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GRØNLANDS GEOLOGISKE UNDERSØGELSE

THE GRØNNEDAL-ÍKA ALKALINE COMPLEX, SOUTH GREENLAND

THE STRUCTURE AND GEOLOGICAL HISTORY OF THE COMPLEX

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WITH 25 FIGURES IN THE TEXT
AND 3 MAPS

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Abstract.

The Grønnedal-Íka alkaline complex consists of predominantly foyaitic nepheline syenites and carbonatite intruding gneisses and metasediments near Ivigtût, South Greenland. The complex is intruded by numerous dolerite, basalt, trachyte and phonolite dykes; it is severely faulted. The complex is considered to be of Pre-Cambrian age.

Several distinct intrusive phases are recognised in the syenites: an early Lower Series, mainly of medium-grained well-laminated foyaite, is overlain by a raft-like mass of gneiss that separates it from a later, Upper Series containing foyaite, a pyroxene-rich syenite, and pulaskite in small amounts. The Upper Series rocks are generally well-laminated and in addition a small amount of conformable mafic layering is developed in the pyroxene-rich member. There are structural and textural similarities between the laminated and layered members of the Lower and Upper Series, and igneous cumulates. The north-western margin of the complex is defined by a curving dyke-like intrusion of granular syenite, considered to be an incomplete ring-dyke. The Upper Series syenites are cut by a steep-sided body of porphyritic xenolithic syenite, the latest major syenite intrusion in the complex.

The nepheline syenites have been intruded by carbonatite which was forcibly emplaced with brecciation and metasomatic alteration of its surroundings. The carbonatite is calcite-rich (Sövite) with variable quantities of siderite, sphalerite, apatite and other minerals.

The earliest dykes cutting the alkaline complex are a sparse set of lamprophyres, these were followed by thin sheets and dykes of dolerite containing numerous plagioclase phenocrysts, often several centimetres in length. There then followed several thick dykes of olivine dolerite, striking between E.–W. and N.E.–S.W. and members of a regional swarm. These are cut by a group of thin, microporphyritic basalts and subsequently by two groups of trachytic and phonolitic dykes; an early sparse set striking approximately N.N.W.–S.S.E. and restricted to the vicinity of the complex, and a later, E.N.E.–W.S.W. striking set that are part of an extensive swarm in the country around Ivigtût. Finally, faulting took place in three stages: i) an early group of dextral transcurrent faults striking about N. 10–30 E., ii) an E.S.E.–W.N.W. striking sinistral transcurrent fault, the Laksenæs Fault, and iii) a late dextral transcurrent group striking approximately N.–S. There is evidence of some overlap between the emplacement of the trachytic and phonolitic dykes, and the faulting.

The present outline of the complex measures approximately 8 km. from N.N.W. to S.S.E. and 2.8 km. from E.N.E. to W.S.W. When allowance is made for the distortion due to dyke intrusion and faulting the original outline is found to have been about 6 km. from N.W. to S.E. and 3.5 from N.E. to S.W. The original structure is seen to have been relatively simple, consisting of two series of laminated and layered syenites with centrally-directed structures separated by a raft of gneiss, and a later central stock of porphyritic xenolithic syenite. The syenites were cut by a central plug of xenolithic carbonatite, zoned from calcite-rich margins to a core containing appreciable quantities of siderite and other minerals. Metamorphism of the siderite-rich core by an olivine dolerite dyke resulted in the formation of a small body of magnetite-rich carbonate rock in the centre of the complex.

PREFACE

The mapping of the Grønnedal-Íka alkaline complex for the Geological Survey of Greenland, Grønlands Geologiske Undersøgelse, was carried out during the summer field seasons of 1956, 1957 and 1958, supplemented by a brief visit during August 1962. The work forms a part of the Survey's programme of regional mapping in South Greenland.

The author gratefully acknowledges the help and encouragement received from members of the Survey, especially Professor Asger Berthelsen, D. Phil., who co-ordinated the mapping of the country around Ivigtût, and K. Ellitsgaard Rasmussen, M. Sc., Director of the Survey. He is particularly grateful to Dr. B. G. J. Upton, Edinburgh University, for assistance with the mapping and for stimulating discussion and useful advice, to J. Bondam, M. Sc., for generously allowing full use to be made of his preliminary field and laboratory studies on the carbonatites and other rocks of the complex, and to stud. mag. P. E. Budtz and stud. mag. H. Andersen for assistance in the field.

Since the area has some economic interest, some geological and geophysical investigations, together with a programme of drilling, were carried out by Kryolitselskabet Øresund A/S. The author is indebted to the Company, and Dr. H. Pauly, for permission to make use of their results and sample the cores, and also for their unstinted hospitality while he was at Ivigtût.

During the field work the Commander of the naval station at Grønnedal very kindly placed the hut at Jernhat at the author's disposal, providing a most welcome refuge from the vagaries of the weather and the attentions of the abundant insect life.

Technical assistance was given by Mr. C. Chaplin and other members of the laboratory staff of the Department of Geology at Durham University, and by the staffs of the drawing and sectioning departments of the Survey at Copenhagen.

The author would also like to thank Professor L. R. Wager, Oxford University, for the essential introductions to Greenland geology, and Professor K. C. Dunham and others at Durham University for help and encouragement during the preparation of this account.

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INTRODUCTION

The Grønnedal-Íka alkaline complex is the oldest of several alkaline intrusions in the country around the cryolite mine at Ivigtût on Arsuk Fjord (Plate 1). The present outline of the complex is elongate, it measures approximately 8 km. from N.N.W. to S.S.E. and 3 km. from N.E. to S.W. It forms a tract of low-lying, relatively accessible ground extending from Eqaluit and Grønnedal on Arsuk Fjord to Íka (Plate 2), scrub-covered valleys rising in gentle slopes from sea level to bare rounded hills about 500 m. in height. Steeper, scree-covered slopes are found on the N.W. side of Íka, to the S.E. of Eqaluit, and in the Cirkus in Grønnedal. The gentle relief and tendency to form scree result from the ease with the syenites disintegrate to a coarse feldspathic gravel, a weathering feature shared with other nepheline syenites in South Greenland (cf. Ussing, 1912, Plate 7).

The complex (Plate 2) may be approached from most directions. A route into the northern parts is provided by the Kontaktelv, or by climbing the steeper slopes near the small stream draining the area around Tøffelsø. This ground is also easily reached from Grønnedal by climbing the gentle slopes north of the track between the coast and the bridge over Bryggerens Elv about 1 km. inland. Further east, the ridge of Skraldebunken gives access to the hills west of the Langesø. The S. E. extremity of the syenites is reached from the shore at Íka. On the N.W. of the fjord there is a good route from the coast to Xenolithsø up Urdal, it is also possible to climb from the hut at Íkasletten straight up the scree-covered slopes to the N.W. and so gain the ridge east of Xenolithsø, from which it is an easy walk to the lake and the hut at Jernhat. Another route, further to the north, starts from the hut at Íkasletten and follows the western side of the western stream leading in to Turistkløft for about 2 km. At this point there is a steep valley cut into the western side of the main valley which leads to the plateau immediately south of Tolvsøer, from here on it is a fairly short walk over undulating ground to the Hytteelv at about 300 m., and on to the track about 800 m. N.W. of the hut at Jernhat.

The recently constructed road from Ivigtût to Grønnedal makes it an easy matter for the visitor to Ivigtût who has a day or two to spare to visit the carbonatites and syenites in the centre and north of the complex. There is a jeep track from the coast near Grønnedal to the hut at Jernhat and at times it is possible to drive as far as the low ridge north of the Øvre Radiosø.

With the exceptions of the settlements at Ivigtût and the harbour area at Grønnedal there are no habitations on or near the complex. Small huts have been built at Eqaluit, Îkasletten, and on the old iron-ore prospect at Jernhat, however these are only occupied at infrequent intervals.

The geological mapping was carried out on 1:10.000 maps enlarged from 1:20.000 sheets supplied by the Geodetic Institute, Copenhagen. These were supplemented by vertical aerial photographs enlarged to about 1:20.000, also supplied by the Geodetic Institute, and by additional aerial photographs on 1:10.000 scale taken from Survey helicopters in 1958.

PREVIOUS INVESTIGATIONS

The earliest record of nepheline syenite at Grønnedal-Íka seems to have been the mention made by TAYLOR who visited the area in 1855 and collected specimens (CALLISEN, 1943). A later visitor in the last century was N. HOLST who collected further material and noted, amongst other things, the occurrence of limestone with iron ore near Íka (HOLST, 1886). The first systematic mapping was begun by N. V. USSING and O. B. BØGGILD about the beginning of this century (CALLISEN, 1943, pp. 10, 11); after this little was done on the complex until the 1930's when Dr. CALLISEN extended her investigations of the igneous rocks of the Ivigtût region to include those of the Grønnedal-Íka area. C. E. WEGMANN makes only passing reference to the complex in his classic account of the geology of southern Greenland (WEGMANN, 1938) and mentions it but briefly in a review article on the geology of southern Greenland published shortly afterwards (WEGMANN, 1939). Samples of sand were collected by WEGMANN from the coast at Eqaluit, Grønnedal, and Íka, though none of the material appears to have been derived from the alkaline rocks (CROMMELIN, 1937, localities 15, 16, 26).

Up to the present the most detailed published account of the complex is that by Dr. CALLISEN (1943). This contains several sketch maps, and petrographic descriptions of specimens she collected, as well as of material from the earlier visits by USSING and BØGGILD. Further reference will be made to this work which provides a valuable contribution to our knowledge of the area. It is perhaps useful at this stage to give a brief outline of some of the conclusions reached by Dr. CALLISEN. She recognised that the alkaline rocks were clearly intrusive towards their surroundings, and that fine-grained facies developed against the gneisses. The syenitic magma was considered to have chilled against the country rocks on emplacement, giving a border series within which the remaining magma crystallized with settling of pyroxene to form a lower series of mafic syenites leaving a magma which crystallized to give pulaskitic upper rocks. It was found that although there was considerable compositional variation within the syenites the majority of the types showed gradational relationships towards one another (ibid., p. 72). An ijolitic facies was discovered and the suggestion made that this might be connected with the small occurrence of limestone within the complex. The paper contains three analyses of nepheline syenites from the complex, with comparisons between these and other similar rocks from Greenland and elsewhere.

In more recent years investigations were made by the late RICHARD BØGVAD, formerly geologist to the Cryolite Company. He published several short papers on the area, including a general description of the magnetite occurrence at Jernhat (BØGVAD, 1947) which contains a discussion of the economic possibilities of the deposit as a source of iron ore, and information on a magnetic survey of the ground. A subsequent paper contains details of the results of drilling of the ore body (BØGVAD, 1951).

A preliminary survey of the complex was carried out by J. BONDAM for the Geological Survey of Greenland in 1954. In the course of this a number of important discoveries were made, including the recognition of a substantial north-south fault zone with a total dextral horizontal movement of about 1600 m. The limestones and iron occurrences mentioned by earlier geologists were shown to have many of the characteristics of carbonatites, and to occupy a central position within the complex. The magnetite in the carbonatite was demonstrated to have a close spatial connection with large dolerite dykes, a conclusion strongly supported by the results of a magnetometer survey (see p. 37 and fig. 13). In a scintillometer survey BONDAM detected an increased amount of radioactivity in association with the carbonatite and later faulting.

GEOLOGICAL SETTING

General.

The broad structural divisions of southern Greenland established by C. E. Wegmann (1938) have been elaborated and modified in the Ivigtût area by the members of the Survey engaged in the detailed mapping. A comprehensive geological history of the region has been built up by A. Berthelsen from the results of the different field parties, this is summarised in Table 1. (Berthelsen, 1958).

The fundamental division is into an early group of gneisses, metavolcanics, metasediments, basic dykes, and granites, which belong to

Table 1. Summary of the geological history of the country around Ivigtût.

Post-Gardar	Quaternary glaciation
	N.N.W.–S.S.E. olivine dolerite dykes
Gardar Period	Kûngnât Intrusive Complex
	WNW-striking sinistral transcurrent faults
	Alkaline dykes (trachytes, phonolites)
	Microporphyritic basalt dykes.
	Movements in the Main Fault Zone of Ivigtût (= First group of Grønnedal-Íka)
	Cryolite mineralization.
	Intrusion of trachyandesite dykes
	Ivigtût granite
	Trachytic dykes
	Movements in the Main Fault Zone of Ivigtût. (= First group of Grønnedal-Íka)
	Intrusion of olivine dolerite dykes (Bd 0, Bd 1, etc.)
	Intrusion of big-feldspar dykes (= Porphyritic dolerites of Grønnedal-Íka)
	Intrusion of lamprophyric dykes.
	ENE crush zone and faulting.
	Grønnedal-Íka nepheline syenites and carbonatites.
	Trachytic dykes.
Sanerutian	Granites of Tigssaluk, etc.
	Basic dykes, now amphibolites.
Ketilidian	Gneisses and metasediments.

Based on a compilation by A. Berthelsen (1958) with slight modifications.

the Ketilidian and Sanerutian phases, and a later group with plutonic intrusions, usually of alkaline character, numerous dykes and, to the south of Ivigtût near Julianehåb, supracrustal rocks including lava flows, pyroclastic deposits, and arenaceous sediments. The igneous activity of the younger members of this later group, the Gardar, took place 1150–1200 m. y. ago (MOORBATH, WEBSTER and MORGAN, 1960).

Country rocks.

The nepheline syenites and carbonatites were emplaced in quartzo-feldspathic gneisses of rather monotonous character. Some variety is introduced by the presence of more basic members including gabbro-anorthosites, and amphibolites of demonstrably igneous origin which form several generations of dykes (BERTHELSEN, 1961). BONDAM found indications of metasedimentary rocks on the ridge between Turistkløft and Forkertekløft N. N. W. of Íkasletten (Plate 2); these are probably the northern continuation of a group of biotite schists, quartzo-feldspathic gneisses, and calc-silicate rocks mapped by the author at the southern end of the complex, S. E. of Íka. These metasediments resemble in some respects members of the Sermilik Group of metasediments at Taylor's Havn and on Arsuk Ø (WEGMANN, 1938).

Along the N. E. side of the complex there is a band of biotite gneiss with prominent red crystals of alkali feldspar (e. g. 27026)[1]). This band is several hundred metres in width and may be followed into the gneisses to the north of the complex; it is not related to the nepheline syenites or other alkaline rocks.

Early Faulting.

Mylonites cut by amphibolite dykes are known on the Ivigtût peninsula, while on either side of the Langesø the biotite gneisses show signs of movements and cataclastic action which have not affected the syenites. Direct evidence of pre-syenite faulting is generally difficult to obtain: near Grønnedal the only well established instance is the Laksenæs Fault which had a long and complicated history of movement before the Gardar period (HENRIKSEN, 1960; see also p. 65–66).

Gardar intrusions.

The syenites and carbonatites of the complex are early members of the Gardar igneous activity. They preceded the extensive suite of

[1]) The numbers (27026 etc.) refer to specimens from the collections of the Geological Survey of Greenland (Grønlands Geologiske Undersøgelse, abbreviated to G. G. U.), which are normally housed at the Mineralogisk Museum, Østervoldgade 7, København K., Denmark.

olivine dolerite dykes and may occupy much the same position in the igneous chronology as some of the earlier intrusions on Tugtutôq (UPTON, 1963). The Grønnedal-Íka intrusions are definitely earlier than the syenites and gabbros of the Kûngnât Intrusion (UPTON, 1960), and the syenites, gabbros and granites of Nunarssuit and Alángorssuaq (HARRY & PULVERTAFT, 1963) all of which are later than the suite of dykes cutting the Grønnedal-Íka complex.

The relative ages of the syenites and carbonatites at Grønnedal-Íka and the nearby granite–cryolite body at Ivigtût are not certain. A suite of alkaline dykes intruding the syenites and carbonatites appears to be cut by the granite at Ivigtût although intersections with the latter are not numerous. None of the late N.N.W.–S.S.E. olivine dolerite dykes cuts either complex.

Although most of the igneous activity at Grønnedal-Íka appears to be of early Gardar age, the complex was the focus for renewed intrusion in later Gardar times when numerous trachytic, phonolitic and other alkaline dykes were emplaced (see p. 57 et seq.).

With the exception of the late N.N.W.–S.S.E. olivine dolerite dykes, which may be of Tertiary age (BERTHELSEN, 1961), there is a complete absence of evidence of any geological activity from the Pre-Cambrian until the Quaternary when the countryside was over-ridden by ice from the main Greenland ice-cap (the Inlandsis of Scandinavian literature). Signs of this glaciation are everywhere in evidence, from the deep trench-like valley of Íka to the blanket of moraine covering parts of central Grønnedal to depths of ten metres and more. These morainic deposits and the ready-weathering qualities of the syenites combine to make the complex one of the poorer exposed amongst the Gardar intrusions.

MEMBERS OF THE ALKALINE COMPLEX

I: The Nepheline syenites.

General.

From the earlier descriptions by CALLISEN (1943) and J. BONDAM it was clear that considerable variation occurred within the syenites of the complex. This has been confirmed by the present survey: it proved possible to map the distribution of several distinct syenite units (Plate 2). In a number of instances the syenites were intrusive towards one another, in other examples complete gradation occurred between petrographically distinct types.

The original forms and inter-relationships have been complicated and to some extent obscured by later intrusions and faulting, and by the glacial deposits, especially in the centre and south of the complex. The north-western part is relatively undisturbed and free from drift so that to a large extent this has served as the key area in interpreting the syenites; the several types distinguished here have been followed through the remainder of the complex.

Petrographically the nepheline syenites include a wide variety of named types. Foyaite predominates, but ditroite, ijolite and malignite are present, and also nepheline-poor types such as pulaskite, which may pass to perthosites occasionally. Since single intrusive units may contain several named types in gradational relationship, even within the limits of a single hand specimen (Fig. 1, 39724), it is considered more profitable to describe the rocks in terms of their mineral content, restricting as far as possible the number of distinctive rock names.

The mineralogy and petrography of the syenites will only be considered briefly in this account as it is intended to deal more fully with this aspect in a later publication. It should be noted that all the syenites are nepheline-bearing with the possible exception of a thin marginal sheet east of Rypefjeld (27131). Nepheline is frequently replaced by alteration products, the commonest is a fibrous, micaceous aggregate termed 'gieseckite'. In this account all references to syenite should be taken to mean nepheline syenite unless the contrary is stated.

The syenites contain abundant thin platy crystals of alkali feldspar which frequently develop a strong form-orientation, giving the rocks

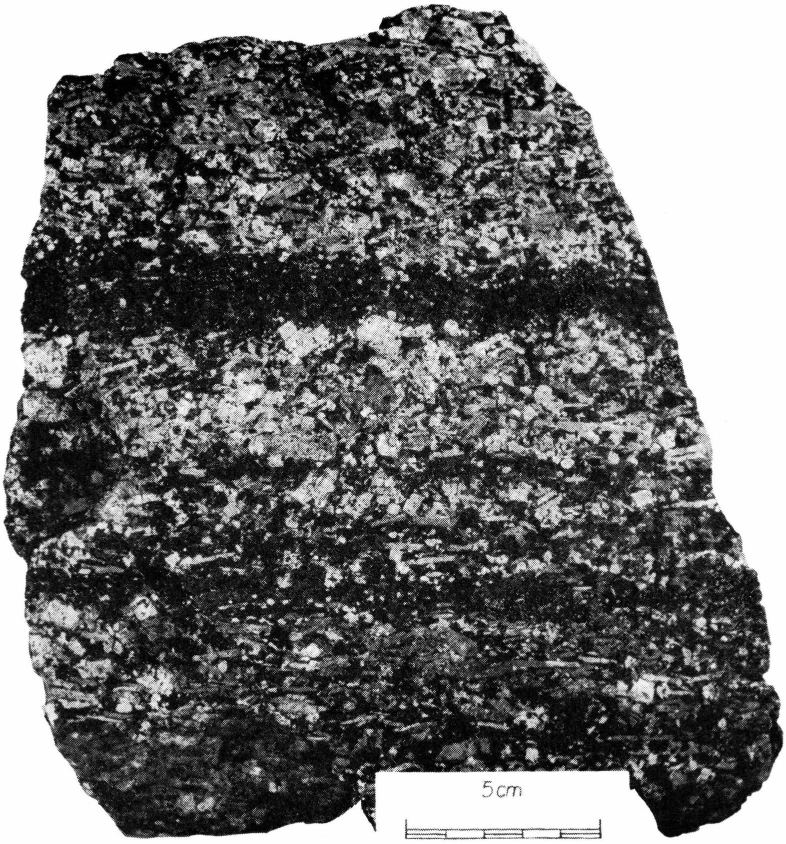

Fig. 1. Specimen of laminated and layered syenite (39724) from the pyroxene-rich syenite of the Upper Series. Specimen collected about 150 metres S.E. of Tøffelsø.

an excellent lamination or trachytoidal texture. The lamination was mapped throughout the complex; in general it is centrally directed and conformable with compositional layering in the two principal syenite series (Plates 2 & 3; see also p. 20 et seq.).

Petrography.

Granular syenite.

The syenite consists of perthitic alkali feldspar, aegirine-augite and nepheline in crystals to 5 mm. across. These are generally equigranular and anhedral to subhedral although occasionally the alkali feldspars are tabular and the rock may be laminated. The equigranular texture characteristic of much of the group is less pronounced in the outer dyke-like intrusion south of Eqaluit where the feldspar is distinctly larger (crystals to 10×7×3 mm.). There are scattered pockets of pegmatitic syenite in this intrusion (27100), biotite can become a prominent constituent, and nepheline is occasionally found in large poikilitic crystals.

Coarse-grained brown syenite.

This syenite is usually altered, only the alkali feldspar crystals escaping these affects. The feldspar is microcline-microperthite and occurs in large platy crystals over 1 cm. in diameter. Other minerals are difficult to identify; gieseckite after nepheline is common, cancrinite is also found as an alteration product of nepheline when it is generally present as aggregates of granular or somewhat acicular crystals. Original aegirine-augite is now represented by areas of chlorite and pale green amphibole. This syenite is generally structureless in hand specimen except in the outcrops immediately below the Foyaite of the Lower Series where it develops lamination.

Foyaite of the Lower Series.

The distinguishing features of this syenite in hand specimen and thin section are the slender plates of alkali feldspar and the extreme lamination (27113), particularly in rocks where the proportions of mafic minerals are low (27136). The alkali feldspar is generally microcline-microperthite in crystals about 1–2 mm. in thickness and measuring 10×7 mm. on the flat surfaces. It is accompanied by small euhedral prisms of nepheline to 2 mm. in length. Interstitial, poikilitic crystals of green aegirine-augite can be up to several millimetres across. In certain parts of the group, as in the Kontaktelv, there may be a high proportion of intensely pleochroic dark brown biotite in poikilitic crystals several millimetres in diameter (27202). Alkali feldspar and nepheline are often enclosed by poikilitic areas of cancrinite. The cancrinite may replace nepheline, in extreme instances small, rounded areas of optically-continuous nepheline occur within single poikilitic, ramifying crystals of cancrinite; it is unusual to find fibrous aggregates of cancrinite as replacements of nepheline. Interstitial carbonate and fluorite are also present. The foyaites are thought to form part of a layered series of syenites which originated by settling and bottom accumulation of alkali feldspar and nepheline, the trapped liquid crystallizing to form the other minerals (see Upton, 1961, pp. 23–27).

In the field the fresh lilac-grey or mauve-grey coloured Foyaite passes into a dull brown syenite of similar grain-size along and across the strike of the lamination. In part the changes may have resulted from post-consolidation alteration connected with faulting and later intrusions, but in some examples it almost certainly reflects primary differences brought about by variation in the amounts of late-crystallizing liquid enmeshed in the early formed minerals of the syenite. It was noted that the brown, altered Foyaite was not always as well laminated as associated fresher rocks. On the assumption that these rocks are igneous cumulates (WAGER et al., 1960), the altered rocks could represent loosely packed cumulates with a high proportion of intercumulus liquid rich in F, CO_2, and water which reacted with and altered the cumulus minerals on final consolidation. By contrast, the well-laminated Foyaite contained little trapped liquid and suffered only slight alteration during the last stages of crystallization. Similar relationships were noted in parts of the Upper Series Foyaite.

The mineral proportions vary quite widely in the Foyaite. In the lower parts of the Radio Elv normal foyaite passes into a rock approaching perthosite, across the strike of the lamination. The biotite-rich syenites in the Kontaktelv appear to be the lateral equivalents of normal foyaites in the cliffs south of Eqaluit. In general, however, sharp variations in mineral proportions take place across the strike of the lamination; there is a fairly large-scale and rather ill-defined mineral layering in the Foyaite which shows up as a weak terracing on the N.W.-facing hillside about 1.3 km. S.S.W. of the huts at Eqaluit.

Foyaite and pulaskite of the Upper Series.

The fresh rocks are pale lilac or grey coloured. They are of medium to coarse grain, containing abundant platy crystals of perthitic alkali feldspar (up to $15 \times 10 \times 3$ mm.), euhedral prisms of nepheline (up to 4 mm. in length), interstitial and poikilitic aegirine-augite, cancrinite, ore, and occasional biotite and amphibole. The thin section textural relationships are very similar to those in the Foyaite of the Lower Series, although on a coarser scale. The nepheline is subject to similar alterations, as is the pyroxene. When alteration has been extensive the rocks take on a dull brown or red-brown colour, similar to the altered Foyaite in the Lower Series, and also the coarse-grained brown syenite of that series. Examination of numerous specimens suggests that the dull, altered syenite can be formed from fresh rocks in a number of ways; there may be reaction between early crystals and late-crystallizing trapped liquid, the alteration may be associated with faulting, and it may take place when the syenite is invaded by carbonatite.

In the Foyaite and pulaskite above the pyroxene-rich syenite, the proportion of mafic minerals decreases towards the south, at higher levels in the laminated sequence. Scattered areas of bright ultramarine sodalite appear in minor amounts and the rocks pass into very feldspathic varieties, some with the composition of pulaskite. These rocks, which are generally altered, are probably transitional between the foyaites making up the majority of the upper group mapped as 'Foyaite and pulaskite' (Plate 2) and the coarse-grained syenite near the confluence of the Hytteelv and Bryggerens Elv.

Pyroxene-rich syenite.

This group is similar to the foyaites except that the proportion of aegirine-augite increases and the mineral sometimes occurs as well-formed crystals instead of in the poikilitic habit characteristic of its occurrence in the foyaite. Parts of the pyroxene-rich syenite are of the composition of malignite. In the more mafic rocks an alkali amphibole may be present where it builds large poikilitic crystals 10 mm. or more in diameter. The greatest concentrations of mafic minerals are found as thin layers in exposures near Øvre Radiosø and on the slopes south of Tøffelsø, and in cognate inclusions and mafic schlieren in the syenites about 1 km. E.S.E. of the latter lake. Stout, short prismatic crystals of apatite are numerous in the mafic rocks, where they are enclosed by pyroxene, amphibole, feldspar and nepheline (27192; see also Upton, 1961, fig. 15).

Coarse-grained syenite.

Only the platy crystals of microcline microperthite remain reasonably fresh in much of this rock, which is generally altered. Interstitial areas of cancrinite and calcite, and fibrous micaceous material probably represent original nepheline and pyroxene; occasionally relics of both are found. Irregular areas of blue sodalite are not uncommon, the mineral is generally disseminated through the rock but it can also develop as the marginal member of carbonate veins with sideritic cores and calcitic margins.

The outcrops of coarse-grained syenite mapped near the head of Urdal (Plate 2) differ somewhat from the rocks in the eastern part of Grønnedal. This syenite contains abundant euhedral crystals of nepheline, sometimes fresh and as much as 2.5 cm. in diameter, along with platy crystals of alkali feldspar up to 5 cm. in length (27253). This syenite appears to be a large inclusion within the Upper Series (see p. 29).

Porphyritic microsyenites.

The rock forming the small sheets and dykes of porphyritic microsyenite is usually very fresh. It consists of small platy crystals of perthitic alkali feldspar, short prisms of nepheline, and interstitial aegirine-augite, biotite and ore. There are occasionally scattered phenocrysts of alkali feldspar. In their mineralogy these rocks correspond with microfoyaites or porphyritic microfoyaites. They are closely comparable with rocks in the fine-grained marginal facies of the Upper Series Foyaite chilled against gneiss near the Kontaktelv.

Fig. 2. Angular syenite fragments in Xenolithic porphyritic syenite. Coin about 33 mm. in diameter. Loose block 400 metres north of the hut at Jernhat.

Xenolithic porphyritic syenite.

In the margins of this syenite there are numerous angular xenoliths of earlier syenites (Fig. 2), trachytes, and rare gneiss and amphibolite (Fig. 3). These are set in a porphyritic matrix with close-packed phenocrysts of grey alkali feldspars sometimes over 1 cm. in length, reddish-brown nephelines of similar size and rather smaller and less common green aegirine-augite crystals often with cores of grey augite. Compositional zoning is also present in the feldspars; these have cores of albite and margins of antiperthite. Slight zoning was noted in nepheline (58320), which is, however, often badly altered. Occasionally the large crystals have originated through the mechanical disintegration of xenoliths, but in general they are quite unlike the minerals of the earlier syenites found as inclusions in the xenolithic porphyritic syenite, particularly in their pronounced compositional zoning, so they are regarded as being true phenocrysts and not of xenocrystic origin.

Fig. 3. Inclusions of gneiss (smooth-surfaced blocks), amphibolite (rounded, dark blocks) and syenite in Xenolithic porphyritic syenite. Exposures west of the Langesø outlet. Hammer shaft 0.6 m. in length.

Structures within the syenites.

The lamination developed in the majority of the syenites usually strikes parallel to the margins of the intrusions and dips inwards at variable angles, commonly between 30° and 70°. Except in the eastern side of the complex, and locally at other points near or at the contacts, the dips of the lamination do not coincide with the attitudes of the margins: the two may diverge sharply.

The two major series of laminated syenites in the north-west of the complex are separated by a sheet of gneiss (Plate 2; fig. 8). Within each series the lamination forms a synclinal structure pitching to the S. E.; in the Upper Series this appears to be a portion of an original elongated basin-shaped structure (Plate 3) resembling structures mapped by W. T. Harry and the author in parts of the Igaliko nepheline syenites, and found in other nepheline syenites including some members of the Khibina Complex on the Kola peninsula (cf. Eliseev *et al*, 1939).

Feldspar lamination is generally the only internal structure in the Grønnedal-Íka syenites. Exceptions are found in the group of pyroxene-rich syenites of the Upper Series on the ridge south of Øvre Radiosø, and at about 400 m. elevation some 1.5 km. S. E. of Eqaluit. Here, and to a lesser extent in other outcrops of this syenite, there are thin mafic layers 1–2 cm. thick and extending laterally for up to and over 40 metres where the rock is unusually rich in aegirine-augite, poiki-

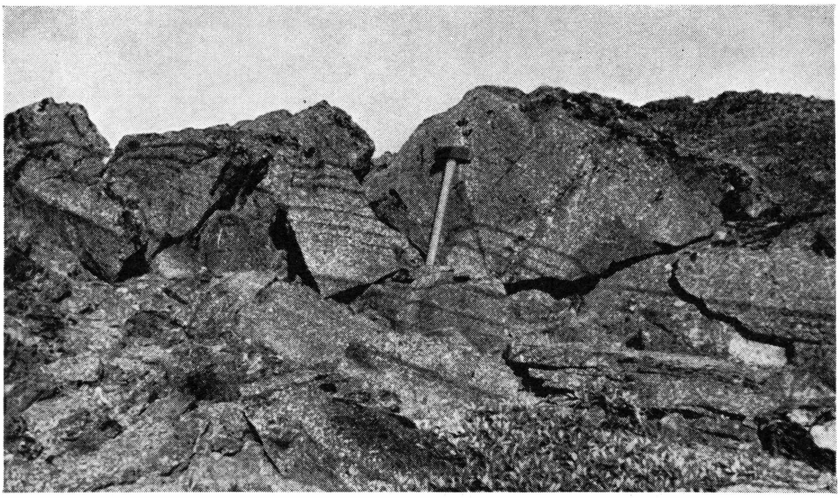

Fig. 4. Mineral layering in the pyroxene-rich syenite of the Upper Series. About 150 metres S.E. of Tøffelsø (as Fig. 1). Hammer shaft 0.6 metres in length.

Fig. 5. Gravity-stratification in a mafic layer in the pyroxene-rich syenite of the Upper Series. About 270 metres south of Tøffelsø. Hammer head 13 cm. in length.

litic alkali amphibole, and apatite (Fig. 1 and fig. 4). There is a rhythmic repetition of the mafic layers, each being separated by 5–15 cm. of normal laminated foyaite. The mafic layers are also laminated and completely conformable with the lamination in the foyaitic rock. Gravity

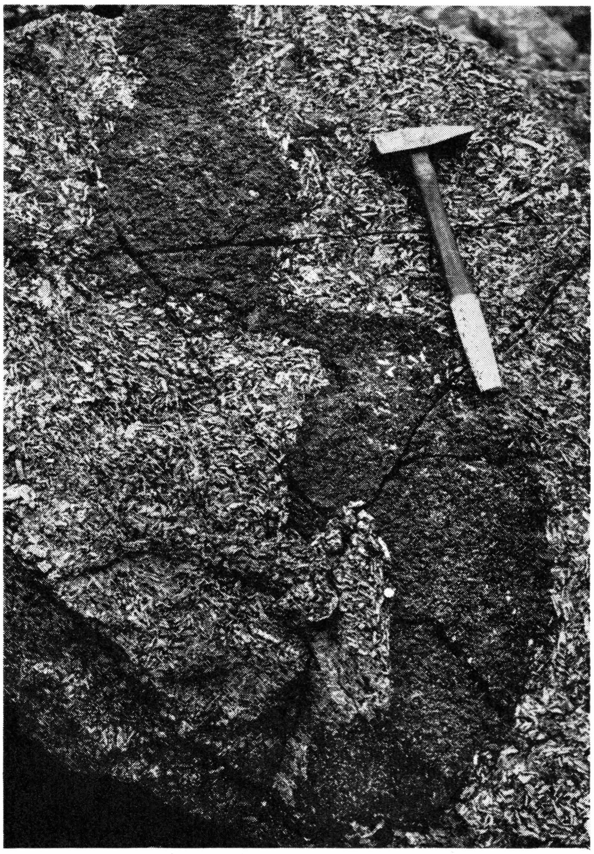

Fig. 6. Irregular area of mafic syenite in the pyroxene-rich syenite of the Upper Series. Note the poorly-developed lamination in the leucocratic syenite. 0.9 km. E. 10° S. of Tøffelsø. Hammer shaft about 0.35 metre in length.

stratification is uncommon in the layered structures, a single rather ill-defined example was found S. E. of Eqaluit where a mafic layer about 1 cm. thick had a sharply-defined base against underlying normal foyaite and passed by gradual diminution in the amount of pyroxene upwards into a similar foyaite (27182; fig. 5).

At much the same structural level as the layered parts of the pyroxene-rich syenite there are irregular schlieren and inclusions of very mafic syenite similar in their mineralogy to the mafic layers. Unlike the localities with layering, the foyaite in the immediate vicinity of the mafic schlieren does not show good lamination, some lamination is present which varies rapidly in direction and amount of dip, and passes into unlaminated rock (Fig. 6). These irregular structures were observed at a number of localities, the most striking exposures are about 1.9 km. S. E. of the huts at Eqaluit.

Fig. 7. Variable lamination in foyaite of the Upper Series. Exposures on slabs on the south side of Langesø. Hammer shaft 0.6 metres in length.

Several features of the syenites in the Upper and Lower Series suggest that these formed part of a layered intrusion, now greatly disturbed by later intrusions and faulting. Evidence in favour of this interpretation includes the large-scale compositional layering within the Upper Series, and present to a lesser degree within the Lower Series rocks: there is also the development of widespread lamination concordant with the major compositional layering, and the occurrence of minor amounts of rhythmically-repeated mineral layering with suggestions of gravity stratification, which is also concordant with the large-scale structures. Texturally the rocks are readily interpreted as igneous cumulates, the early cumulus minerals would have been alkali feldspar and nepheline, occasionally joined by pyroxene and apatite, while crystallization of the intercumulus material would give the poikilitic aegirine-augite, amphibole, cancrinite, ore, and biotite. However, textural features alone would not be adequate to establish the cumulate origin of the rocks.

When the syenites are compared with intrusions where the evidence of layering and bottom accumulation is more forthcoming there is found to be much in common. It seems therefore permissable to interpret the Grønnedal-Íka syenites as igneous cumulates; a somewhat similar conclusion was reached by CALLISEN from a study of these rocks (1943, p. 72).

It could be argued that the lamination in the syenites had resulted from the emplacement of a partially crystalline magma carrying a fair proportion of alkali feldspar crystals; the structure would be essentially brought about by flow. Two of the features of the syenites make this interpretation unlikely, though not impossible. The alkali feldspars show true lamination, there is no suggestion of lineation in the syenites although the structure may be found in some of the porphyritic microsyenite bodies. It is, however, true that there is not a large difference between the length and breadth measurements of the platy feldspars, the length/breadth ratios range from 1.5:1 to 2.5:1 so even with strong flow it might be difficult to attain lineation. The marginal syenites provide stronger evidence that the magma was largely liquid on emplacement. As mentioned earlier the marginal rocks are fine-grained and carry only rather sparse alkali feldspar phenocrysts; their grain-size increases fairly rapidly away from the contacts to that of the normal foyaite.

The regular, conformable pattern of the lamination in much of the N.W. of the complex does not obtain throughout. South of Langesø the structures are steep, vertical, or possibly overturned (Plate 2). The lamination may also be very irregular on a small scale, with local swirl-like structures (Fig. 7) and patches of unlaminated rock several metres in extent. The syenites with these steep and often irregular structures are at structurally higher levels than the majority of those exposed in the N.W. of the complex and it is possible that the steep dips were attained as crystals accumulated on steeper and steeper slopes formed as successive crystal crops banked against the walls of the complex (cf. WAGER and DEER, 1939, pp. 123–125; UPTON, 1960, p. 117). The suggestion has been made that the poorly laminated rocks were formed when the movement of magmatic currents was sluggish, the perfect lamination forming during periods of particularly active movement (UPTON, 1961, p. 11). Another possibility is that some of the structures resulted from slight slumping during crystal accumulation. Such an explanation could be the reason for the highly irregular structures, and for the mafic schlieren and inclusions associated with some of the ill-laminated rocks in the pyroxene-rich syenites.

The moderate to steep inclination of the lamination in the Grønnedal-Íka syenites raises the more general question whether it is possible for crystals to accumulate on and against highly inclined surfaces without extensive slumping of the crystal mush. In the reconstruction of the complex (Plate 3) the laminations in the Upper Series syenites dip centrally on all sides. It seems inescapable that these dips are original, although a slight correction may be necessary to give the Lower Series a uniform distribution below the Upper Series. However, this will only involve tilting the complex a small amount towards the N.W.

In basic and ultrabasic layered intrusions where post-consolidation tilting is slight, or can be calculated, the dip of mineral layering and lamination is often low, as in the Skaergaard Intrusion (WAGER and DEER, 1939, fig. 14) and the Bushveldt complex (HALL, 1932). Compared with the more basic intrusions there is little information available on layering and lamination in nepheline syenites. ELISEEV *et. al.* figure steeply inclined trachytoidal structures in the Khibine complex (1939, plate 2), steeply inclined mineral layering and lamination is present in the Lovozero alkaline massif (VLASOV *et al.*, 1959), and W. T. HARRY and the author have mapped apparently primary steep lamination and concordant mineral layering in units of the Igaliko complex. However, not all layering and lamination in nepheline syenites is steep, the layered structures in the kakortokites in the lower levels of the Ilímassaq Intrusion dip at low angles (USSING, 1912).

The general impression gained by the author from his field experience, and from the literature, is that primary layering and lamination in layered basic intrusions usually dip at low angles while similar structures in nepheline syenites may be at low angles but quite frequently are moderately to steeply inclined.

Evidence supporting original moderate to steep angles of dip of mineral layering is found in two augite fayalite syenites in southern Greenland (Plate 1), the Kûngnât Intrusion and the large syenite body of Nunarssuit. In the layered and laminated syenites of the Western Centre of the Kûngnât Intrusion UPTON describes primary layered structures with dips up to 50° (1960, p. 116), while in the Nunarssuit syenite PULVERTAFT estimated on the basis of slump structures in layered rocks that the maximum angle of rest in the crystal mush was about 45° (HARRY and PULVERTAFT, 1963, p. 111).

Comparing basic and ultrabasic bodies with syenites and nepheline syenites there are a number of obvious differences that might contribute to the stability of steeply inclined structures in the latter. They include the viscosities of the magmas, the density contrasts between the magmas and their cumulus phases, the rates of deposition of the cumulus phases, and the rapidity with which the intercumulus material crystallized and cemented the crystal mush. Comparatively little is known about the viscosities of syenitic melts; by analogy with melts of granitic composition they are probably more viscous than basaltic melts although the relatively high concentrations of fluorine, water and other volatiles in some syenites melts might well reduce their viscosities considerably, especially under conditions of plutonic crystallization. Syenitic magmas will have lower densities than those of basaltic composition. Some indication of a likely upper limit is gained from the knowledge that under certain conditions both nepheline and feldspar form bottom accumulations, thus an upper limit of about 2.5 gm. cm.³ seems probable. The lower limit is less easy to predict. In the Ilímaussaq Intrusion Ussing adduced evidence to show that there had been flotation of sodalite during the formation of the naujaites (1912, p. 352). There is therefore the suggestion of a lower limit of the order of 2.2–2.3 gm. cm.³ although it should be remembered that conditions at Grønnedal-Íka did not approach the extreme fractionation of the Ilímaussaq nepheline syenites. Nevertheless, it is likely that only slight density contrasts existed between the cumulus minerals and the magma at Grønnedal-Íka with the result that thin, platy crystals accumulating on and adhering to relatively steep slopes may have been quite stable.

While the slight density contrasts between crystals and magma can help to explain the steep laminations observed in the Grønnedal-Íka complex and other intrusions where the principal cumulus minerals are alkali feldspar and feldspathoids, this cannot be the only factor as evinced by the steep dipping layered structures at Kûngnât, Nunarssuit, and other intrusions where iron-rich olivine and pyroxene were important cumulus minerals in syenitic magmas. The formation of steeply-dipping banded structures may also have been facilitated by the rate of crystallization of trapped liquid keeping pace with the accumulation of early-formed minerals. From studies on silicate melts this condition would obtain most readily in magmas approaching or at minimum-melting compositions: granitic or syenitic magmas should show this effect whereas it would probably not be nearly so important in the crystallization of basic magmas.

Conclusions.

The consolidation of the major part of the syenites in the Upper Series, and the Foyaite of the Lower Series at Grønnedal-Íka was achieved by a combination of bottom accumulation of early-formed minerals and their adhesion to steep-sided cooling surfaces provided by the walls and possibly the roof of the complex. Cyclic convective circulation of the magma may have achieved brief importance during the formation of the layered rocks in the pyroxene-rich syenite, otherwise a slight and fairly steady movement of the magma is envisaged to account for the close packing of crystals in the well-laminated rocks.

The syenites of the Upper Series accumulated on the floor formed by the upper surface of the gneiss sheet; there is close conformity between the layering and lamination, and the upper surface of the sheet (Plate 2; and Fig. 8). The S. E. extent of the gneisses under the Upper Series is a matter for conjecture. It is possible that they extend under the Jernhat area (p. 57) where they may be underlain by the Foyaite of the Lower Series (p. 38). The floor to the Lower Series Foyaite is formed by

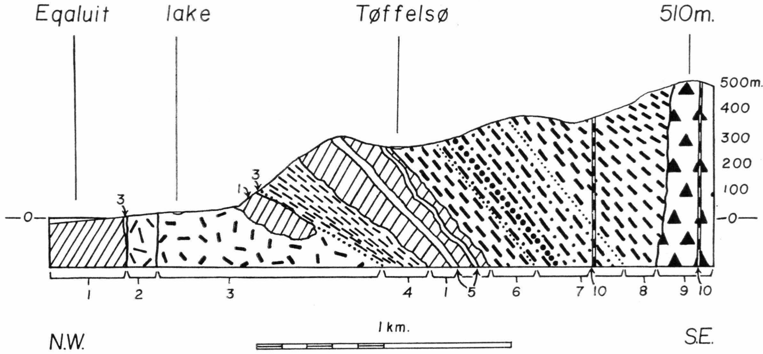

Fig. 8. Cross-section from Eqaluit to 510 m. hill S.E. of the bay.
1, gneiss; 2, granular syenite; 3, coarse-grained brown syenite; 4, Foyaite of the Lower Series; 6, Foyaite of the Upper Series; 5, microporphyritic syenite; 7, pyroxene-rich syenite of the Upper Series; 8, Foyaite and Pulaskite of the Upper Series; 9, xenolithic porphyritic syenite; 10, alkaline dykes.

the coarse-grained brown syenite and a large, flat-topped gneiss inclusion exposed in and near the Kontaktelv (Fig. 8).

On reconstructing the original form of the nepheline syenite-carbonatite pluton (Plate 3) the gneiss sheet is found to extend through the N.W. of the complex, separating the two syenite series except near the edges of the complex. The gneiss sheet is considered to be a raft that flaked off the roof of the complex during crystallization, rather than a roof pendant (Callisen, 1943, p. 18). The raft subsided through the magma and came to rest upon the upper surface of the bottom accumulation of early crystals, now represented by the Foyaite of the Lower Series, producing some buckling in the laminated rocks (steeply-inclined lamination develops in the Foyaite close to the raft). The raft also became brecciated towards its extremities, the fragments mixing with the partly-consolidated Foyaite to give the very complex syenite-gneiss breccias found in the Radioelv. After the raft had settled, crystallization continued in the overlying magma, the crystal crops building up from the floor provided by the upper surface of the raft. It is possible that the subsidence of this raft coincided with, or was initiated by a new injection of magma — there are grain-size and other differences between the Foyaite of the Lower Series and the lower parts of the Upper Series.

There may be another large body of gneiss inside the complex, lying within the S.W. part of the Upper Series a short way above the gneiss raft shown on the reconstruction diagram (Plate 3). Gneiss is exposed in Bryggerens Elv and some of the streams in the southern part of Grønnedal. These rocks appear to lie between coarser-grained syenites than any in the Lower Series Foyaite so they may be wholly within the Upper Series syenites.

Structurally similar raft-like inclusions of country rock are present in the syenites of the Western Centre of the Kûngnât Intrusion (Upton, 1960, Plate 5 and figs. 7 & 8) and in the large syenite of Nunarssuit (Harry and Pulvertaft, 1963, pp. 72–81); in the latter they have been interpreted as roof pendant wedges. They provide an indication of the mechanism by which these complexes were emplaced.

Age relationships between the syenites.

There are few opportunities for observing members of the two main groups of syenite in contact, the raft of gneiss forms an effective barrier between the Lower and Upper Series except in the Radioelv and the upper part of the Kontaktelv. At neither of these places was very satisfactory evidence of their relative ages obtained; the observations are conflicting. The Radioelv exposures are complex. Near the thick olivine dolerite Master Dyke xenoliths of gneiss, amphibolite and a coarse-grained syenite were found in a matrix of fine-grained syenite which resembles the finer grained members of the Lower Series, although it was not possible to establish any connection in the field. In the Kontaktelv the two series are separated by a sheet of porphyritic microsyenite. Porphyritic microsyenite cuts the Foyaite of the Lower Series near the river and in exposures at about 240 metres elevation south of Eqaluit. It also closely resembles marginal facies of the foyaites of the Upper Series and on this evidence the Upper Series is tentatively assigned to a slightly later date than the Lower Series.

Within the Lower Series the coarse brown syenite exposed in the lower ground south of Eqaluit and either side of the entrance to Grønnedal encloses areas of altered gneissose rock. The syenite is generally unlaminated but develops a moderate lamination near the contact with the Foyaite of the Lower Series into which it is seen to grade on a small cliff exposure about 1.5 km. S.S.W. of the huts at Eqaluit.

The rocks shown as granular syenite on the map (Plate 2) include two fairly distinctive types. One is a biotite-bearing syenite, the other contains less biotite and is characterised by the presence of thick platy feldspars generally with a random orientation. The biotite-rich variety is seen to pass gradually into a medium-grained, equigranular syenite similar to the marginal facies of the Foyaite of the Lower Series. The biotite-rich syenite forms sheets apparently cutting the coarse-grained brown syenite and the gneiss between the outer dyke-like body of syenite and the base of the Lower Series Foyaite. No xenoliths were found within the sheets of biotite-rich syenite which are probably approximately equivalent to the Foyaite of the Lower Series. The other rock classified as granular syenite forms the distinctive dyke-like body of syenite which extends from Eqaluit and the Kontaktelv to the northern side of the Laksenæs Fault. Close to the Kontaktelv this syenite is seen in fine-grained chilled contact with coarse-grained brown syenite. In exposures close to the southern shore of Eqaluit, some 750 metres S.W. of the huts, there are xenoliths of gneiss, amphibolite, an olivine-bearing lamprophyric rock, and fine-grained laminated syenite identical with the Foyaite of the Lower Series. Close to this locality the syenite cuts a dyke-like branch of the biotite-rich syenite mentioned above. The dyke-like body of granular syenite with large platy crystals of alkali feldspar is therefore probably the latest member of the Lower Series, and might be of even later date.

The sheets of porphyritic microsyenite cut the Lower Series Foyaite and similar rocks are seen intruding some of the marginal rocks of the Upper Series Foyaite near Tøffelsø. There is, however, a close resemblance between marginal rocks of the Upper Series and the porphyritic microsyenites and they are considered to be contemporaneous.

Within the Upper Series there is complete gradation from the lower layer of Foyaite to the pyroxene-rich syenite, and from this into the structurally higher Foyaite and pulaskite. In the eastern part of Grønnedal there is probably complete gradation to the coarse-grained syenite which is considered to be the youngest member of a layered series of syenites.

To the south of Xenolithsø there are outcrops of a coarse-grained syenite characterised by the presence of large euhedral crystals of nepheline as much as 3 cm. in diameter. This syenite appears to be an inclusion in the Upper Series. About 400 metres south of Xenolithsø laminated Foyaite in the Upper Series cuts across a weak lamination in the coarse-grained syenite.

The xenolithic porphyritic syenite is clearly the latest major syenite intrusion in the complex, it cuts members of the Upper Series, enclosing blocks of syenite as well as occasional fragments of gneiss and amphibolite, and rather rare trachytic rocks.

The assumed sequence within the syenites is summarised in Table 2.

Table 2. Sequence within the syenites of the Complex.

Xenolithic porphyritic syenite:

Cuts and includes members of the Upper Series.

Porphyritic microsyenite:

Sheets cut the Foyaite of the Lower Series, gneisses of the gneiss raft and marginal Upper Series. Closely resembles marginal members of the Upper Series and may be contemporaneous.

Upper Series:

Complete upwards gradation from Foyaite through pyroxene-rich syenite to Foyaite and pulaskite. Probably complete gradation to coarse-grained syenite of central Grønnedal. Includes large area of a coarse-grained syenite near the head of Urdal.

Lower Series:

i) Granular syenite. The outer dyke-like body with large feldspars cuts coarse-grained brown syenite and carries xenoliths of Lower Series Foyaite. It also cuts the biotite-rich syenite of the granular syenite. This biotite-rich syenite cuts coarse-grained brown syenite and may be contemporaneous with the Foyaite of the Lower Series, the marginal facies of which it resembles.

ii) Foyaite apparently grades downwards into the coarse-grained brown syenite. Inclusions of gneiss common in the coarse-grained brown syenite.

The Margins of the Complex.

The combination of relatively low relief, the strong tendency of the syenites to weather to sand, and the presence of moderate amounts of glacial drift frequently obscures the contacts between the syenites and the country rocks. Despite these difficulties it is generally possible to define the limits of the complex to within a few tens of metres and the actual junction between syenite and gneiss is exposed at several points. This section consists of a brief review of the marginal relationships along the limits of the complex when examined in a clockwise direction from the bridge over Bryggerens Elv in Grønnedal.

Syenite does not outcrop much below 100 m. elevation in Grønnedal although gneisses are found in the river a short distance below the bridge. To the north, between the bridge and the Laksenæs Fault, there is an apparently steep-sided dyke of biotite-rich granular syenite separated from the Foyaite of the Lower Series by a strip of gneiss and coarse-grained brown syenite. The Laksenæs Fault next forms the boundary for almost 1 km.: details of this fault and others defining the margins of the complex are given in a subsequent section. Between the Laksenæs Fault and Eqaluit the margin is formed by an incomplete ring dyke of granular syenite. A steep, outward-dipping contact between the N.W. edge of this syenite and gneiss occurs about 1 km. from the bay. The overall steep, dyke-like form of the granular syenite is confirmed by the outcrops between the Laksenæs Fault, Eqaluit and the Kontaktelv where the topography appears to exercise little control, in marked contrast to the south-east - dipping junction between the other two members of the Lower Series which maintains a fairly uniform level in the cliffs south of Eqaluit. (Plate 2).

Between Eqaluit and the western shore of Langesø the contact between syenite and gneiss is exposed at several places. Fine-grained syenite is seen in contact with greenish-grey gneiss about 300 m. east of Eqaluit. Foyaite of the Lower Series and gneiss are in contact on the lower edge of the cliff just north of the Kontaktelv, at about 500 m. elevation east of the bay, and Foyaite of the lower part of the Upper Series is in sharp chilled contact with gneiss near the small lake close to the head of the Kontaktelv. The second locality mentioned is of some interest as the vertical nature of the contact is clearly displayed and on a smaller scale the lamination in the foyaite appears to bank against the gneiss, although the actual line of contact is disturbed by a small fault. Nearer to Langesø the curving outcrop of the contact over a ridge suggests that there is a steep southerly (inwards) inclination.

For about 1 km. to the south of Langesø the margin is defined by the Main Fault. At some 300 m. south of the Tolvsøer and 650 m. north of the hut at Jernhat a fine-grained syenite with areas of poikilitic amphibole to 15 mm. in diameter is seen in contact with gneiss. The syenite increases in grain size to the south, grading into a feldspar-rich variety of the Upper Series. Continuing along the contact towards the south there are numerous small faults parallel to the Main Fault and although exposures are fairly good the junction between syenite and gneiss is not seen again until the top of the cliffs about 1 km. N.W. of the hut at Íkasletten. Here, fine-grained syenite is in sharp contact with gneiss. Between this point and the fjord the contact is a faulted one.

No original contacts were found in the ground to the S.E. of Íka. The junction between syenite and metasediments is faulted for the most part and closer to the fjord an extensive cover of drifts effectively obscures the contacts even in the coastal sections.

For about 1 km. up Urdal the syenite and gneiss are in faulted contact. Between the valley and the southern side of Øvre Radiosø the contact can often be located to within 10 metres but the crumbling nature of the syenite obscures the actual junction. From the map it will be seen that the contact undergoes a marked change in outcrop direction between the fault and the higher ground to the N.W.; this is attributed to a steep S.W. or S.S.W. dip of the junction. Near the outlet of Nedre Radiosø fine-grained foyaite is in contact with gneiss in indifferent outcrops. North of the Radioelv at the lake the contact was not exposed again until about 1 km. S.S.E. of Rypefjeld where fine-grained slightly porphyritic syenite shows a fluxion structure against gneiss, the flow-featuring being brought out by occasional schlieren of coarser grained or more mafic rock, as well as feldspar orientation. Nearby a fine-grained magnetite-rich syenite outcrops close to the gneiss (39766). On the N.E. shoulder of Rypefjeld the contact is fairly easily followed although only actually exposed in the river section to the east of the summit, at about 270 m. elevation on the north bank. At the eastern end of this section Foyaite of the Lower Series ends against a feldspathic syenite which is in steep to vertical contact with strips and screens of gneiss and altered syenite several metres in width. Sometimes the syenite and gneiss are so intimately mixed that they become difficult to distinguish. North of this section the contact follows a curved course over the hillside, suggesting a steep, E.N.E. (inwards) dip.

From the examination of actual exposures of the contacts, and on a larger scale by interpreting the relationships between the outer margins of the complex and the topography, it emerges that in general the contacts are steep and outward dipping, or vertical. The principal exceptions are found in the section across Rypefjeld, and that west of Langesø. There is thus a marked contrast between the external form of the complex and the internal structures which are generally inward-dipping at moderate to steep angles.

The syenite sends very few apophyses into the country rocks, with the significant exception of the rafts of gneiss. A few thin veins were mapped by M. Burri in the ground to the south of the two Radio lakes and Callisen reports pegmatites in the gneisses at Grønnedal and on Laksepynt (= Laksenæs; Callisen, 1943, p. 70). A dyke-like mass of syenite parallels the contact on the north of the complex; this is probably a continuation of the main syenite body.

The gneisses adjacent to the syenites show only slight signs of contact metamorphism and metasomatism, although the effects of soda metasomatism can be quite striking in mafic inclusions within the complex (e.g. 27182). The alteration is usually confined to the development of small crystals of alkali pyroxene at crystal boundaries in specimens taken at the contacts. These effects do not extend for more than a few metres from the syenites.

Fig. 9. Blocks of syenite in carbonatite. Upper Urdal. Coin about 33 mm. in diameter.

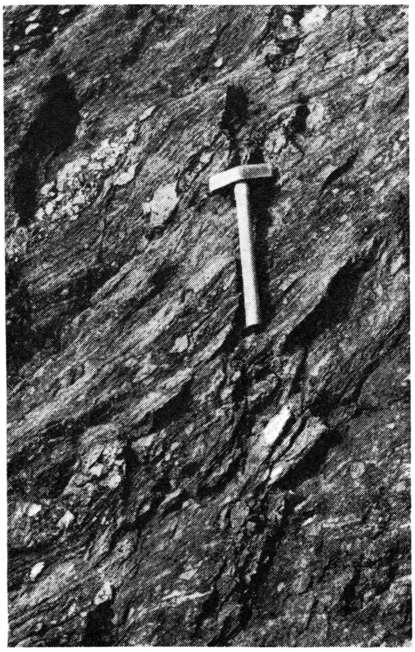

Fig. 10. Flow-banded carbonatite with inclusions as trails parallel to the banding. Upper Urdal. Hammer shaft 0.6 metres in length.

II. The Carbonatites.

General.

There are three major outcrops of carbonatite within the nepheline syenites, the largest covering about 0.7 square kilometres around and to the south of the hut at Jernhat. Another is on the eastern side of Urdal (about 0.4 sq. km.), and a third at the eastern edge of the Cirkus (about 0.2 sq. km.) where exposure is indifferent. Smaller masses appear sporadically throughout the complex and extend into the country rocks, as on the cliff north of the Kontaktelv, and by the lake about 0.5 km. south of the western end of Øvre Radiosø. A number of the small outcrops are closely associated with faulting, as at the lake mentioned above, and again about 0.9 km. north of the bridge in Grønnedal on the line of the Laksenæs Fault.

The carbonatites weather readily to give gentle gravel-covered slopes. This is most marked where there are appreciable quantities of iron-bearing minerals and is well seen near the hut at Jernhat where

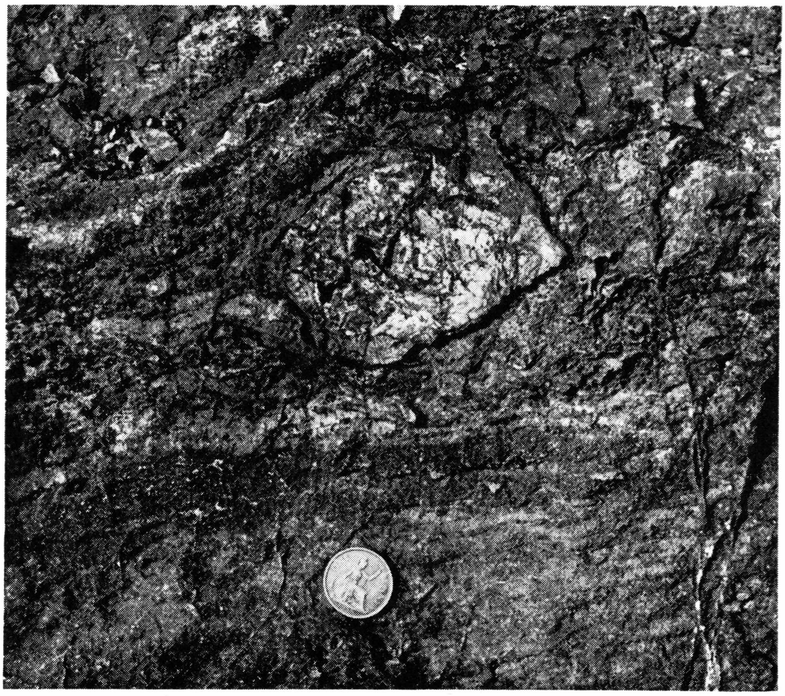

Fig. 11. Flow-banding in carbonatite deflected around inclusion of syenite. Upper Urdal. Coin about 33 mm. in diameter.

the ground is strewn with brown gravel and boulders of siderite and magnetite carbonatite, broken here and there by small outcrops of silicate rocks enclosed in the carbonatites, or low walls and ridges along the lines of late trachytic dykes. Fresh carbonatite is difficult to obtain in surface outcrops; quite good specimens were taken from large blocks near the hut and in the stream section below Xenolitsø, and better material was also found in the carbonatite outcrops east of the river in Urdal where outcrops are of a less iron-rich variety; the freshest specimens were obtained from the drill cores.

Two features are particularly noticeable when the carbonatites can be examined on clean, *in situ* exposures. The rock is often xenolithic (Fig. 9), with angular to rounded fragments of syenite and other rocks, and there may be conspicuous flow banding brought out on the slightly weathered surfaces by dark trails of slightly oxidised siderite in a calcitic matrix (Figs. 12). In xenolithic flow-banded carbonatite the flow structures wrap around the inclusions (Fig. 11), and trails of smaller inclusions may provide the only indication of flow-banding, or accentuate banding already apparent (Fig. 10). An attempt was made to map the flow banding in the hope that some systematic pattern might emerge. None is

Fig. 12. Flow-banded carbonatite. The dark ridges are formed by the weathering of siderite-rich layers. Hytteelv near the outlet of Xenolithsø. Hammer head about 18 cm. in length.

N.B. The banding in the right-hand side of the photograph has been shattered by later faulting.

apparent; for the most part the bands are very much influenced by inclusions, the edges of earlier rocks and other local irregularities. The only general conclusion reached was that the banding is vertical or steep.

Petrography.

A fairly simple mineral assemblage characterises the carbonatites which consists essentially of varying amounts of calcite, siderite and magnetite, along with minor quantities of apatite, sphalerite, pyrite, strontium-rich barytes and other minerals. The grain size is variable, the typical rock is a medium-grained marble with clean white calcite to 0.5 cm. and golden-brown siderite in somewhat larger grains; where both carbonates occur together siderite is euhedral towards calcite. The coarser-grained varieties, with crystal to 1 cm. and over, are generally those rich in siderite.

The mineral proportions differ quite appreciably from place to place. In the exposures in Urdal and on the eastern edge of the Cirkus the rocks is predominantly of calcite, with small quantities of siderite and little or no magnetite or other minerals.

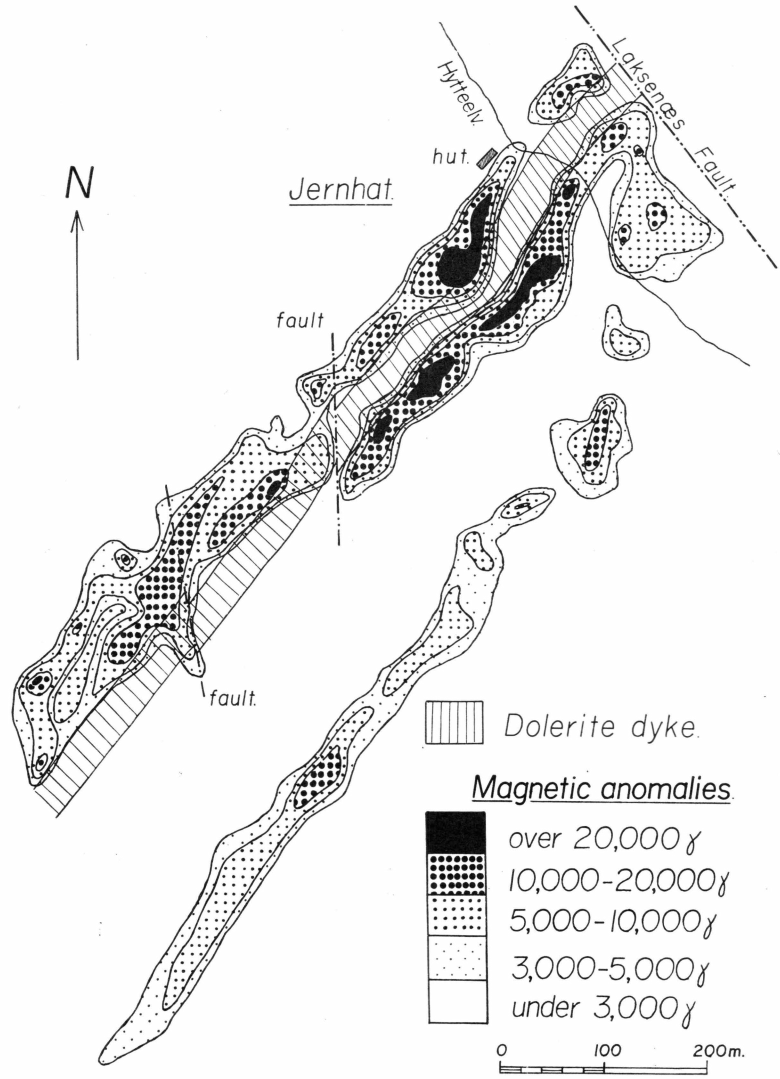

Fig. 13. Sketch map showing the magnetic anomalies associated with the iron-ore body at Jernhat. The southern, smaller anomaly is associated with a swarm of close-spaced dykes of microporphyritic basalt. Based on a systematic magnetic grid survey carried out by J. Espersen using a BMZ magnetometer.

N.B. The hut at Jernhat is at approximately 61°11′20″ N. Lat. and 48°2′ W. Long.

The carbonatite around Jernhat is rich in siderite and magnetite (as the locality name implies) and sulphides are found, particularly sphalerite (39757). Magnetite is most abundant in the rocks near the hut where it is found in carbonatites flanking an olivine dolerite dyke. Thin section examination of specimens from surface exposures and several of the drill cores shows that the magnetite is pseudomorphous after original siderite, various stages in the replacement process being apparent, increasing in intensity towards the dyke. The magnetite evidently owes its origin to the contact metamorphism of original siderite-calcite carbonatite.

Restriction of the magnetite-bearing carbonatite to the vicinity of the dyke is particularly well demonstrated by the results of a magnetometer survey carried out by R. Bøgvad, J. Bondam and J. Espersen (reproduced in Fig. 13). Magnetite also forms close to the olivine dolerite dykes cutting carbonate-impregnated syenites near the outlet of Langesø.

Chemical composition.

A summary of the chemical data on the carbonatite is given below and more detail will be available in a subsequent publication. The data presented is mainly from determinations carried out by the Cryolite Company, Copenhagen, supplemented by some work performed by the Greenland Survey.

Some trace element data for the carbonatites

Semi-quantitative data for sp. 39757
(as p. p. m.)

(A)	Ti	n. d.	(B)	Sr abundant
	Mn	1300		Zn abundant
	Sc	n. d.		Y present
	Cr	trace		Th present
	La	>500		
	V	n. d.		
	Sr	>500		
	Ba	1500	(A)	Determined on optical spectrograph
	Pb	n. d.		
	Ga	n. d.	(B)	By X-ray fluorescence
	Cu	20		
	Ni	trace		Determinations by author
	Zr	trace		
	Co	trace		

(C) Drill Hole 'T'

	T. 121.8 metres	T. 127.7 metres
Mg	1500	4000
La	2000	1000
Y	600	300
Ba	500	200
Sr	> 10000	> 10000

Spectrographic analyses by Cryolite Co.

(D) Chem. determinations on above 2 specimens

	121.8	127.7
Sr	2.63 wt. %	2.63 wt %

(Analyst: E. Hamilton, GGU.)

The rocks resemble other carbonatites in their fairly high concentrations of strontium and rare earths, yttrium and lanthanum being recorded. Unlike some carbonatites, there is little titanium or zirconium, and baddelyite and similar minerals have not been recorded. The moderate concentration of zinc is correlated with the fairly common occurrence of macroscopic sphalerite. Pyrochlore may be present but has not been confirmed. Some of the carbonatites are slightly radioactive. X-ray fluorescence indicated slight traces of thorium but not uranium; so far no satisfactory mineral host has been identified.

Contact relationships.

A wide zone of xenolithic carbonatite outcrops on the eastern side of Urdal, south of Jernhat near the old radio station, and in the ground about 300–400 metres west of the hut, and in parts of Grønnedal. At the outer fringe of this zone the nepheline syenites are invaded by dykes, sheets and irregular bodies of carbonatite, with brecciation and disruption of the igneous lamination (31837; figs. 14 A & B). Within the breccia zone the inclusions range in size from slabs several tens of metres in diameter to small angular fragments about ten centimetres across. In mapping the carbonatites it was unusual to find outcrops completely free from included material, although some of the deeply-weathered iron-rich rocks at Jernhat are fairly pure iron-rich carbonatites. The syenites in the invaded zone outside the breccias are altered, as are the included fragments within the carbonatite. The altered syenite loses its fresh appearance in outcrop and becomes dull, brown and lustreless with platy alkali feldspar frequently the only recognisable mineral in hand specimen. Thin sections of the altered rocks show all the original mineral altered to some extent; in the feldspars this is confined to a dusting with brown material and a general turbid appearance. Nepheline and pyroxene are replaced by aggregates of micaceous material and there may be small amounts of cancrinite after nepheline. The rocks are impregnated by calcite.

The syenites enclosed in the carbonatite can usually be matched with nearby, undisturbed types. However, this is not always possible and there are indications that some of the inclusions have been carried for some distance by the carbonatite. Examples were found in the exposures close to the western side of Xenolithsø where the syenite inclusions are of a well-laminated rock with very thin, platy feldspars (eg. 31837) resembling some of the more feldspathic members of the Lower Series foyaites (cf. 27136) and quite unlike any of the adjacent Upper Series rocks. At this locality there is a fair degree of rounding of the larger fragments although the smaller pieces remain angular.

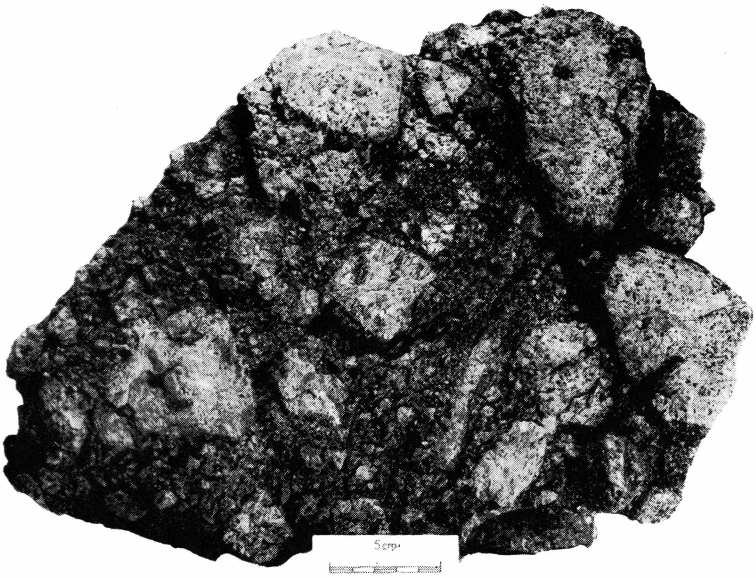

Fig. 14 A.

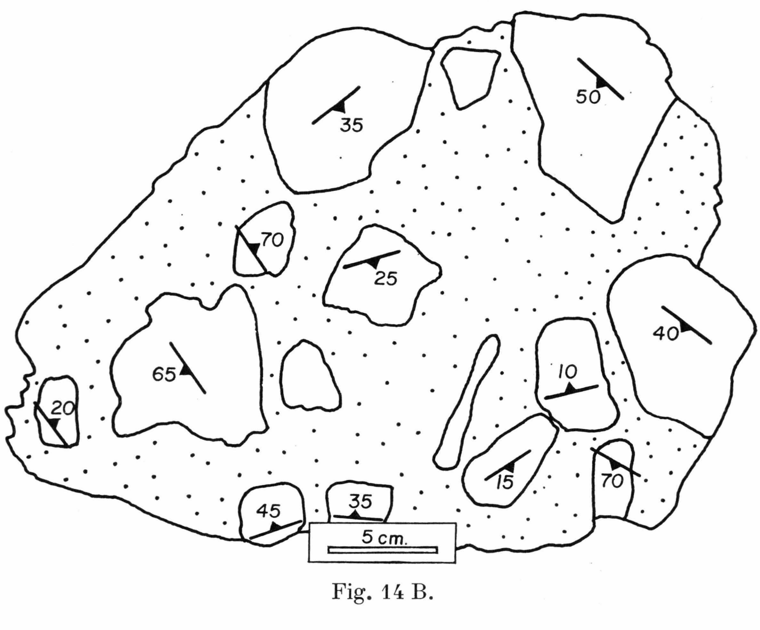

Fig. 14 B.

Fig. 14. (A & B). Photograph and diagram showing disoriented fragments of laminated syenite in carbonatite (31837). Specimen taken on the south side of the Hytteelv at the outlet of Xenolithsø.

Low ridges of altered syenite invaded by thin basic dykes stand up in the carbonatites south of the hut at Jernhat, and the syenite contributes to the fragments in the enclosing breccias. This syenite is medium to fine-grained with remains of feldspar and nepheline phenocrysts to about 1 cm. length. It is thought to be altered syenite derived from the central, non-xenolithic part of the xenolithic porphyritic syenite.

A fine-grained white or pale cream flinty rock found as inclusions in the breccias could not be correlated with rocks of the complex or its immediate surroundings. It occurs as angular xenoliths to ten centimetres across. In thin section the rock consists of an interlocking aggregate of very fine-grained albitic plagioclase. Unlike the feldspar in the syenite inclusions these are extremely fresh.

When there are no complications due to later faulting, a zoning may be detected in the carbonatites and the surrounding syenites. In the syenites the first signs of alteration are in the pyroxene and nepheline, followed by a dusty turbidity within the perthitic alkali feldspars. Small veins of carbonate minerals cut the rocks; these increase in size and number until the syenite passes into a breccia with blocks in a sövite carbonatite matrix. Inwards the amount of siderite increases and the blocks become less frequent, they are now isolated in carbonatite which flows around them; the inclusions may be of rock types unrelated to the nearby syenites. Finally, in exposures furthest from the unaltered syenites, the carbonatite is siderite-rich, with noticeable amounts of accessory sphalerite and apatite. The above sequence is simplified, in particular it should again be emphasized that almost all exposures are xenolithic to some extent, even in the most siderite-rich parts of the carbonatite sampled by the drill cores.

The carbonatites have been emplaced by forcible injection, carrying up some material from lower levels, at the same time there has been a noteworthy amount of carbonate impregnation and alteration of the surrounding rocks, possibly accompanied by hydration. In its highly xenolithic character the Grønnedal carbonatites resemble recently described carbonate masses in Northern Rhodesia (Bailey, 1960) where carbonate is thought to have arisen along numerous channels with notable metasomatism of the country rocks.

The breccias and carbonatites are intruded by numerous dykes; in addition to the olivine dolerites there is a small swarm of trachytes (Plate 2) and microporphyritic basalts. The field relationships between the dykes and carbonatites occasionally give conflicting age relations. The large-scale intrusive relationship of the dykes to the carbonatites is clear, but on a small scale the reverse sometimes holds. Examples where this was observed include the olivine dolerites, a generation of big feldspar basalt dykes, microporphyritic basalts, and trachytes. On the southern side of Xenolitsø a dyke of porphyritic basalt exposed in a small stream is seen as off-set fragments in a carbonatite matrix, while nearby the same rock type cuts across flow banding in carbonatite. On the southern side of the thick dyke at Jernhat, the carbonatite is divided into strips several metres in length and from ten to thirty centimetres wide by a local swarm of fine-grained acicular basalt dykes. At the same locality some of these dykes appear completely enclosed by carbonatite. A short distance east of the dolerite dyke a trachyte dyke cuts syenite, breccia and carbonatite. When traced to the S.E. the dyke is found invaded and brecciated by carbonatite in the flat-lying ground about 120 metres S.W. of the Xenolithsø outlet. These conflicting relationships are the result of faulting, the dykes were brecciated but the carbonatite was deformed plastically and forced into the gaps between the dyke fragments. The intrusive appearance of the carbonatite is entirely secondary. Similar secondary intrusive effects occur in porphyritic basalt and trachyte dykes in ground where there are known to be small subsidiary faults parallel to the Main Fault. Another possiblity was that the carbonatite had been mobilised locally when the dykes were emplaced. However none of the contact relations between dykes and carbonatite lent unequivocal support to this hypothesis although small blister-like bodies of carbonatite close to the dolerite dyke 500 metres S.W. of the hut at Jernhat could be so interpreted; rheomorphism in carbonate masses may not require excessive pressures or temperatures (cf. Wyllie and Tuttle, 1960).

Economic potential.

The Jernhat area has been extensively drilled and surveyed by the Cryolite Company in order to prove the extent of the magnetite deposit and to determine whether it formed an economic ore body. The investigations did not reveal magnetite or other minerals in workable quantities and were abandoned. The results of the present survey hold out little hope that the occurrence could become a profitable ore reserve since the magnetite appears to be very restricted, occuring only where basic dykes cut the siderite-rich central part of the carbonatite. Increased depth might be a further limitation. At the present level the pressure conditions were such that the carbon dioxide evolved from the breakdown of the siderite was able to escape freely, but suitable conditions might not have been found in depth, although much of the carbon dioxide probably left the altered carbonatite by way of the basaltic magma in the dykes rather than the solid wall rocks. Were the south of Greenland an agricultural area there might be some future for the sövite carbonatite as a source of lime and phosphate, since the amount of apatite can be significant

Summary.

The carbonate rocks at Grønnedal come well within the accepted meaning of the term carbonatite (Pecora, 1956), they are 'intrusive limestones' and have some of their chemical and mineralogical characterisitics, particularly high strontium, fairly abundant apatite and higher than normal radioactivity. When the original shape of the carbonatite is reconstructed the body is seen as a zoned plug with margins of brecciated and altered syenite.

The Grønnedal carbonatite differs from some other bodies in that there is no suggestion at the present level that the associated alkaline rocks owe their origin to fenitization and *in situ* transformation of country rocks by an active carbonate magma or emanations (cf. Eckermann, 1948). It is clear that several distinct intrusions of nepheline syenite pre-date emplacement of the carbonatites. It is perhaps of some significance that the youngest syenite was of a particularly explosive type (as evidenced by the abundant xenoliths near its margins) although it is true that there is not much evidence of carbonate-rich alteration products in the xenoliths or surrounding syenites, or in the development of carbonate minerals in the syenites itself. The assemblage at Grønnedal bears some resemblance to that at Napak in the Karamoja District of Uganda (King, 1949) where carbonatite is associated with an earlier ijolitic syenite. In available reviews of carbonatite occurences (Campbell Smith, 1956; Pecora, 1956) the association is usually with biotite pyroxenites, ijolites, and ultramafic alkaline rocks and less commonly with nepheline syenites of foyaite type. Although the source of the Grønnedal carbonatite will not be discussed here, the close association in place and time with foyaite intrusions should be emphasized. Carbonatites are uncommon amongst the Gardar alkaline rocks of southern Greenland. The Grønnedal-Íka complex contains the largest occurrence found up to the present, though recently other small intrusive carbonate bodies have been mapped in and to the west of the nepheline syenites of the Igaliko Batholith (GGU field reports by W. T. Harry and C. H. Emeleus, J. Stewart, and B. Walton), and a small occurrence was discovered to the N.E. of Ivigtût (GGU field report by N. Henriksen).

DYKES LATER THAN THE ALKALINE COMPLEX

General.

A large selection of dykes intrudes the alkaline complex. The majority is clearly of earlier date than most of the faulting affecting the syenites and carbonatites although there was some overlap between the emplacement of a late group of alkaline trachytic dykes and certain of the fault movements. One group is often intruded along the lines of weakness provided by pre-existing fault structures and crush zones.

The dykes include a variety of lamprophyres, two or more generations of feldsparphyric basalt and dolerite, at least three generations of olivine dolerite, and two or more groups with members of trachytic and phonolitic composition. The principal strike directions are between 60° and 90°, with the exception of an early group of trachytic dykes which strike between about 130° and 150°. The total thickness of the dykes cutting the Complex is difficult to estimate accurately, individuals may be quite thick and the total distention produced in a N.W.–S.E. direction amounts to at least 400 m. Compared with this figure the effects of the earlier group of trachytes was slight, the total distention in the N.E.–S.W. sense probably does not amount to over 70 m.

Lamprophyres.

Relatively few lamprophyric dykes were identfied iduring the field work. Subsequent petrographic examination of thin sections cut from dykes provisionally classified as 'basalt' or 'basic' has shown that many are in fact lamprophyric, covering a variety of compositions and extending over a considerable time-range within the complex.

The presence of pre-syenite lamprophyres is indicated by an inclusion in the outer granular syenite ring intrusion south of Eqaluit. The specimen (31894) is porphyritic with olivine and plagioclase phenocrysts set in a fine-grained groundmass of biotite, chlorite, augite and small amounts of plagioclase, with conspicuous accessory apatite in slender needles. The rock is an olivine-bearing augite kersantite.

One of the dykes initially recognised as a lamprophyre (27049) outcrops intermittently in the ground about 200–400 m. to the north of

Øvre Radiosø. It is of early date and is cut by dolerite and trachyte dykes. In thin section biotite is the most abundant mineral, with smaller amounts of pale green amphibole and poikilitic plagioclase (An 30), opaques, haematite, apatite and carbonate; it has the composition of kersantite.

Thin section examination of a widespread group of fine-grained basic rocks shows these to be lamprophyres of augite kersantite type. Together with other lamprophyres they intrude sheared olivine dolerite exposed in the Hytteelv at about 280–300 m. The dykes have escaped the effects of the severe shearing affecting the dolerite although their contacts with the crushed rocks are sometimes carbonated (27223). In one dyke phenocrysts of a violet-brown titanaugite to 2 mm. across are set in a groundmass crowded with intensely pleochroic red-brown biotite, opaques, and chlorite, with some interstitial plagioclase. In other dykes nearby the plagioclase of the groundmass has much the same acicular form as the biotite and augite (31870), occuring in an intermeshed and intergrown manner. Apatite is a common accessory constituent. A rather similar type forms a thick (? pre-Syenite) dyke outcropping at the S. E. corner of Langesø and intruding gneisses (not shown on Plate 2).

Other lamprophyres of later date than the olivine dolerite dykes include a camptonite (31814) at 260 m. in the Hytteelv and a vogesite (27021) cutting dolerite at a distance of about 300 m. from the outlet of Langesø in the bed of Bryggerens Elv. It is possible that the latter example is an altered porphyritic basalt; in section the whole rock is found to be altered, with severe sericitisation of several large plagioclase phenocrysts.

Other varieties occur which cannot be readily placed in the dyke time sequence. These include a spessartite (27061) intruding syenite some 300 m. to the north of the hut at Jernhat, a minette or alkali-feldspar bearing kersantite (27109) which cuts syenite exposed in the cliff of the Cirkus, a number of other kersantites intruding syenites, and a dyke of alnöitic affinities (31838) intruding carbonatite in the Hytteelv immediately below the hut at Jernhat.

The lamprophyre dykes are generally not thick or continuous over long distances, nor are they particularly numerous. However, the occurrences within the Complex extend the known types and the time range of the lamprophyres on the Ivigtût peninsula. Previous workers had concluded that they were largely restricted to an early phase of the Gardar igneous activity (cf. Berthelsen, 1958, Table 1).

Porphyritic dolerites.

Dykes and inclined sheets of highly porphyritic dolerite and basalt form conspicuous minor intrusions in the central parts of the complex

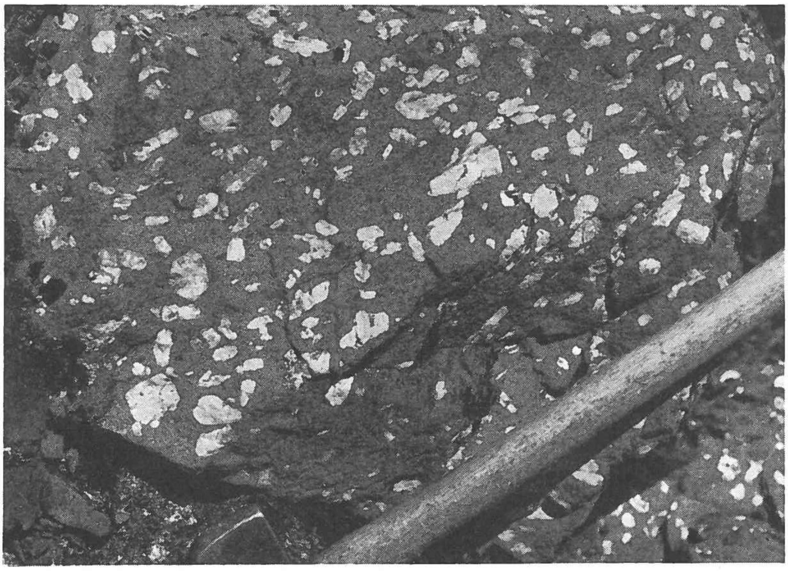

Fig. 15. Porphyritic dolerite with numerous phenocrysts of plagioclase. S.E. of Xenolithsø. Hammer shaft about 4 cm. in diameter.

(Fig. 15). These contain abundant well-formed plagioclase crystals to 2 cm. diameter in a fine or medium-grained groundmass. In the rare examples of fresh rock the plagioclase phenocrysts are lustrous grey or white crystals and set in a red-brown matrix. It is more usual for the porphyritic dolerites to contain dull, matt-white plagioclase crystals in an iron-stained groundmass which has a dull greenish-grey colour on the freshly broken surface. Modally the plagioclase crystals do not generally exceed 20 % (vol.) of the rock although occasionally the proportion may rise to over 40 % (vol.) as estimated from several outcrops. The phenocrysts are apparently randomly oriented, showing neither lamination or lineation.

Completely fresh material has not been obtained from the members of this group within the Grønnedal-Íka area. In thin slice the large plagioclase crystals are wholly or in part replaced by aggregates of sericitic mica. Typically the phenocrysts lie in a groundmass of average grain size about 0.1–0.2 mm. consisting of dull brown biotite, chlorite, sericitised plagioclase, relic areas of brown augite, and opaque minerals in finely disseminated grains or elongated aggregates (after original pyroxene). Apatite is a common accessory. Secondary calcite is present in most sections, epidote and pale green amphibole may develop as late-stage or alteration products. A relatively fresh specimen (39694) cut by later microporphyritic basalt contained pale coloured hypersthene as well as augite. The fresh phenocrysts in this specimen are of labradoritic composition (ca. An 58).

The age relations of this group are fairly certain. Porphyritic dolerite intrudes lamprophyre about 200 m. to the north of Øvre Radiosø and cuts flow banded carbonatite. Dykes of porphyritic dolerite and basalt are cut by the alkaline dykes (trachytes and phonolites) and the microporphyritic basalts, a three-fold contact was obtained on one specimen (31804) with microporphyritic basalt chilled against porphyritic dolerite and both rocks cut by a later trachyte. In the same area, about 300 m. to the south of the hut at Jernhat, isolated strips of porphyritic dolerite were seen intruded by later dykes of olivine dolerite. At several localities in the ground immediately to the south of Xenolithsø carbonatite invades and brecciates thin dykes of porphyritic dolerite, contrary to the evidence of this type cutting banded carbonatite (see above). The intrusive relationship is considered to be secondary (see pp. 40–41).

The porphyritic dolerites are probably related to the extensive development of petrographically similar rocks occurring as dykes in the country between Kobberminebugten south of Ivigtût and the Igaliko complex east of Julianehåb. They are almost certainly related to the dykes mapped by the writer in the ground north of Tigssaluk fjord, and found by others in the country around Ivigtût. Although the examples at Grønnedal, and in the Ivigtût area generally, do not have the giant plagioclase crystals of the dykes in the south, their widespread occurrence and compositional peculiarities pose much the same petrogenetic problems as those presented by the more spectacular southern examples.

Olivine dolerites.

Several wide dykes of olivine dolerite intrude the alkaline complex and the country rocks (Plate 2; Fig. 16). Three strike approximately east–west on either side of Íka, another extends from near Nedre Radiosø to the northern end of Langesø while a fifth may be followed from the southern side of this lake through the complex to the Ivigtût plateau, and beyond. There are also a number of smaller olivine dolerites between Urdal and Xenolithsø. One moderately thick basic dyke at the northwestern margin of the complex belongs to the later group of microporphyritic basalts.

The different dykes are fairly distinctive in hand specimen. The three near the head of Íka, and that north of the Radio lakes (Bd 0 (4), Fig. 16), are all of moderately coarse-grained dolerite with laths of plagioclase and lustrous dark areas of interstitial pyroxene. Olivine is present but is not a conspicuous feature of these rocks in the hand specimens. The dyke striking N.E.–S.W. is coarse-grained and almost gabbroic at times, containing fresh laths of plagioclase 5 mm. in length, shining dark pyroxenes in ophitic plates, and rounded green olivine

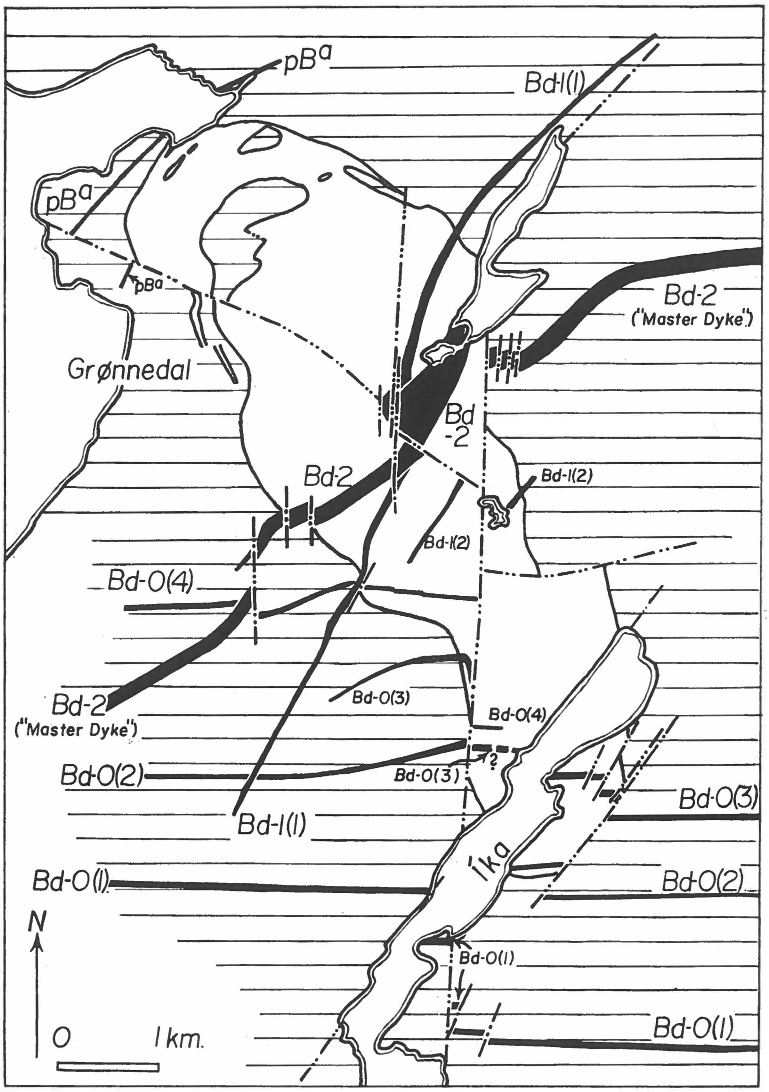

Fig. 16. Sketch map of the Grønnedal-Íka complex showing the positions of the major dykes:

pB^a = microporphyritic basalt
Bd0 = early olivine dolerite dykes (1–4)
Bd1 = second generation of olivine dolerite dykes (1–2)
Bd2 = latest olivine dolerite dyke in complex (the Master Dyke).

Gneiss marked with horizontal lining, unornamented area in the centre of the diagram = alkaline complex of syenites and carbonatites. Coasts shown with double line.

crystals to 2–3 mm. in diameter. This rock weathers to an attractive warm red-brown colour and is a typical representative of Wegmann's (1938) group of Brown Dykes. The youngest of the dykes, that striking about W.S.W.–E.N.E., is generally of medium grain and equigranular with interlocking plagioclase, pyroxene and olivine to 2–3 mm. in diameter. It sometimes develops patches of pegmatite, as in the Radioelv at about 250 m.

Because of their uniform petrography both in hand specimen and thin section, and to some extent by their constancy in width, the large olivine dolerite dykes provided a valuable key in elucidating the complexities of faulting in the Grønnedal-Íka area.

Mineralogy.

The mineralogy of the olivine dolerites is relatively uncomplicated. The principal constituents are a fairly magnesian olivine, augite or titanaugite, plagioclase ranging in composition from labradorite to basic andesine, and opaques. There are also accessory amounts of apatite, chlorite, biotite and carbonates. Quartz was found in the earlier dykes (Bd 0 generation), but was not detected in others. There is sometimes analcite in the later dykes. Hypersthene, pigeonite and micropegmatite were not found.

Although the detailed mineralogy of these dykes will not be considered here, a few petrographic notes are in order. The variation in habit of the olivines is noticeable; in the earliest group of dykes and in some members of the group striking N.E.–S.W., the mineral occurs as microphenocrysts to over 2 mm. in diameter. The crystals may be subidiomorphic, although more often they show an intergranular relationship towards other minerals, particularly plagioclase, and in some instances the olivine may be poikilitic (27132). In all dykes it is not unusual for the olivines to be present as clusters of small equigranular crystals. (27018) and in some examples intergranular and aggregated olivines are present in the same thin section without any detectable differences in composition (27070). The clino-pyroxene is almost always brown or purple-brown augite, occasionally with indications of compositional zoning in the increased intensity of brown colouration towards the margins and the rare development of a thin outer rim of green pyroxene (31872), particularly against biotite, chlorite, or rare analcite (27017). The plagioclase is often normally zoned, occasionally there are signs of an oscillatory zoning (27070). It is generally in well-formed laths up to 3–4 mm. in length and of early crystallization judging by the euhedral faces developed towards olivine and pyroxene, and the occurrence as phenocrysts in fine-grained marginal facies (31872). Plagioclase generally appears to be randomly orientated; however, fluxion alignment has been noted (27029). The specimens with flow alignment of the feldspars are finer-grained than normal, suggesting that close packing of the early crystals may have inhibited later growth.

Age relationships and courses of the major dykes.

The course of the latest dyke, the Master Dyke of the Ivigtût peninsula (BERTHELSEN, 1958) can be traced westwards from a prominent cliff exposure on the western side of Forkertekløft about 3.5 km. from Íkasletten. Intermittent exposures for about 2 km. link this exposure with the 2 km.–long outcrop on the southern side of Langesø where the dyke, here about 130 m. in width, weathers to form a broad, gravel-strewn roadway along the crest of a ridge. About 450 m. to the east of the small stream draining from Tolvsøer to Langesø the first of a series of faults displaces the dyke dextrally along a line at about N 10° E. A succession of similar dextral transcurrent faults is encountered up to the gully occupied by the small stream between the lakes, where the dyke ends abruptly. There is no sign of the dyke to the west of the gully, which marks the site of a major fault (p. 66). It is exposed again on the small peninsula on the N.W. side of the lake, at the outlet to Langesø, and continuously to the Hytteelv on the ridge south of Bryggerens Elv and on the slopes on the north side of this river. In this ground there is an appreciable thickening in the dyke outcrop; from 130 m. south of Langesø it has increased to an apparent thickness of over 600 m. in the outcrops extending either side of the river. In the exposures on the north side of the river it is found that a part of this increase in thickness results from systematic small scale dextral displacements of the dyke along a series of closely-spaced faults striking at 40°–50°. Examination of the outcrops either side of the river, and particularly on the rounded ridge east of the lower Hytteelv, reveals a multiplicity of minor crush lines and shear planes. On the southern side of Skraldebunken the Master Dyke truncates the thick olivine dolerite striking N.E.–S.W. with a normal intrusive contact complicated by later faulting. To the S.W. of the Hytteelv exposures are sparse. A doubtful occurrence of dolerite from the Master Dyke was recorded at 370 m. S.S.E. of the confluence of the Hytteelv with Bryggerens Elv. To the west the full normal width of the dyke is again exposed at about 250 m. in the Radioelv, and intermittently in streams to the west up to the eastern edge of the plateau where there is slight complication because of the coincidence of a fault with a discontinuity in the dyke. On the eastern edge of the Ivigtût plateau the Master Dyke cuts a member of the early group of east-west dykes.

The next youngest dyke (Bd 1(1), fig. 16) has a N.E.–S.W. strike and enters the complex near Nedre Radiosø. At this point the dyke cuts a member of the early east–west group (Bd 0 (4), fig. 16) and is itself involved in later faulting and crushing parallel to its strike. The dyke may be followed N.E. for about 1.5 km. into the complex until lost in the drift covered ground N.W. of the hut at Jernhat. Up to this point there is a little of note except that a small apophysis in the upper part of the Radioelv gives a local increase in width. Rather altered dolerite is exposed at 550 m. elevation, N.W. of the hut. The next definite exposures of the dyke are those on Skraldebunken where it is cut by the Master Dyke. From this point the dyke is continuously exposed cutting various syenites for about 1.5 km. to the N.E. margin of the complex. Further exposures occur along the western edge of Langesø and at the north end of the lake where the width has decreased to 15 m. from about 70 m. on Skraldebunken. From other mapping it appears that this dyke dies out a short distance to the north of Langesø.

The southern member of the early group of four east-west dykes is the most reliable in effecting a correlation across Íka. From the maps (Plate 2; fig. 16) these dykes are seen to be much broken up by faulting and in part obscured by the fjord and drift deposits. The effects of the faulting are to break each dyke into a number of segments. The larger sections of the southern dyke are on coast and cliff exposures west of the fjord about 3.2 km. from Íkasletten, and on the opposite eastern shore on the peninsula and to the south-east. Although the pieces have undergone considerable relative movements they can be correlated with certainty because of their petrographic identity, and similarity in thickness and strike. The total displacement is of the order of 1.4 km., the main movement occurring between the eastern segments which are off-set about 1 km. It can be seen that the dyke to the north (Bd 0 (2)) is equally broken, with the main displacement of about 1 km. taking place at the southern end of Urdal. The connections between the several pieces of the more northerly dyke (Bd 0 (3)) were difficult to establish. Originally it was thought that this dyke extended from west of Nedre Radiosø to the east of Íka, the gap between Íka and Urdal being bridged by a small swarm of microporphyritic basalt dykes. This has proved to be incorrect, the two northern dykes consist of two members in 'en bayonet' relationship (fig. 16), the prominent bent dyke on the western slopes of Urdal being the continuation of the thick dyke marked east of Íka about 1.4 km. south of the hut at Íkasletten. The rocks in the two sections of this dyke (Bd 0 (3)) are petrographically identical (27242, 27211). Correlation of the two sections carries the implication that a part of this dyke is present on the lowest part of the ridge between Íka and the base of Urdal. Dolerite was not mapped on this ground. However exposures are poor and a dyke of badly weathered rock (the olivine dolerites disintegrate fairly readily) could have escaped notice on the Íka shore and on the southern end of the spur east of Urdal. The course of the dyke west of Urdal provides some evidence of pre-dyke faulting; the dolerite intrudes crushed syenite and is itself severely crushed in the attenuated exposures lower in the valley. Badly crushed dolerite at 250 m. in the Urdal stream provides a link between the segments of this dyke.

The dyke (Bd 0 (4) fig. 16) north of the Radio lakes is equivalent to the dolerite at 200–250 m. on the ridge between Urdal and Íka; crushed dolerite near the head of Urdal links the two outcrops. Although this dyke was thought to be related to the northern of the three east of Íka, it is more feldspathic in section, and more altered, so there is the probability that there are four early east-west olivine dolerite dykes (Bd0) cutting the complex.

From a detailed examination of the courses of the olivine dolerite dykes it emerges that the complex is traversed by major faults and fault zones. One is associated with the line from Íka, up Urdal to the cleft on the S.E. side of Langesø, another follows near the line of the Hytteelv, and yet another follows Íka.

Other olivine dolerite dykes.

East of Xenolithsø a 15–20 m. wide olivine dolerite dyke extends for about 400 m. from the syenite near the lake to gneisses to the N.E. Close to the lake exposures of the dyke failed because of drift; at the N.E. end the dyke terminates abruptly and is continued for several tens of metres by a minor swarm of later microporphyritic basalt dykes, one of which chills against the olivine dolerite.

Finally, mention should be made of the olivine dolerite dyke intruding carbonatite at Jernhat. This is a coarse-grained rather altered olivine dolerite, resembling the N.E.–S.W. dyke N.E. of Xenolithsø, with which it is provisionally correlated. It is well exposed in the Hytteelv close to the hut and is mappable for about 1.2 km. to the S. W. until it ends suddenly at a small cliff on the S.E. side of the 585 m. hill. To the N.E. no satisfactory extension of this dyke was discovered, a possible continuation is in some rather coarse-grained dolerite on the S.E. side of the sheared and faulted Master Dyke some 510 m. to the N.N.W. of the hut at Jernhat. The dyke at the hut has metamorphosed the siderite carbonatite forming the small magnetite deposit (see p. 37 and fig. 13).

Discontinuous lengths of olivine dolerite are present in the carbonatites a short distance to the S.E. of this dyke, close to the hut.

Olivine dolerite dykes: A summary.

The olivine dolerite dykes in the Grønnedal-Íka area are members of a remarkably widespread suite of thick dykes occurring in southern Greenland from at least as far north as Sermiligârssuk to the south and east of Julianehåb. Excluding a group of later N.W.–S.E. striking olivine dolerites (BERTHELSEN, 1958, 1961) the strike direction is generally between east–west and N.E.–S.W.. A general change with time from earlier east-west dykes to later ones striking N.E.–S.W. is demonstrable in the Ivigtût area, although exception are found within the Grønnedal-Íka complex. Individual members of this dyke swarm may persist over great distances, the Ivigtût Master Dyke probably extends from the Davis Strait at Arsuk Ø to the Ice Cap, a distance of over 50 km., while another prominent dyke with a width of some 150 m. or more was mapped from Sermersut for over 60 km. to the E.N.E. The dykes occupy a fairly consistent place in the sequence of Gardar igneous events (Table 1), and are fairly uniform in their petrography, olivine dolerite being predominant. Unfortunately, chemical data for this important group of intrusions is at present very limited, one analysis of the dyke

Table 3. Comparison of the Jernhat olivine dolerite with the average of three olivine basalts from Mull, Scotland.

	(1)	(2)
SiO_2	45.77	45.5
TiO_2	1.64	3.1
Al_2O_3	16.77	15.0
Fe_2O_3	3.89	3.5
FeO	8.31	10.4
MnO	0.14	0.2
MgO	7.37	8.1
CaO	7.52	8.7
Na_2O	2.38	2.6
K_2O	1.78	0.4
P_2O_5	0.19	0.3
H_2O+	2.51	1.7
H_2O-	0.09	1.0
CO_2	1.7	0.1
Rest (S)	0.17	-
	100.23	100.6
$-O=S$	0.09	
	100.14	

(1) Olivine dolerite dyke. At 64.5–64.6 metres depth in drill hole 'T' at Jernhat. Grønnedal-Íka Complex. (Analyst: A. H. NIELSEN)

(2) Average analysis of Plateau Type olivine basalts, Mull, etc., Scotland. (BAILEY et al., 1924, p. 15, analyses No. i, ii, & iii).

at Jernhat is available (Table 3,1), this is closely comparable with the alkaline olivine basalt Plateau Magma Type of Mull (Table 3, 2; BAILEY et al., 1924).

The dykes provide eloquent proof of the availability of basaltic magma more or less contemporaneously over a wide part of southern Greenland. Judging from the rheomorphic effects observed at some contacts (e. g. the Master Dyke, S. of Langesø) they may well have acted as feeders to surface flows in the Ivigtût and Tigssaluk areas (BERTHELSEN, 1958). In total outcrop area the basaltic dykes must follow closely after the more spectacular syenites and nepheline syenites in southern Greenland.

Microporphyritic basalts.

A widespread group of thin microporphyritic basaltic dykes is intermediate in age between olivine dolerite dykes and those of trachytic composition. In hand specimen the dyke-rocks are fine-grained, black or dark grey with conspicuous white needle-like plagioclase crystals one or two millimetres in length. The microphenocrysts are occasionally flow aligned, especially near the margins of the dykes, but more often they show no preferred orientation and may be in stellate clusters.

In thin section the rock consists of clear, rectangular plagioclase crystals normally (An 65) and zoning to marginal acid andesine (An 30–35). The larger crystals are set in a groundmass of granular augite, a mesh of minute andesine laths and opaque minerals. Alteration is common; chlorite is seen after pyroxene and sericitic mica pseudomorphs the plagioclase in both phenocrysts and groundmass. Calcite and occasional epidote are found in the altered rocks. Biotite and apatite are accessory minerals and very small amounts of alkali feldspar and quartz have been noted (e. g. 31807). Original, fresh olivine was not found in the material sectioned although serpentine-calcite pseudomorphs after olivine are occasionally present (31805).

The dykes of microporphyritic basalt are generally less than 1 metre in width although thicker examples are known. Multiple intrusions can have an aggregate width of several metres. Very fine-grained chilled margins are a characteristic feature of the dykes, whether cutting country rocks or against one another in the multiple intrusions.

The group has some peculiarities in its mode of occurrence. The most notable is the tendency to be intruded along fault and crush zones. This may be seen outside the complex on the hillside north of Eqaluit where close-set crush lines (striking at ca. 60°) in the gneisses are followed by numerous thin, fresh, microporphyritic basalt dykes that are uncrushed. Within the complex the microporphyritic basalt intrudes highly

Fig. 17. Olivine dolerite dyke (Bd 1 (2)) intruded by numerous thin dykes of microporphyritic basalt. About 300 metres S.S.W. of the hut at Jernhat.

crushed olivine dolerite between the outlet of Langesø and the Hytteelv. Small swarms of short length are also present in areas devoid of detectable crushing, as within the carbonatites about 0.5 km. S. E. and south of the hut at Jernhat. Here, the dykes provide the resistant element in a small ridge that also includes altered syenite and carbonatite.

Microporphyritic basalt is found in close association with olivine dolerite (Fig. 17). In a number of places the fine-grained rock continues the line of strike of a dolerite dyke that has ended abruptly, as on the ridge between Urdal and Íka, and N. E. of Xenolithsø.

An unusually thick member of the group intrudes the gneisses at the N. W. end of the complex. The dyke is between 15–20 m. wide and intermittently exposed between the south side of Eqaluit and the Laksenæs Fault (where it is off-set sinistrally about 600 m.). It is also present near the huts at Eqaluit where it is eroded to form a small gorge at the mouth of the river from the northern valley. Near the huts the margins of the dyke are typical microporphyritic basalt which passes towards the centre into a medium-grained vesicular dolerite with cavities lined with bright yellow-green epidote and calcite (39717). The central part of the dyke is rather inhomogeneous, there are irregular schlieren of coarser dolerite enclosed in normal medium and fine-grained rock. In thin section the mineralogy is much as in the finer-grained types; the plagioclase is normally zoned (from cores of labradorite to margins of acid andesine), the clinopyroxene is a violet-brown augite with thin green rims formed adjacent to the epidote-calcite–filled cavities and interstitial areas (39717). Possible alkali feldspar was noted in the interstices of the other minerals. Biotite and apatite are present as accessories. Olivine was not found in the rocks sliced although pseudomorphs after olivine are seen in the slices from the continuation of this dyke S.W. of the Laksenæs Fault (39784).

Dykes of microporphyritic basalt are fairly common throughout the country around Ivigtût, particularly along crush zones and other lines of weakness in the Main Fault Zone (Berthelsen, 1958). The writer has found petrographically similar dykes intruding the Sanerutian granites in the Tigssaluk area, again in association with faulting and crushing.

In conclusion, mention should be made of an explosive phase apparently associated with a member of this group of dykes. In a fault zone striking slightly east of north either side of Øvre Radiosø there are later xenolithic basic dykes containing syenite, gneiss and basalt fragments in a matrix of basic rock similar to the microporphyritic basalts. In the shallow saddle north of the lake the syenite near the dyke is increasingly brecciated towards the intrusion, passing from a rock consisting of angular syenite fragments several tens of centimetres across to one resembling a crystal tuff close to the dyke (31830). The basic intrusion veins the brecciated rocks, carrying fragments of syenite and xenocrysts of syenitic origin. Similar microporphyritic basalt also occurs as small rounded inclusions in the main body of the dyke and with the marginal brecciated syenite. The sequence of events is thought to have been first an intrusion of microporphyritic basalt along the fault, then explosive brecciation preceding a second intrusion of microporphyritic basalt, the second intrusion probably taking place before the first had completely chilled and consolidated.

Thin sections of the xenolithic and tuffaceous rocks reveal more variety than is apparent in hand specimens. In addition to the microporphyritic basalt fragments and the syenitic material, there are also fragments consisting of quartz and alkali-feldspar in contact, and of crystal aggregates of quartz. Some of the xenolithic material in the dyke and the tuffaceous rocks has probably been derived from the gneisses, as the quartz-bearing rocks are very similar to those found associated with gneiss xenoliths in the dyke at the hut at Jernhat.

The matrix of the xenolithic rocks is sometimes a very fine-grained basalt with small plagioclase phenocrysts embedded in a variolitic groundmass (31832).

Fig. 18. Xenolithic basic dyke near the hut at Jernhat. The inclusions are of a leucocratic gneiss, with a rounded, dark amphibolite inclusion near the top of the exposures. Hammer shaft 0.6 m. in length.

Near the hut at Jernhat and at a few other places in the complex there are highly xenolithic dolerite dykes. The Jernhat dyke extends from the Hytteelv at about 390 m. for some 600 m. to the south, cutting an olivine dolerite dyke and itself cut by a trachyte dyke, and faulted. The xenoliths are mainly of leucocratic gneiss (Fig. 18) with occasional fragments of amphibolite (27298) and syenite. In section the gneiss fragments show signs of thermal alteration, and reaction between quartz and the feldspars to give rims of fine-grained felsitic rock with abundant greenish to brown biotite and opaque minerals (27299). Corrosion of the quartz and feldspars is less marked along the mutual boundaries of like minerals, monomineralic aggregates are seen embedded in fine-grained felsitic surroundings. The rocks have a resemblance to the textures developed in certain altered granodiorites (Reynolds, 1941),

The abundance of inclusions, with a preponderance of gneiss fragments, is difficult to explain in a dyke near to the original centre of the complex. A possible connection to the country rocks is provided by the somewhat similar xenolithic dyke near Øvre Radiosø. No connection was established between these two dykes during the mapping. A source close to hand is indicated by the abundance and angularity of the fragments; in this connection it could be postulated that the gneiss raft exposed in the N.W. of the complex extended under the Jernhat area.

An uncommon variety of the microporphyritic basalts contains fresh plagioclase phenocrysts (An 65) to 2 cm. in length. These occur in the normal microporphyritic basaltic base. The dykes of this type are generally much fresher than the superficially similar porphyritic dolerites which they cut south of Xenolithsø.

Other basic dykes.

Several thin dykes of medium to fine-grained dark-coloured rock cannot conveniently be assigned to any of the groups described; this is often because the rocks are so altered that it is impossible to decide their origins. One exception is a dark green fine-grained dyke (39790) cutting syenite at about 450 m. elevation on the ridge between Urdal and Íka. In thin section this consists essentially of brown to red-brown biotite, and riebeckite, with a small amount of alkali feldspar. A few turbid phenocrysts of alkali feldspar were found together with scattered large crystals of apatite up to 2 mm. in length. Compositionally the rock is intermediate between the trachyte and the lamprophyres. No intersection was obtained with other dykes although two trachytic dykes are displaced dextrally by a small fault that did not appear to affect the dark green dyke. However, exposures are indifferent in the critical area.

Another thin dyke (31803) that was provisionally correlated with the 'Scott's Diabase' (tinguaite) group of Ivigtût (Berthelsen, 1958) intrudes syenite about 300 m. to the N.E. of the hut at Jernhat. It consists of aegirine-augite, nepheline, biotite, and alkali feldspar, and is almost certainly related to the alkaline igneous activity either of the main phase of syenite emplacement or possibly with the emplacement of the later trachytic dykes. No intersection with another dyke was found.

Alkaline dykes.

The numerous thin leucocratic alkaline dykes intruding all members of the alkaline complex and the basic dykes, stand out from their surroundings because of their pale colouration and resistance to weathering. They often occur as long, low ridges of light coloured rock traversing a waste of dark-coloured rubble derived from the easy weathered carbonatites or altered syenites. Individual dykes are generally from one to five metres in width, several are thicker and one attains a thickness of over 15 metres. Although they are thin compared with the olivine dolerite dykes, it was possible to map several individuals for distances of over

2 km. and one particularly distinctive dyke was traced for over 3 km. Mapping was greatly facilitated by the manner in which individual dykes preserved their characteristic textures, width, and even colour over long distances.

The dykes are generally aphyric or sparsely porphyritic, fine-grained, and coloured in tints of grey, pink, green, blue, brown and creamy white. Although colour was used successfully as a diagnostic feature during the mapping, it was necessary to exercise caution since colour changes do occur, particularly where dykes are involved in shear zones or faulting. In several of the dykes the rocks displayed a satiny sheen on freshly broken surfaces, an effect that could be related in thin section to near parallel orientation of numerous minute laths of feldspar (31821, 39730). A small number of dykes contains mineral-lined cavities a centimetre or so in diameter. Elongated cavities in a 2 m. wide dyke (39689; strike 50°) 650 metres S.S.E. of the hut at Jernhat plunged at 35–40° in a direction about 250°.

The leucocratic alkaline dykes were collectively mapped as 'trachyte' or 'porphyritic trachyte'. From an examination of about sixty thin slices these terms are seen to have included quartz-bearing, saturated, and feldspathoidal varieties, covering the compositional range of quartz trachyte, orthotrachyte, and phonolite (or tinguatite). Grain-sizes range from macrocrystalline rocks with platy alkali feldspars over one millimetre in length (39795) to extremely fine-grained flow-banded rocks with the felsitic texture of a devitrified glass (31895). True trachytic texture is developed to varying degrees of perfection regardless of the composition and grain-size except in the very fine-grained specimens. When present, phenocrysts are usually of alkali feldspar (orthoclase or microcline perthites). Aegirine phenocrysts are occasionally found (27184, 27800, 39756, 39762) and abundant large crystals of fresh nepheline occur in one dyke (27200).

Of the several well-defined compositional groups that may be distinguished amongst the alkaline dykes, the commonest is a feldspathoidal variety consisting of a mesh of needle-like crystals of alkali feldspar 0.1–0.2 mm. in length, with equigranular areas of greenish aegirine or aegirine-augite 0.1 mm. in diameter, the interstices of the rock being filled with anhedral nepheline, analcite or natrolite. The dykes are often slightly altered, in thin section the alteration is seen to affect the nepheline first to produce an aggregate of micaceous material (gieseckite) and sometimes resulting in replacement by aggregates of cancrinite (27007, 39751). With more severe alteration the pyroxene becomes replaced by an aggregate of dark brown or opaque granular decomposition products accompanied by ironstaining in the adjacent crystals. The mesh-like arrangement of feldspar crystals characteristic of many of the dykes may give way to trachytic texture (cf. 39762 with 39779) in the long dyke followed through the central parts of the complex (see p. 60).

The nomenclature of the feldspathoid-bearing dykes is rather unsatisfactory; compositionally they are equivalent to nepheline syenites yet the grain size rarely corresponds with the definition of nepheline microsyenite. They are termed phonolites, following the definition of HATCH, WELLS and WELLS (1961, p. 272) although others might have preferred tinguaites (ibid., p. 275).

Orthotrachytes and quartz-trachytes comprise about one-quarter of the sections examined. The dominant mineral is a perthitic alkali feldspar in lath-like crystals to 1.0×0.2 mm. which are noticably less acicular than the feldspars of the phonolites. The mafic mineral is generally a strongly pleochroic brown mica (X = golden brown, Y = Z = dark brown, $2V\alpha$ very small) often rimmed by inky-blue riebeckite, (27037). Riebeckite is also present in discrete crystals, and occasionally it is the only dark mineral in the rock (39733). Arfvedsonite was tentatively identified in several sections (e. g. 39795). Aegirine-augite or aegirine is fairly often present in the orthotrachytes but almost invariably absent from the quartz-trachytes; it is not usually found when riebeckite is present. In general feldspathoids or their alteration products were not present if the mafic minerals included an alkali amphibole.

The mineralogy of the quartz-trachytes is essentially similar to that of the orthotrachytes except that the mafic minerals are usually brown biotite and/or riebeckite. The quartz is present only in very small amounts, as anhedral areas between feldspar laths or as small areas of highly irregular outline in the finer-grained rocks.

Dykes with mineral-filled vugs are restricted to the phonolites. Fillings of the cavities include calcite, pyrite, deep-purple fluorite (e. g. 31818 A) and rarely galena (31824). In another example (31821) the central part of a calcite-lined cavity was filled with a granular aggregate of pale yellow-green analcite.

The majority of the alkaline dykes strikes in a direction approximately N.E.–S.W. to E.N.E.–W.S.W. (from about 40° to near 80°). A lesser group has a strike between W.N.W.–E.S.E. and N.W.–S.E (about 110°–150°). Dykes with the more north-westerly strike extend from north of the cliffs at the Cirkus to the cliffs to the N.W. of Íkasletten, while the major group is concentrated to give a minor swarm cutting the central carbonatite — syenite area of the complex, with isolated examples throughout the syenites except towards the northern and southern extremities (Plate 2).

Intersections between dykes striking in different directions may be seen north of the Cirkus and on the steep slopes N.W. of Íkasletten, in each instance the more north-easterly intrusion is the later. Less direct evidence supporting this age relationship comes from the ground immediately to the north of the eastern end of Laksenæs Fault, in the steep hillside N.W. of Íkasletten, where a dyke striking about 120° is cut by faults at 20° which do not appear to disturb the nearby, later dykes striking E.N.E. to N.E. (fig. 19).

From the intersections the earliest dyke is found to be a quartz-bearing riebeckite trachyte (39733; strike 20°) north of the Cirkus which is cut by a biotite quartz-trachyte (39734; 40°) and almost certainly by a phonolite (39731; 55°). South of the Xenolithsø a typical phonolite (39751; 120°) is cut by an orthotrachyte (39752: 50°) containing riebeckite-rimmed biotite; both are cut by another orthotrachyte (39750; 50°) with dark green biotite. About 400 m. south of the hut at Jernhat orthotrachyte (39795; 40°) cuts a highly feldspathic orthotrachyte (39798; 35–40°) which in its turn cuts a normal phonolitic dyke (39797; 40°), all three being members of the swarm in the central carbonatite area. The sequence of intrusion in the alkaline dykes is summarized below.

Relative ages of the Alkaline Dykes (generalised).

	Rock type	Approximate strike direction.	
↑	orthotrachytes with riebeckite, biotite, etc.	NE. - SW.	↑
	phonolites	ENE. - WSW. to NE. - SW.	
Time	phonolites	NW. - SE.	
	quartz trachytes	NW. - SE.	

The distinctive field and petrographic characteristics of the alkaline dykes made them particularly valuable in elucidating the late faulting within the Complex. The map (Plate 2) reveals two persistent features connected with the dykes: long single dykes repeatedly off-set by large and small faults and groups of sub-parallel faults, and the termination of minor swarms of alkaline dykes against the major fault zones.

The most illustrative example of the first feature is seen in southern Grønnedal where a chalky-white to cream-coloured phonolite (39762) about 5 metres wide outcrops in the Radioelv at 180 m. elevation, in a stream some 600 m. to the E.N.E., and again in Bryggerens Elv at 150 m. elevation where it is dextrally displaced about 150 m. by a north-south fault. To the E.N.E. the dyke crosses the ridge of Skraldebunken about 150 m. to the north of the 370 m. top, continuing in intermittent exposures towards the edge of Langesø. About 400 m. south of Tolvsøer the continuation of the same dyke outcrops as several small segments of white-weathering rock on the low, westward-facing scarp formed by the Main Fault. East of the fault the dyke strikes at about 75° for over 1 km. as far as Turistkløft, and is probably continued east of this valley in the prominent white-weathering dyke seen on the eastern slopes. Although the exposures are far from continuous this particular dyke was followed across almost the entire width of the complex because of its constant petrography and mineralogy (cf. 39762, 39779, 27007), thickness of between 4–5 metres, and fine-grained creamy-white appearance in hand specimen.

Amongst the swarm south of the hut at Jernhat one dyke is thicker than usual (over 15 m. at times) and is petrographically distinctive with platy alkali feldspars visible in hand specimen (39795). Close by there is another dyke that is rather unusual in that it has numerous cavities (31818, 39689). Both were mapped from near the outlet of Nedre Radiosø to Xenolithsø, and both were recognized amongst the alkaline dykes south of the head of Urdal, east of the Main Fault. In this area the coarser-grained of the pair undergoes a sudden change in strike direction, from about 60° to near 130° when followed west towards the valley floor and the Main Fault (Fig. 23). From the changed and sheared condition of both dykes in this area it was evident that the Main Fault produced a wide zone of small scale movements in the upper part of Urdal which affected a zone at least 150 m. wide on the eastern side of the main line of movement. A short way to the N.E. the same dykes are sinistrally displaced by the eastern continuation of the Laksenæs Fault which to some extent counteracts the effects of the Main Fault, a feature that may be seen for the whole swarm (Plate 2) as well as the two individual intrusions considered.

Another instance of a dyke being systematically displaced by small faults is seen in the cliffs north of the Cirkus (Plate 2; Fig. 19), and a further example was found during the mapping north and N.E. of the Xenolithsø (Plate 2; Fig. 20).

Summary.

Alkaline dykes extend well beyond the limits of the Grønnedal-Íka complex. To the east many were mapped intruding the gneisses between Arsuk Fjord, the western edge of the Ice Cap and Forkertekløft. To the west they are abundant throughout the Ivigtût peninsula (Berthelsen, 1958).

The alkaline dykes are amongst the latest Gardar intrusions in the ground between the Ivigtût peninsula and the Ice Cap; they represent renewed alkaline igneous activity after a long period when the majority of intrusions were of basaltic magma. They parallel the sequence now known from the country around Julianehåb, where syenites and nepheline syenites at Igaliko, Ilímaussaq and Nunarssuit are amongst the youngest Gardar intrusions, following the emplacement of a numerous suite of basaltic dykes and earlier extrusion of olivine basalt lavas.

There are indications of a close association between the phonolitic dykes and nepheline syenites. Near Ivigtût small xenoliths of foyaite (19083–19086) were found in a phonolite dyke (Berthelsen, 1958). The inclusions resemble foyaites in the Upper Series of the Grønnedal-Íka syenites. However, they were found about 10 km. from the complex and as the phonolites cutting the syenites and country rocks are not generally xenolithic it is possible that the inclusions were derived from another source, possibly of later Gardar age.

FAULTING OF THE COMPLEX

Introduction.

Three principal groups of faults cut the members of the alkaline complex. The earliest consists of dextral transcurrent faults striking about 0° to 30°. These are cut by the sinistral transcurrent Laksenæs Fault, striking between 100° and 120°. The third and youngest group, which includes the Main Fault zone (p. 66), comprises a set of dextral transcurrent faults striking between 0° and 10°.

Although all the faults within the complex appear to be later than the carbonatites and the majority of the dykes, carbonatite is found intruding the fault planes at several localities. This is considered to be a secondary effect, resulting from plastic deformation and flow of the earlier carbonatite in response to compressive forces connected with the transcurrent movements. From the general mapping (Plate 2) both the Main Fault and the Laksenæs Fault are clearly later than the carbonatites.

First group.

Faults of this group displace alkaline dykes and syenites north of the Cirkus. In the ground south of Langesø they are responsible for movements affecting olivine dolerite dykes and gneiss, while east of Xenolithsø they displace the four thick dykes of olivine dolerite (Bd 0 generation). The relatively early age of the group may be demonstrated near the confluence of the Hytteelv with Bryggerens Elv, and in the higher parts of the cliffs to the N.W. of the hut at Íkasletten. At the latter locality several faults striking between 10° and 30° displace a phonolitic dyke striking approximately 100°, but have no effect on the eastern continuation of the Laksenæs Fault between 150–300 metres to the south (Fig. 19).

The amount of movement on individual faults in this group is generally slight, except near Íka. Although the individual movements are not usually more than 100 metres in the horizontal sense, the total horizontal displacements caused by the early faults are considerable since the faults are very numerous in several parts of the complex. Using some of the distinctive dykes as markers it can be shown that aggregate displacements are of the order of several hundred metres (Figs. 19, 20,

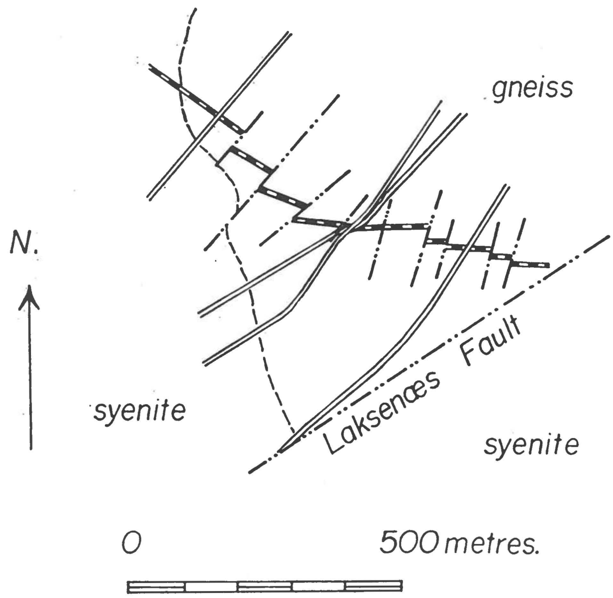

Fig. 19. Sketch of the fault and dyke relationships about 1 km. N.W. of Íkasletten. Faults shown by broken lines and dots, the syenite/gneiss boundary by a broken line, and alkaline dykes with double lines. An early alkaline dyke is shown ornamented.

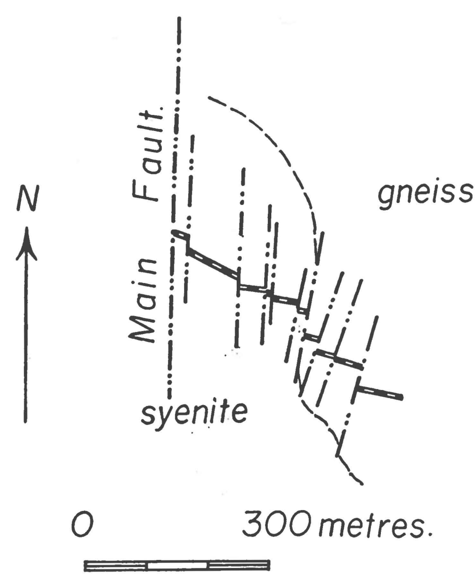

Fig. 20. Phonolitic dyke off-set systematically by dextral transcurrent faults of the first group and faults associated with the Main Fault. Symbols as for fig. 19. About 700 metres E.N.E. of the hut at Jernhat.

21), when these are considered over the complex as a whole they are seen to have caused a significant amount of distortion and elongation in the original outline of the complex in a direction approximately N.N.W.-S.S.E.

A part of the unusual width of the Master Dyke (Bd 2) S.W. of Langesø is attributed to small-scale early faulting; sheared and crushed dolerite of the dyke is displaced by the Laksenæs Fault. The outcrops of the dyke are minutely dissected by a multiplicity of small crush lines,

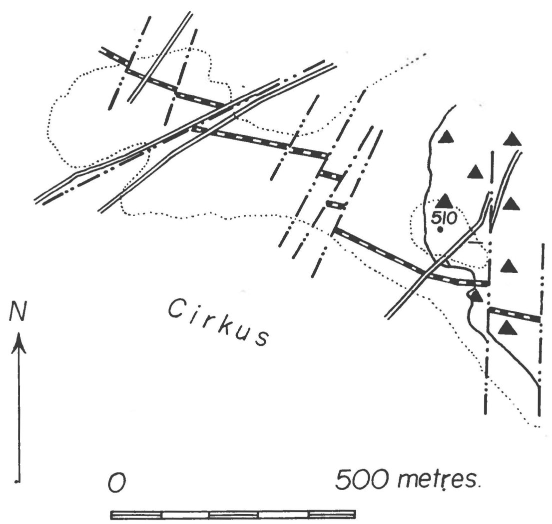

Fig. 21. Alkaline dyke cut by later alkaline dykes and displaced by first group faults towards west and two of the third group at the east. Cliff top to the north of the Cirkus. Symbols for dykes and faults as in fig. 19. Xenolithic porphyritic syenite marked by triangles, Upper Series syenites unornamented.

faults and shatter belts (Fig. 22). These show some persistence in direction over limited areas, those on the rounded hill overlooking the Hytteelv strike between 175°–5° in one zone, changing to the N.E. to a strike of 120°–140°. The relations of the two sets were not obtained. Further towards Langesø, the small-scale dislocations strike fairly consistently at 25°–35°. The margins of the dyke are irregular on the northern edge where displacements occur along north–south faults. On the southern side there are small irregularities, and secondary intrusion by carbonatite was noted.

The faulting partially responsible for thickening the Master Dyke is the continuation on the N.E. side of the Laksenæs Fault of the wide and rather diffuse zone of crushing and faulting traced intermittently from close to the outlet of Nedre Radiosø towards the Hytteelv. The

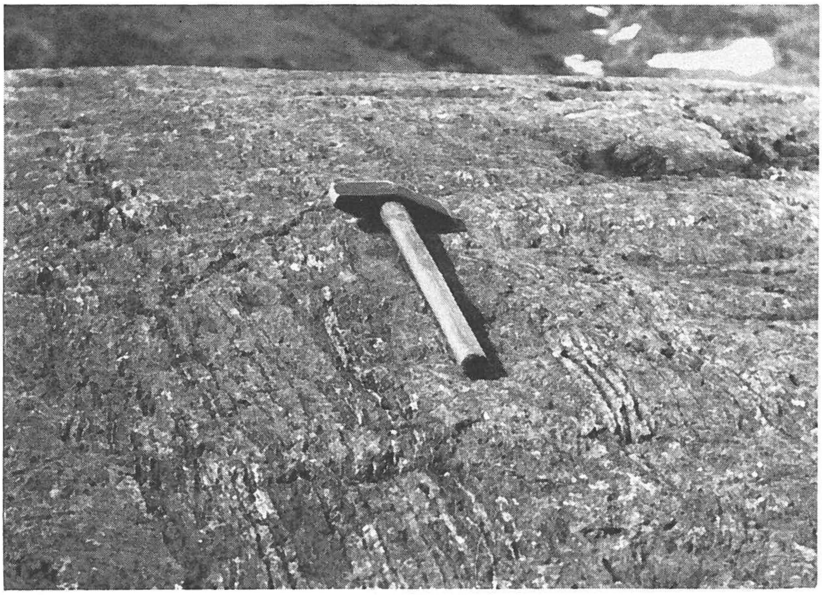

Fig. 22. Close-set crush lines in the Master Dyke (Bd2) about 0.85 km. north of Jernhat. Hammer head about 18 cm. in length.

faults have a slightly more northerly strike than the dyke (about 60°). The mechanism of thickening can be compared with the act of pushing together a pack of playing cards arranged 'en echelon', the thin extended pack being equivalent to the original dyke, the planes separating cards corresponding to the lines of movement in the fault system.

Along and to the S. E. of Íka the several early N. N. E.–S. S. W. striking faults produce a total dextral transcurrent movement of about 1 km. All are off-set about 0.75 km. by the southern part of the dextral transcurrent Main Fault.

Second group.

The Laksenæs Fault is the principal member of this group. The amount of movement on this fault is readily assessed in the well-exposed N. W. part of the complex, between Eqaluit and Grønnedal, where the contact between gneiss and syenite is displaced sinistrally for about 800 metres in a horizontal sense. The greater part of the post-syenite movement on this fault was horizontal, fixed points on the fault plane given by the intersection of the base of the Lower Series Foyaite with the steeply-inclined granular syenite are at approximately the same heights on either side of the fault.

The Gardar movements on this fault took place at a relatively late stage as the fault cuts the faults of the first group and displaced several phonolitic dykes up to 800 metres. However, a phonolitic dyke followed through the complex (p. 60) appears to be later. To the north of Grønnedal the fault has a northerly hade, its course is convex to the south where it crosses the spur N. N. E. of the bridge over Bryggerens Elv (Plate 2).

In the east of the complex the Laksenæs Fault gives horizontal sinistral displacements of about 0.5 km. In this area, about 1 km. N. W. of the hut at Íkasletten the outcrop of the fault undergoes a sudden change in direction about 0.5 km. to the east of the head of Urdal (Plate 2), consistent with a steep northerly inclination to the fault plane. Exposures of the fault plane in this area show strong horizontal slickensiding and grooving.

Between the northern end of Xenolithsø and the Cirkus in the north of Grønnedal the fault is not well exposed. Its position can be estimated with relative ease but outcrops are confined to a single exposure at about 310 m. elevation in the Hytteelv.

The zone of crushing and alteration associated with the Laksenæs Fault is very narrow and does not usually exceed two or three metres in width. Several minor faults parallel with the Laksenæs Fault were mapped north of the Hytteelv, and it is possible that two sinistral faults on the spur north of the bridge over Bryggerens Elv are branches from the Laksenæs Fault.

Third group.

A large north–south mylonite zone was mapped in the east and south of the complex by J. BONDAM during the preliminary survey for G. G. U. This fault zone is now termed the Main Fault, and it extends north from Íka to Langesø.

Tracing the fault north from Íka, dextral horizontal displacements of the order of 750 metres are found between olivine dolerite dykes (Bd 0 generation) either side of the fjord and at the foot of Urdal. In the valley the contact between syenite and gneiss is displaced at least 700 metres dextrally. Further to the north about the head of Urdal the Laksenæs Fault and alkaline dykes are also displaced dextrally about 800 metres, and movements in the same sense and of similar amount are found between Urdal and Langesø. Between Íka and Langesø the fault follows an approximately north–south course with slight deviations suggesting a steep westerly inclination to the fault plane. At Langesø it seems probable that the course of the fault has been influenced by the earlier zone of dextral faulting that contributed to the thickening of the Master Dyke (p. 65); the Main Fault almost certainly swings into a direc-

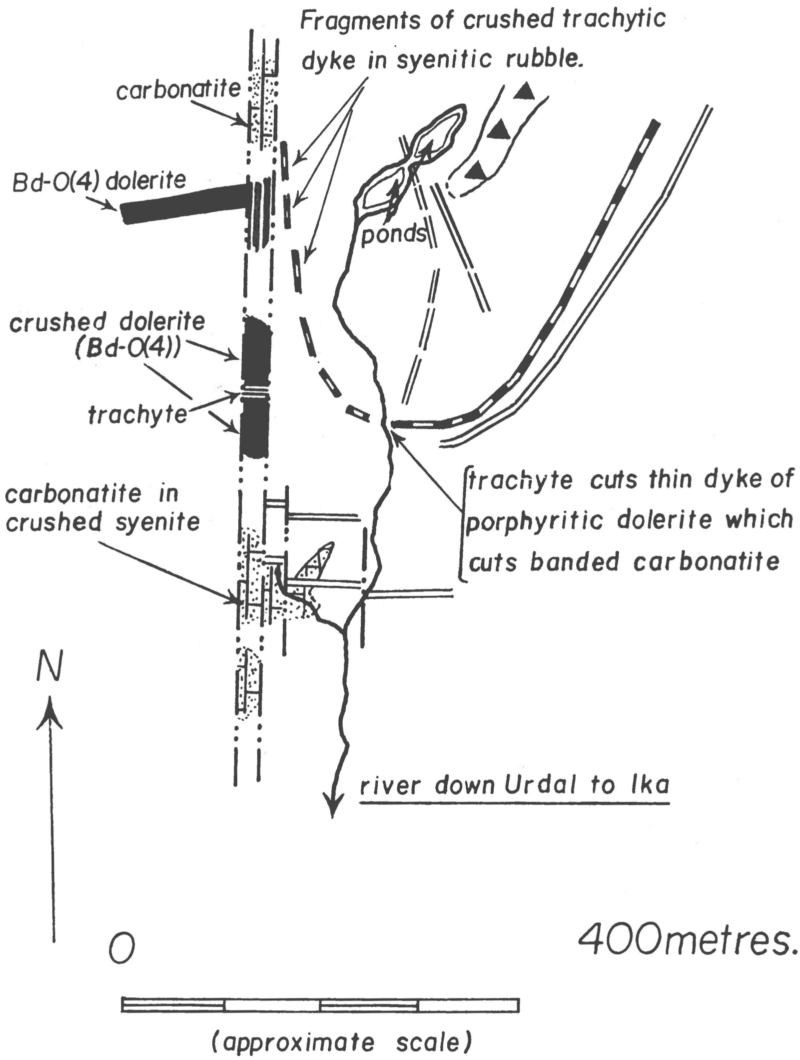

Fig. 23. Dyke and fault relationships near the head of Urdal. Symbols indicated on diagram, otherwise as for previous figures.

tion east of north to follow the line of the lake since the olivine dolerite (Bd 1 (1)) close to the western shore is not faulted. A possible N.E. continuation of the Main Fault is found in the marked zone of crushing striking at about 35° in exposures of gneiss at the N.E. end of Langesø.

Most of the movement on the Main Fault was taken up along a zone of about 20 metres width. However, the effects of the faulting were much greater and minor crushing and systematic small-scale dextral movements are detectable for 150 metres or more on either side (Fig.

23). Movement along parallel fractures is demonstrated by the presence of isolated slices of olivine dolerite dykes (Bd0 generation) at elevations of about 250 m. and 500 m. in the river in Urdal, and also by the distortion and segmentation of the phonolitic dyke 750 metres N.E. of the hut at Jernhat (Plate 2).

Lesser late dextral transcurrent faults are found in the N.E. of the Cirkus on the west and N.W. of Skraldebunken, and near the confluence between the Hytteelv and Bryggerens Elv. On the western side of

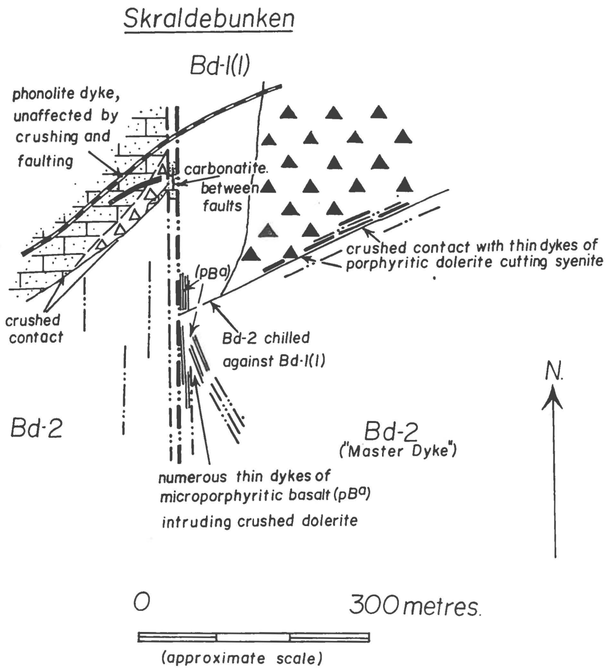

Fig. 24. Fault and dyke relationships on Skraldebunken. Dotted brick ornament = carbonatite, open triangles = carbonite-syenite breccia. Other symbols indicated or as in previous figures.

Skraldebunken one fault cuts the Master Dyke, is itself cut by a phonolitic dyke (Fig. 24) and further to the south the same fault probably displaces the Laksenæs Fault in a dextral sense. Another nearby north–south fault produces a dextral horizontal movement of about 150 metres in the phonolitic dyke mentioned above, providing evidence of some overlap between the intrusion of the alkaline dykes and faulting.

The Main Fault and the associated late movements are the youngest faults in the complex. They are also probably the latest Gardar movements in the country around Ivigtût and are unusual in that elsewhere the last Gardar movements were those on the Laksenæs Fault or associated E.S.E.—W.N.W. sinistral transcurrent faults.

Other faults.

Several of the faults in the north and N.W. of the complex cannot be readily classified with any of the three groups described. One fault, striking nearly N.E. - S.W., is responsible for the long shallow valley close to the northern side of the Cirkus; this fault may continue N.E. to the margin of the complex. It displaces a phonolite (39735) striking at about 40°, but it is earlier than the Laksenæs Fault (Plate 2). Another, with W.N.W.—E.S.E. strike, displaces syenite and gneiss in contact at the upper and lower margins of the gneiss raft south of Eqaluit but does not intersect any dykes. Close to the S.E. end of this fault and about 1.5 km. N.N.E. of the bridge over Bryggerens Elv in Grønnedal, there is another fault displacing a phonolitic dyke (39783) and striking at about 80°. This fault ends against another striking at about 20° and belonging to the first group, thus the faults in the northern part of the complex may be of relatively early date.

STRUCTURAL DEVELOPMENT OF THE COMPLEX

The results of the mapping and to a lesser extent the laboratory investigations allow the construction of a relative time scale for the events making up the history of the complex (Table 4). The relations between igneous intrusion and faulting are reasonably clear. The country rocks were faulted before the emplacement of the syenites, carbonatites, and olivine dolerite dykes, but there was little if any faulting of the complex until after the emplacement of the olivine dolerite dykes when a series of fairly severe faulting episodes took place largely following but in part

Table 4. Summary of the geological history of the Grønnedal-Íka complex.

POST-GARDAR	Quaternary glaciation.
	Faults of the 3rd Group (Main Fault, etc.)
	Alkaline dykes.
	Faults of 2nd Group (Laksenæs Fault, etc.)
	Alkaline dykes
G	Microporphyritic basalts, xenolithic dykes.
A	Faults of the 1st Group.
R	Olivine dolerite dykes (Bd 0–> Bd 1–> Bd 2)
D	Porphyritic dolerites (Big feldspar dolerites)
A	Lamprophyres (Range in time to younger than olivine dolerite dykes).
R	Carbonatites and breccias with carbonate matrix.
	Xenolithic porphyritic syenite.
	Porphyritic microsyenite (probably contemporaneous with Upper Series)
	Upper Series:
	Coarse-grained syenite
	Foyaite and pulaskite
	Pyroxene-rich syenite
	Foyaite
	Lower Series:
	Granular syenite
	Foyaite
	Coarse-grained brown syenite
PRE-GARDAR	Metasediments, amphibolites and gneisses.

contemporaneous with the intrusion of the alkaline dykes. The sequence of faulting and intrusion is comparable with the events up to mid-Gardar times at Tugtutôq (Upton, 1964).

Because of the steep-sided nature of the majority of the boundaries within the complex the sense of the fault movement almost always appears to have been horizontal. The apparent fault pattern for the complex thus resembles that in many metamorphic terrains, and is in marked contrast to the assumed movements of faults in flat-lying sediments where casual observation will usually only reveal movements in the vertical sense. In support of the predominance of horizontal movements at Grønnedal-Íka it was found that the slickensided surfaces of the fault planes indicated horizontal movements, and movement of the Laksenæs Fault had been horizontal. The amount of horizontal movement could be estimated with fair accuracy in a number of instances. However, the sum of all the movements connected with any one group of faults is likely to be an underestimate because of lack of exposure or the absence of reliable reference points on the fault planes. Another factor to be remembered is that the movements measured on many faults were based on displacements of dykes which are relatively late members of the complex, consequently estimates of the extent of the movements of the syenites and carbonatites are likely to be somewhat in error and generally underestimates.

From even a cursory examination of the map of the complex (Plate 2) it will be evident that the original outlines of the intrusions have been much disturbed and modified. Taking the nepheline syenites and carbonatites as comprising the original alkaline complex, subsequent distortion will have been produced by the emplacement of the numerous dykes, particularly the thick olivine dolerites. The most significant effects will be those resulting from the several groups of transcurrent faults. In this section an attempt will be made to estimate the magnitude of these various effects, and from these estimates to make a reconstruction of the original shape of the complex, and hence obtain some idea of the initial structure of the nepheline syenite — carbonatite pluton.

For the purposes of reconstruction the faults and dykes will be considered in the reverse order of their occurrence, the youngest event being taken first.

The Main Fault produced a dextral movement of about 0.75 km. in a north—south direction. Smaller dislocations in the same sense and direction connected with faults of the third group amount to about 0.4 km. The minimum estimate for the group is therefore 1.15 km.

The sinistral movements of the Laksenæs Fault are about 0.85 km., to which 0.1 km. may be added to account for the parallel faults north of Grønnedal and the Hytteelv. The total movement for the second

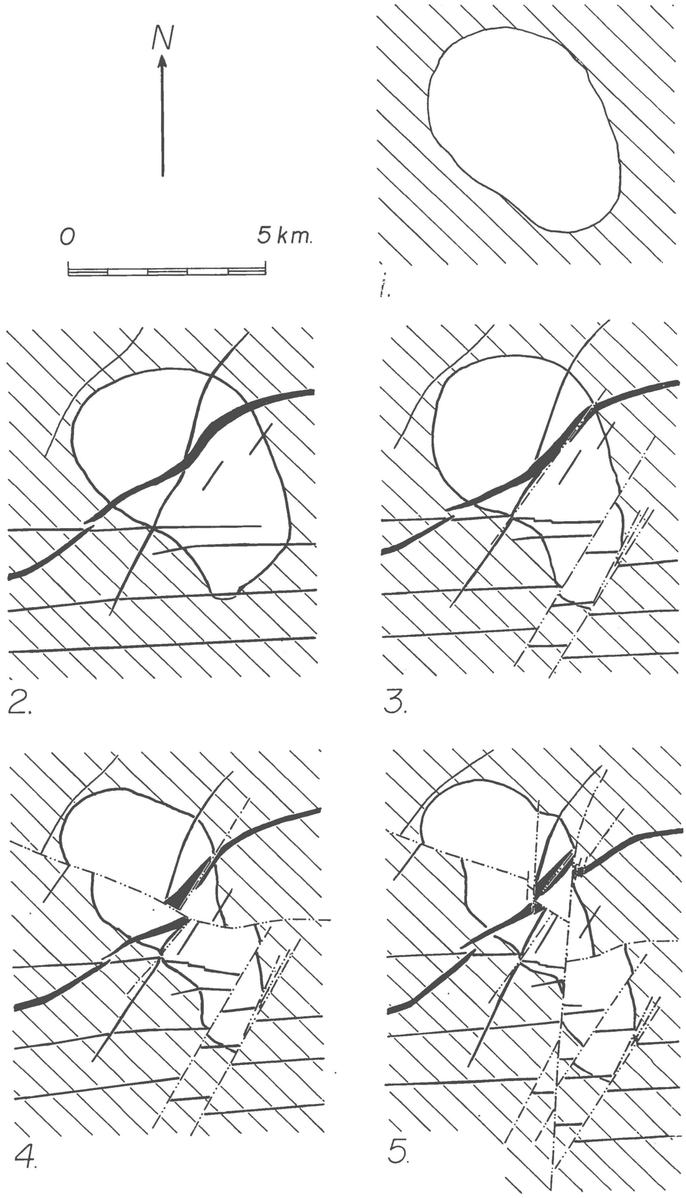

Fig. 25. Structural development of the Grønnedal-Íka complex:

1. Assumed original outline of complex (Plate 3)
2. Complex intruded by major basic dykes.
3. Complex and dykes after first group faulting.
4. Complex, dykes, and first group faults cut by Laksenæs Fault (second group).
5. Complex, etc., after movements on the Main Fault and other third group faults.

group is therefore about 1 km. of sinistral displacement in the E.S.E. – W.N.W. direction .

Estimation of the total effects due to the first group of faults is less straightforward. Along Íka and to the S.E. of the fjord these total between 0.9–1.0 km. In the cliffs N.W. of Íkasletten the total movements, estimated from displacements of alkaline dykes, come to about 0.3 km. Between Langesø and the Laksenæs Fault the movements connected with the widening of the Master Dyke may amount to 0.5 km., or more. North of the Cirkus the displacements of the alkaline dykes total about 0.3 km. The sum of these dextral north – south to N.N.E. – S.S.W. transcurrent movements is over 2 km., which is almost certainly an underestimate.

The total dilational effect of the olivine dolerite dykes is of the order of 0.4 km., that of the alkaline dykes very much less and probably not more than 70 metres. Both will have expanded the complex in a direction approximately N.N.W. – S.S.E.; the effects of the N.W. – S.E. alkaline dykes will have been very slight.

The various stages in the reconstruction of the complex are shown diagramatically (Fig. 25). When they have been made the original outline of the alkaline complex is found to have been about 6 km. from N.W. to S.E. and 3.5 km. from N.E. to S.W. (Plate 3). The reconstruction suggests a relatively simple internal structure for the complex. The Upper and Lower Series nepheline syenites formed a centrally-directed pair of laminated intrusions separated by a large gneiss raft and each with indications of layering on a large scale, particularly in the Upper Series. These earlier syenites were cut by an elongated steep sided plug of xenolithic porphyritic syenite and finally a centrally-situated plug of carbonatite was emplaced, having a marginal zone with brecciation and carbonation of the syenites, and passing from calcite-rich carbonatite at the margins to a siderite-rich core containing sphalerite, apatite and other minerals.

The structural reconstruction provides a basis from which an attempt may be made to interpret the petrology of the complex. This will form the substance of a later account.

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Erratum:

Plate 2. The eastern tip of the peninsula on the western side of Langesø, about 550 m. N.E. of the outlet, should be coloured pale purple as for foyaite and pulaskite of the Upper Series, and not olive green.

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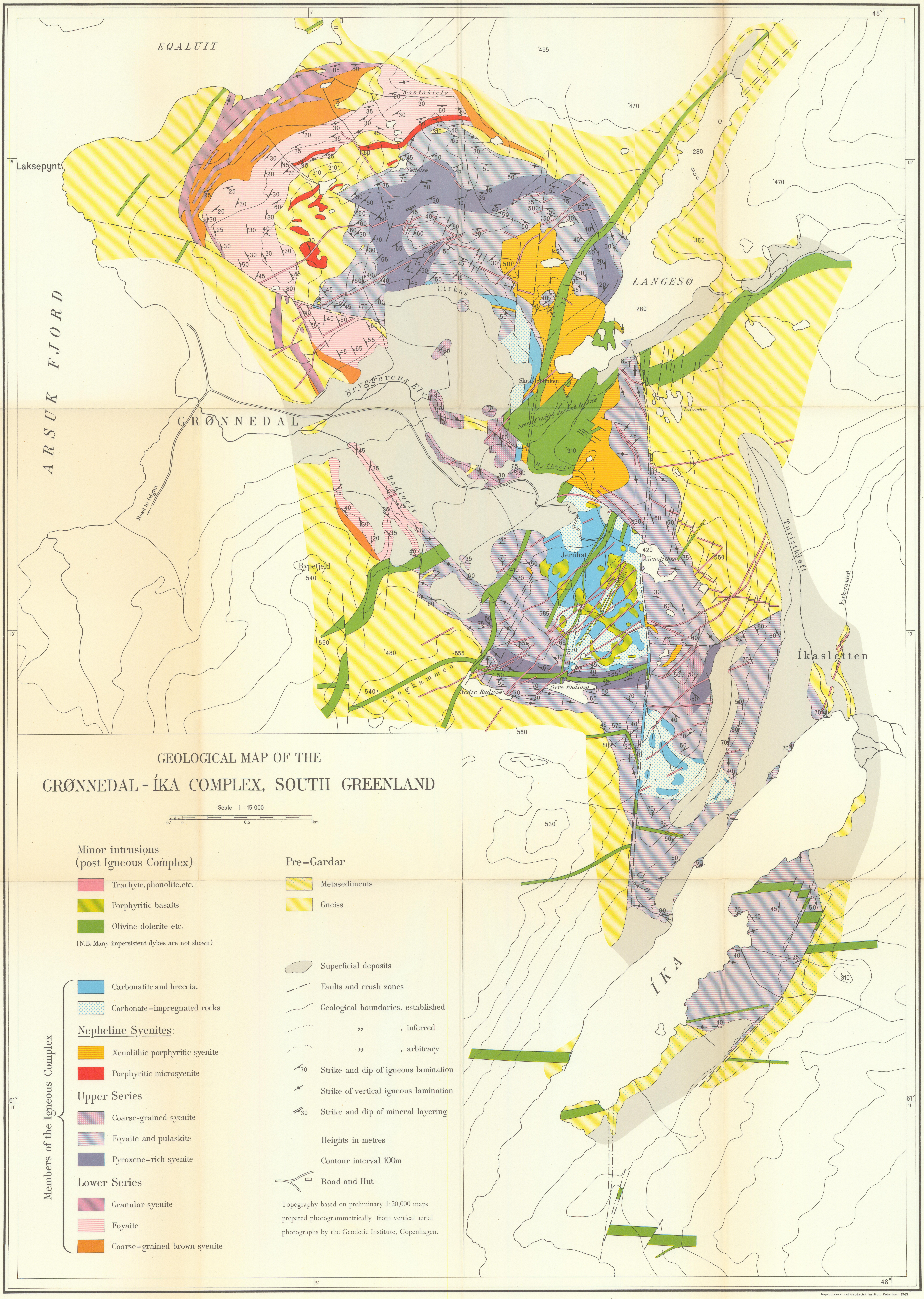
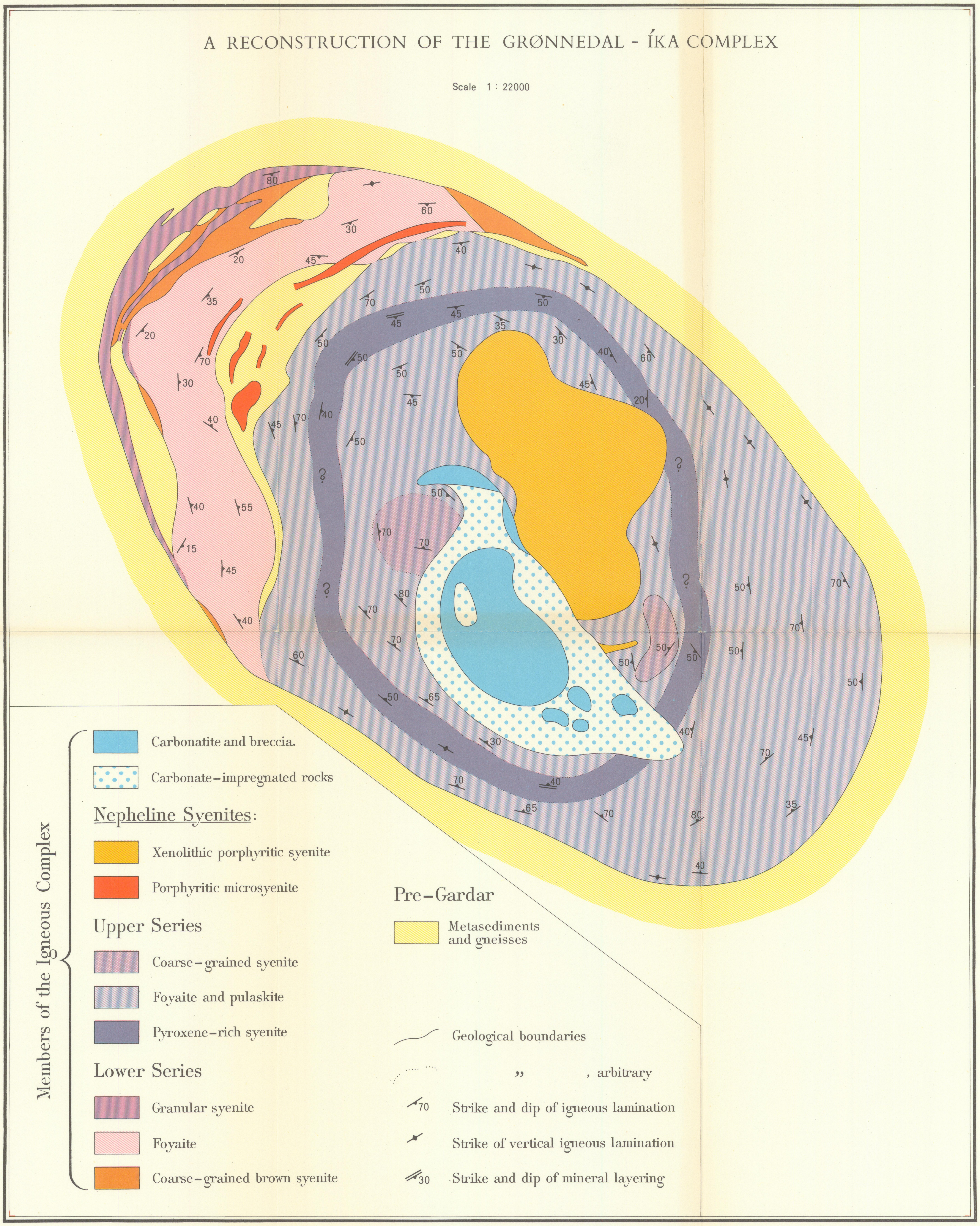
Færdig fra trykkeriet den 24. juni 1964.

GRØNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND

GRØNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND



GRØNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND



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