rocks in this compositional range are distinctly uncommon in the Gardar province (Sørensen, 1966) although the norms tabulated by Watt (1966) show them to be far from rare. Macdonald (1969) shows that rocks with normative quartz in the 11–20 % range are quite absent from the Tugtutôq dyke suite. They occur at Puklen only as members of the limited transition group suite. Locally in the heterogeneous quartz syenites the quartz content may exceed 10 %, but this is due to deposition from the late vapour phase and the quartz syenite magma must have contained considerably less than 10 % normative quartz. It therefore seems unlikely that the entire Puklen sequence was generated from one magma of roughly the composition of the transition group rocks both on local and regional grounds.

The textural contrast between heterogeneous quartz syenites and quartz syenites in the transition group suggest that the Puklen body was fed by two major magmatic pulses. The earliest phase, a slightly over-saturated augite syenite, generated quartzose derivatives and was emplaced under conditions permitting the retention of a sodic vapour phase. This vapour phase gave rise to the drusy and patchily pegmatitic nature of many rocks, and is always associated with the more quartzose derivatives of the first phase of intrusion. The sporadic development of quartz is perhaps best explained as a result of local filter pressing as a result of periodic magmatic movement. The textural evidence is that the rocks formed a rather open network of feldspar crystals. The porphyritic syenites, which are compositionally early members of this sequence may represent recrystallized xenoliths, representing an earlier phase of crystallization, caught up in a later magma pulse of broadly identical composition.

The second intrusive phase involved the transition group rocks, the soda granites, and their final fine-grained derivatives. Texturally the rocks form a continuum, closing with fine-grained members, in contrast to the coarse acid derivatives so conspicuous in the Nunarssuit and Kûngnât intrusions (Harry & Pulvertaft, 1963; Upton, 1960). In terms of quartz content the rocks also form a complete gradation from 9 % modal quartz up to thoroughgoing soda granites with 30 % modal quartz. The break between the two groups is not well defined but the appearance of large crystals (as opposed to fringes or rims) of riebeckite-arfvedsonite and the appearance of strongly acmitic pyroxenes is the most distinctive feature of the soda granites. Quartz-rich (22 %) transition group rocks and quartz-poor granites (12 %) are found. The transition group show unequivocal evidence of crystal accumulation *in situ*, and they could be regarded as rocks produced by feldspar accumulation from a soda granite magma lying within the feldspar field close to a unique fractionation curve in the An-poor part of the system Ab-Or-An-Qz. The situation is complicated by the existence of dykes of intermediate quartz content, which suggest that this feldspar enriched melt was mobile. The fine-grained dykes, and the occasional dykes with lath-shaped alkali feldspars suggest that the cumulus feldspars were not carried along as a crystal mush on intrusion of the dykes, so that a limited development of a magma of intermediate quartz content appears to have existed, at least transiently, during development of the Puklen rocks.

The granite intrusive phase produced coarse soda granites, with strongly peralkaline affinities, and the rocks were affected by a late, volatile-rich phase which crystallized replacive acmite, quartz and albite. The leucocratic residua were subjected to a sudden pressure loss before crystallization was complete, and feldsparphyric granophyres and fine-grained micrograinites (some showing spherulitic structures) resulted. Acmite does not appear in the micrograinites, which is also consistent with loss of volatiles on pressure reduction. The appearance of *an* in the norms of the micrograinites may be attributable to contamination by country rock, because of the relatively high CaO content and presence of altered early plagioclase crystals.

The observation that the Puklen rocks lie so close to the trend of the experimentally established thermal minimum in the feldspar field of the system Ab-Or-Qz suggests that the two main Puklen magmas, whilst themselves able to fractionate, were in turn generated at depth by fractionation processes. It remains to be established whether there are real differences between Puklen and the other Nunarssuit intrusives. Whether the mass represents tappings from the much larger fractionated bodies nearby, or a distinct and complete intrusive cycle in itself could only be established by chemical comparisons between the various bodies elsewhere in Nunarssuit, and in particular of the Malenefjeld intrusion. Existing analyses (as tabulated by WATT, 1966) do show certain differences, of which the peraluminous nature of the Nunassuit syenites and contrastingly more peralkaline nature of the analyzed Nunarssuit soda granite are the most striking (fig. 22). Normative feldspar compositions (plotted on fig. 23) are very similar, however, but there is a complete lack (in the analyzed rocks) of thpes with intermediate quartz contents. However, in view of the detailed chemical work in preparation by P. B. GREENWOOD, it seems unwise to further pursue these comparisions.

The demonstration that the Puklen intrusion involved two magmatic pulses, of strongly differing quartz contents, and that essentially *in situ* fractionation produced the continuum of rock types now found seems to be the most useful conclusion, in terms of regional petrogenesis, produced by this study. It would be interesting to establish whether the two magma pulses correlate chemically with other Nunarssuit rocks. Perhaps the retention of volatiles at the close of the syenite phase of intrusion, and the 'pressure quench' envisaged at the close of the intrusive history of the body, can also be related to conditions during the emplacement of the larger Nunarssuit intrusives.

ACKNOWLEDGEMENTS

The writer's visit to Nunarssuit in 1966 was financed by the Carnegie Trust for the Universities of Scotland. P. B. GREENWOOD, who accompanied me, was supported by an NERC Research Studentship. We are indebted to the Director of Grønlands Geologiske Undersøgelse, K. ELLITSGAARD-RASMUSSEN, for his permission to use G.G.U. facilities at Dyrnæs, and to numerous personnel at Dyrnæs, in particular Mr. J. HANSEN and Mr. E. SCHOU JENSEN for their energetic help with the provision of transport and supplies out to Nunarssuit. I am grateful to Mr. T. C. R. PULVERTAFT for allowing me to follow up his fieldwork on the Puklen body, and to Dr. C. H. EMELEUS for introducing me to Greenland geology.

Thanks are also due to members of the Geology Department at Aberdeen, in particular Dr. M. MUNRO, Mr. R. MAITLAND and Mr. G. MORRIS for XRF analyses, and Dr. M. A. LAPPIN and Mr. R. J. CLARK for wet analyses.

REFERENCES

BAILEY, D. K. 1969: The stability of acmite in the presence of H_2O. *Am. J. Sci.*, **267** A., Schairer vol. 1–16.

BAILEY, D. K. & SCHAIRER, J. F. 1966: The system Na_2O-Al_2O_3-Fe_2O_3-SiO_2 at 1 atmosphere, and the petrogenesis of alkaline rocks. *J. Petrology*, **7**, 114–170.

BARTH, T. F. W. 1969: *Feldspars*. New York: Wiley-Interscience.

CARMICHAEL, I. S. E. 1963: The crystallization of feldspar in volcanic acid liquids. *Q. Jl. geol. Soc. Lond.* **199**, 95–131.

DUNHAM, A. C. 1965: The nature and origin of the groundmass textures in felsites and granophyres from Rhum, Inverness-shire. *Geol. Mag.*, **102**, 8–23.

HARRY, W. T. & PULVERTAFT, T. C. R. 1964: The Nunarssuit Intrusive Complex, South Greenland. Part 1: General description. *Bull. Grønlands geol. Unders.*, **36** (also *Meddr Grønland* **169**, 1).

JAMES, R. S. & HAMILTON, D. L. 1969: Phase relations in the system $NaAlSi_3O_8$ $KAlSi_3O_8$-$CaAl_2Si_2O_8$-SiO_2 at 1 Kilobar water vapour pressure. *Contr. Miner. Petrol.*, **21**, 111–141.

LEIGHTON, M. W. 1954: Petrogenesis of a gabbro-granophyre complex in northern Wisconsin. *Bull. geol. Soc. Am.*, **65**, 401–442.

LUTH, W. C. & TUTTLE, O. F. 1969: The hydrous vapor phase in equilibrium with granite and granite magmas. *In* Igneous and Metamorphic Petrology, *Geol. Soc. Am. Mem.* **115**, 513–548.

MACDONALD, R. 1969: The petrology of alkaline dykes from the Tugtutoq area, South Greenland. *Meddr dansk geol. Foren.*, **19**, 257–282.

MARTIN, R. F. 1969: The hydrothermal synthesis of low albite. *Contr. Miner. Petrol.*, **23**, 323–339.

MEHNERT, K. R. 1968: *Migmatites and the origin of granitic rocks*. Amsterdam: Elsevier.

MORSE, S. A. 1970: Alkali feldspars with water at 5kb pressure. *J. Petrology*, **11**, 221–251.

NOLAN, J. & EDGAR, A. D. 1963: An X-ray investigation of synthetic pyroxenes in the system acmite-diopside-water at 1000 kg/cm^2 water-vapour pressure. *Mineralog. Mag.*, **33**, 625–634.

PARSONS, I. 1965: The feldspathic syenites of the Loch Ailsh intrusion, Assynt, Scotland. *J. Petrology*, **6**, 365–394.

PARSONS, I. & BOYD, R. 1971: Distribution of potassium feldspar polymorphs in intrusive sequences. *Mineralog. Mag.*, **8**, 295–311.

PULVERTAFT, T. C. R. 1961: The Puklen intrusion, Nunarssuit, SW Greenland. *Bull. Grønlands geol. Unders.*, **29** (also *Meddr Grønland* **123**, 6).

RILEY, J. P. 1958: Simultaneous determination of water and carbon dioxide in rocks and minerals. *Analyst*, **83**, 42–49.

SØRENSEN, H. 1966: On the magmatic evolution of the alkaline igneous province of South Greenland. *Rapp. Grønlands geol. Unders.*, **7**.

THOMSON, R. N. 1969: Tertiary granites and associated rocks of the Marsco area, Isle of Skye. *Q. Jl. Geol. Soc. Lond.*, **124**, 349–385.

THOMSON, R. N. & MACKENZIE, W. S. 1967: Feldspar — liquid equilibria in peralkaline acid liquids: an experimental study. *Am. J. Sci.*, **265**, 714–734.

TUTTLE, O. F. 1952: Origin of the contrasting mineralogy of extrusive and plutonic salic rocks. *J. Geol.*, **60**, 107–124.

TUTTLE, O. F. & BOWEN, N. L. 1958: Origin of granite in the light of experimental studies. *Geol. Soc. Am. Mem.*, **74**.

TYLER, RUTH C. & KING, B. C. 1967: The pyroxenes of the alkaline igneous complexes of eastern Uganda. *Mineralog. Mag.*, **36**, 5–21.

UPTON, B. G. J. 1960: The alkaline igneous complex of Kûngnât Fjeld, South Greenland, *Bull. Grønlands geol. Unders.*, **27** (also *Meddr Grønland* **123**, 4).

— 1961: Textural features of some contrasted igneous cumulates from South Greenland. *Bull. Grønlands geol. Unders.*, **29** (also *Meddr Grønland* **123**, 6).

— 1964: The geology of Tugtutôq and neighbouring islands, South Greenland. Part II. Nordmarkitic syenites and related alkaline rocks. *Bull. Grønlands geol. Unders.*, **44** (also *Meddr Grønland* **169**, 2).

VOGT, J. H. L. 1928: On the graphic granite. *Norske Videnskapselskapets*, *Förh.* **1**, 67 only.

VOLL, G. 1960: New work on petrofabrics. Lpool. Manchr. Geol. J., **2**, 521–525.

WATT, W. S. 1966: Chemical analyses from the Gardar Igneous Province, South Greenland. *Rapp. Grønlands geol. Unders.*, **6**.

WILSON, A. D. 1955: A new method for the determination of ferrous iron in rocks and minerals. *Bull. geol. Surv. G.B.*, **9**, 56–58.

Færdig fra trykkeriet den 12. juli 1972.

PLATE

Plate 1

Fig. 1. Photomicrograph of typical Puklen granophyre from the southern granite body (926). Euhedral microperthitic alkali feldspars are set in a matrix showing the characteristic granophyric intergrowth nucleated on the margins of the phenocrysts and becoming progressively coarser away from them.

Crossed nicols. Vertical height of photograph 5 mm.

Fig. 2. Photomicrograph of fine-grained microgranite cutting the northern granite body (948). Rudimentary spherulitic structures appear at intervals in this fine, felsitic rock, which does not otherwise show textures of granophyric type (see sketch, fig. 17). The left of the field shows an altered and corroded plagioclase phenocryst (see text). Note that this phenocryst has not acted as a nucleus for the spherulitic structures as have the alkali feldspars in the upper photograph.

Crossed nicols. Vertical height of photograph 1.25 mm.

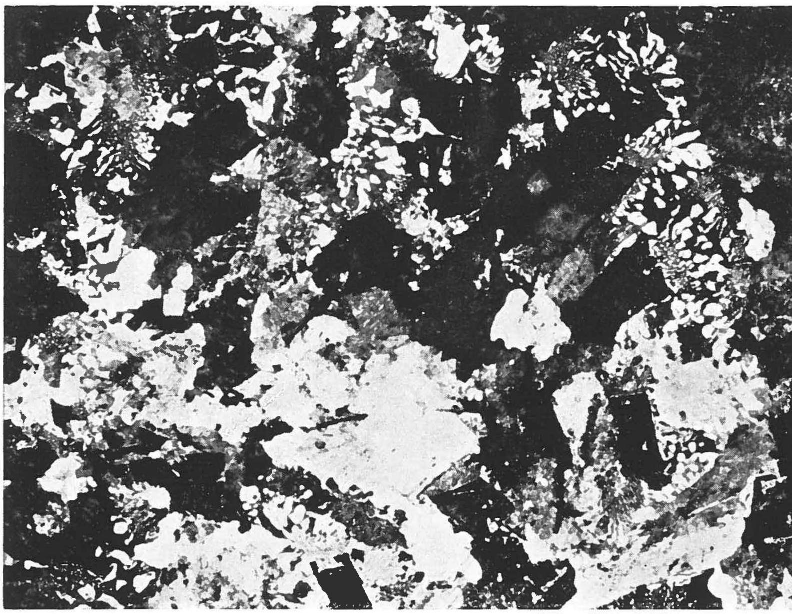

Fig. 1.

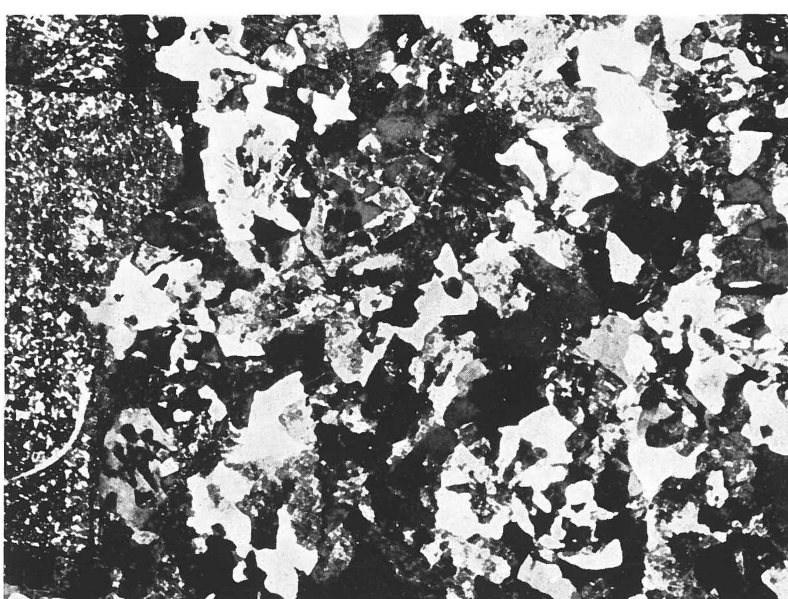

Fig. 2.