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The mode of occurrence and petrogenesis of the sapphirine-bearing and associated rocks of West Greenland

by

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THE MODE OF OCCURRENCE AND PETROGENESIS OF THE SAPPHIRINE-BEARING AND ASSOCIATED ROCKS OF WEST GREENLAND

by

R. K. Herd, B. F. Windley and M. Ghisler

With 9 figures and 3 plates

1969

Abstract

Seven occurrences of sapphirine-bearing rocks in the Fiskenæsset region are described in detail. They occur within a chromite-layered anorthosite complex that was metamorphosed by a hornblende-granulite facies metamorphism and then by a cordierite-amphibolite facies metamorphism. They were derived from spinel-layered ultramafic rocks that mostly occur as layers and lenses along the contacts between major meta-anorthosite and pyribolite/amphibolite horizons within the complex. There are four types of sapphirine-bearing rocks - enstatite, pargasite, gedrite and phlogopite types, which represent a petrogenetic sequence involving increasing degrees of Si, Ca, K and H_2O metasomatism related to shearing and deformation along meta-anorthosite-pyribolite junctions. Their relationship to associated non-sapphirine-bearing rocks is described. Brief mineralogical and petrological data are given for the principal minerals and rocks.

In addition, two occurrences in the Sukkertoppen region are described in detail; these are also localised in meta-norite-ultramafic lenses in high grade gneisses.

It is concluded that sapphirine is stable within a wide range of pressure and temperature conditions, but within a limited range of chemical environments.

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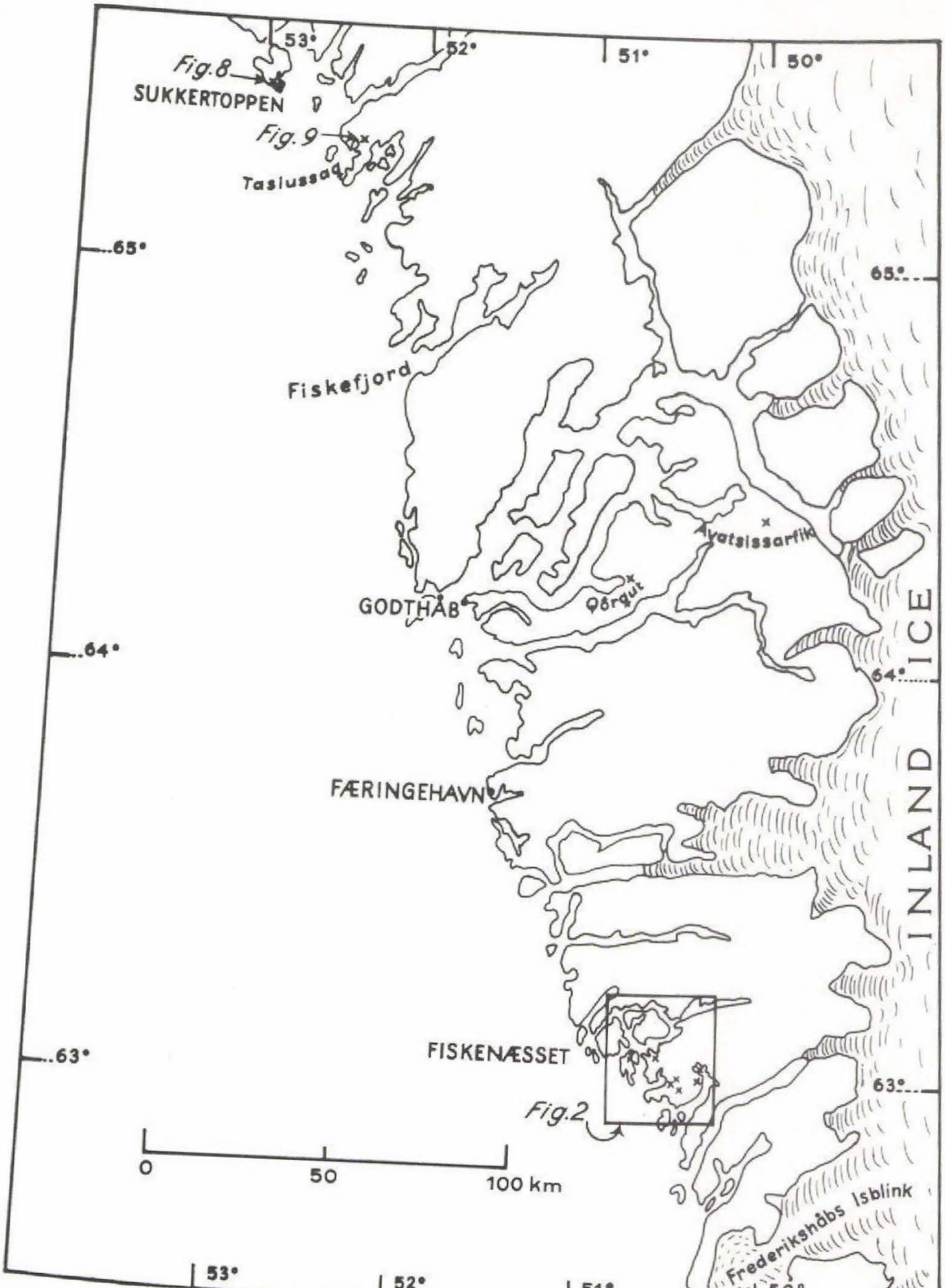

Fig. 1. Map of southern West Greenland. The known occurrences of sapphirine-bearing rocks are indicated by crosses.

INTRODUCTION

Sapphirine has been known to occur in West Greenland for about a hundred and fifty years and it is now clear that this is one of the principal areas of its occurrence in the world. At least ten localities are known at present (fig. 1). The sapphirine-bearing rocks from all the localities have a common mode of occurrence and thus their development in general can be ascribed to a particular set of compositional and physical conditions.

The mineral sapphirine was originally found by Giesecke in 1809 at Fiskenæsset harbour. During the nineteenth century there were about a dozen mineralogical and chemical investigations of the Fiskenæsset sapphirine, the last of which was made by Ussing (1889), who finally clarified the various properties of the mineral. These early studies are summarised by Bøggild (1953, pp. 193-194).

Giesecke (1910) also found sapphirine-bearing rocks at Avatsissarfik at the head of Godthåbsfjord (fig. 1).

Ramberg (1948) described a sapphirine occurrence in a basic inclusion in gneisses near Sukkertoppen (fig. 1). Sørensen (1955) described an occurrence in hornblendite at Tasiussaq, south-east of Sukkertoppen (fig. 1), another occurrence in a loose boulder of hornblendite at Qôrqut, Godthåbsfjord (fig. 1), and he also described the petrography of the Fiskenæsset harbour locality. Both authors discussed the stability relations necessary for the formation of sapphirine in general.

The field work on which the present study is based started in 1964 as part of the current mapping programme of the Geological Survey of Greenland (GGU). During regional mapping the second author (BFW) reinvestigated the classic Fiskenæsset harbour locality and discovered three new sapphirine localities (Lower Angnertussoq, Siggartartulik and Sarfaq). During his study of the chromite deposits of the area in 1965-66 the third author (MG) discovered the Upper Angnertussoq and Rubin Ø localities. K. Gormsen (personal communication) found the Taseq localities in 1966 during detailed mapping of that area.

It was realised that all these sapphirine localities occurred within a metamorphosed chromite-layered anorthosite-pyribolite-ultramafic complex (Ghisler and Windley, 1967), now termed the Fiskenæsset complex (Windley, in press, a).

In 1967 the second author (BFW) visited the Sukkertoppen locality, which was found to occur within a metamorphosed layered norite mass, and the Tasiussaq locality, which was associated with metamorphosed layered norites, meta-bronzitites and chromite-bearing meta-dunites.

The first author (RKH), who is at present undertaking a detailed mineralogical and chemical (electron-probe) study of the sapphirine and its associated minerals and rocks, has determined the mineral parageneses which provide a main basis for the petrogenetic discussion in this paper. He will later be publishing a detailed petrological account of all the sapphirine-bearing rocks.

Recent studies on the crystal structure of the Fiskenæsset sapphirine have been published by Fleet (1967) and the determination of its crystal structure has been made by Moore (1968).

The present paper describes the various types of sapphirine-bearing rocks of West Greenland in relationship to their geological setting, demonstrates the common factors in their occurrence and outlines the principal metamorphic and chemical conditions responsible for the formation of sapphirine and its associated minerals in this particular environment.

REGIONAL GEOLOGICAL SETTING

In West Greenland there is a central basement gneiss unit more than 2600 m.y. old flanked to the north and south by younger fold belts (Pulvertaft, 1968). The basement unit is characterised by the presence of relic layers and inclusions of meta-anorthosites commonly associated with mafic and ultramafic rocks; anorthositic rocks are traceable, with interruptions, for at least 400 km (Windley, in press, a). They are best developed in the Fiskenæsset region where the Fiskenæsset complex contains a minimum of 125 km of chromite-layered calcic meta-anorthosites intercalated with major pyribolites (pyroxene amphibolites),

amphibolites, and minor ultramafic rocks among which there are spinel-layered meta-peridotites, chromite- and spinel-layered meta-bronzitites and meta-norites (Ghisler and Windley, 1967). This intercalated suite of rocks occurs in the gneisses as conformable stratigraphic horizons up to about 2 km wide. All evidence suggests that these horizons are the metamorphosed remains of an extensive igneous complex formed by gravitative differentiation, which has certain affinities with the Bushveld complex (Windley, in press, a).

Elsewhere the anorthosites are neither chromite-layered nor so well preserved as those at Fiskenæsset. In the Fiskefjord region minor meta-anorthosites and meta-norites occur within a conformable pyribolite suite also containing minor chromite-layered meta-peridotites. There are several small areas of meta-anorthositic rocks a few kilometres across near Færingehavn and several tens of kilometres of migmatised horizons in inner Godthåbsfjord. At Sukkertoppen there is a single relic of meta-norite and at Tasiussaq there are relic meta-norites associated with meta-bronzitites and chromite-rich meta-dunites.

All the anorthosites and associated rocks of West Greenland have been highly folded and thoroughly reconstituted by a granulite facies metamorphism which in the Fiskenæsset region has been shown to have taken place at least 3200 m.y. ago (Lambert and Simons, 1969). In most areas there has been a subsequent amphibolite facies metamorphism which has variably downgraded the higher grade assemblages. In Fiskenæsset and Fiskefjord regions the hypersthene gneisses have been almost entirely converted to hornblende-biotite gneisses, whilst the pyribolites and ultramafic rocks have been less affected. In many other regions retrogression has gone almost to completion; at Buksefjord just north of Færingehavn, and at Tasiussaq there are only a few isolated inclusions of hypersthene gneiss in the widespread hornblende-biotite gneisses to witness the earlier higher grade metamorphism. The retrogressive metamorphism in the eastern Fiskefjord and southern Fiskenæsset regions is believed to have taken place about 2600 m.y. ago (Windley, in press, b).

It is in this environment that the sapphirine-bearing rocks occur; they are situated in the anorthositic-noritic rocks that have been doubly metamorphosed. Fig. 2 shows that the seven localities in the Fiskenæsset region occur within the chromite-layered meta-anorthosite complex. None

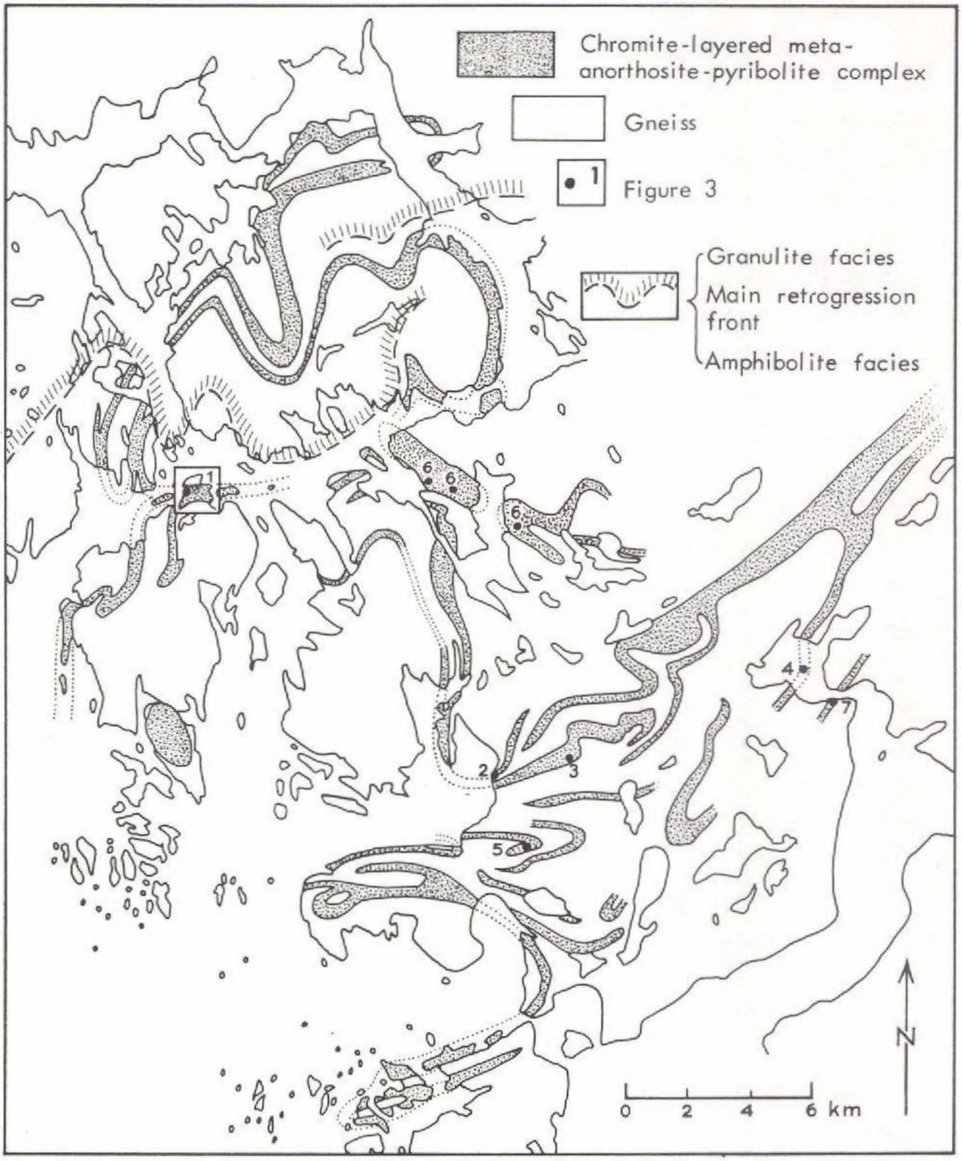

Fig. 2. Simplified geological map of the Fiskenæsset region showing the location of the seven sapphirine localities within the chromite-layered meta-anorthosite-pyribolite complex. The localities are marked with dots and their numbers correspond to those used in the text.

appear to occur in the weakly retrogressed area to the north. Fig. 8 shows that the sapphirine-bearing hornblendite at Sukkertoppen occurs within the meta-norite mass in hypersthene gneisses not far from the retrogression boundary to the east. Fig. 9 shows that the sapphirine-bearing hornblendite at Tasiussaq is associated with the meta-norites, meta-bronzitites and meta-dunites in hornblende-biotite gneisses that contain inclusions of hypersthene gneiss.

Nine localities are described in detail, seven from the Fiskenæsset region plus those at Sukkertoppen and Tasiussaq. Short notes are added on what is known about the Avatsissarfik locality and the loose boulder at Qôrqut.

The seven Fiskenæsset localities are numbered as follows:

1. Fiskenæsset harbour	Fig. 3 and Plate 1
2. Lower Angnertussoq	Fig. 4
3. Upper Angnertussoq	Figs. 5 and 6
4. Rubin Ø	Fig. 7
5. Siggartartulik	
6. Taseq	
7. Sarfaq	

These numbers are kept throughout the text. Plate 1 and figs. 4-7 are detailed drawings of the main occurrences positioned on fig. 2. Fig. 8 is of the Sukkertoppen locality and fig. 9 shows that at Tasiussaq. Those in the Fiskenæsset region will be described first, as this is clearly where the majority of sapphirine-bearing rocks occur and where their host rocks are best preserved.

THE FISKENÆSSET REGION

Mineral assemblages

The sapphirine-bearing rocks of the Fiskenæsset region have been divided into four types, - A, B, C and D - depending on which of the ferromagnesian minerals enstatite, pargasite, gedrite and phlogopite is prevalent or characteristic. The four types form a petrogenetic sequence observable in thin section as a series of replacement reactions among the ferromagnesian constituents.

Types:

A. Enstatite type;
Sapphirine + Enstatite + Spinel + Phlogopite ± Pargasite

B. Pargasite types;
B_1. Sapphirine + Pargasite + Spinel + Phlogopite ± Enstatite ± Plagioclase
B_2. Sapphirine + Pargasite + Plagioclase ± Spinel ± Corundum ± Phlogopite ± Cordierite

C. Gedrite type;
Sapphirine + Gedrite + Corundum + Phlogopite ± Cordierite ± Pargasite ± Plagioclase

D. Phlogopite types; (D_1, D_2, D_3)
Sapphirine + Phlogopite + Corundum ± Plagioclase ± Cordierite ± Spinel

The B_1 and B_2 types have been distinguished by the degree of recrystallisation of the sapphirine and by the relative abundance of plagioclase. There are also several phlogopite types depending on the variable concentrations of plagioclase and cordierite.

The identification of pargasite as the hornblende characteristic of these rocks and of gedrite (aluminous anthophyllite) is based on unpublished geochemical data collected by the first author (RKH). These identifications agree with Ussing's (1889) characterisation of the amphiboles in the Fiskenæsset harbour rocks. Descriptions of sapphirine, enstatite, pargasite, gedrite, phlogopite, plagioclase, and kornerupine in the Fiskenæsset harbour rocks are summarised by Bøggild (1953).

Associated with the sapphirine-bearing rocks are the following seven different types of non-sapphirine-bearing rocks:

1. Olivine + Clinoamphibole + Spinel + Enstatite or Bronzite
2_a. Pargasite + Spinel + Phlogopite
2_b. Pargasite + Plagioclase + Corundum + Cordierite ± Spinel ± Phlogopite
3. Gedrite ± Cordierite ± Clinoamphibole ± Plagioclase ± Phlogopite ± Corundum
4. Plagioclase + Phlogopite + Corundum ± Cordierite ± Spinel
5. Olivine + Spinel + Phlogopite + Zircon
6. Hornblende ± Spinel ± Plagioclase
7. Pegmatite

Letters A-D and numbers 1-7 used in the text correlate with the layers shown in Plate 1 and figs. 4-7. There is an obvious correspondence between types A, B, C and D and types 1, 2, 3 and 4, respectively. However, the correspondence is not exact, especially between types C and 3. Type 3 rocks contain much more pargasite or other clinoamphibole, and usually much more plagioclase than the type C assemblages. More details on the assemblages in all these types are given in the table, Plate 2. Properties of the major rock-forming minerals are given in the table Plate 3.

Petrographic descriptions

Sapphirine-bearing rocks

Type A

Sapphirine occurs in an enstatite-rich spinel-layered matrix, exhibiting a sequence of overgrowth and replacement textures with respect to spinel, and a sequence of mutual intergrowth textures with respect to enstatite. These relationships are most characteristically developed at the Fiskenæsset locality.

Sapphirine is least abundant where it occurs (along the coastal part of the Fiskenæsset harbour outcrop) as incipient, narrow rims (0.2 mm) on anhedral spinel grains in a compact, coarse-grained, granoblastic to nematoblastic enstatite matrix (Ussing's type II, cf. Sørensen, 1955, pp. 14-15). The spinel layers, which are usually about 1 cm apart, consist of broken and rodded spinel aggregates up to 1 cm in diameter. Enstatite has grown between the layers, as well as across and within spinel-rich zones containing enstatite with spinel inclusions, and enstatite with sapphirine-rimmed spinel inclusions. The coarsest prismatic enstatite crystals are in the spinel-free zones, where they appear to define a poor foliation (nematoblastic fabric) sub-parallel to the spinel layers. Minor phlogopite replaces the enstatite along cleavage planes.

The spinel layers were probably present in the original layered igneous parent and the metamorphic textures seem to represent mimetic recrystallisation and contemporaneous minor movement sub-parallel to these layers.

Where sapphirine is more abundant (up to about 30 % of the rock) relative to enstatite, complicated enstatite-sapphirine intergrowths exist, and spinel is reduced to relics in the body of the sapphirine. Coarse enstatite prisms include euhedral, twinned sapphirine laths with the long axes of the prisms approximately parallel to the longest dimensions of the laths. In hand specimen this texture can be seen to result from a radiating to rosette-like, very coarse (up to 4 cm), enstatite-sapphirine intergrowth. The rosettes seem flattened in a plane sub-parallel to the spinel layers (cf. above), or to what are now zones of maximum sapphirine concentration with relic spinels. Phlogopite occurs in microshears replacing sapphirine and enstatite, often extensively, and also as patchy replacements on cleavages, fractures and enstatite-sapphirine contacts. Very massive, compact, coarse-grained, well-crystallised specimens of this type of rock exist where phlogopite forms coarse interstitial crystals, and the phlogopite-bearing microshears form a sheath around the sapphirine-enstatite (-spinel) rock.

Type B_1

Sapphirine is abundant in this type of pargasite-bearing rock forming a compact matrix of intergrown laths with tiny spinel remnants. Enstatite in large prisms up to 2 cm long and pargasite crystals up to 1 cm long occur in this matrix. Phlogopite is abundant on microshears and imparts a distinct but coarse planar fabric to these rocks. The plane of this foliation cuts the plane of the original spinel layers at a low angle. Enstatite-sapphirine rosettes have been flattened and now lie in the plane of the phlogopite foliation, whilst pargasite has grown in the sapphirine-rich matrix sub-parallel to the foliation.

In thin section sapphirine laths (with spinel inclusions) either with attached enstatite remnants or intergrown with larger amounts of enstatite (texture as in type A) are set in a matrix of pargasite prisms and phlogopite flakes. The weak layering inherited by the laths from the pre-existing spinel layering is still very evident. All stages of replacement of enstatite by pargasite can be followed. Sapphirine prisms are often embayed by pargasite, but are still fresh and transparent. Where phlogopite is in contact with sapphirine, fine-grained corundum sometimes develops; some sapphirine granulation at lath boundaries is also seen. Where pargasite only occurs in these rocks, phlogopite is less abundant and the rock is much more compact. This suggests that at the height of pargasite development, the phlogopite foliation was overgrown by abundant pargasite.

Type B_2

This pargasite-bearing rock type occurs at Lower Angnertussoq and Siggartartulik. Pargasite-rich layers about 1-2 cm wide are interbanded with plagioclase-phlogopite (-corundum) or cordierite-phlogopite (-corundum) layers (type 4 - see under mineral assemblages). The pargasite occurs as coarse-grained, radiating, rosette-like aggregates (cf. enstatite in type A rocks) and has inclusions of spinel. Patchily developed within this pargasite matrix are areas rich in plagioclase, corundum and sapphirine, and these merge at the edges of the pargasite-rich bands with the plagioclase-rich assemblages of types D and 4.

Microscopic examination reveals that the sapphirine occurs as rims on both spinel and corundum, where pargasite and plagioclase respectively are most abundant. It is difficult to be certain of the relationship between the plagioclase and pargasite; their mutual contacts are scalloped and there are pargasite remnants in plagioclase, so that it appears that the latter results from pargasite breakdown both within the pargasite-rich layers and in immediately adjacent areas. Vermicular spinel blebs are present in the plagioclase.

Another variety of B_2 rock, which is found at Siggartartulik, has large corundums (up to 1 cm in diameter) successively rimmed by narrow zones of spinel and sapphirine in a coarse pargasite matrix.

Type C

Gedrite-rich sapphirine-bearing assemblages of this type occur at Fiskenæsset harbour, Lower and Upper Angnertussoq and Rubin Ø. Gedrite is also a common accessory in type B_1 rocks from all localities where it is seen replacing pargasite and sapphirine, and in some type D rocks where it is breaking down to cordierite.

Gedrite is especially abundant at Lower Angnertussoq in assemblages in which coarse gedrite prisms up to 2 cm long form radiating, rosette-like aggregates (cf. enstatite and pargasite under types A and B) in a matrix of sapphirine, phlogopite, cordierite and corundum. The rocks have a coarse foliation defined by the phlogopite and by the parallel orientation of the gedrite "suns".

Sapphirine is found as disrupted prisms and irregular fragments in a matrix of subhedral gedrite prisms. The sapphirine contains many blebs of corundum, often pinkish, which were absent in sapphirine in types A and B; spinel relics are no longer present. Where corundum development is extensive, the individual blebs coalesce into ragged subhedral crystals. Cordierite can be seen developing at corundum-gedrite, sapphirine-gedrite and sapphirine-corundum contacts, while phlogopite varies in the extent of its replacement of all minerals. Ussing's first type of sapphirine-bearing rocks falls in this category (see Sørensen, 1955, pp. 15-16).

Type D_1

Sapphirine occurs usually as disrupted laths or angular fragments of laths in a lepidoblastic matrix of phlogopite flakes, minor cordierite and/or minor plagioclase. Gedrite or pargasite may also occur as corroded remnants, the former inverting to cordierite, the latter to plagioclase. Corundum is invariably present, dispersed throughout the matrix as subhedral grains or angular fragments. This corundum (as that in type C rocks) has an undeniable secondary relationship to the sapphirine. It not only forms as granular aggregates at the edges of sapphirine laths (cf. Sørensen, 1955, p. 16), but also as micro-pseudomorphs of one end of a sapphirine lath. Subhedral corundums surrounded by phlogopite grow between the two parts of a sapphirine prism which are in optical continuity. Sapphirine laths may be granulated at their boundaries. Spinel remnants may be present.

Macroscopically these rocks are rich in phlogopite and highly sheared. Areas rich in sapphirine and corundum weather out as resistant knots in the phlogopite matrix. The corundum-rich margins of these areas are whitish, and the granulated sapphirine is paler blue around the darker laths of sapphirine.

Type D_2

As in type D_1, sapphirine crystals are disrupted, granulated and partly altered to corundum. Cordierite is the abundant colourless mineral and the matrix is composed of equidimensional cordierite grains and elongate phlogopite flakes. These rocks occur at Lower Angnertussoq and on Rubin Ø.

Kornerupine occurs on Rubin Ø in tiny aggregates of prismatic crystals 0.2 mm in diameter in a cordierite-rich veinlet in one of these rocks, accompanying corundum and phlogopite (type 4 assemblage). The kornerupine described by Ussing (1889) from Fiskenæsset harbour apparently also occurs in a phlogopite-rich rock.

Type D_3

The assemblage sapphirine-plagioclase-phlogopite-corundum is characteristic of these rocks. They occur as layers up to a few centimetres thick in which the concentrations of plagioclase and corundum with respect to phlogopite are highly variable, but cordierite is scarce. Often these plagioclase-rich areas alternate with type B_2 rocks in centimetre-wide layers, as well as with plagioclase-gedrite layers (type 3 below).

In thin section a lepidoblastic texture of equidimensional plagioclase grains and elongate phlogopite crystals can be seen. The plagioclase mosaic contains corundum with sapphirine rims. Tiny epidote crystals may be seen at plagioclase-plagioclase interfaces growing inwards from the contacts.

Types D_1, D_2 and D_3 are related by having phlogopite as the dominant stable ferromagnesian mineral. The sequence D_1 - D_2 - D_3 reflects a trend in shearing and increasing recrystallisation under the lowest grade of metamorphism in the Fiskenæsset region.

Non-sapphirine-bearing rocks

Type 1

These rocks are compact grey-green to yellow-green medium-grained meta-peridotites or meta-pyroxenites, with spinel layers. They are present mainly at Fiskenæsset harbour, Upper Angnertussoq and Taseq. At the first locality they can be seen to grade into type A rocks. The spinel layers in both type 1 and type A have the same orientation. Microscopically they are granoblastic to nematoblastic and contain olivine, bronzite, spinel and clinoamphibole with some serpentine. The gradational contact from type A to type 1 is not marked by reaction textures, but merely by a decrease in the amount of olivine in the rock and an increase in the grain size of the matrix (enstatite laths in type A).

Type 2_a

Occurrring only at Siggartartulik and Fiskenæsset harbour, these rocks are the least abundant of the major non-sapphirine-bearing rocks in the sapphirine-bearing lenses. They are compact, coarse-grained, pargasite-spinel hornblendites, in which the spinels are in layers. The textures are granoblastic to nematoblastic. The type 2_a rock at Fiskenæsset harbour contains minor sulphide mineralisation (pyrrhotite with pentlandite, and pyrite).

Type 2_b

Corundum-bearing pargasite-rich layers at Upper Angnertussoq and Rubin Ø are placed in this category. They exhibit subhedral to euhedral pink corundum porphyroblasts in a nematoblastic to lepidoblastic matrix of green pargasite inverting to plagioclase, cordierite, and phlogopite. This assemblage is interlayered with, and merges into, assemblages characteristic of types C and D, and types 3 and 4 rocks. The rocks differ little macroscopically from type B_2 rocks, except in their more abundant corundum, and they differ microscopically only in their high cordierite content and in their lack of sapphirine.

Type 3

There are two main types of rock classified as type 3: those rich in gedrite and cordierite and those rich in gedrite and plagioclase. Cordierite-bearing types are only common at Lower Angnertussoq. At all localities where gedrite-plagioclase rocks are found, the gedrite is accompanied by a hornblende or other calcic clinoamphibole, which may be overgrowing it, transecting and replacing it, or apparently in equilibrium intergrowth with it. These rocks are very coarse-grained (gedrite crystals up to 2 or 3 cm) and usually quite massive.

Type 4

Rocks entirely analogous to type D rocks but lacking sapphirine are included here. They occur in thin layers intermingled with types B_2, D, C, and types 2_b and 3, especially at Lower and Upper Angnertussoq and Rubin Ø. Some varieties are very rich in ruby corundum (up to 30 % of a centimetre-wide layer). The corundums, in thin section, are subhedral to fractured euhedral crystals, occurring in an lepidoblastic matrix of plagioclase and phlogopite, or phlogopite with minor plagioclase and cordierite, or of phlogopite and cordierite. Some of this corundum has definitely arisen through the breakdown of sapphirine, and is the end product of the pseudomorphing of sapphirine laths seen in type D. Since sapphirine has not recrystallised as rims on corundum in type 4 rocks, there must be a delicate chemical or physical control on the preservation of sapphirine in plagioclase-phlogopite rocks (i.e. in types D and 4).

Type 5

Only one rock with the mineralogy olivine-spinel-phlogopite (-zircon) is known; this occurs at Siggartartulik. It is rather homogeneous, with large (up to 1 cm) yellow-green olivines and dark green spinel bands being patchily replaced by coarse phlogopite. Rounded subhedral zircons are abundant in the phlogopite and also occur in the spinel. This rock may be related to type 1 peridotites; the zircon must be primary as it is present in the spinels, which are igneous concentrations.

Type 6

Hornblendites are only known at Fiskenæsset harbour where they are found as lensoid bodies within the larger sapphirine-bearing lens next to the anorthosite. They are massive compact confused aggregates of subhedral green-black hornblende with minor plagioclase and iron oxides and/or sulphides. One type grades into a nematoblastic amphibolite as plagioclase increases in concentration and foliation becomes distinct.

Type 7

All pegmatitic rocks are included here. A specimen from Fiskenæsset harbour shows intergrown crystals of plagioclase up to several centimetres across altering to saussurite etc. Fresh plagioclase occurs as irregular greyish remnants in a yellowish-white altered plagioclase matrix.

Description of localities 1-7

1. Fiskenæsset harbour

The chemistry, mineralogy and petrography of the sapphirine and its associated minerals from this original locality have been described in some detail by Ussing (1889) and Sørensen (1955). There exists, however, no map or description of the mode of occurrence.

Fig. 3 shows that the chromite-layered meta-anorthosite-pyribolite complex within the retrogressive biotite-hornblende gneisses passes through Fiskenæsset. Three layers of anorthosite are intercalated with four pyribolite-amphibolite layers with which are associated minor pyroxenites. The sapphirine-bearing rocks occur well within the complex along the western contact of a lens of pyroxenite (enstatite rock) where it borders anorthosite; this relationship is illustrated in detail in Plate 1.

The locality is situated on the north side of the larger, southern harbour, where the main sapphirine-bearing layers are discontinuously exposed for about 40 m and occur as hummocks a few metres across within a desert-like, white, rubbly area typical of the weathered anorthosites; the lack of exposure is indicated on Plate 1. The main layers rise to about 30 m inland, where they and the pyroxenite disappear under the cover. Further to the north the anorthosite and pyribolite horizons lie in mutual conformable contact.

All four main varieties of sapphirine rocks occur at this locality; their mineral assemblages (listed in order of decreasing abundance) are as follows:

A. Enstatite type;

Enstatite + spinel + (sapphirine) + (phlogopite)

B. Pargasite type;

B_1 : Sapphirine + enstatite + pargasite + phlogopite + (spinel) + (gedrite)

B_1 : Sapphirine + pargasite + gedrite + phlogopite + (spinel) + (plagioclase)

C. Gedrite type;

Sapphirine + gedrite + phlogopite + (pargasite) + (corundum)

D. Phlogopite types;

D_1 : Sapphirine + phlogopite + (corundum) + (plagioclase)

D_3 : Phlogopite + plagioclase + sapphirine + (corundum)

Minerals given in brackets are minor constituents.

In the enstatite type sapphirine largely occurs in microscopic form as rims around spinel. There is most sapphirine in the phlogopite-bearing types, which stand out as a sky-blue layers up to about 1.5 m wide, and these types contain the laths and granular aggregates of sapphirine. Thus the sapphirine is best seen in the phlogopite-bearing layers inland and not on the coast.

The four textural forms of sapphirine listed in the table, Plate 2 - rims_a around spinel, laths, granular aggregates and rims_b around corundum - represent a genetic sequence of growth, development, granulation and recrystallisation of sapphirine.

The sapphirine-bearing rocks are layered on a small scale, marked particularly by the variable concentration of the blue sapphirine. In the main phlogopite type it is intensely concentrated to the extent of about 60 % of the rock, whilst in adjacent layers it is less densely packed. In some layers the sapphirine is sparsely distributed, but occurs in coarse aggregates up to 4.5 cm long.

It is convenient to remember here that the order A, B, C, D is a genetic sequence; starting from the enstatite type the sequence represents an increasing degree of metasomatism of meta-igneous rocks. At Fiskenæsset harbour it can be seen that the well-preserved spinel-layered enstatite rock with relic peridotite layers of the main lens (type 1) passes westwards into the enstatite rock with incipient, microscopic sapphirine - type A - (in the lower right-hand corner of Plate 1), which passes westwards via the type B and C rocks to type D rocks. The maximum sapphirine formation is seen in type D rocks which lie against the anorthosite. Here, where metasomatism was greatest, hornblendites and plagioclase pegmatites were formed and shear zones developed. This spatial-genetic relationship between the different sapphirine- and non-sapphirine-bearing rocks is better seen in this locality than in any of the others, where enstatite-rich rocks have largely been removed by a more advanced metasomatism.

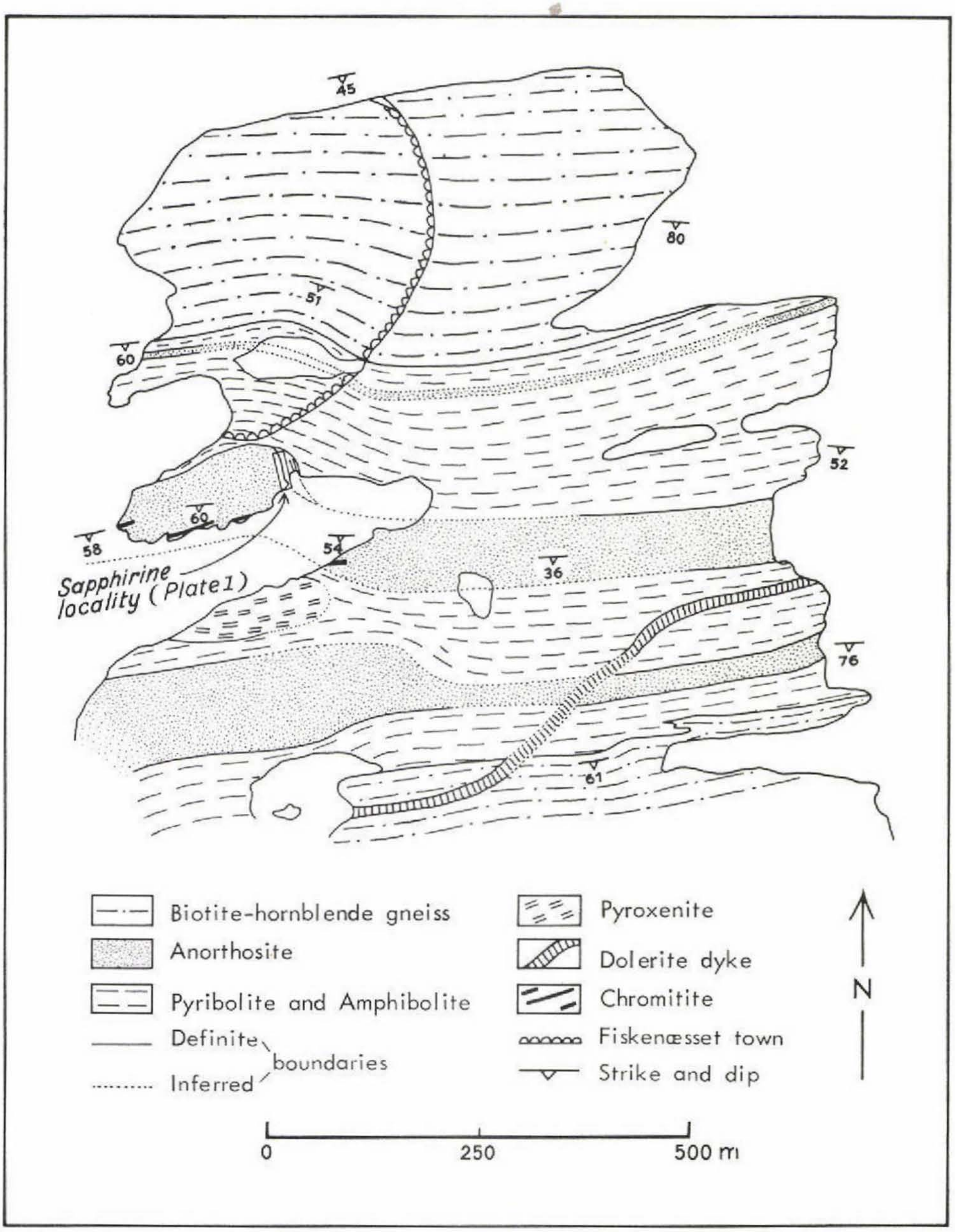

Fig. 3. Map of part of the meta-anorthosite-pyribolite complex around Fiskenæsset. The Fiskenæsset harbour sapphirine occurrence lies astride the junction between anorthosite and pyroxenite.

The non-sapphirine-bearing rocks at this locality have the following assemblages;

1. Clinoamphibole + olivine + spinel + enstatite
   Clinoamphibole + spinel + olivine
   Diopside + olivine + clinoamphibole + spinel

2_a. Pargasite + spinel + (sulphides)

3. Gedrite + clinoamphibole + plagioclase
   Plagioclase + gedrite + phlogopite

4. Cordierite + phlogopite + plagioclase

6. Clinoamphibole (green-black hornblende)

7. Plagioclase

2. Lower Angnertussoq

Angnertussoq mountain lies at the eastern end of Kigutilik bay about 13 km south-east of Fiskenæsset (fig. 2). The sapphirine rocks are situated at a height of about 25 m, some 30 m from the coast on the south side of the main promontory below Angnertussoq mountain.

The sapphirine-bearing rocks are found within a moderately exposed lens about 26 m long and 2 m wide situated along the contact of a chromite-layered anorthosite and a pyribolite/amphibolite horizon. There is also a thin pyribolite along part of the northern contact (fig. 4).

The sapphirine here occurs in types B, C and D rocks which are mutually interlayered and have the following assemblages:

B_2. Pargasite type;
Pargasite + plagioclase + (gedrite) + (sapphirine) + (corundum) + (phlogopite) + (spinel)

C. Gedrite type;
Gedrite + sapphirine + (phlogopite) + (cordierite) + (corundum) + (pargasite)

D. Phlogopite types;
D_1 : Phlogopite + sapphirine + (corundum)
D_2 : Phlogopite + sapphirine + (cordierite) + (corundum)
D_3 : Plagioclase + phlogopite + (sapphirine) + (corundum) + (spinel)

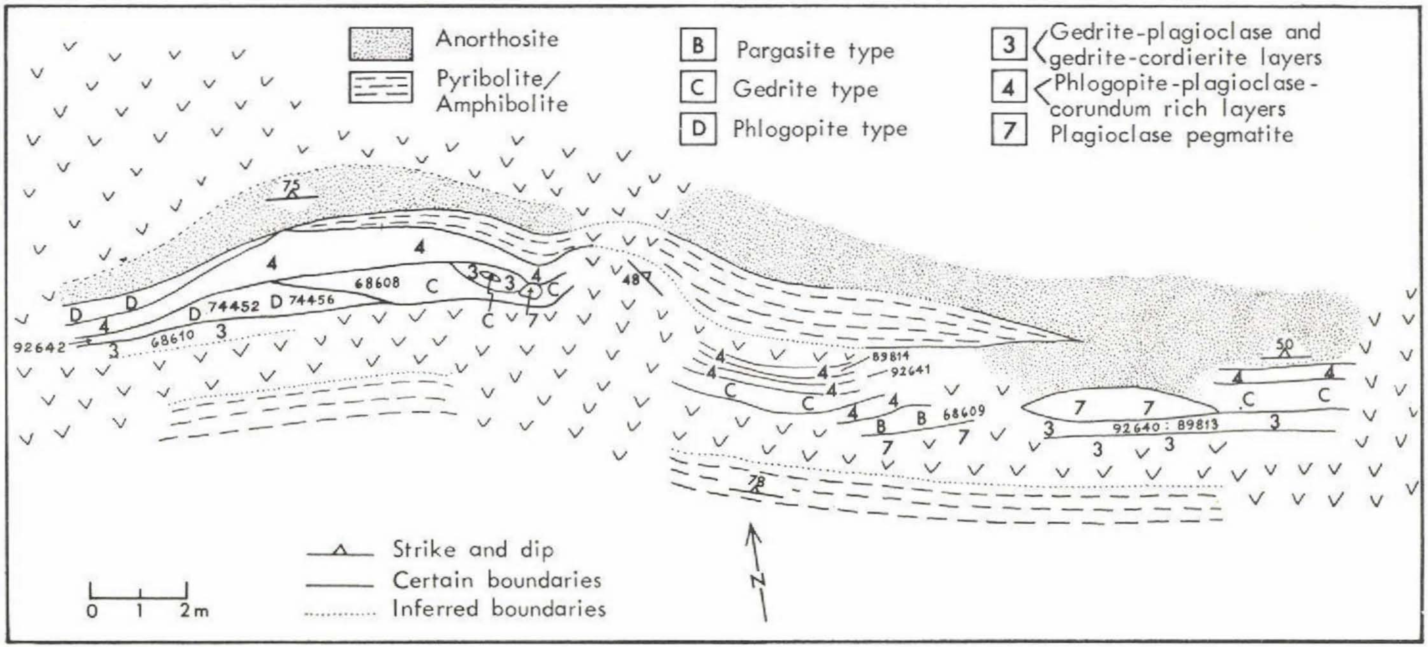

Fig. 4. Detailed sketch map of the sapphirine occurrence at Lower Angnertussoq.

There is more megascopic sapphirine in the phlogopite-rich rocks which form a sheath around the lens where it borders on the anorthosite. The occurrence is noteworthy for the development of cordierite-rich layers at the eastern end. Corresponding to the lack of type A rocks is the presence of several lenses of plagioclase pegmatite and other plagioclase-rich rocks (types 3, 4 and 7), indicating advanced metasomatism. These non-sapphirine-bearing layers have the following parageneses:

3. Gedrite + plagioclase + phlogopite + (clinoamphibole) + (cordierite)
   Plagioclase + gedrite + phlogopite + (corundum)
   Gedrite + cordierite + (phlogopite)

4. Phlogopite + plagioclase + corundum + (spinel)

7. Plagioclase

The rocks at Lower Angnertussoq have been more heavily metasomatised than those at Fiskenæsset harbour with the result that none of the enstatite-bearing rocks are preserved. Interesting in this respect is the fact that in the anorthosites about 50 m to the south chromitite layers, originally pyroxene-bearing, have been downgraded to chlorite-epidote-plagioclase-chromite rocks - clear evidence of appreciable retrogression. The surrounding gneisses in the Angnertussoq area have been reduced to hornblende-biotite-bearing types and the only witness of the earlier granulite facies metamorphism is the presence of occasional hypersthene in the pyribolite horizons.

3. Upper Angnertussoq

The sapphirine locality lies on the south-east side of Angnertussoq mountain at an altitude of 390 m in a layer within the same anorthosite horizon as that of Lower Angnertussoq (fig. 2). The sapphirine-bearing layers, which reach a maximum width of 14 m, are continuous for about 300 m (fig. 5), but must in fact extend at least for 600 m, as loose blocks have been found further to the west below the steep side of the mountain. There is a thin pyribolite/amphibolite layer along the northern contact, and a chromite horizon 1-2 m thick within the anorthosite extends along the whole southern side of the sapphirine-bearing layer and in one place lies in direct contact with it.

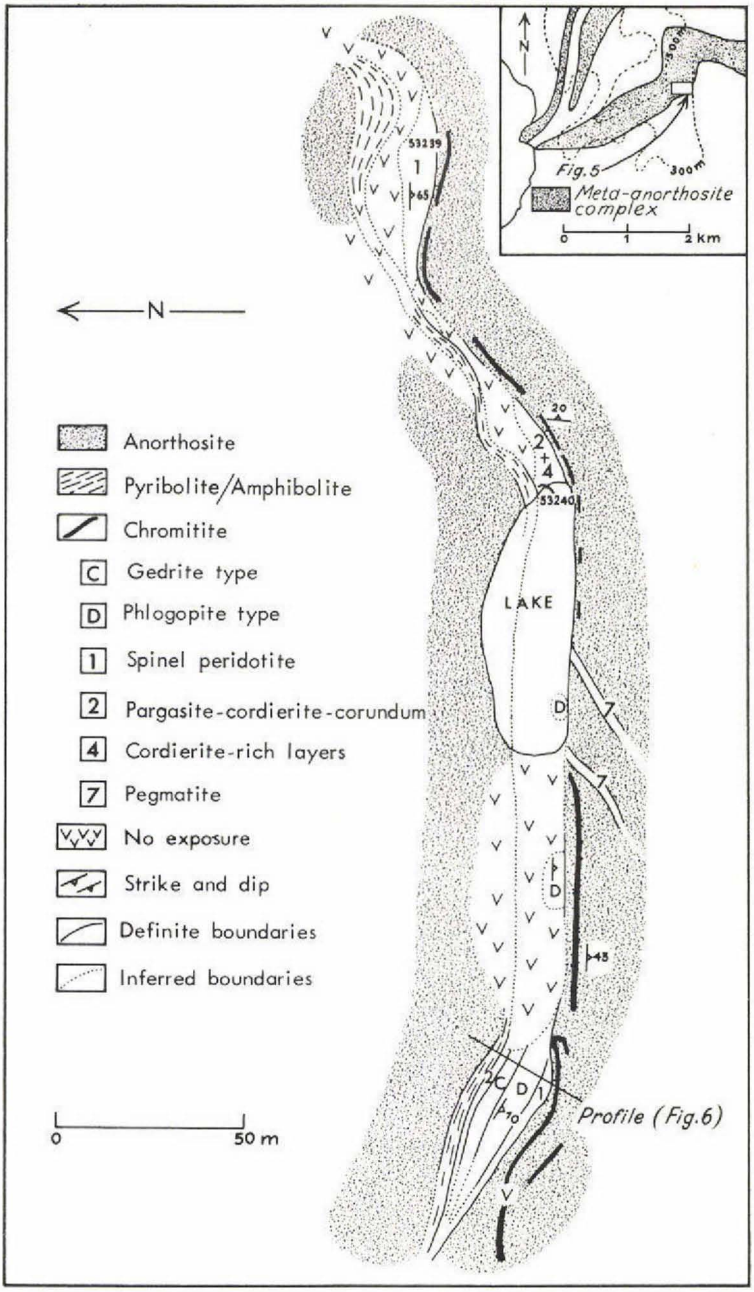

Fig. 5. Detailed sketch map of the Upper Angnertussoq sapphirine locality.

The sapphirine occurs in types C and D rocks with the following assemblages;

C. Gedrite type;
Sapphirine + gedrite + (enstatite) + (pargasite) + (phlogopite)
Spinel + gedrite + enstatite + (phlogopite) + (sapphirine) + (corundum)

D. Phlogopite type;
D_1 : Phlogopite + sapphirine + (spinel) + (corundum)
D_1 : Sapphirine + phlogopite + corundum

Where the main sapphirine-bearing layer reaches its maximum width, distinct interlayering of different rock units can be seen as shown in the profile (fig. 6). The southernmost 2 m consists of meta-peridotite rich in spinel, but with no sapphirine. Then follows a layer almost 7 m wide characterised by the assemblage phlogopite-sapphirine-(spinel)-(corundum), about 1.25 m of which is very rich in sapphirine. The following 2 m consists of a more compact rock, in which sapphirine is subordinate to spinel, forming the assemblage spinel-gedrite-enstatite with subsidiary phlogopite, sapphirine and corundum. The last major unit some 4 m wide, consists mostly of sapphirine and gedrite. A 40 cm

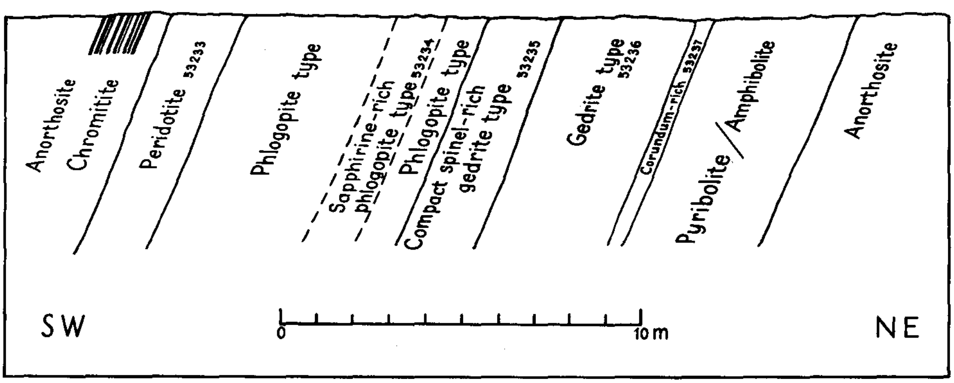

Fig. 6. Profile across the southern part of the sapphirine-bearing and associated layers at Upper Angnertussoq (see fig. 5).

wide pargasite-cordierite-rich layer (type 2_b) at the northern contact with the pyribolite contains abundant pink corundum crystals up to 10 cm long and 1.5 cm across. This rock contains patches up to 2 cm across very rich in sapphirine (type D_1). On account of the considerable extent and width of the main phlogopite type layer, there is clearly more sapphirine at this locality than any other yet found in West Greenland.

A hundred and fifty metres along the strike on the east of the lake a banded rock representing the type 2_b and type 4 assemblages contains cordierite + pargasite + corundum + plagioclase + phlogopite. Further to the east there is a spinel-rich peridotite (type 1) with no sapphirine.

4. Rubin Ø

The sapphirine locality on Rubin Ø in Tasiussâ bay at the head of Tasiussarssuaq fjord (fig. 2) occurs in an ultramafic layer with anorthosite to the west and amphibolite to the east and is only some 10 m from a boudinaged chromite horizon in the anorthosite. The intensely folded sapphirine-bearing layer is up to 8 m wide and about 100 m long (fig. 7) with considerable variations in mineralogy along the strike. The sapphirine lies within gedrite- and phlogopite-type layers.

Where the layer reaches its maximum width in the southern part of the outcrop sapphirine is only an accessory, occurring as narrow rims around spinel (rims_a - Plate 2). This is a type C rock with the assemblage gedrite + enstatite + spinel + (pargasite) + (phlogopite) + (sapphirine); in addition a single grain of molybdenite has been found here.

Only 15 m to the north the rock has quite a different appearance (type D), sapphirine and phlogopite now being the dominant minerals with subordinate cordierite and corundum. A few metres further to the north there is a banded rock with no sapphirine which is layered with variable concentrations of cordierite, corundum, phlogopite, gedrite, pargasite, spinel and plagioclase (types 2_b, 3, and 4).

Near the north coast of the island (top part of fig. 7) there are two mesoscopic folds within which are relic layers of a phlogopite rock in which numerous (up to 30 % by volume) small (3-5 mm) red corundum crystals are embedded (type 4). In the core of the western fold sapphirine

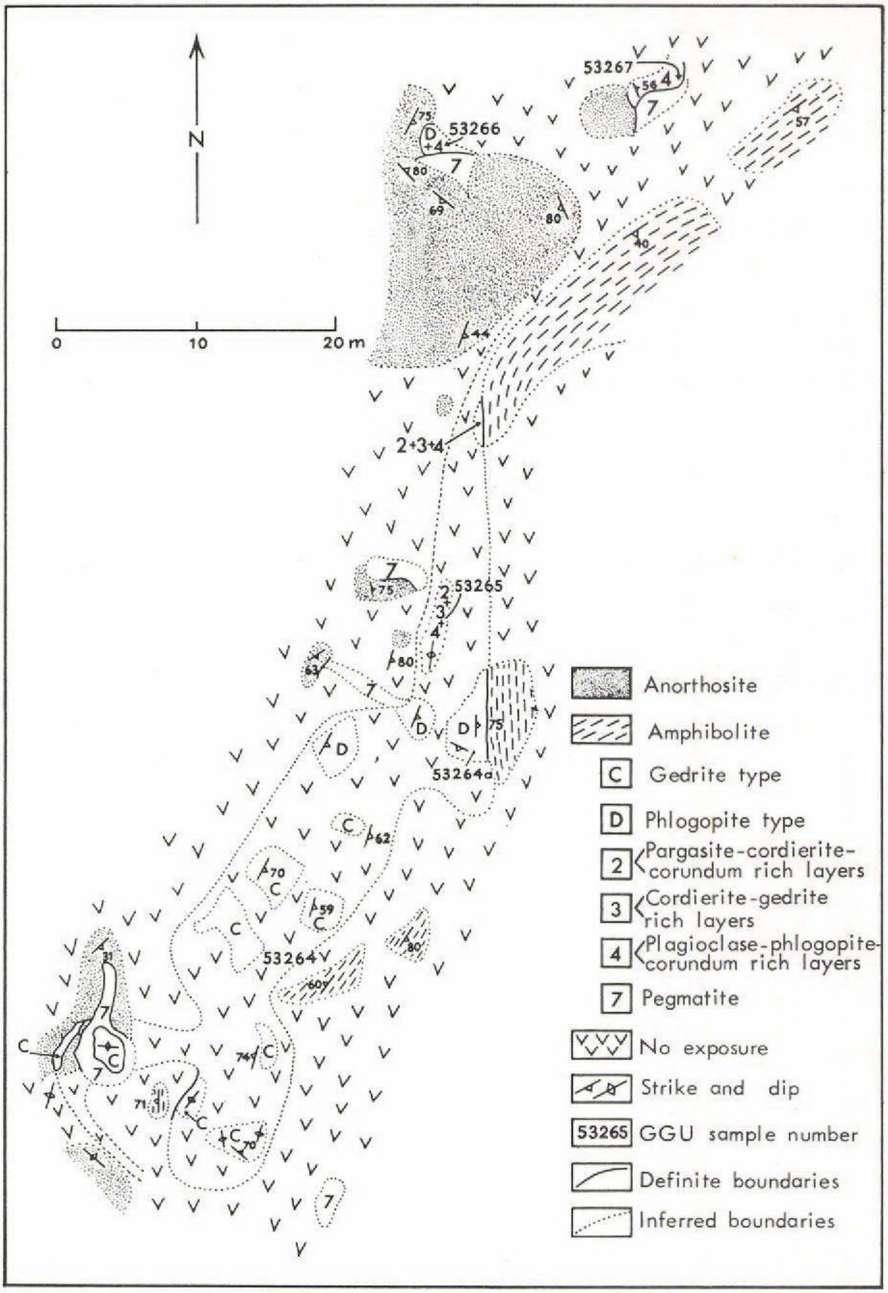

Fig. 7. Detailed sketch map of the Rubin Ø sapphirine locality.

is an accessory mineral (type D) and microscopic kornerupine? has been found in veinlets with cordierite and corundum. Glomeroblastic aggregates of cordierite reach 10 cm across.

5. Siggartartulik

The 10 m wide anorthosite horizon here has been extensively pegmatised with the result that the anorthositic and associated rocks are found as inclusions within what is essentially a pegmatite horizon. It is a common feature for some anorthosite horizons in the more heavily retrogressed rocks of southern West Greenland to be preferentially pegmatised in this way. Within the pegmatite there are separate inclusions up to about 6 m long of sapphirine-bearing rocks mainly of the pargasite type. On account of the mode of occurrence the relationship between these types cannot be seen here as in the above localities. There are several loose blocks of sapphirine-bearing and other ultramafic rocks at the bottom of the gully.

Sapphirine-bearing assemblages are as follows:

Pargasite types;

B_1; Pargasite + enstatite + (sapphirine) + (spinel) + (gedrite) + (gedrite) + (phlogopite)

B_2; Pargasite + phlogopite + sapphirine + plagioclase + (spinel) + (corundum)

Pargasite + phlogopite + sapphirine + corundum + cordierite

Non-sapphirine-bearing rocks have the following parageneses:

2_a. Pargasite + spinel + phlogopite

4. Corundum + plagioclase + phlogopite

5. Phlogopite + olivine + spinel + (zircon)

This is the only rock that has been called type 5, and the presence of olivine suggests that it is related to the type 1 meta-peridotites.

6. Taseq

Sapphirine has been found on both the east and west side of Taseq, a brackish lake on the south side of Fiskenæsset fjord (fig. 2). The Taseq area has been mapped in detail by K. Gormsen (personal communication) who has kindly provided the ultramafic samples containing sapphirine.

The main sapphirine rocks lie about 400 m from the east side of Taseq within an ultramafic lens, 19 m long and up to 4 m wide, situated along the contact of a pyribolite and an anorthosite horizon near a chromitite layer in the anorthosite. This is a phlogopite-type rock with much megascopic sapphirine flanked on its south side by a pure phlogopite rock. The main assemblage is sapphirine-phlogopite-(corundum)-(plagioclase).

On the west side of Taseq about 400 m from the shore there are several ultramafic lenses at the contact between chromite-layered anorthosite and pyribolite horizons. One is a spinel-rich enstatite-pargasite rock from a 30 m x 5 m lens with the assemblage enstatite-spinel-pargasite-(gedrite)-(phlogopite)-(sapphirine), which is similar to one of the main types in Fiskenæsset harbour except that it contains only microscopic sapphirine.

Another lens (15 m x 3 m) consists of a spinel-rich pargasite rock with the assemblage pargasite-spinel-(enstatite)-(phlogopite)-(sapphirine). The rock contains incipient microscopic sapphirine formed during disintegration of spinel.

The following non-sapphirine-bearing assemblages have been found:

1. Clinoamphibole + enstatite + spinel + (olivine) + (rutile)
   Olivine + clinoamphibole + spinel + enstatite + (rutile)

3. Gedrite + plagioclase + clinoamphibole + phlogopite + (cordierite)

7. Sarfaq

At the head of Tasiussarssuaq fjord at the exit of the final bay (Tasiussâ) a narrow anorthosite horizon flanked by two conformable amphibolite horizons crosses the narrows in a north-easterly direction (fig. 2).

The sapphirine, which has only been observed microscopically, occurs in a phlogopite-garnet-plagioclase-(spinel)-(corundum)-(muscovite) rock on the coast on the south-west side of the narrows. This is the only garnet-bearing sapphirine rock in the Fiskenæsset region. The garnets, which are up to 3 cm across, contain inclusions of green spinel, colourless corundum, plagioclase, phlogopite and sapphirine, and are clearly the latest constituent. The sapphirine occurs as rims (0.05 mm wide) around the spinel, but not around corundum. The garnet-rich parts occur in a matrix of phlogopite-plagioclase-(corundum) rock.

SUKKERTOPPEN-GODTHÅB REGION

Description of localities 8-11

8. Sukkertoppen

Ramberg (1948) described sapphirine-bearing rocks in hornblendite inclusions within "white plagioclase-rich rocks" some 3-4 km north of Sukkertoppen on the south-east side of Mánisât island. No sapphirine-bearing or indeed any other ultramafic rocks could be found this distance north of the town, but a large body of meta-norite containing lenses of sapphirine-bearing hornblendite was located about 2 km north-west of it. It is assumed that this is the same area of sapphirine formation but the rocks here described may not be from precisely the same lens as that of Ramberg.

Ramberg's hornblendite is composed of green hornblende, plagioclase, bronzite, spinel, sapphirine, phlogopite and olivine, the first three of which tend to occur in monomineralic bands and lenses. The sapphirine is found as large grains without spinel in the pure bronzite bands and as reaction rims around spinel elsewhere in the same rock.

The meta-norite lies in hypersthene gneisses as a conformable body about 2 km long and 200-500 m wide, the southern end of which

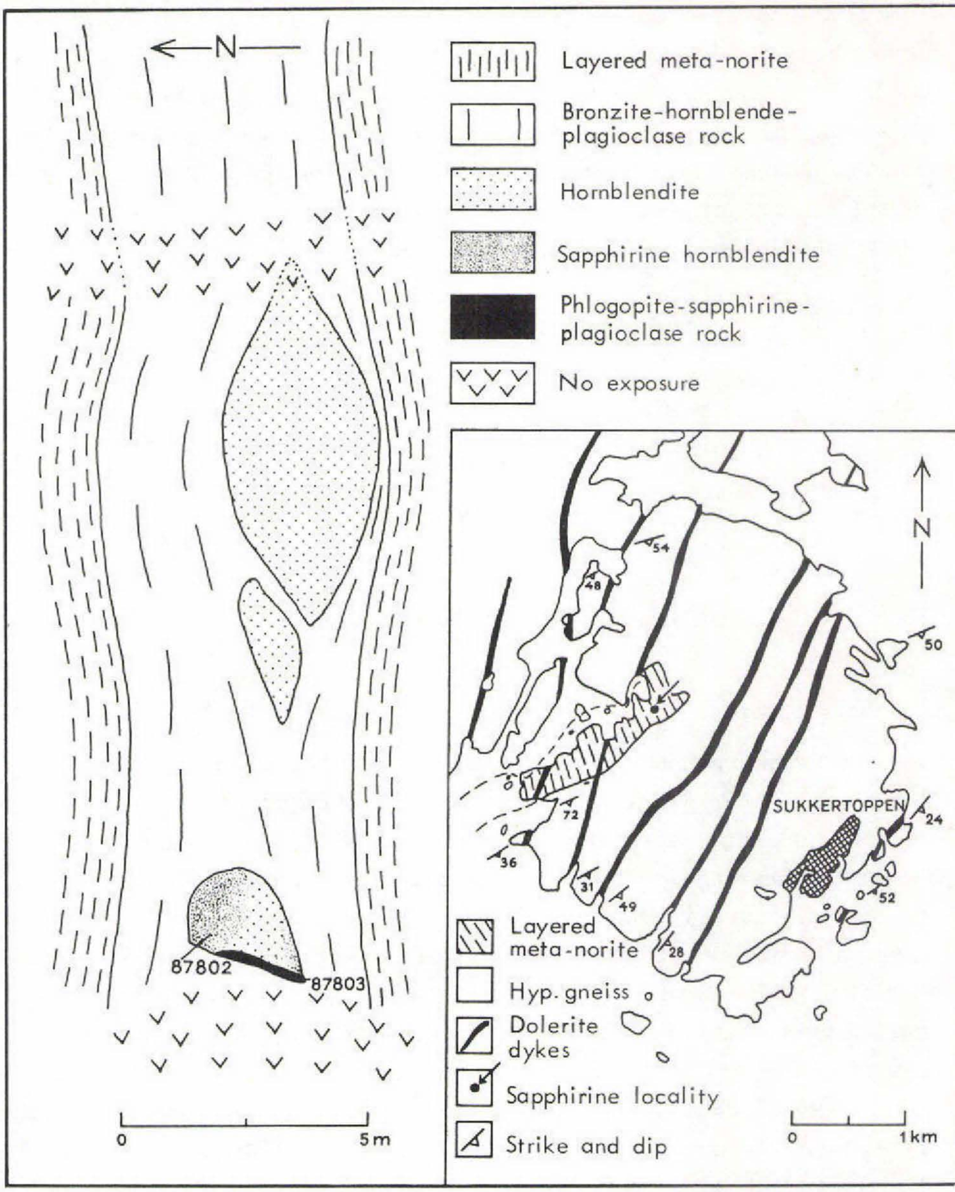

Fig. 8. Sketch map showing the main features and location of the Sukkertoppen sapphirine occurrence.

passes into the sea (fig. 8). A retrogression boundary passes just to the east of Sukkertoppen itself (i.e. there is a downgraded amphibolite facies region to the east), so the meta-norite relic lies in the border zone of the granulite facies region which is extensive to the north. Most of the body consists of hypersthene-plagioclase rock, but near the eastern contact there is a 10 m wide medium-grained gabbro anorthosite that passes inwards via a layered hypersthene-bearing anorthosite into the main norite, within which there are areas of pure anorthosite up to several tens of metres across. In the border zone these rocks are cut by migmatising veins of hypersthene gneiss and hypersthene pegmatite which decrease in number inwards towards the centre of the body which is unmigmatised.

Within the meta-norite there are lenses of hypersthene-hornblende rock up to 5 m wide and 20 m long flanked by 1 m wide layers of coarse-grained plagioclase-hypersthene rock; there are smaller lenses of meta-peridotite.

In the meta-norite at the northern end of the body there are several lenses and layers of green hornblendite, varying to a hornblende-hypersthene rock, up to 30 m wide and many smaller lenses about a metre in size. Most of them contain no sapphirine.

The sapphirine-bearing hornblendite lies at an altitude of about 25 m near the innermost bay (fig. 8). Several hornblendite inclusions are situated in a brown bronzite-hornblende-plagioclase rock which forms an easterly-trending conformable layer between 4 m and 6 m wide in the meta-norite. There are two lenses that contain no sapphirine but a third lens which is about 2 m across (bottom left-hand corner, fig. 8) contains sapphirine in its northern part as single crystals and as aggregates ranging up to a few centimetres wide, whilst the southern half is free of sapphirine. However, sapphirine is concentrated in a marginal layer up to 4 cm wide on the western side of the hornblendite. This layer has the assemblage sapphirine-plagioclase-phlogopite-spinel-hornblende-(corundum), the sapphirine being rimmed by plagioclase.

Petrographically these rocks strongly resemble the type B_2 rocks of the Fiskenæsset region. Sapphirine laths with relic spinels are contained in a matrix of equidimensional plagioclase grains. The plagioclase is apparently forming from the breakdown of the hornblende, and very complicated spinel-plagioclase symplectites may be seen. The phlogopite is concentrated in marginal zones between the plagioclase and the massive hornblende aggregate, in flakes parallel to the contact.

9. Tasiussaq

This locality was described by Sørensen (1955, pp. 6-10) who called it Ol.1. It is situated about 28 km south-east of Sukkertoppen (fig. 1) on a northerly facing headland in Tasiussaq bay.

It was not possible to find any more sapphirine here in 1967. Professor Sørensen (personal communication) has stated this is no doubt because he sampled what little sapphirine there was originally. However it is now possible to see the mutual relationships between the different rocks associated with the sapphirine-bearing hornblendites and to relate these to the regional metamorphic setting.

Tasiussaq is situated in an amphibolite facies terrain (the Alangua region) that bears evidence of having originally had a granulite facies grade of metamorphism. The most common rock is a hornblende-biotite gneiss within which there are at least eight major relics of hypersthene gneiss ranging in size up to about 1 km wide and 4 km long. There also are many relic bodies of meta-norite, bronzitite, dunite and peridotite up to about 0.5 km across. In places these are found within the remaining hypersthene gneisses, whilst in others they are in their retrogressed amphibolite facies equivalents, where they have usually been heavily downgraded. Fig. 9 shows one of these areas of hypersthene gneiss associated with various types of metamorphosed mafic and ultramafic rocks. The surrounding gneisses are all hornblende-biotite bearing (seen on the left of the figure). The hypersthene gneisses are confined to a narrow strip about 40-60 m wide on the east; these are the only remaining hypersthene gneisses for several kilometres. The meta-bronzitites and meta-dunites form layers and broken lenses in the meta-norites and the gneisses. Sørensen (1951) has shown that one of these ultramafic occurrences contains 1.30 % Cr_2O_3 due to about 2 % chromite.

According to Sørensen (1955) the "norites" and "bronzite gneisses" belong to a hybrid zone formed by <u>in situ</u> replacement of the bronzitites by the hornblende-biotite gneisses. However, from more detailed mapping it now appears that the various rocks here are not essentially different from those at Sukkertoppen or Fiskenæsset.

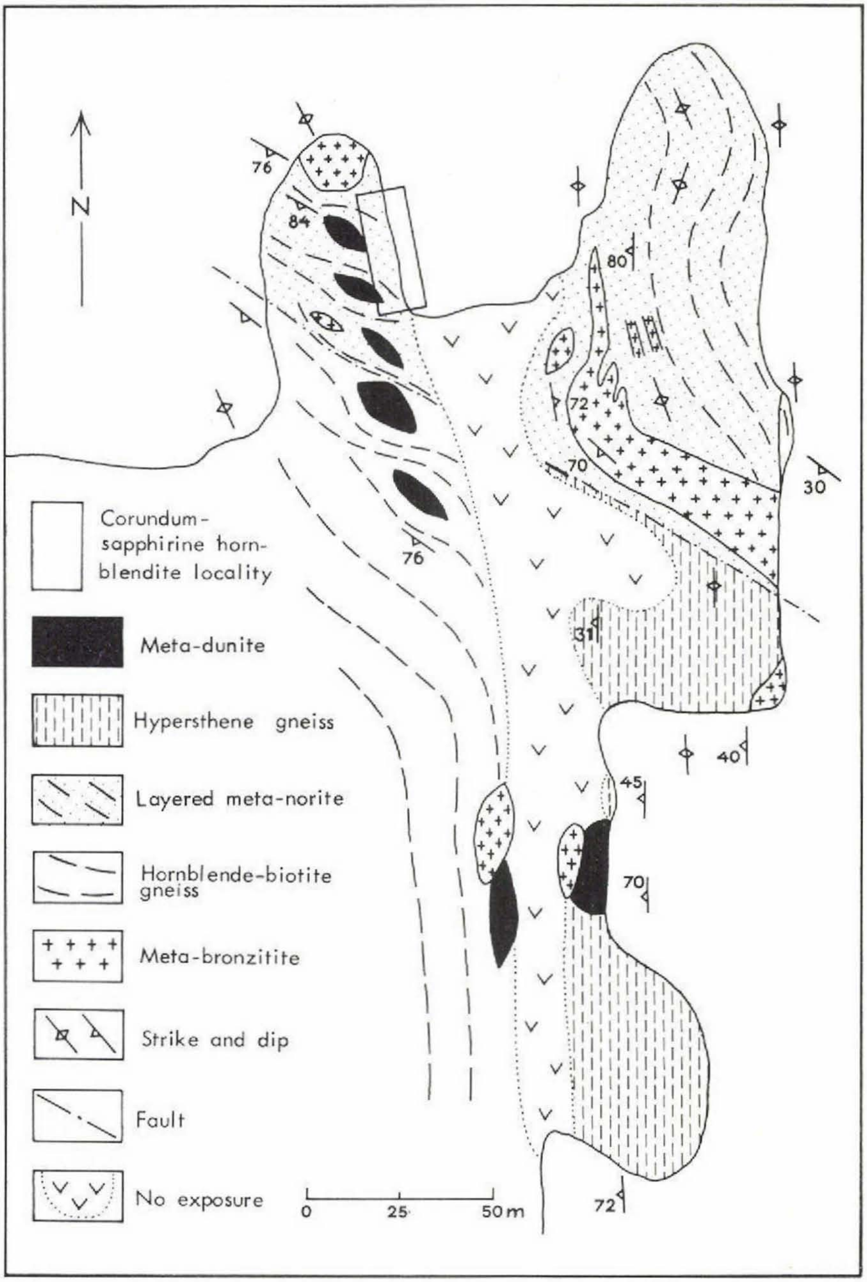

Fig. 9. Sketch map of the Tasiussaq area showing the probable location of the sapphirine-bearing rocks.

Søensen describes the sapphirine as occurring in green hornblendites, forming small masses in the meta-norite near the coast in the northern part of the outcrop. In places the hornblendites have small patches up to 1 cm across that have cores of corundum rimmed by plagioclase and locally there is a thin reaction zone of sapphirine between the two. Spinel occurs in places as thin rims between the corundum and sapphirine and as inclusions in the sapphirine where corundum is absent. Adjacent to the white patches the hornblendites are commonly rich in biotite.

It can be seen that this mineral assemblage is strikingly similar to that of the type B_2 rocks of the Fiskenæsset region.

10. Qôrqut

Sørensen (1955) described the petrography of a loose boulder of hornblendite with microscopic sapphirine at Qôrqut, a bay lying about 45 km east of Godthåb (fig. 1).

Petrographically the rock is similar to that at Tasiussaq. The hornblendite, which has the assemblage green hornblende + plagioclase + biotite ± anthopyllite, contains white patches up to several centimetres wide with a core of corundum rimmed successively by green spinel, blue sapphirine and plagioclase; locally there is an incomplete marginal zone of garnet. In the centre the corundum is also associated with basic plagioclase, chlorite, muscovite and clinozoisite. Again, affinities to the type B_2 assemblages are obvious.

11. Avatsissarfik

Giesecke found sapphirine in 1810 at Avatsissarfik, also written as Auvaitsersarfik, or Avisisarfik (Ramberg 1948) near the head of Godthåbsfjord (fig. 1). There has been no subsequent investigation of this locality. According to Ramberg the rock is composed of gedrite, phlogopite, corundum, sapphirine and spinel, the sapphirine forming reaction rims around gedrite where it borders against corundum and spinel. This appears to be a normal gedrite-type occurrence with affinity to the C-type of the Fiskenæsset localities.

PETROGENESIS

Sapphirine occurs as a rare rock-forming mineral in many high-grade metamorphic terrains throughout the world, in assemblages which have been interpreted as derived by the metasomatism of mafic or ultramafic rocks or from pelites (Deer, Howie, and Zussman, 1962). There are obviously many originally pelitic or ultramafic rocks in these terrains which have undergone a high degree of metamorphism and/or metasomatism, but do not contain sapphirine.

As an aid to understanding the limiting factors for sapphirine growth, the following discussion is aimed at ascertaining the compositional, metamorphic and metasomatic requirements necessary for its formation in West Greenland. From the various modes of occurrence described above the following general points can be made:

1. The fact that the seven Fiskenæsset sapphirine localities occur only within the chromite-layered meta-anorthosite-pyribolite complex is strong evidence of the strict control of host rock composition. The original rock appears to have been a spinel-bearing ultramafic rock which formed an integral though minor part of the layered complex and which provided the high Mg and Al content necessary for sapphirine growth. The evidence of the extensive chromite-layering indicates that the Fiskenæsset complex originated as a gravity-stratified igneous complex (Windley, in press a).

The sapphirine at Sukkertoppen and Tasiussaq occurs within relatively small meta-norites, which can reasonably be regarded as highly tectonised relics of originally more extensive noritic bodies. The chromite-rich dunites associated with the Tasiussaq norites are indicative of an igneous origin for this suite of rocks also, and Ramberg (1948) has suggested a similar origin for the Sukkertoppen rocks as well.

2. All the anorthosites, norites and associated host rocks in question were subjected to a granulite facies metamorphism. Evidence for this is seen in areas where stable assemblages of hypersthene and biotite consistently occur in the gneisses, and stable assemblages of hypersthene and hornblende occur in the pyribolites of the complex. Both

assemblages indicate hornblende-granulite sub-facies conditions. Within these granulite facies relic areas, there is no evidence that the biotite or hornblende content of these rocks increases towards the retrogression boundaries.

3. Much of the basement of southern West Greenland was subsequently affected by a cordierite-amphibolite facies metamorphism which heavily retrogressed many of the earlier granulite facies rocks. Their degree of retrogression was roughly inversely proportional to their basicity. The hypersthene gneisses in many areas were entirely recrystallised to hornblende-biotite derivatives, whilst the pyribolites and ultramafics in the same areas were less affected and so still retained part of their granulite facies mineralogy.

From Fiskenæsset the amount of retrogression increases progressively southwards with the result that in the extreme south of the area shown in fig. 2 all rocks have attained equilibrium under the new lower grade conditions. Although the meta-pyroxenites still show a well-preserved granulite facies assemblage at Fiskenæsset harbour and Taseq just south of the retrogression front, they have been completely altered to equivalent amphibolite facies assemblages further to the south.

The amphibolite facies metamorphism was responsible for sufficient introduction of water to allow some pyroxenes in the chromitites, norites, pyribolites and ultramafics to be converted to hornblendes. The chromitites of the complex rarely contain pyroxene; if they were originally Bushveld-type chromite norites (chromite + plagioclase + orthopyroxene), their conversion to their metamorphic equivalents in the Fiskenæsset-type chromitites (chromite + hornblende) suggests that both the granulite and amphibolite facies metamorphisms were essentially isochemical with respect to the main horizons of the original igneous complex, except for ingress of water (calcium plagioclase + orthopyroxene + water $\rightarrow$ hornblende). This is probably the main reason for the remarkable state of preservation of the complex.

4. The formation of the sapphirine-bearing rocks was related to a selective metasomatism, confined to certain structural positions in the complex, in contrast to the isochemical metamorphism of the whole complex.

It is important to note that the sapphirine-bearing rocks at Fiskenæsset harbour, Lower Angnertussoq, Upper Angnertussoq, Rubin Ø, and Taseq all occur along the contact between anorthosite and pyribolite/amphibolite horizons. These contacts clearly were zones of movement during deformation with the result that the narrow ultramafic layers were variably thinned, broken and boudinaged.

Sørensen (1955) suggested that the marked paucity of sapphirine-bearing rocks in general may be due to the widespread presence of an active dispersed phase (migrating ions, vapours and solutions) during high-grade metamorphism. The evidence presented supports this contention and demonstrates more precisely that this phase was ineffectual in the Fiskenæsset region. Metasomatism within the complex was largely confined to the channels between major anorthosite and pyribolite horizons and thus it was here that sapphirine formed in rocks of suitable composition. Silica, lime, potash and water were introduced and the formation of extensive phlogopite-type rocks, the most metasomatised and foliated of the four petrogenetic types, took place along the sheared contacts of the lenses. The growth of late cordierite in types C and D rocks requires that part of the metasomatism took place under cordierite-amphibolite facies conditions as a late phase of the main retrogression. If similar ultramafic rocks had occurred as inclusions within the quartzo-feldspathic gneisses, they would have been altered so considerably during the same two periods of regional metamorphism that original spinel etc. would have been entirely removed by a more active silica and water metasomatism. Supporting evidence for this hypothesis may be provided by the existence of many zoned ultrabasic talc "bolle" in the gneisses of the Fiskenæsset area. It was only well within the confines of the layered complex that the ultramafic rocks were sufficiently protected to prevent the complete breakdown and disappearance of the spinel-sapphirine parageneses.

At Sukkertoppen and Tasiussaq the hornblendites that contain sapphirine must have formed from ultramafic rocks by preferential metasomatic retrogression of certain minor layers. Their constituent corundum, spinel and sapphirine give the clue to their original high content of Al and Mg.

It can be no coincidence that at Sakeny, Madagascar, where "sapphirinites" are also intensely developed, the sapphirine-bearing rocks occur within stratigraphic horizons of meta-anorthosite that contain chromite-bearing ultrabasics (Lacroix, 1941; Boulanger, 1959).

5. The study of the sapphirine-bearing and associated rocks in the Fiskenæsset region has reached the stage where preliminary conclusions can be drawn about the physical and chemical conditions that produced the observed mineralogical and lithological changes. These conditions are implicit in much of what has been said previously under "petrography" and "description of localities". However, it should be noted that while the sequence A B C D defines the major stages in the rock genesis the minerals present and listed for each of the A, B, C, and D types are not strictly coexisting stable assemblages, but polymetasomatic assemblages composed of overlapping groups of stable assemblages. A detailed spatial-genetic account of the complex sequence of chemical reactions that have occurred in these rocks is beyond the scope of the present paper; this is the subject of continuing study by the first author (RKH) to be published at a later date.

Sapphirine has developed progressively in the presence of introduced silica from rims on spinel to full crystal laths under hornblende-granulite facies pressure/temperature conditions, from a parent rock which in all cases in West Greenland was a spinel-rich member of an igneous ultramafic suite. The silica metasomatism was accompanied by minor potash and water metasomatism. Minor stress facilitated crystal growth but textures remained mostly mimetic after layering in the igneous rock.

Under continuing hornblende-granulite facies conditions calcium was introduced and pargasitic hornblende characteristic of type B rocks replaced the enstatite and probably also the phlogopite in type A rocks. The lime metasomatism accompanied continuing minor silica, potash and water metasomatism. B_2 rocks (pargasite without enstatite) may well have formed entirely under these conditions (i.e. without a preceding silica metasomatism to form type A).

Type C rocks arose from types A and B solely through a change in metamorphic P-T conditions to those of the cordierite-amphibolite facies. Gedrite became the stable ferromagnesian mineral, sapphirine began to alter to corundum and phlogopite, and pargasite began inverting in part to plagioclase. All these changes, plus that of gedrite to cordierite, neared completion under continuing amphibolite facies conditions in type D rocks.

In D_3 rocks sapphirine survived as well-crystallised rims on corundum. The formation of type D rocks was accompanied by much shearing and by further potash metasomatism (hence the large amounts of phlogopite).

Sapphirine was thus formed under hornblende-granulite facies conditions, was stable in reduced amounts under cordierite-amphibolite facies conditions and was stable even in relatively calcium-rich assemblages where it was able to recrystallise under amphibolite facies conditions.

CONCLUSION

A wide range of pressure and temperature conditions within which sapphirine is stable is thus proposed. Its formation or survival is crucially dependent upon the bulk chemistry of its immediate environment (high Mg, Al; not too much K, Si, or Ca) - i.e. upon parent rock composition, the distribution of elements in the parent rock, the controlled metasomatic introduction of specific elements, and the resultant distribution of the introduced elements - rather than upon a narrow range of P-T conditions.

The associated rocks (types 1 to 4) were formed by the same sequence of metamorphic P-T conditions that formed the sapphirine-bearing rocks, but in their formation one or more of the above crucial chemical conditions was not fulfilled; this either precluded sapphirine formation or prohibited sapphirine survival. The most important element in this respect was calcium; for example, excess calcium expressed as abundant plagioclase in types 3 and 4 meant that sapphirine could not be present as in types C and D.

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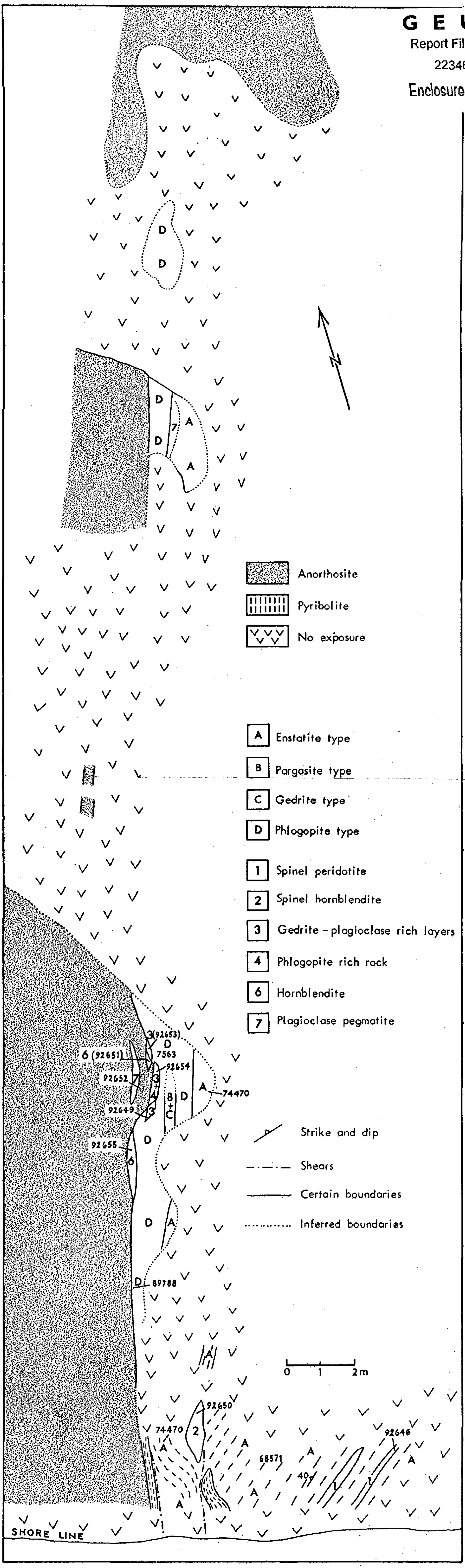
Plate 1. Detailed sketch map of the Fiskenæsset harbour sapphirine locality.

Plate 2. Mineral assemblages occurring in rocks from the sapphirine localities. Specimen numbers are those of the Geological Survey of Greenland.

Plate 3. Properties of the major rock-forming minerals.


N
Anorthosite
Pyribolite
No exposure
A Enstatite type
B Pargasite type
C Gedrite type
D Phlogopite type
1 Spinel peridotite
2 Spinel hornblendite
3 Gedrite - plagioclase rich layers
4 Phlogopite rich rock
6 Hornblendite
7 Plagioclase pegmatite
Strike and dip
Shears
Certain boundaries
Inferred boundaries
0 1 2 m
6 (92651)
92653
7563
92654
92652
74470
92649
92655
89788
92650
74470
68571
92646
40
SHORE LINE

GEUS
Report File no.
22346
Enclosure (2/3)

PLATE 2

LOCALITY: FISKENÆSSET HARBOUR (Sapphirine Type Locality)

	GGU SPECIMEN NUMBER	68571	74470	86876	86878a	86878b$_1$	86878b$_2$	86884	92648	7563	74457	74469 (89788)	86875a, b$_1$	86875b$_2$	86875b$_2$	86876	86875b$_2$	7563	89789	92649
	ROCK TYPE	A	A	A	A	A	A	A	A	B_1	B_1	B_1	B	B_1	B_1	B_1	C	D_1	D_3	D_3
MAJOR ROCK-FORMING MINERALS	Sapphirine rims$_a$	x	x		x	x		(x)			x									
	Sapphirine laths		x	x	x	(x)	x		x	x		x	x	x	x	x	x	x	(x)	
	Sapphirine grains						(x)			x		(x)	x	x	(x)		x	x		(x)
	Sapphirine rims$_b$																		x	
	Olivine (forsteritic)																			
	Enstatite/bronzite	x_1	x_1	(x_2)	x_1	(x_2)	x_1	x_1	x_1		x_1	(x_4)	x_1	(x_4)		(x_2)				
	Diopside																			
	Pargasite						(x_3)			x_1	x_2	x_1	x_2	x_1	x_1	x_1	(x_3)	(x_2)		
	Clinoamphibole							x_2												
	Hornblende																			
	Gedrite											(x_3)	(x_4)	x_2	(x_3)	(x_3)	x_1			(x_2)
	Phlogopite	(x_2)	x_2	x_1	(x_2)	x_1	(x_2)	(x_3)	x_2	x_2	(x_3)	x_2	x_3	x_3	x_2	(x_4)	x_2	x_1	x	x_1
	Biotite																			
	Cordierite													(x)						
	Plagioclase									(x)		(x)						x	x	x
	Corundum		(x)	(x)			(x)			(x)		(x)	(x)	(x)			(x)	(x)	x	(x)
	Spinel	x	x	x	x	x	(x)	x	x	(x)	x	(x)	(x)	(x)	(x)	(x)				
	Garnet																			
ACCESSORY MINERALS	Epidote group (crystals)																			
	Zircon											x								
	Kornerupine																			
	Muscovite										x						x		x	
	Magnetite-ilmenite	x						x		x	x	x	x					x		
	Rutile		x			x							x		x				x	
	Sulphide	x						x			x									
SECONDARY MINERALS	Epidote group	x								x	x		x			x		x		x
	White mica	x								x						x		x		
	Chlorite	x			x			x			x			x	x	x				
	Serpentine																			
	Hematite/goethite	x		x	x	x	x		x		x	x	x	x	x	x	x	x		x
	Carbonate	x	x	x				x		x	x	x	x	x		x		x	x	

LOCALITY: FISKENÆSSET HARBOUR (Sapphirine Type Locality) (continued)

	GGU SPECIMEN NUMBER	68570 (92646)	74460	86884	86888	74458 (92650)	92649	92653	92654	92654	92651	92655	92652
	ROCK TYPE	1	1	1	1	2_a	3	3	3	4	6	6	7
MAJOR ROCK-FORMING MINERALS	Sapphirine rims$_a$												
	Sapphirine laths												
	Sapphirine grains												
	Sapphirine rims$_b$												
	Olivine (forsteritic)	x_2	x_2	x_3	x_2								
	Enstatite/bronzite	x_3		x_1									
	Diopside		x_1										
	Pargasite					x_1		x_2					
	Clinoamphibole	x_1	x_3	x_2	x_1				x_2				
	Hornblende										x	x_1	
	Gedrite						x_1	x_1	x_1				
	Phlogopite			(x_4)		(x_2)	x_2		(x_3)	x			
	Biotite							(x_3)				(x_2)	
	Cordierite							(x)	(x)	x		(x)	
	Plagioclase						x	x	x	x		(x)	x
	Corundum						(x)			(x)			
	Spinel	x	x	(x)	x	x							
	Garnet												
ACCESSORY MINERALS	Epidote group (crystals)												
	Zircon		x			x				x		x	
	Kornerupine												
	Muscovite	x											
	Magnetite-ilmenite	x	x			x			x		x	x	
	Rutile												
	Sulphide	x	x	x	x	x						x	
SECONDARY MINERALS	Epidote group						x	x	x				x
	White mica		x						x				x
	Chlorite		x	x	x	x		x					
	Serpentine	x	x	x	x								
	Hematite/goethite					x	x	x	x	x	x	x	
	Carbonate	x	x	x	x	x				x			

LOCALITY: LOWER ANGNERTUSSOQ

	GGU SPECIMEN NUMBER	68609	86992c$_1$ (92641)	86992f	86992g$_1$	68608	86992b	86992f	74452 (92642)	86992b	68609	86992c$_1$	86992h$_2$
	ROCK TYPE	B_2	B_2	B_2	B_2	C	C	C	D_1	D_2	D_3	D_3	D_3
MAJOR ROCK-FORMING MINERALS	Sapphirine rims$_a$	x		x	x							x	
	Sapphirine laths	(x)		x	x	x	(x)		x	x			
	Sapphirine grains			x			x	x	(x)				(x)
	Sapphirine rims$_b$	x	(x)	x	x		(x)	x		x	x	x	(x)
	Olivine (forsteritic)												
	Enstatite/bronzite												
	Diopside												
	Pargasite	x_1	x_1	x_1	x_1		(x_3)	(x_3)			(x_3)		(x_3)
	Clinoamphibole												
	Hornblende												
	Gedrite	(x_3)	(x_3)	(x_3)	(x_3)	x_1	x_1	x_2	(x_2)	(x_2)	(x_2)		(x_2)
	Phlogopite	x_2	x_2	x_2	x_2	(x_2)	(x_2)	x_1	x_1	x_1	x_1	x	x_1
	Biotite												
	Cordierite					x	x			(x)			
	Plagioclase	x	x	x	x	(x)	(x)	x			x	x	x
	Corundum	x	x	x	x	x	x	x	x	x	x	x	x
	Spinel	x	x	x	x			(x)				x	
	Garnet												
ACCESSORY MINERALS	Epidote group (crystals)												
	Zircon												
	Kornerupine												
	Muscovite												
	Magnetite-ilmenite						x						
	Rutile				x		x	x					
	Sulphide												
SECONDARY MINERALS	Epidote group		x	x	x						x	x	x
	White mica	x	x	x	x	x	x				x	x	x
	Chlorite	x			x		x		x		x		
	Serpentine												
	Hematite/goethite	x				x	x		x	x	x		x
	Carbonate	x	x	x	x	x	x		x		x	x	x

LOCALITY: LOWER ANGNERTUSSOQ (continued)

	GGU SPECIMEN NUMBER	74456	86992c$_2$	86992d (89813)	86992e (68610)	86992g$_2$	86992h$_2$	92643	68609	86992a (89814)	86992c$_1$	86992f
	ROCK TYPE	3	3	3	3	3	3	3	4	4	4	4
MAJOR ROCK-FORMING MINERALS	Sapphirine rims$_a$											
	Sapphirine laths											
	Sapphirine grains											
	Sapphirine rims$_b$											
	Olivine (forsteritic)											
	Enstatite/bronzite											
	Diopside											
	Pargasite	x_2					(x_3)	x_1				(x_3)
	Clinoamphibole					x_2						
	Hornblende											
	Gedrite	x_1	x_1	x_1	x_1	x_1	x_1	x_2	(x_2)			(x_2)
	Phlogopite	(x_3)	x_2	(x_2)	(x_2)	(x_3)	x_2	(x_3)	x_1	x	x	x_1
	Biotite											
	Cordierite	x		x	(x)	(x)		(x)				
	Plagioclase	x	x	(x)	x	x	x	(x)	x	x	x	x
	Corundum		x				x	(x)	x	x	(x)	x
	Spinel									x		(x)
	Garnet											
ACCESSORY MINERALS	Epidote group (crystals)											
	Zircon			x								
	Kornerupine											
	Muscovite											
	Magnetite-ilmenite			x	x	x		x				
	Rutile				x	x				x		
	Sulphide					x						
SECONDARY MINERALS	Epidote group		x	x			x		x	x	x	x
	White mica	x	x		x	x	x		x	x	x	x
	Chlorite	x		x								
	Serpentine											
	Hematite/goethite	x	x	x	x	x	x	x	x			
	Carbonate	x	x	x	x		x		x	x	x	x

LOCALITIES: UPPER ANGNERTUSSOQ; RUBIN Ø

	LOCALITY	UPPER ANGNERTUSSOQ									RUBIN Ø								
	GGU SPECIMEN NUMBER	53235	53236 (78668)	53234	53237	53233	53239	53237 (78667)	53240	53240	53264	53264a	53266	53265	53265	53265	53266	53266	53267
	ROCK TYPE	C	C	D_1	D_1	1	1	2_b	2_b	4	C	D_2	D_2	2_b	3	4	4	4	4
MAJOR ROCK-FORMING MINERALS	Sapphirine rims$_a$	(x)		x							(x)								
	Sapphirine laths		x	x	x						(x)		x						
	Sapphirine grains			x								x	x						
	Sapphirine rims$_b$																		
	Olivine (forsteritic)					x_1	x_1												
	Enstatite/bronzite	x_2	(x_2)			x_2	x_3				x_2								
	Diopside																		
	Pargasite	$(x_4?)$	(x_3)					x_1	x_1	(x_2)	(x_3)			x_1		(x_2)			
	Clinoamphibole					(x_4)	x_2												
	Hornblende																		
	Gedrite	x_1	x_1			(x_3)			(x_3)		x_1				x_1	(x_3)			
	Phlogopite	(x_3)	(x_4)	x	x			(x_2)	x_2	x_1	(x_4)	x	x	x_2	(x_2)	x_1	x	x	x
	Biotite																		
	Cordierite		(x)					x	x	x	(x)	x	x	x	x	x	x	(x)	x
	Plagioclase							x	x	x				x		x		x	(x)
	Corundum	(x)	(x)	x	x			x	x	x	x	x	x	x		x	x	x	x
	Spinel	x	(x)	x		x	x		(x)	x	(x)								
	Garnet																		
ACCESSORY MINERALS	Epidote group (crystals)									x									x
	Zircon						x?												
	Kornerupine																x?		
	Muscovite																		
	Magnetite-ilmenite					x	x		x		x	x							x
	Rutile	x	x	x		x					x			x	x	x			x
	Sulphide					x	x												
SECONDARY MINERALS	Epidote group									x									
	White mica														x				
	Chlorite	x	x	x	x	x				x	x		x	x		x	x	x	x
	Serpentine					x	x												
	Hematite/goethite		x		x	x							x						
	Carbonate	x	x	x	x	x	x				x		x	x	x	x	x	x	

LOCALITY: SIGGARTARTULIK

	GGU SPECIMEN NUMBER	68601	68603	68606	74448	68603	68604	74449a	68601	68605	74449b	68602
	ROCK TYPE	B_1	B_1	B_1	B_1	B_2	B_2	B_2	2_a	2_a	4	5
MAJOR ROCK-FORMING MINERALS	Sapphirine rims$_a$	x	x		x	x		x				
	Sapphirine laths	x	x	x	x		x					
	Sapphirine grains											
	Sapphirine rims$_b$											
	Olivine (forsteritic)											x_2
	Enstatite/bronzite	x_2		x_3	x_1				(x_3)			
	Diopside											
	Pargasite	x_1	x_1	x_2	x_2	(x_2)	x_1	x_2	(x_2)	x_1		
	Clinoamphibole											
	Hornblende											
	Gedrite				(x_3)							
	Phlogopite	x_3	x_2	x_1	(x_4)	x_1	x_2	x_1	x_1	x_2	x	x_1
	Biotite											
	Cordierite				(x)		x					
	Plagioclase		(x)			x		x			x	
	Corundum	(x)	(x)		(x)	x	x	x	(x)		x	
	Spinel	x	x	x	x	x		x	x	x		x
	Garnet											
ACCESSORY MINERALS	Epidote group (crystals)											
	Zircon											x
	Kornerupine											
	Muscovite											
	Magnetite-ilmenite		x		x	x	x			x		x
	Rutile			x						x		
	Sulphide											
SECONDARY MINERALS	Epidote group											
	White mica											
	Chlorite	x	x	x	x				x			x
	Serpentine											
	Hematite/goethite				x		x	x		x		x
	Carbonate	x	x	x	x	x	x		x			x

LOCALITIES: TASEQ; SARFAQ; SUKKERTOPPEN

	LOCALITY	TASEQ West					TASEQ East			SARFAQ		SUKKERTOPPEN	
	GGU SPECIMEN NUMBER	73037	73179	73181	73182	73028	73162	73163	73158	68545	68545	87802	87803
	ROCK TYPE	B_1	B_1	1	1	3	B_2	D_1	3	D_1	4	B_2	B_2
MAJOR ROCK-FORMING MINERALS	Sapphirine rims$_a$	(x)	(x)				x			x		x	x
	Sapphirine laths		(x)				x	x				x	x
	Sapphirine grains									x			
	Sapphirine rims$_b$						x	x					
	Olivine (forsteritic)			(x_3)	x_1								
	Enstatite/bronzite	x_1	x_1	x_2	x_3								
	Diopside												
	Pargasite	x_2	x_2	x_1	x_2	(x_2)							
	Clinoamphibole					(x_3)	x_1		x_2			x_1	x_1
	Hornblende												
	Gedrite	(x_3)				x_1			x_1				
	Phlogopite	(x_4)	(x_3)			(x_4)	(x_2)	x	(x_3)	x_1	x_1	x_2	x_2
	Biotite									x_2	x_2		
	Cordierite					x			(x)				
	Plagioclase					x	x	(x)	x	x	x	x	x
	Corundum						x	x		(x)	x	(x)	(x)
	Spinel	x	x	x	x		x			x		x	x
	Garnet									x			
ACCESSORY MINERALS	Epidote group (crystals)								x				
	Zircon								x				
	Kornerupine												
	Muscovite										x		
	Magnetite-ilmenite	x	x					x					
	Rutile	x	x	x	x	x			x				
	Sulphide			x	x								
SECONDARY MINERALS	Epidote group												
	White mica												
	Chlorite		x	x	x								
	Serpentine												
	Hematite/goethite	x	x	x		x		x	x				
	Carbonate	x	x	x	x	x		x	x	x	x	x	x

Notes: (i) Many more specimen numbers appear in the table than are shown on the detailed locality maps. The extra assemblages are listed to show the wide variation in relative mineral abundances within any rock type, and also to show the overlap among the constituent minerals of the different rock types. Where a number appears more than once, the several assemblages listed for that number all occur within one hand-specimen or within one thin-section.

(ii) Sapphirine rims$_a$ = rims on spinel
Sapphirine rims$_b$ = rims on corundum

(iii) x_1, x_2, x_3, x_4 : The relative abundance of ferromagnesian minerals has been estimated within each thin-section, and is defined by the numerical subscripts.

(iv) Brackets, as (x), indicate that a mineral is of minor abundance relative to its associates within any one thin-section. Accessory and secondary minerals are all in minor abundance, though shown by unbracketed crosses.

GEUS
Report File no.
22346
Enclosure (3/3)

MINERAL and FORMULA	COLOUR and CRYSTALLINE FORM	TWINNING FEATURES; CLEAVAGE ETC	RELIEF and BIREFRINGENCE	PLEOCHRONISM	OPTICAL CHARACTERISTICS	REMARKS
Sapphirine; $(Mg,Fe)_2Al_4SiO_{10}$ (Deer, Howie, and Zussman 1962) $(Mg,Fe)_{3.5}Al_9Si_{1.5}O_{20}$ (Moore, pers.comm., 1968)	pale blue, sky-blue, blue-green, blue-grey, or grey subhedral prisms, also as moderate blue or blue-green rims on spinel ($rims_a$ - Plate 2) and on corundum ($rims_b$ - Plate 2), or as angular crystal remnants and saccharoidal areas of tiny grains (grains - Plate 2)	lath-shaped sections of prisms exhibit simple lamellar twinning on {010}, or {110} penetration twins (rosettes); persistent fractures which may be poor {011} and {110} cleavages	high relief and high refractive indices; very low birefringence	shades of blue, green, grey, brown or orange, to colourless: $\alpha<\beta<\gamma$	2V negative, varying from $60^{\circ}\pm 2^{\circ}$ to $81^{\circ}\pm 2^{\circ}$ indicating substantial variations in the percentages of component elements	Often contains inclusions of spinel, corundum and phlogopite S
Olivine; $(Mg,Fe)_2SiO_4$	pale green to colourless; equidimensional grains, often with characteristic curved fractures	no twinning; no cleavage; curved fractures	high relief, refractive indices and birefringence	non-pleochroic	2V nearly neutral, indicating Fo_{70-90}.	Sometimes serpentinised, chloritised NS
Enstatite/Bronzite; $(Mg,Fe)SiO_3$ (aluminous : c. 5.00 % Al_2O_3)	pale yellow-brown to whitish-brown prisms, elongate with equidimensional cross-sections; usually very fresh, sometimes altering to chlorite or serpentine; also as irregular remnants	characteristically with fine lamellae, probably of clinopyroxene, parallel to (010) (Bushveld type); excellent {210} cleavages	high relief and moderate to low birefringence	virtually non-pleochroic (bronzite slightly pleochroic)	biaxial positive, 2V $82^{\circ}\pm 2^{\circ}$ to $65^{\circ}\pm 2^{\circ}$ indicating En_{90-96}; bronzite neutral to negative with 2V large	Enstatite: S Bronzite: NS
Diopside; $Ca(Mg,Fe)Si_2O_6$ (probably aluminous)	pale green to colourless subhedral prisms; serpentinised and chloritised	good {110} cleavage	high relief and birefringence	non-pleochroic,	positive 2V, c. 60°, large extinction angle	Occurs in one rock only at Fiskenæsset harbour; very common in major pyribolites, and other types of ultramafic bodies. NS
Pargasite; $(K,Na)Ca_2(Mg,Fe)_4$ - $Al_3Si_6O_{22}(OH)_2$	pale green, pale brown to almost colourless; euhedral to subhedral elongate fresh prisms; also as remnants	simple lamellar (100) twins occur	moderate relief and high to moderate birefringence	slightly pleochroic, pale green or brown to colourless	biaxial positive, 2V $74^{\circ}\pm 2^{\circ}$ to $88^{\circ}\pm 2^{\circ}$, γ : z 16° - 22°	BOTH
Clinoamphibole; probably Tremolite or Edenite	pale green to colourless, euhedral to subhedral prisms	simple lamellar (100) twins	moderate relief and birefringence	pale green to colourless	biaxial negative, 2V large	Found with olivine and bronzite in some type 1 rocks, with gedrite in some type 3 rocks. NS
Hornblende;	dark green or green-black; euhedral to subhedral elongate fresh crystals	simple lamellar (100) twins	moderate relief and birefringence	green to bluish green to pale yellow-green	biaxial negative 2V large	Found in hornblendites in the Fiskenæsset harbour lens. NS
Gedrite; $(Mg,Fe)_5Al_4Si_6O_{22}(OH)_2$	pale grey-brown to pink-brown to colourless subhedral or euhedral elongate prisms, very translucent and fresh; also as irregular crystal remnants	untwinned; good {210} cleavages	moderate relief and low birefringence	pale brown to colourless	biaxial negative, to neutral; 2V $75^{\circ}\pm 2^{\circ}$ to $90^{\circ}\pm 2^{\circ}$	BOTH
Phlogopite $K_2(Mg,Fe)_6Si_6Al_2O_{20}$ - $(OH)_4$	honey brown to pale yellow-brown euhedral flakes, sometimes partly altered to chlorite and leucoxene	untwinned; perfect basal cleavage	low relief and characteristic high birefringence	strongly pleochroic, brown to colourless, $\alpha<\beta=\gamma$	slightly biaxial, negative, 2V 0° - 15°, or 20° maximum	BOTH
Biotite;	green to green-brown, or red-brown	untwinned; perfect basal cleavage	low relief and moderate birefringence	pale green or pale red-brown to pale yellow, strong	optics very similar to phlogopite, above	Appears in place of phlogopite at Sarfaq, and in some non-sapphirine rocks, Fiskenæsset harbour BOTH
Cordierite; $(Mg,Fe)_2Al_4Si_5O_{18}$	colourless, pale blue-grey or pale red, equidimensional grains exhibiting some partial alteration to "pinite"	sector twinning, not always present	very low relief and moderate to low birefringende	non-pleochroic	biaxial positive only; 2V $76^{\circ}\pm 2^{\circ}$ to $82^{\circ}\pm 2^{\circ}$	BOTH
Plagioclase; $NaAlSi_3O_8$ - $CaAl_2Si_2O_8$ An_{60-70}	colourless, white; in equidimensional grains, usually very fresh	albite and pericline twinning	low relief and low birefringence	non-pleochroic	biaxial negative, 2V large; rarely shows wandering extinction (i.e. crude zoning)	Maximum composition range, An_{50-80} (from U-stage measurements) BOTH
Corundum; Al_2O_3	colourless to reddish pink to deep red (var. ruby); anhedral, to euhedral equidimensional grains, also as fine-grained dust and as irregular crystal fragments	rhombohedral partings common	extremely high relief and low birefringence	ruby varieties strongly pleochroic, pink to colourless or orange	uniaxial to slightly biaxial, negative	BOTH
Spinel; $(Mg,Fe)(Al,Fe,Cr)_2O_4$	colourless, grey, pale green, green or deep blue-green, pale blue; also pink, pale brown to dark red-brown; always as subhedral to anhedral rounded grains and inclusions, showing colour zoning in dark red-brown varieties	octahedral parting very common, especially in dark green varieties	high relief	faint pleochroism	completely isotropic	Often clouded with inclusions of opaque oxides, and rarely containing inclusions of zircon; altered in a few cases to colourless optically positive chlorite. BOTH
Garnet; $(Mg,Fe,Ca,Mn)_3$ - $(Al,Fe)_2Si_3O_{12}$	pale pink to colourless subhedral poikiloblasts	no twinning, cleavage or parting	high relief	non-pleochroic	completely isotropic	From Sarfaq only; garnet is very common and characteristic mineral within both the gneisses and the meta-anorthosites, amphibolites and ultramafics of the metamorphosed igneous complex. BOTH

Notes: (i) All 2V determinations based on universal stage measurements
(ii) S = occurs in sapphirine-bearing rocks only
NS = occurs in non-sapphirine-bearing rocks only
BOTH = occurs in both sapphirine- and non-sapphirine-bearing rocks