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THE ULTRAMAFITES AND LAYERED GABBRO SEQUENCES

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CHAPTER I

CHAPTER II

CHAPTER III

CHAPTER IV

CHAPTER V

CHAPTER VI

Insert in backflap:
Geological map of the Stjernöy region

CHAPTER I

THE ULTRAMAFIC AND MAFIC ROCKS OF FINNMARK'S COASTAL REGIONS

INTRODUCTION

Ultramafic and mafic rocks occur over considerable distances in the province of Finnmark and in the northern part of the province of Troms. A vast area of these rocks extends over the islands of Seiland, Stjernöy and Söröy and the peninsulas of Öksfjord and Bergsfjord (fig. 1). These islands are separated by fjords and sounds from the mainland with the nappes of the Caledonian orogen which curves along Finnmark's coast from NNE to ENE.

On the geological map of Norway prepared by Holtedahl and Dons (1953) other occurrences of mafic rocks are indicated at Kvaenangenfjord, on the islands of Arnöy, and Kågen, while on the peninsula of Lyngsfjord an extensive oblong occurrence of mafic rocks lies in the midst of the Caledonian rocks. On the mainland gabbro occurs in the phacolitic bodies of Vaddas Gaissa and Haldde, which are synclinal masses of gabbro with concordant borders against the Caledonian sediments. Of all these occurrences of ultramafic and mafic rocks only the latter two have been described in detail by Vogt (1927) and Hausen (1942); concerning the other little is known.

It is doubtful that there is a genetic relationship between all these occurrences. This investigation is not primarily concerned with the general problem of emplacement of gabbro in the Caledonian orogen. It deals mainly with the petrology and mineralogy of ultramafic and mafic rocks on the islands of Stjernöy, Seiland, and the Öksfjord peninsula, with its focus on the island of Stjernöy.

A geological description of the islands of Seiland and Stjernöy was given as early as 1878 by Pettersen. Several decades then passed before Barth (1927) attracted attention to this area with his thesis: "Die Pegmatitgänge der Kaledonischen Intrusivgesteine im Seiland-Gebiete", based on an investigation dealing mainly with the albite-nepheline pegmatite dykes in this petrographic province. The Norwegian geologists Kvale and Neumann visited the islands in 1938 during a reconnaissance tour and their unpublished notes have been of considerable help in the present work. Further, Strand (1952) has published the results of an investigation of the carbonatitic rocks at Gammevann on Stjernöy. Barth (1953) also visited the island of Seiland once again and reported on the peculiar layered gabbro occurring there.

During the summer of 1953 these investigations were resumed by a small team of geologists under the leadership of Professor Barth. The author participated in these surveys of Seiland, Stjernöy, and the Öksfjord peninsula. It was in co-operation with the other participants that experience was gained with the problems of this region and how to tackle them. A guide for this purpose were the results obtained by Krauskopf (1954) in his survey of the Öksfjord peninsula, which served as a basis for the author's investigation of the eastern and central part of Stjernöy.

The task of continuing the investigation of the western part of Stjernöy was entrusted to the Norwegian geologist Hysingjord. The geological mapping in the

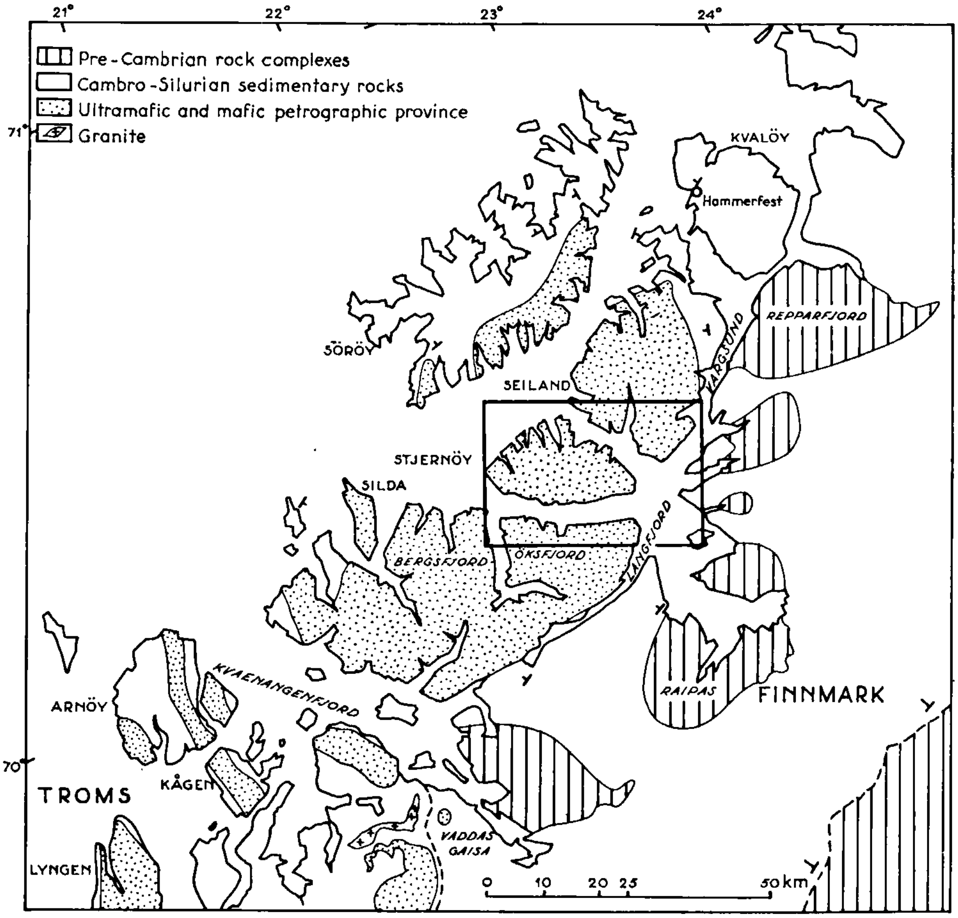

Fig. 1. The geological setting of the ultramafic and mafic province of Finnmark in northern Norway. The area covered by this paper is outlined.

"border-zone" across the island from Smalfjord to Lillebukt is the result of common efforts.

In the final stage of the preparation of this manuscript publications have appeared by Heier (1961) on the carbonatite- and nepheline-syenite from Gammevann, and by Sturt (1961) on the nepheline-syenite from the adjacent island of Söröy.

GEOGRAPHICAL AND TOPOGRAPHICAL FEATURES

The mountainous and indented islands of Stjernöy and Seiland and the peninsula of Öksfjord, which are separated from the mainland by the Vargsund and the Langfjord (fig. 1), are very rugged, with summits ranging in elevation from 700 to about 1000 metres. From these altitudes the steep slopes often descend without interruption to the water-level of the fjords. This wild countryside is of a fascinating beauty and the region is a petrologist's paradise because of its splendid exposures of peculiar and intriguing rock associations.

The investigated area, at a latitude of over 70° N, is rather inhospitable and is consequently very sparsely inhabited. On the southern coast of Seiland, Hakstabben and Altenes are small communities of fishermen and traders, and there is also a tiny settlement at Store Kvalfjord on Stjernöy. Throughout the rest of the area isolated fishermen's dwellings may be encountered in protected places along the southern coasts of Stjernöy. In the summer a few Lapp herdsmen tend their herds of reindeer on moss and lichen clad slopes.

During the short arctic summer snow patches remain on the flat parts of the higher summits, feeding many small waterfalls either directly into the sea or into the deep valleys of the bigger brooks. The summits once formed part of an old erosion surface, most of which is now so much dissected by younger valleys that very little of the original surface has survived.

Seen from a distance, the topography of the island of Stjernöy and of large parts of the Öksfjord peninsula may be described as a system of narrow ridges with deep valleys in between. To reach the ridges between the valleys requires long inland detours. To reach places of geological interest without actual rock-climbing was often impossible, and some summits could not be surveyed, e.g. the summit 949 at Store Kjerringfjord. The ultramafic core of the island of Seiland is a less indented, mountainous region with elevations varying between 600 and 900 metres.

Many of the valleys on Stjernöy have their continuation in the fjords, thus forming a number of excellent natural harbours. The only practicable communication is by means of boat and on the ocean side of the islands a sea-going vessel is required.

There are no roads on Stjernöy and Seiland, and local coastal paths are rare and always discontinuous. Such conditions make it impossible to visit every spot on the map.

With the exception of the boulder-strewn parts on the flat summits of Rottenhallerfjell and Simavikfjell and some other scree-covered slopes which consist of local material, the whole region is magnificently exposed. A cover of alluvials [1]) only exists at the mouths of some small rivers; black sands, rich in pyroxene and hornblende, are found where such alluvials are subject to waves and currents. It is interesting to note here that in the valley of Smalfjord, for example several old shorelines may be observed which demonstrate the recent rise of the land.

The islands are generally very barren; only the lower parts of the valleys show some growth of birches and low shrubs, especially on the southern slopes. Rather luxuriant vegetation with patches of old birch forest is found around Halvorvikelv in the southeastern part of Stjernöy, as well as in the southern part of Seiland from Oldervik to Altenes. In some of the larger valleys, e.g. in Store Kvalfjord valley, strips of peat bogs have developed.

Evidence of glacial action can be found on some bare parts of the flat summits. Here the layering or foliation of the rocks can be followed over distances of a hundred metres or more. In the lower regions of the valleys the smooth rounded appearance of the rock at certain places also indicates the passage of gouging and polishing ice-masses (plate A, fig. 2). On Seiland and on the Bergsfjord peninsula glaciers still exist which have been retreating rapidly for the last fifty years or so.

Although the whole area is wild and rugged, it is noticeable that the topo-

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[1]) Alluvial deposits (also bogs, etc.) and coverings by float have been marked on the field maps made for Norges Geologiske Undersökelse. Because these deposits nowhere obscure the bed-rock relations, they have been omitted from the map (see insert in backflap).

graphical features are influenced by the distribution of the various rock types. In general, the bodies of gabbro and ultramafite stand out in relief against the surrounding gneisses, although the latter rock can also be found in the highest parts of the mountains, for instance in the Öksfjord-peninsula. The layered gabbro of the plateaus of Rottenhallerfjell and Simavikfjell has resisted erosion more effectively than the ultramafic rocks. The olivine-rich rocks on Stjernöy seem to have been particularly susceptible to erosion, since they are found in topographical depressions. Even less resistant are the rocks of the hornblendite and carbonatite suites.

Geological mapping of the investigated part of Stjernöy was carried out on an enlarged copy (scale 1 : 50,000) of the original topographical map of Norway, sheet T 4 — Öksfjord (1904). Some of the topographical features included in the geological map of central and eastern Stjernöy, such as brooks and lakes, were improved on the basis of field observations or aerial photographs. These aerial photographs consist of several strips in various directions across the island, but no complete series was available.

THE GEOLOGICAL SETTING

As an introduction to the petrological, mineralogical, and chemical investigations, the general geological setting of the rocks will be dealt with first. In the earlier investigations in the Öksfjord-Stjernöy-Seiland region the ultramafic and the mafic rocks were treated as a single intrusive suite related to the Caledonian orogeny. Now, the rocks of the Caledonian nappes along the coast of Finnmark's mainland seem to dip under the mafic region; moreover, the SE-border of the mafic region exhibits a slightly curved line roughly parallel to the Raipas-anticline in which the Precambrian windows (fig. 1) along the coast are disclosed (Holtedahl 1953). In the conventional hypotheses of orogenesis this would mean that the gabbro and ultramafic rocks were formed by crystallization of huge amounts of basaltic magma emplaced at the bottom of the geosyncline.

Barth (1927), in his study on the pegmatites in southern Seiland, also refers to the peridotitic and gabbroic rocks there and suggests a process of igneous differentiation from mafic magma as the origin of the alkali-rich pegmatite dykes.

In later studies, however, he reports the occurrence of a layered gabbro complex in the western part of Seiland at Söndre Bumannsfjord — in appearance very similar to metamorphic banded gneisses — which seems to extend without a clear break into an equally layered amphibolite-gneiss complex (Barth 1953). In several places in the layered gabbro gneiss, bands of diopside-garnet-spinel rock and also a band of a most unusual spinel-sillimanite rock occur (Barth 1961).

In his investigation of the Öksfjord-peninsula, Krauskopf (1954) distinguishes between three types of gabbro gneisses, each having its characteristic foliation and layering and its specific association with other metamorphic rocks. One of his types occurs in a triangular area west of Ytre Kåven, where anorthositic gabbro and olivine melagabbro form conspicuous broad bands of foliated but otherwise homogeneous rock. Krauskopf discusses the possibilities of a metamorphic as against an igneous origin of these mafic rocks.

The subdivision of the mafic rock types on Stjernöy obviously meets with difficulties because of the very complex petrological relations in the region. After careful evaluation of the results of former investigators in relation to his own observations, the author has come to distinguish the following three groups of rocks on the basement map (see insert in backflap):

The rocks of the ultramafic sequence

In the central and eastern parts of Stjernöy there occur layered gabbroic rocks that are comparable in texture and structure to layered mafic rocks in such well-known occurrences as the Skaergaard, the Stillwater, and the Bushveld lopoliths. In these lopoliths there is a genetic relation between layered mafic rocks like gabbro or norite and their ultramafic counterparts.

Field evidence supports the conclusion that the layered gabbro encountered in Rottenhallerfjell and Simavikfjell on Stjernöy is genetically related to the underlying ultramafic pyroxene-peridotite. Between these two rock types, both of which are abundant on Stjernöy, olivine-melagabbro occurs as a transitional rock. It is the author's opinion that there is sufficient ground to justify the mapping of the paragenesis of layered gabbro and ultramafite on Stjernöy as a separate sequence of rocks within the mafic province of Finnmark's coastal area.

Essentially the same minerals, e.g. augite, bytownitic plagioclase, magnesian olivine, and magnesium-aluminium spinel, occur in these rocks. A very characteristic phenomenon in this sequence is a myrmekitic intergrowth of spinel and orthopyroxene as a reaction corona, where olivine borders on plagioclase. Mineralogical investigation established a slight variation in the composition of these major minerals, but there is no evidence of a differentiation comparable to the crystallization-differentiation found in the lopoliths referred to above.

Gabbro gneiss and allied rocks

The predominant rock in the northern and northeastern regions of Stjernöy is a gabbro gneiss ¹), a kind of rock the mineral composition of which is similar to an ordinary igneous gabbro but also shows a highly metamorphic, gneissic appearance. In texture and structure, as well as in mineral composition, a variation of types exists which are similar to the types of gabbro gneiss on the Öksfjord-peninsula described by Krauskopf (1954). However, Krauskopf's type of gabbro gneiss with anorthositic and melagabbroic intercalations does not occur in the northern regions of Stjernöy. In the author's opinion the latter type is related rather to ultramafic rocks such as dunite and peridotite, and should be separated from the gabbroic rocks of metamorphic appearance.

The idea of a supracrustal origin of at least part of these gabbro gneisses is strongly supported by the presence within the gabbro gneiss complex of intercalations of such rocks as amphibolite, syenite gneiss, acid granulite, and garnet-bearing hypersthene gneiss (sometimes also containing quartz). On the northern peninsulas of Stjernöy the country rock consists mainly of amphibolite, a rock consisting of medium-grained hornblende and plagioclase with pyroxene, biotite, and garnet as accessory minerals; layers of syenite are particularly abundant in this unit. Just as in the Öksfjord-area, a few concordant layers of metamorphosed limestone and garnet-diopside rock are also found on Stjernöy.

In these metamorphic mafic rocks a mineral-association consisting of pyroxenes (little orthopyroxene, however), hornblende, and intermediate plagioclase is found. In the intercalated layers of acid granulite, syenite gneiss, and metamorphosed limestone minerals such as hair-perthite feldspar, hypersthene and garnet occur. This mineral association is indicative of the high grade of metamorphism such as found in the granulite facies.

At their contacts, the rocks of the ultramafic sequence are not obviously

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¹) The term gabbro gneiss has been used here, although strictly speaking the term gneiss implies a foliated quartz-feldspar-bearing rock.

intrusive; dykes of peridotite have only occasionally intruded into the gabbro gneiss. Although the rocks of the metamorphic complex evidently are the older rocks into which the ultramafic rocks were emplaced, prolonged metamorphism must have obscured the contact relations.

Metasomatic hornblendite and carbonatite

The rocks of the carbonatite-nepheline syenite association constitute a third group of rocks of widely varying mineralogical composition; their relationship follows in the first place from their emplacement in more or less structurally-defined locations, both on Stjernöy and on Seiland. Obviously, the rocks of the carbonatite-nepheline syenite association are younger than the rocks of the ultramafic or the metamorphic group.

Hornblendite is a particularly abundant rock in the western and southern regions of Stjernöy; hornblendite also occurs at Ytre Pollen in the northern region of Stjernöy. From the mode of its emplacement it is assumed that the hornblendite is largely metasomatic in origin and has replaced rocks like peridotite and gabbro gneiss. In the occurrence of Ytre Pollen a gradual transition of hornblendite into carbonatite is found; in the carbonatite occurrence of Gammevann, surrounded on all sides by hornblendite, there is a clear borderline between both rocks and no transitional types are found. Carbonatite and nepheline syenite, either as bosses or as dykes, are frequently met with in the hornblendite, but they also penetrate into the surrounding rocks.

In their mode of emplacement and mineral composition there is a great similarity between the rocks of the carbonatite-nepheline syenite association on Stjernöy and occurrences of carbonatitic and alkaline rocks in the Fen-area of southern Norway and on the Kola peninsula of the Sovjet Union. For this reason the term fenitic suite of rocks is considered applicable to the alkaline and carbonatitic rocks on Stjernöy. It is concluded that this suite of rocks is not directly related to the rocks of the ultramafic sequence but is contemporaneous with and probably related to the hornblendite.

In brief, the age relations of the rocks encountered in the Öksfjord-Stjernöy-Seiland area may be represented schematically as follows:

↑ younger rocks	Metasomatic suite	Albite-nepheline pegmatite Nepheline syenite Carbonatite Hornblendite
	(metamorphism)	
	Ultramafic sequence	Gabbro, anorthosite Olivine melagabbro Pyroxene-peridotite Dunite → dykes in gabbro and gneiss
older rocks	(metamorphism)	
	Metamorphic complex	Syenite gneiss → syenite Metalimestone Granulite Gabbro gneiss

OUTLINE OF THE PRESENT STUDY

Due to the complexity of the problems involved, it cannot be expected that geological field data alone will supply conclusive information about the origin or the history of the mafic rocks on Stjernöy. The field data in Chapter II have to be considered as an introduction to petrographical, mineralogical, and petrochemical investigations carried out on the mafic and ultramafic rocks of the mapped area. Such investigations also provide the material necessary for a comparison of the Stjernöy mafic province with other occurrences of mafic magmas.

Chapter III contains a report of the main results of the petrographical investigation:

a. the mineralogical composition and its quantitative variation within the rocks of the ultramafic sequence and within the mafic rocks of the metamorphic complex (e.g., gabbro gneisses);
b. the texture and structure of these rocks with special reference to the phenomena of deformation and recrystallization of the composing minerals;
c. reactions between the composing minerals such as coronas, symplectitic intergrowths and alterations, indicative of deuteric or metamorphic processes.

In Chapter IV dealing with the mineralogical investigations of pyroxenes and olivine, the following items were the subject of detailed research:

d. calculation of the WoEnFs composition of the clinopyroxenes from their chemical analyses;
e. construction of the tie-lines in the ternary WoEnFs diagram for co-existing clinopyroxene and orthopyroxene, also considered in relation to the equilibrium-constants between the magnesium and iron contents of both minerals;
f. establishment of the distribution trends of magnesium and iron in co-existing orthopyroxene, and olivine.

In the petrochemical Chapter V the chemical analyses of the igneous and metamorphic rocks have been subjected to standard diagrammatic representations such as:

g. QLM and mg/γ variation diagrams which express possible differentiation trends in normative composition within the mafic rocks and by means of which deviations may be discerned from those seen in other mafic provinces consisting of rocks of similar bulk composition;
h. ACF diagrams of the metamorphic rocks in order to find out whether the bulk chemical compositions of the gabbro gneiss and related rocks could represent mineral parageneses critical of the granulite facies.

Through these efforts, more clearly defined ideas about the igneous or metamorphic character of the rocks in the Stjernöy region can be developed, as seen in the light of the physical and chemical conditions prevailing at the time of their formation. In a petrogenetic synthesis in Chapter VI a co-ordination between the results of these structural, mineralogical and petrochemical investigations will be attempted. Clearly an ultimate solution of the complex problems of the origin and genesis of the ultramafic and metamorphic rocks in the Seiland-Stjernöy-Oksfjord region will require further investigation.

CHAPTER II

GENERAL GEOLOGY AND LITHOLOGY OF CENTRAL AND EASTERN STJERNÖY

Parts of the mafic region of Finnmark's remote coasts have been subjected to several geological investigations. Because the area is so vast, these investigations could serve only as reconnaissances of the complex geological and petrological history of this region.

The island of Stjernöy, with its outcrops of rocks of the ultramafic suite — including those of the layered gabbro sequences in Central and Eastern Stjernöy — and its outcrops of enclosing metamorphic banded gneisses of mafic bulk composition, occupies a central position in the Seiland-Stjernöy-Oksfjord area. As such it deserves closer investigation, which may contribute considerably to the petrology of this area.

The petrological sketch map of the Central and Eastern parts of Stjernöy shows the distribution of the rock types. In this respect the mapped area forms a felicitously selected link between the southern part of Seiland, with its outcrops of ultramafic rocks in a highly metamorphosed supracrustal amphibolite-gneiss complex (Barth 1953), and the metamorphic para- and ortho-gneisses of gabbroic composition on the Öksfjord-peninsula (Krauskopf 1954). Moreover, important outcrops of hornblendite, carbonatite, and massive nepheline-syenite occur on Stjernöy, rock types which are absent, or in any case of rare occurrence, on the other islands.

In the following paragraphs the geology and petrology of each rock type will be discussed under separate headings. Due attention has been paid to their mutual relationship and genetic association, which is also indicated by the nature and the intensity of the symbols on the map in insert.

ULTRAMAFIC ROCKS

An extensive field of ultramafic rocks occurs in the eastern and central parts of Stjernöy. A similar area of ultramafic rocks is situated in the South and East of the nearby island of Seiland, and was described cursorily by Barth (1927). No other outcrops of ultramafic rocks of corresponding size have been found in the area; however, no systematic surveys have been made in the Bergfjord-peninsula, west of the Öksfjord-peninsula (fig. 1).

On Stjernöy an area of about 30 km^2 is covered by peridotitic and perknitic ultramafic rocks which include dunite, peridotite, pyroxenite, and olivine-bearing melagabbro. The hornblendite, although a perknitic rock according to the definition given by Johannsen (1939), will be excluded from the paragenesis of ultramafic rocks in this province. It will be dealt with in a later chapter on carbonatitic and alkaline rocks.

On Seiland there is more ultramafic rock, but a petrological study of Stjernöy is more rewarding because its ultramafites are more varied and exhibit a close relationship with the overlying gabbro.

In the field a distinction could be made between such rocks as dunite and olivine-rich peridotite and rocks such as pyroxene-rich peridotite and, in minor amounts, perknitic ultramafite, which consists almost completely of augite. The distinction was possible on the basis of a difference in the colour of the weathered surface: the olivine-rich rocks have a yellow ochreous weathering colour and the pyroxene-rich rocks have a more reddish brown shade of the weathering crust. This thumb rule is supported by the thin-section study made of these rocks.

In addition to the two large occurrences of ultramafite on Seiland and Stjernöy there are many smaller outcrops throughout this region. There are medium-sized occurrences, like the one at Store Kjerringfjord, and small ones, such as those on the peninsulas of northern Stjernöy and at Halvorvikfjell. There are also many ultramafic dykes too small to be drawn on the map. These ultramafic dykes occur both in the layered gabbro of Rottenhallerfjell and in the metamorphic rocks of northern Stjernöy.

DUNITE

An outcrop of massive dunite, or at least dunitic peridotite with more than 75 per cent olivine, occurs in the topographical depression between Simavikfjell and Middagsfjell. Another occurrence of dunite is found on the western side of the Store Kjerringfjord-ultramafite. There, too, the olivine-rich rock occupies a topographical depression in the very steep eastern slope of the mountainrange between summits 894 and 949 of the inaccessible Kjerringfjordfjell. The term dunite has been used, according to Johannsen's definition (1939), for rock consisting of more than 90 per cent olivine.

The dunite, or dunitic peridotite, is a fairly dense rock of medium grain-size consisting of about 75 to 95 per cent olivine, the remainder being made up mainly of augite and hornblende (see table 2, page 216). In general, the rock has suffered only moderate serpentinization, which in many cases is almost negligible. More information about the petrography and the mineralogy of the dunitic rocks will be found in Chapter III.

The contact of the dunite with the surrounding peridotite is fairly transitional, but the difference in weathering-colour makes it possible to map the approximate contours of the olivine-rich outcrop.

Veinlike spots of a more pyroxene-rich ultramafite occur inside the dunite but, on the other hand, spots of dunite may be found in the surrounding pyroxene-peridotite. This proves that there is a genetic relationship between the two types of ultramafite.

The dunite occurs more or less in the centre of the mafic and ultramafic rocks on Stjernöy and is apparently the older rock. Dykes and small intrusions of dunite such as are typical of, for instance, the alpine type of peridotites, do not occur on Stjernöy.

With the exception of a few grains of brown spinel (picotite) no chromium-bearing ore-deposits were encountered in the survey of the rocks on Stjernöy. There was no noticeable chromite in the investigated heavy-mineral samples from the alluvials of brooks and small rivers on Seiland and Stjernöy.

PYROXENE PERIDOTITE

According to Johannsen's definition, a peridotite is an olivine-bearing and feldspar-free ultramafic rock. Within these limits all rocks with more than 5 per cent olivine should be called peridotite. Rocks consisting of more than 50 per cent olivine are olivinites, and rocks consisting of more than 90 per cent olivine should be called dunite.

In this study the somewhat obsolete term olivinite [1] is omitted; all rocks with 75 to 40 per cent olivine will be called peridotite. Rocks with 40 to 5 per cent olivine are named pyroxene-peridotite, a term which in the author's opinion simply expresses what the rock really is.

Rocks ranging in composition from peridotite to pyroxene-peridotite make up the largest part of the ultramafic area on Stjernöy, which is well-exposed in the valleys of Store and Lille Kvalfjord. The ultramafic rock can be recognized even at a distance by its brown weathering colour and hummocky morphology. This characteristic appearance is caused by weathering to more or less rounded hillocks. Furthermore, the terrain is strewn with large boulders of ultramafic rocks, which makes the going very heavy in many places.

The most common type of pyroxene-peridotite is a coarse to very coarse grained rock; crystals of up to one centimetre in size are the rule rather than the exception, but pyroxene crystals of up to 5 centimetres have also been observed.

In general, the pyroxene-peridotite does not exhibit layering but schlieren of very coarse grained, pyroxene-rich rock and schlieren of plagioclase-bearing rock indicate the preferred orientation of fabric elements in the ultramafic body (plate A, fig. 1).

On the average the rock consists of 55 to 65 per cent pyroxene and 30 to 25 per cent olivine, the balance being made up by various amounts of hornblende, spinel, and oxide ore (see table 3). Sometimes a few grains of plagioclase also appear in the rock.

According to Tröger (1935), a rock composed predominantly of clinopyroxene with olivine as the second constituent should be called wehrlite, or perhaps koswite, but neither the first nor the second name exactly covers the composition of the typical Stjernöy-peridotite. Most occurrences of pyroxene-rich peridotites, like lherzolite, bahaite, or harzburgite (saxonite) have orthopyroxene as the predominant pyroxene-mineral. The ultramafic rocks on Stjernöy and Seiland are, however, characterized by the subordinate presence or absence of orthopyroxene. As has been explained, the term pyroxene-peridotite seems preferable in this context.

It must be added that the rock is actually very heterogeneous, grading in one place into dunitic peridotite and in another into pyroxenite with only a few per cent of olivine.

A typical phenomenon in the pyroxenite is the occurrence of olivine melagabbro in patches varying from a few square decimetres to large mappable outcrops. The size of the crystals in this melagabbro varies from coarse grained to pegmatitic, with crystals of up to 5 centimetres in size.

This is, as yet, a simplified picture of the pyroxene-peridotite, because small patches of dunitic rock are incorporated throughout the ultramafic outcrop on Stjernöy.

The whole ultramafic body looks as though the pyroxene-peridotite has almost completely digested a pre-existing rock of dunitic composition in a pene-contemporaneous process of formation.

In the ultramafic rocks there also occur „schlieren" of somewhat younger age and of pyroxene-peridotitic or even pyroxenitic composition. The dominant mineral in this rock is augite and not diopside or diallage, the minerals usually mentioned in descriptions of clinopyroxene-rich ultramafites (Johannsen 1939).

Hornblende-bearing peridotite dykes are abundant near the transition of

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[1] The term olivinite has acquired a metamorphic connotation in present petrographical literature.

peridotite to melagabbro at Örnefjell, where they form a dense network near, and sometimes across, the contact. Near the summit 720 ultramafic dykes are also abundant in the gabbro.

Fine-grained mafic dykes (lamprophyres), usually a few centimetres in thickness and consisting mainly of hornblende and biotite, are found at many places and in different rocks; they are not necessarily related to the ultramafic rocks.

Except for the dunitic part, the ultramafic body at Store Kjerringfjord consists of a pyroxene-rich peridotite, with 65 to 75 per cent pyroxene. The ultramafic occurrence at Havnbukt also consists of pyroxene-peridotite. At its northern side the latter occurrence exhibits a transition to melagabbro with a beginning of crude layering. From the point of view of genesis it is interesting to note that, like the occurrences at Kjerringfjord and Havnbukt, the numerous smaller bodies and dykes of ultramafite consist of pyroxene-rich peridotite which does not attain an olivine-content of more than 50 per cent. The exception to this rule is the small peridotite body in the hornblendite-occurrence of Bukkebuktfjell.

Peridotitic rocks similar in composition to those on Stjernöy occur in the ultramafic area on the neighbouring island of Seiland. Barth (1927) describes them as hornblende-pyroxene-peridotites with an olivine-content of about 80 per cent. During the survey made in 1953 it was found that, here too, a peridotite occurs with about the same mineral content as the ultramafic rocks on Stjernöy.

In the Seiland-peridotite, plagioclase is somewhat more abundant than on Stjernöy; in some places there is as much as 10 to 15 per cent plagioclase in the ultramafite. According to Johannsen (1939), this rock could be named tilaite. At the western side of the Seiland-peridotite a similar very mafic gabbro is abundant at the contact with gabbro gneiss.

According to Barth (1927), rocks consisting of plagioclase with olivine as the main mafic mineral occur in the slope of Happovarrefjell at the eastern side of the Seiland-peridotite, but such troctolites have not been found on Stjernöy. In conclusion, it can be said that in general the ultramafites on Seiland contain more plagioclase than do similar rocks on Stjernöy, but on Seiland a complex of layered gabbros, probably developed from the ultramafite, is lacking.

Dunitic rocks in the ultramafite on Seiland are found in places around Steinfjellvann near Store Kufjord, where slightly serpentinized olivine makes up 90 to 95 per cent of the rock.

The hornblenditic ultramafites on Seiland, described as cortlandtite by Oosterom (1954), will be discussed below in the section on hornblendites.

At the NE-side of the ultramafic body on Stjernöy the contact with the gabbro gneiss is well-defined and sharp. Less well-defined is the contact between the ultramafite and the gneisses on Seiland, where ultramafic and especially lamprophyric dykes obscure the contact. It is the opinion of the author that these contacts are tectonic rather than intrusive. The lamprophyric dykes are in all probability related to a post-tectonic magmatic activity. The smaller outcrops of pyroxenite also have sharp contacts with the enclosing gabbro gneiss; in some places around the contact of the ultramafic intrusion at Store Kjerringfjord small tongues or fringes of peridotite protrude into the gneiss. In the field there is no obvious contact metamorphism between these rocks. The gabbro gneiss only shows a somewhat coarser and less foliated texture than usual. In thin-section, however, an increase in spinel can be observed in samples of the gabbro gneiss taken from near the contact. There are no indications of linear structures in the ultramafic occurrences parallel to the lineation in the enclosing gabbro gneisses; but the thin-section study nevertheless reveals indications of cataclasis in the former rocks (plate B, fig. 4).

OLIVINE MELAGABBRO

Olivine-melagabbro [1] occurs in patches in the ultramafic rocks of Stjernöy. Usually it is a very coarse and homogeneous rock with an average grain-size of up to a centimetre, but much coarser pegmatitic rock has also been observed. In composition the rock varies from a very mafic rock, mottled by a 10 to 20 per cent plagioclase content (tilaite according to Johannsen), to an ordinary olivine-bearing gabbro. The olivine remains a very moderate constituent, ranging from a few to about 10 per cent.

In the transitional zone from ultramafite to gabbro on the steep eastern slope of Rottenhallerfjell, the pyroxene-peridotite passes gradually into olivine-melagabbro by an increase of its plagioclase content. It starts with streaks of melagabbro of parallel orientation in the pyroxene-peridotite (plate A, fig. 1) and ends in a distinctly banded rock which includes anorthositic bands in the olivine-melagabbro. The range of composition for an average olivine-melagabbro can be given as 40 to 70 per cent augite, 40 to 25 per cent plagioclase, accessory hornblende, spinel, and ore minerals making up the rest (see table 4). Olivine also remains a moderate constituent in this zone between ultramafite and layered gabbro; no olivine-rich melagabbro (troctolite) has been observed anywhere.

From the field relations it is clear that the olivine-melagabbro on Stjernöy has gradually developed from pyroxene-peridotite and not from olivine-rich rocks such as peridotite or dunite. Further arguments to support this view will be given in the petrographical and mineralogical chapters.

Olivine-bearing gabbro North of Örnefjell and at Halvorvikfjell exhibits an intrusive appearance. Irregular streaks of olivine-bearing gabbro, somewhat varied in its content of mafic minerals, are brecciated by schlieren of anorthositic gabbro. Fragments of the light variety occur in the dark gabbro and the reverse has also been observed. This phenomenon can be called autobrecciation.

On the plateau of Rottenhallerfjell between summits 795 and 787 a more or less oblong body of very mafic olivine-melagabbro is exposed. The borders with the surrounding layered gabbro are transitional. The melagabbro is very coarse, with grain-sizes of up to 1 centimetre; locally the rock is pegmatitically developed with crystal sizes of up to 3 or 4 centimetres.

THE LAYERED GABBRO SUITE

The gabbro of Rottenhallerfjell and Simavikfjell rises in very steep cliffs 300 to 400 metres above the hillocky ultramafic rocks of Store and Lille Kvalfjord valleys. These layered occurrences of gabbro can be recognized even from a distance by their grey weathering colour, which contrasts markedly with the dark colours of ultramafite and melagabbro. The flat summits of these gabbro mountains with their steep slopes also exhibit a marked difference from the rounded topography of the lower ultramafic regions. A further distinction is, of course, the occurrence of a distinct layering in the gabbroic rocks with conspicuous bands of anorthositic and melagabbroic composition (for a description of the phenomenon of layering in an igneous series see pages 195 to 197).

Well-developed joint systems may be seen in the almost sheer eastern precipices of Rottenhallerfjell, e.g. near the 907-triangulation mark, and also in the eastern slope of Simavikfjell. These joint systems cause a rough splitting of the rock, which contributes to creating the sheer gabbro cliffs. The plane of the subhorizontal

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[1]) Per definition a melagabbro is a rock composed essentially of basic plagioclase and a dark mineral, the latter exceeding the former in quantity (JOHANNSEN 1939).

joint system dips in some places about 20 to 40 degrees, causing the so-called mural joints to dip in the direction of the slope somewhat like tiles on a roof. This feature is typical of several slopes in this region; they are risky to descend, although this is not immediately apparent. This is the case, for example, on the eastern and southern slopes of Halvorvikfjell and the northern slope of Rottenhallerfjell.

The mineral composition in the gabbro layers varies within wide limits (see also table 5); the composition of an average gabbro layer is, however, approximately 60 per cent plagioclase, 30 per cent pyroxene (mainly augite, but also a few per cent hypersthene) and about 7 per cent hornblende. The balance is made up of olivine, spinel, spinel-pyroxene symplectite, and ore. More information about the mineral composition, texture, and structure of these gabbroic rocks will be given in the petrographical chapter.

The gabbro in the layers is a medium to coarse granular rock with grain-sizes of up to 1 centimetre; it can occur as a massive rock but more often it has a more or less pronounced foliation [1]) through the planar habit caused by the parallel orientation of clusters of the mafic minerals (plate D, fig. 1).

A definite foliation in a much finer grained gabbro can be observed locally, e.g. North of summit 795 on Lassefjordfjell. Here there is a different type of layering, characterized by thin alternating layers of anorthositic and melagabbroic composition, only a few centimetres in width. These thin bands are amazingly straight and continuous and this striated gabbro gives a metamorphic impression rather than that of a layered igneous structure. Hess (1960) mentions a similar phenomenon from the Stillwater igneous gabbro complex, which he describes as inch-scale type of layering. In accordance with his observations, the lamination in the gabbro of Stjernöy is termed centimetre-scale layering in this study.

Bands of anorthositic gabbro already occur in the olivine-melagabbro on the steep slope, East of the 907 mark. The layering is, however, most beautifully developed on the plateau of Rottenhallerfjell, about 400 metres West of the 907 mark and on Lassefjordfjell (see fig. 2). Here bands of anorthositic gabbro, varying in width from a few decimetres to a few metres, alternate with bands of melagabbro, which in general are narrower in width than the anorthositic bands. Gabbro bands of less extreme composition are also incorporated in the layered system. Other bands have a more finely grained texture or may exhibit a composite foliation with alternating thin plagioclase- or pyroxene-rich layers, 1 or 2 centimetres in width. The anorthositic rock in this part of the layered suite of Rottenhallerfjell can be estimated as roughly being twice as abundant as melagabbro and normal gabbro together.

The melagabbroic layers may be massive, but they usually exhibit a subdivision in very thin strips of plagioclase-rich gabbro.

The anorthositic gabbro is more homogeneous in composition and shows only faint mafic streaks or dispersed, but aligned, mafic minerals. Locally, the anorthositic layers attain widths of between 10 and 20 metres (fig. 2) if the intercalated mafic streaks are disregarded. The broader bands are usually richer in plagioclase and bands with even 90 to 95 per cent plagioclase are encountered.

The mineralogical compositions of a few adjacent bands on Rottenhallerfjell of melagabbro and anorthosite are given in table 1.

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[1]) The definition used here is in agreement with the American usage of the word foliation. In English literature „foliation" means a thinly and irregularly laminated structure.

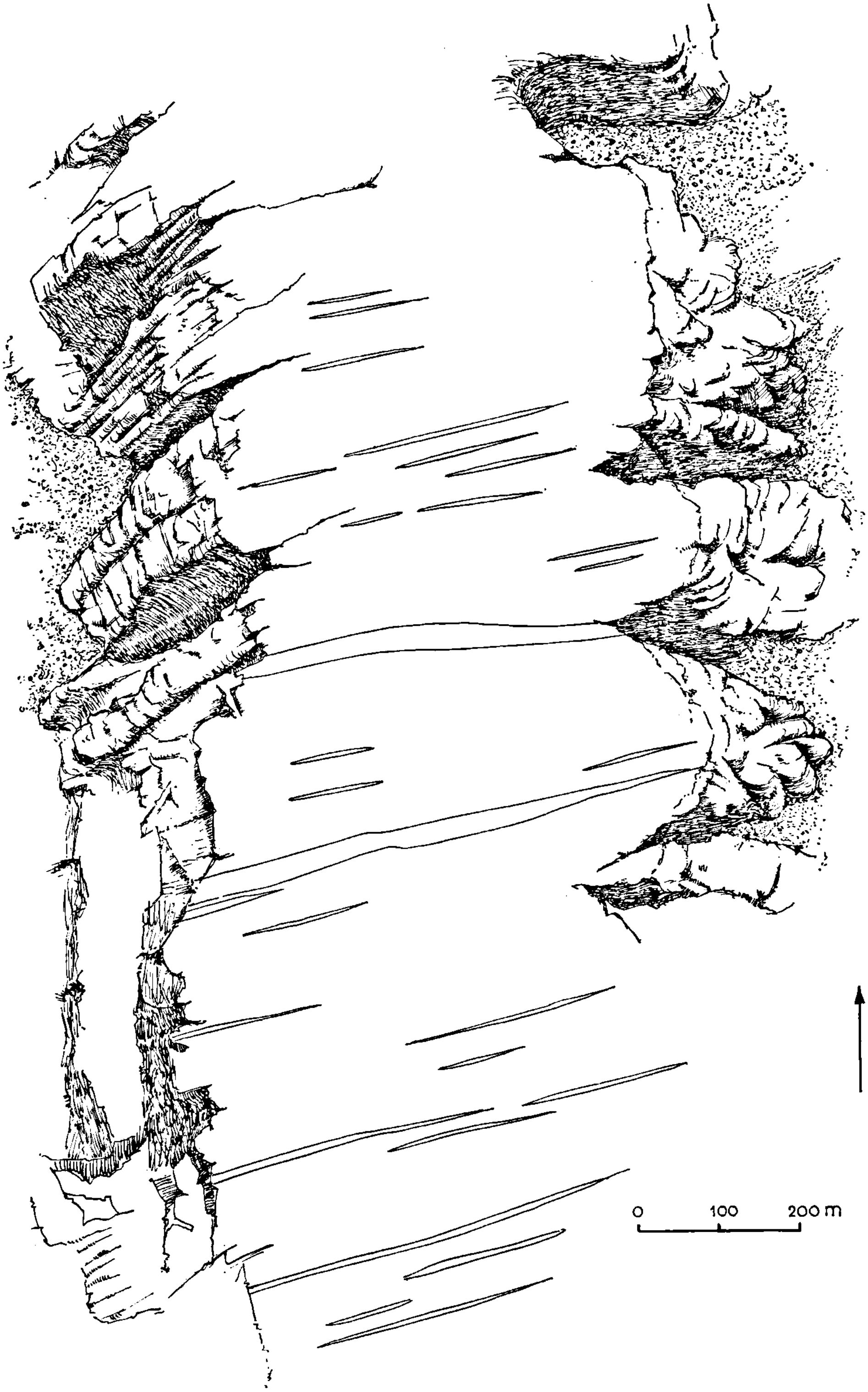
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TABLE 1 *Modal compositions of adjacent melagabbro- and anorthosite-layers of the ultramafic sequence*

	T 4.98	T 4.97	T 4.62^{a}	T 4.62^{b}	T 4.63^{a}	T 4.63^{b}
plagioclase	26.0	85.3	23.6	77.7	21.3	90.2
olivine	—	—	2.8	—	2.1	—
pyroxene	54.7	14.1	57.7	13.4	58.0	6.0
spinel-pyroxene symplectite	4.0	—	8.7	0.8	10.5	—
spinel	1.3	—	1.3	—	2.6	0.3
hornblende	9.9	0.5	5.6	7.8	5.5	3.4
ore	4.2	0.2	0.2	0.3	0.1	0.1

The compositions of samples T 4.98, T 4.62^{a}, and T 4.63^{a} represent the melagabbroic type of rock, samples T 4.97, T 4.62^{b}, and T 4.63^{b} are representative of the anorthosite.

The layering in the gabbro of Rottenhallerfjell remains about the same from the 907 mark to the contact at Store Kjerringfjord valley, although the banding in the northern slope of Rottenhallerfjell becomes thinner and less varied in composition (plate A, fig. 2). The leucocratic bands here do not contain more than about 70 per cent plagioclase.

The layers on Rottenhallerfjell have a steep attitude everywhere. In the region North of summits 795 and 787 they dip 65° to 80° to the NW; in the region bordering on the olivine-melagabbro zone between ultramafite and gabbro they dip 55° to 75° to the SE. In respect of the NW dipping contact between the ultramafite and gabbro in Store Kvalfjord valley and Indre Simavik valley, the attitude of the layering in the latter region is markedly unconformable.

In the zone of the most pronounced layering W of the 907 mark on Rottenhallerfjell and also along the NW-contact of the same layered gabbro occurrence, the bands are straight and continuous up to hundreds of metres before they ultimately wedge out. At other locations, however, the layering is less regular and a typical schlieren-texture may be found (plate A, fig. 3).

Northeast of summit 787 on Rottenhallerfjell this well-layered rock grades into gabbro, which is still distinctly layered but has a less extreme variation in the composition of the layers. In rather broad bands there is a new textural element with leucocratic streaks in the mafic bands and melanocratic streaks in the lighter bands (plate A, fig. 3).

Locally, the rock no longer exhibits any layering, but has a perfect planar structure, caused by the parallel arrangement of nonequant minerals, which may indicate laminar flow in an igneous environment.

In the direction of the strike, the gabbro changes into an almost massive, coarse grained rock on the East side of Indre Pollen, where only a crude and irregular

Fig. 2. Sketch view after areal photograph showing the spacing and width of individual layers of anorthosite within layered gabbro on the flat summit of Lassefjordfjell, S of the 795-triangulation mark. Stjernöy.

type of schlieren is found in olivine-bearing gabbro. These schlieren of slightly different composition are mutually brecciating.

Gabbro with the same type of layering as that found on Rottenhallerfjell is developed at Simavikfjell. From the narrow strip of pyroxene-peridotite in the Indre Simavik valley there is, here too, a transition into olivine melagabbro, a zone which is less well-developed here. The olivine melagabbro grades into gabbro, which to the West of summit 846 exhibits a rather indistinct layering in a coarse grained leucogabbroic rock of only slightly varying composition.

East of summit 846, however, the layering is well developed, with marked bands of anorthositic gabbro intercalated with gabbro of about normal composition. In the very steep eastern slope of Simavikfjell a transition from layered gabbro into melagabbro and ultramafic rock is again evident.

On the southern slope of Simavikfjell a leucocratic and foliated gabbro occurs with banding only a few centimetres in width. In the direction of Storfjell this centimetre-scale layering fades out and the rock grades into a foliated rock of medium grain-size; still further to the East the texture disappears completely, giving way to the coarse grained and massive gabbro of Halvorvikfjell. Thus roughly the same transition from well-layered to massive gabbro from Simavikfjell to Halvorvikfjell is found as that from Rottenhallerfjell to Indre Pollen.

From the field evidence it may be concluded that in the eastern part of the flat Simavikfjell-plateau well-layered gabbro with gently (about 30°) westward-dipping bands overlies the ultramafic rock. At the other side of this plateau the indistinct layering in the western slope indicates a dip in the opposite direction.

Economically, the rocks of the ultramafic sequence in this area offer little or no prospects. Bands of ilmenite or magnetite ore, or even bands with a substantial content of those minerals were not found in the course of a survey of the layered gabbro rocks of central and eastern Stjernöy. A little oxidic ore may be present here and there, but apparent concentrations of ore are absent.

Occasionally a grain of sulphide can be detected in the gabbro. Investigation of similar grains in the Lille Kufjord occurrence on Seiland has identified pyrrhotite, pentlandite, chalcopyrite, and sphalerite in these sulfides (Oosterom 1955). Such sulphide minerals form a perfectly normal association with mafic igneous rocks of this composition.

Secondary alteration of ultramafic and mafic rocks might yield deposits of such minerals as chrysotile-asbestos or talc of considerable economic importance. Serpentinization of ultramafic rocks exists on Stjernöy but the proper conditions for the formation of economic deposits probably never occurred.

Layering in intrusive rocks, also called banding, density- or pseudo-stratification is rather uncommon and as such has a special appeal to petrologists. It occurs mainly in mafic types of rocks such as gabbro, norite, anorthosite, and pyroxenite; but in rare cases other igneous rocks also exhibit the phenomenon. Ussing (1912) has described a layered alkaline intrusion from Ilimaussaq in the Julianehaab area of Greenland. Further, a fine rhythmic layering can be observed in certain granitic pegmatites (Poldervaart and Taubeneck 1960).

Layered rocks of gabbroic or noritic composition in the mafic plutons are invariably associated with ultramafic rocks such as pyroxenite and peridotite. Classic examples of layering in such rocks are found in the Stillwater and Bushveld lopoliths, large lenticular igneous masses witk concordant contact relations, which originated by subsidence of the underlying strata. This kind of occurrence has been named the stratiform type of gabbro-peridotite complex (Thayer 1960).

Mafic and ultramafic rocks distributed along former eugeosynclinal belts (the alpine type of gabbro-peridotite complex) may exhibit layering as well. Thus, the olivine gabbro-phacoliths in the Caledonian Chain in Norway are examples of concordantly layered intrusions, occupying the crest or trough of a fold. But even under less regular circumstances, layering is known to occur in mafic rocks connected with the initial magmatism of orogenetic belts.

It may be useful to explain here first a few essential facts about the phenomenon of layering in igneous rocks. Such layering can be described as an internal structure of bands or sheets in which the rock consists of alternate layers differing in the proportions of light and dark minerals, in grain-size, etc. Usually the width of the layering is analogous to that found in the stratification of sedimentary rocks. From the Stillwater occurrence and also from Stjernöy a type of layering is known that is characterized by thin layers of about a centimetre in width, in some cases repeated hundreds of times.

Several theories have been advanced to account for the layering observed in the mafic plutons; they will be discussed below.

Some rocks, layered or massive, exhibit a preferred orientation of platy crystals, e.g. tabular feldspar crystals or flat aggregates of minerals with their longer axes parallel to the plane of the layering. This parallelism of non-equidimensional rock constituents is termed foliation (e.g. see plate D, fig. 1) or planar structure. When the crystals or aggregates are preferentially oriented in the same direction within the plane of layering, the rock is said to exhibit linear structure or lineation. It is clear that layered igneous rocks have a tendency to planar structure or foliation of their fabric elements; lineation may also accompany layering, but only in rare cases.

More or less isolated streaks or bands differing in composition and lacking sharp contacts are termed schlieren or flow layers. Such schlieren may vary in size from small strings, a few decimetres in length, to thick lenses of several tens of metres (plate A, fig. 3). These schlieren are probably of igneous origin, structurally intermediate between a layering and a foliation.

1. *Types of layering in igneous mafic rocks*

In the course of the investigation of layered mafic plutons, several types of layering have been recognized. Thus Wager and Deer (1939) have made a distinction between rhythmic and cryptic layering.

Rhythmic layering is defined as a succession of layers of mineralogically different rocks with a regular pattern in the increase or decrease of a distinct mineral phase or phases within one layer. According to Peoples (1936), it is associated with the concept of a gravity stratification, with the heavier minerals decreasing upwards in the bands. The term cryptic layering is given to an internal igneous structure which is characterized by a progressive or relatively sudden change in the mineral composition, with or without an accompanying change in the chemical composition of the constituent minerals as seen, for example, in the transition from magnesium-rich to iron-rich pyroxenes.

More important for the present investigation is an abrupt cryptic layering or phase layering (1) with the sudden appearance or increase, disappearance or

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(1) The term phase layering was coined by Hess in his study on the Stillwater igneous complex (1960).

decrease, of a particular mineral phase, as is shown, for instance, by chromite bands in certain horizons of the ultramafic zone of mafic intrusions. But the appearance of the first augite crystals in the gabbro zone or the appearance of an olivine-rich band are also examples of abrupt cryptic layering.

Rhythmic layering, of course, is a very striking feature that cannot be overlooked in the field. Abrupt cryptic layering is also, in most cases, a conspicuous phenomenon, and is commonly more obvious in the field than it is in thin-sections.

Cryptic layering may or may not be present in rocks with normal rhythmic layering. Its presence is usually established by thin-section investigation; in the field it is not very obvious and in some cases may not be visible at all.

Poldervaart and Taubeneck (1960) have also surveyed the problem of layering in igneous rocks; their article reviews the most recent literature:

Summarizing it may be said that cryptic layering is produced by progressive changes in the mineral composition during crystallization. Of all the different processes which govern the differentiation of crystallizing bodies of magma, the most important single process is crystal fractionation. By the crystallization changes in mineral composition will occur in magmatic bodies, which is also shown by some basalt flows, for instance. Such differentiation is an example of gradual cryptic layering.

Abrupt cryptic layering —. This type of layering is commonly related to crystal fractionation under the influence of gravity, which leads to the sinking of the early-formed heavier minerals. Poldervaart and Taubeneck, however, warn against overestimating the effects of this process, because other processes might also be important for the generation of abrupt cryptic layering. They point out that changes in the PT-conditions of the magma by undercooling coincident with a sudden loss of water might also contribute to the formation of an abrupt cryptic layering. This might, for instance, be the explanation of the origin of an olivine-rich layer in the mafic rocks of the Palisade-sill. Further multiple, repeated pulses of magma and mixing of this magma with the already partially crystallized former flow can result in abrupt cryptic and even large-scale rhythmic layering if the pulses follow one another at sufficiently short intervals (Walker 1940).

Rhythmic layering —. It is clear that rhythmic layering in igneous rocks can result only from cyclic processes that may or may not be super-imposed on another process such as crystal fractionation or gravitational settling in a freezing magma.

Such cyclic processes might be, as has already been said, large-scale multiple injections of magma (Lombaard 1934) or cyclic variations of the water pressure in a crystallizing magma (Yoder 1954). In addition, cyclic currents of a more or less convective or turbulent nature may result in rhythmic layering (Wager and Deer 1939).

Two types of rhythmic layering have been recognized so far; one is represented by the Skaergaard occurrence in Greenland and the other by the Willow Lake intrusion in Oregon.

Skaergaard type —. According to Wager and Deer, this type of layering is in all probability caused by the superposition of cyclic convection currents upon the gravitational movement of the crystallizing minerals of the various phases formed in the higher regions of the magma chamber. The type of layering formed in this way has many features in common with the graded bedding in sedimentary rocks. A typical feature in the layering of the Skaergaard intrusion is the appearance of bands of completely different (earlier) mineral composition in the layered sequence caused by, for example, a renewed magma pulse.

Willow Lake type —. Poldervaart and Taubeneck describe another type of rhythmic layering in the Willow Lake intrusion, "in which highly elongated crystals of various mineral phases (plagioclase, pyroxenes, iron ores, hornblende) are characteristically oriented with their longer dimensions at high angles (60°—90°) to the plane of layering". And again quoting these authors, "layering is normally on a fine scale, with individual bands from less than 1 mm to maximum 1 m thick". These authors attribute this type of banding to often-repeated undercooling caused by convective and turbulent currents. The elongated crystals at high angles are probably due to the rapid heat flow resulting from the repeated migration of water (undercooling) through the rocks. The Willow Lake type of layered mafic intrusion is usually small, has steep contacts, and shows a layering on a fine scale. Its emplacement is located late in the epizonal phase of the regional metamorphic cycle.

An important argument has been put forward by Hess (1960), who accentuated the rôle of the liquid in the freezing crystal-mush of a magma. Once a crude layering has been produced, the mafic crystal phases formed earlier will continue to grow by diffusion from the interstitial liquid. Material from this interstitial liquid — enriched in silica, alumina and alkalis — may by a mechanical process such as filter pressing be injected into the layers above and below. This mechanism would satisfactorily explain the nearly monomineralic bands of anorthosite in many rhythmically layered mafic plutons.

2. *Layering in gabbro on Stjernöy*

The type of layering in the gabbro occurrences on Stjernöy, with more or less homogeneous anorthositic bands intercalated between more variable gabbro- and melagabbro, has been described on pages 191 and 194. An effort was made to discover any regularity in the increase or decrease of the mafic or felsic minerals within one layer, but no regularity was found in a constant direction. West of summit 907 of Rottenhallerfjell there is, in places, a slight tendency towards concentration of the mafic minerals on one side of some layers, but in others such indications are absent or may even point in the opposite direction. Thus the evidence for a gravitational mechanism of differentiation is very slight, and conflicting at that.

In other places the contact between the gabbro layers is gradational and shows no regular pattern of mineral accumulation. In large sections, where the gabbro is layered, the contacts between the individual bands are fairly sharp. There seems to be no regularity in the change from melanocratic to leucocratic gabbro in the layering or any regularity in the thickness of the successive layers. It should be kept in mind here that in still other places the gabbro is striated or exhibits a schlieren-pattern.

It may therefore be concluded that the layered gabbro at Rottenhallerfjell is not the result of a rhythmic process of igneous differentiation but has features in common with the layered mafic occurrences of the cryptic type. There is, for example, a gradual decrease in the olivine content from pyroxene-peridotite, via the olivine-melagabbro in the transition-zone, towards the gabbro of the layered suite. In the appearance of melagabbroic layers, rich in pyroxene, between the anorthosite layers in the central zone of Rottenhallerfjell, signs of abrupt cryptic layering (phase layering) may be seen, although this is decidedly not an ideal example of such layering.

The largely monomineralic composition of the anorthosite bands might be explained by the theory advanced by Hess in which an initial crude layering is accentuated by the diffusion of interstitial liquid between earlier-formed crystals, which resulted in some places in the crystallization of more plagioclase and in others in that of the mafic components.

It does seem indeed hazardous to assume an igneous origin for the amazingly straight and continuous centimetre-scale type of layering found North of summit 795 of Lassefjordfjell. Hess (1960) ascribes an igneous origin to a similar type of layering from the Stillwater gabbro occurrence. In the present author's opinion, however, the flawlessly striated structure of the gabbro at Lassefjordfjell seems hardly compatible with a process of settling crystals in a magma; a process of tectonic or metamorphic differentiation seems to be a more probable explanation of the extremely narrow layering, in which the thin plagioclase-rich laminae could have acted as preferred horizons of movement or segregation.

In parts of the gabbro complex, e.g. SE of Indre Pollen, the rock exhibits a perfect igneous flow-structure (plate A, fig. 3); in other places there is evidence of both a typical igneous schlieren structure and pronounced tectonic disturbance of this layering.

Hess (1960) describes disturbances of the layering in gabbro which he attributes to movements before the final solidification of the magma had taken place.

It seems evident, that after its solidification the layered gabbro complex on Stjernöy was subjected to tectonic forces to such a degree that locally a completely tectonized gabbro has resulted with hardly any textural or structural relics of its igneous origin.

Phase layering of the same type as found in the gabbro of Rottenhallerfjell and Simavikfjell is found in the occurrence of Lille Kufjord, Seiland, where layers of peridotite are intercalated in the lower part of the gabbro suite (Oosterom 1955). The mineral composition in the latter occurrence is about the same as in the occurrences on Stjernöy, except that orthopyroxene is somewhat more abundant.

No indications of the operation of a gravitational differentiation process are available to explain the layering at Lille Kufjord, as is also the case in the occurrences on Stjernöy. An important difference is, however, that ultramafic bands of peridotitic composition do not occur in the layered gabbro of Stjernöy.

Krauskopf (1954) reported the occurrence of a layered sequence at Ytre Kåvenfjell on the Öksfjord peninsula containing gabbro, norite, anorthositic gabbro, olivine gabbro, troctolite, and dunite. These form a conspicuously layered sequence, strongly resembling the occurrences on Stjernöy and at Lille Kufjord. In common with the latter, the Ytre Kåven occurrence has the appearance of ultramafic layers. On the other hand, a gradual transition from ultramafic rock via olivine-melagabbro towards layered gabbro is lacking at both Ytre Kåven and Lille Kufjord.

Krauskopf commented that locally uniform gradations in the amounts of mafic minerals from one side of a layer to the other can be observed. Concerning the gradation, however, he says that "some layers show the concentration of dark grains increasing in one direction, while adjacent layers show an increase in the other direction".

3. *The contact relations of the gabbro*

The layered gabbro at Lille Kufjord (Seiland) is a good example of an occurrence of igneous rock with concordant contacts against supracrustal rocks on all sides, without apparent signs of contact metamorphism. The Ytre Kåven occurrence (Öksfjord peninsula) also exhibits concordant contact-relations with gabbro gneisses and garnet-gneisses on all sides.

It may be useful to bear in mind that the contacts of the ultramafic rocks are not obviously intrusive and that in several places the concordant relations indicate a tectonic contact. At both Halvorvikfjell and Normandsnes, too, the coarse grained, massive gabbro exhibits no intrusive relations with the surrounding metamorphic rocks.

In the valley of the brook of Store Kjerringfjord the contact of layered gabbro and gabbro gneiss can be seen from a distance, owing to an obvious difference in colour between the brownish weathered gabbro gneiss and the light-grey weathered layered gabbro. A difference in mechanical weathering of the rock can also be noticed: the layered gabbro exhibits a more or less regular block-like jointing, whereas the gabbro gneiss makes a rather fractured impression by reason of a densely spaced and irregular pattern of joints.

On closer inspection at the contact, it is observed that the leucocratic gabbro belonging to the layered complex changes across a more or less well-defined line into a more homogeneous and denser gabbro with here and there a more pronounced irregular streak of somewhat coarser gabbro. Only at a distance of 50 to 100 metres from the transition zone can strikes and dips of the foliation be read in the strongly discordant gabbro gneiss. However, in the northern slope of Lassefjordfjell the strike of the foliation in the gabbro gneiss is concordant with the contact.

Neither apparent contact-metamorphism nor igneous brecciation has been found along this contact. It is tentatively suggested here that contact-phenomena between the layered gabbro and the gabbro gneiss were obscured by later dynamometamorphic processes or that the difference in temperature between a dry basaltic magma and country rock was negligible.

A similar transition zone of dense and homogeneous rock in the gabbro gneiss can be observed at the contact with the massive gabbro about 500 metres West of Stjernodden in the south-eastern tip of Stjernöy.

In summary it may be said that the layered gabbro of Rottenhallerfjell and Simavikfjell very probably developed from the olivine melagabbro, which in its turn originated from the pyroxene-peridotite. In this respect the Stjernöy suite, with its gradual transitions from one rock type to the other, shows great similarities with sequences found in such igneous occurrences as the Bushveld and Stillwater layered gabbros.

On the other hand, parts of this layered gabbro must be highly tectonized and in many places the contact-relations may have been obscured by this process. In that case the difference between tectonized gabbro and the surrounding gabbro gneiss of the metamorphic complex is quite small. Both types of rock exhibit a marked foliation, the mineral composition being almost the same.

THE METAMORPHIC ROCK COMPLEX

In the investigated area the oldest rocks, in which the ultramafic sequence with its related layered gabbro occurrences is emplaced, consist of a complex mainly formed of basic metamorphic rocks. These country rocks include such widely varying rocks as gabbro gneiss ¹), amphibolite, plagioclase gneiss, syenite gneiss, hypersthene-plagioclase gneiss (norite gneiss), calc-silicate rocks, and garnet-bearing granulites of various silica contents.

Definitely mafic rocks such as gabbro gneiss and amphibolite predominate strongly in the complex of metamorphic rocks. For this reason it is understandable that these rocks in the Öksfjord-Stjernöy-Seiland area, together with the rocks of the ultramafic sequence, have been considered as a single petrological province which has had a long magmatic and tectonic history. In this conception the alkaline and acid rocks in this area could be considered as derivates of an original basic magma.

However, the detection by Krauskopf (1954) of calc-silicate rocks in the way of concordant layers and lenses of highly metamorphic, skarn-like diopside-garnet rocks on the Öksfjord peninsula, and the subsequent recognition of similar outcrops

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¹) The term gabbro gneiss is used here, although strictly speaking most definitions of gneiss imply a quartz-feldspar-bearing rock of gneissic texture. However, in this study the term gabbro gneiss is preferred to pyroxene-granulite, mainly because Krauskopf used it for similar rocks on Öksfjord.

in the gabbro gneiss on Stjernöy and Seiland make it hard to believe in their magmatic origin.

At least part of the metamorphic rocks must be of supracrustal origin. As Krauskopf suggests, a supracrustal origin can readily explain the intercalated syenite layers as the metamorphic equivalents of original alkaline effusives and tuffs. The calc-silicate layers, and probably the acid granulite layers as well can then be accepted as sedimentary beds interbedded in a predominantly volcanic sequence. It must be added, however, that for a sedimentary sequence this is quite an unusual association of rocks.

Besides their pronounced metamorphic character the country rocks, taken as a whole, are characterized by an intense jointing and fracturing; occasionally also micro-faulting and -folding. The intense deformation undergone by the metamorphic rocks is beautifully demonstrated by an exposure in the belt of metamorphic rocks bordering the olivine-bearing gabbro at Nordmandsnes. Here an apparently rigid amphibolite layer is broken, while the more feldspathic rock has been deformed plastically (plate A, fig. 4). In the same locality the rock is virtually riddled with segregations and dykes of several generations and of various composition. Such phenomena have rarely been observed in layered gabbro.

Krauskopf has divided the gabbroic rocks of the Öksfjord-peninsula into three types of gabbro gneisses. As a result of the present author's investigations on Stjernöy, the possibility that the layered gabbro (the equivalent of Krauskopf's gabbro gneiss II) is a para-gneiss can be excluded; its relations to the ultramafic rocks have been satisfactorily established in the preceding Chapter. The two other types of Krauskopf's gabbro gneisses [1]) occur in abundance in the northern and north-eastern regions of Stjernöy. Hysingjord (1960) in his study of western Stjernöy also recognized only two types of gabbro gneiss.

If the layered gabbro is no longer considered to be a gabbro gneiss in Krauskopf's sense, it is not necessary to look for oddities such as effusive or tuffaceous parents of the anorthosite and peridotite layers, such as occur in layered gabbro.

In the present study of the central and eastern parts of Stjernöy it seemed better to map the gabbroic gneisses and the amphibolitic rocks as individual units because in large areas these rocks are of monotonous composition, interrupted only by single, easily mappable syenite- and acid granulite-layers.

Evidently there is exposed in this mafic area of West-Finnmark a complex of highly metamorphic rocks derived from various primary materials, showing great similarities to such rocks as pyroxene-granulites and basic charnockites. The mineral paragenesis in any case indicates granulite facies as the critical and typomorphic minerals such as diopside, hypersthene, almandine-pyrope garnet, sillimanite, rutile, hair-perthite (orthoclase) and hair-antiperthite (plagioclase) were observed in the various rocks composing the metamorphic complex.

GABBRO GNEISS

In the central area of Stjernöy and along the northwestern contact of the ultramafic rocks on this island, large areas are covered by a monotonous, fine to medium grained gneissic rock, which consists mainly of plagioclase and pyroxene. Because of its compositional and textural affinities with gabbro and gneiss, this rock has been named gabbro gneiss, although pyroxene-gneiss or even pyroxene-granulite would also be appropriate terms for a rock of such a composition.

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[1]) The gabbro gneiss in this study is equivalent with Krauskopf's gabbro gneiss I; the amphibolite shows similarities to Krauskopf's gabbro gneiss III.

The rock has a grey weathering colour, but as a whole shows quite a fresh appearance. It has already been stated that the gabbro gneiss is more fractured than the gabbro of the layered sequence. The slopes in the gabbro gneiss landscape are often thickly covered by rough scree. The gabbro gneiss landscape exhibits somewhat smoother contours than that in the layered gabbro area.

From a distance the gabbro gneiss makes a fairly homogeneous impression. On closer inspection a marked foliation is revealed, deriving from the parallel arrangement of flat, lenticular aggregates of mafic minerals — some millimetres or even a centimetre in diameter. These mafic minerals may also be scattered, but most often they are gathered in aggregates. In places the rock also exhibits a narrow banding, accentuated by remarkably straight streaks of leucocratic or melanocratic composition (plate B, fig. 1).

Mylonitic zones, often parallel to the regional foliation, bear witness to mechanical deformations suffered by the gabbro gneiss. The mylonitized gabbro often contains ore minerals in amounts of up to ten per cent. These ore minerals may be iron oxides, but pyrrhotite-bearing zones have also been observed, e.g. North of Kufjordtind (Lille Kufjord, Seiland). In the latter case they can be easily identified from great distances by their dark-brown weathering colours. There is also microscopic evidence of strain, since bent twin-lamellae and mortar structures occur in many thin-sections (see also page 240 and fig. 3, plate E).

The mineral composition of the samples of gabbro gneiss varies considerably, as indicated by their modes in table 8. The ratio of leucocratic to melanocratic minerals in the gabbro gneiss varies from one sample to the other, the average amount of plagioclase being 50 per cent, although percentages as low as 35 per cent and as high as 70 per cent have been found in individual samples. Pyroxene is the next most important mineral; in most samples diopsidic augite predominates over rhombic pyroxene.

The amount of orthopyroxene attains a maximum of 5 per cent in average gabbro gneiss. However, in a few distinctly leucocratic bands, hypersthenic orthopyroxene is the main mafic mineral. Hysingjord (1960) reports the occurrence of bands of leucocratic gneisses, about 10 to 100 metres in thickness, containing up to 75 per cent andesine and garnet or orthopyroxene as next most important minerals (hypersthene-plagioclase gneiss).

There is considerable variation not only in the mineral composition but also in the texture within the gabbro gneiss. In some localities the rock is highly foliated and rather dense, in other localities the rock exhibits an indistinct, coarse grained texture. In the latter case elongated and eye-shaped aggregates of mafic minerals were observed, e.g. SE of Lille Kvalfjord. Macroscopically such gabbro gneiss resembles "flasergabbro" (Johannsen 1939). A clastoporphyritic texture has been attributed by Barth (1927) to a sample from the gabbro gneiss occurrence near Lille Kvalfjord.

In the petrography a description of the several types of gabbro gneiss with their textural variations will be given.

Krauskopf (1954) describes lense-shaped, concordant calc-silicate bodies within the gabbro gneiss, consisting of garnet-diopside-plagioclase with accessory scapolite and wollastonite.

Hysingjord (1960) mentions the occurrence of similar calc-silicate lenses in gabbro gneis from western Stjernöy. He proved that the dominant mineral is a calcium-rich garnet with about 80 per cent grossularite ¹).

¹) The garnets occurring in the quartz-rich granulitic gneisses are magnesium-rich almandine-pyrope garnets with about 20 per cent grossularite (Hysingjord).

At Stjernodden these calc-silicate layers are also present, in this case containing a considerable amount of calcite (see page 206).

Granted the overall metagabbroic composition of the rocks in the gneissic area, the problem remains of reconciling such conflicting features as clastoporphyritic textures in the gabbro gneiss — indicating an igneous origin — with the occurrence of metasedimentary bands such as the calc-silicate rocks. It is felt by the present author that most mafic rocks could very well be of igneous origin from the mineralogical and chemical point of view, but in the regions where the calc-silicate lenses, acid granulites, and syenite gneiss layers occur within the gabbro gneiss, Krauskopf's hypothesis of a "gabbroization" of an original bedded volcanic sequence seems almost inescapable.

Even in the light of results of several field investigators, the conclusion must be that in the gabbro gneiss, which undoubtedly is of complex metamorphic history, it remains difficult to decide what are ortho- and what are para-rocks. However, in the petrographical, mineralogical and chemical chapters this matter will be discussed again. The present investigations were set up expressly to determine the relation between layered gabbro and gabbro gneiss. For the moment it is clear that:

1. There is no gradual transition in the gabbro gneiss complex from ultramafic to gabbroic rocks. Olivine has not been found in the gabbro gneiss. Apatite and biotite, on the other hand, are lacking in the layered gabbro.
2. Layering of markedly different composition is absent in the gabbro gneiss, and the absence of anorthosite layers in the gabbro gneiss of the northern and northwestern part of Stjernöy especially deserves recording. However, inch-scale layered gabbro and certain types of gabbro gneiss are very similar in appearance.
3. Highly metamorphic calc-silicate lenses, probably of supracrustal origin, occur only in certain regions of the gabbro gneiss complex; they are absent in the layered gabbro of the ultramafic sequence.

AMPHIBOLITE

On the peninsulas between Smalfjord and Ytre Pollen in the northern part of Stjernöy, a medium or even coarse grained rock of dark appearance occurs, consisting mainly of andesine and hornblende in about equal amounts. In most places it is distinctly foliated due to a planar arrangement of small clusters and lenses of hornblende crystals; locally these lenses are oblong in shape so that the structure approaches a lineation. In addition to the foliation, the rocks show a narrow layering on a decimetre-scale by bands somewhat more leucocratic or melanocratic in composition. However, locally the rock may be of such a coarse grain-size, and so nearly massive, that it resembles a diorite.

On the average the rock consists of about 50 per cent plagioclase, 35 to 40 per cent hornblende, and 10 to 5 per cent diopsidic augite.

In places, e.g. near the carbonatite patch at the western side of Kjerringfjordklubben, the amphibolite is thickly studded with garnet crystals in amounts ranging up to 10 or 15 per cent, which together with the black and white mottling of hornblende and plagioclase results in a handsome rock. The impression is gained that garnet-rich rocks are especially found in the more leucocratic layers. Some of the garnets occur as reaction-coronas around grains of ore. According to Eskola (1954), such coronas are indicative of retrograde metamorphism of the rock in question.

The rock does not consist everywhere of hornblende and plagioclase in dominant amounts; in some places the main mafic mineral is pyroxene. In composition the rock then resembles a mafic granulite or gabbro gneiss rather than an amphibolite.

Both Krauskopf and Hysingjord describe a type of gabbro gneiss interlayered with amphibolite, garnet-bearing granulite, and syenite gneiss, from the Öksfjord peninsula and from the western part of Stjernöy. It seems plausible that on these locations the amphibolite belongs to this gabbro gneiss unit. In northern Stjernöy it has been mapped as amphibolite because in this case it is the strongly predominant rock. Intimate intermingling of both rocks being apparent, it may be justifiably asked whether the amphibolite originated from the gabbro gneiss by retrograde metamorphic processes under limited availability of water.

A characteristic feature in the outcrop of amphibolitic rocks in the northern part of Stjernöy is the occurrence of several layers of syenite gneiss. These layers of peculiar composition (see below) seem to be particularly abundant in the amphibolite. It should not be concluded, however, that syenite layers occur solely in the amphibolitic type of rock. Both on Stjernöy and on the Öksfjord peninsula syenite layers also occur in the gabbro gneiss type that is free of amphibolite-intercalations.

Massive outcrops of syenite also occur in the amphibolite of northern Stjernöy and small dykes of medium to relatively coarse grained saccharoidal syenite are very common.

SYENITE GNEISS

In the region of the peninsulas between Smalfjord and Ytre Pollen on northern Stjernöy, layers of syenite gneiss in the amphibolite are a striking phenomenon. This syenite is visible from great distances by reason of its reddish weathered surface, which contrasts markedly with the dark colour of the enclosing rocks. At Udsiktfjell and Lassefjordfjell similar syenite gneiss layers occur in the gabbro gneiss. At Stjernodden, too, an important syenite layer has been found in the gabbro gneiss. This syenitic rock is very similar to the syenite in the layers distinguished by Krauskopf (1954) in the western part of the Öksfjord peninsula.

The syenite layers of northern Stjernöy are from fifty to several hundred metres in width and can be continuous for several kilometres before they ultimately wedge out. In actual fact, most of the layers are cut off by the fjords, and only the most southern layer across Lille Kjerringfjord wedges out.

The syenite is of fine to medium grain-size and, on a fresh surface, has a sugary appearance with a greenish to yellowish colour. In most cases a faint foliation is visible owing to the presence of subordinate mafic minerals. Streaks of different grain-size also occur in the syenite, which give the rock a gneissic texture. The contacts of the syenite gneiss with the amphibolite are sharp and straight and absolutely concordant with the foliation in the latter rock.

Under the microscope these peculiar rocks appear to consist of 85 to 95 per cent (anti)perthitic feldspar (plate E, fig. 4) with small amounts of additional plagioclase; the mafic minerals are green diopsidic pyroxene, hypersthene, biotite, and ore-minerals. Rocks consisting mainly of (anti)perthitic feldspar have been named perthosite by Johannsen (1939).

The occurrence of narrow concordant mylonite zones in the syenite testifies to mechanical deformation; signs of deformation are also frequently found in the thin-sections (plate E, fig. 3). Apparently the syenitic rocks exhibit a more plastic behaviour during orogenetic deformation than the rigid mafic gneisses.

In the syenite intercalations within the northern Stjernöy amphibolite, dark lamprophyric bands a few decimetres wide run about parallel to the contact and the foliation of the rock. These bands are slightly crinkling and cross-cutting, which proves a later emplacement than the syenite.

In the syenite layer at Stjernodden lamprophyric dykes are also found; this layer occurs in juxtaposition with a calc-silicate layer; calc-silicate rocks in minor amounts have been found in or near the other occurrences of syenite as well.

The Lassefjordfjell occurrence is an oblong outcrop of conspicuously yellowish-weathered syenite, which at its southern border exhibits a sharp contact against the layered gabbro. But at the northern contact, narrow and irregular dykes, a few metres long with small apophyses, penetrate the gabbro gneiss, which suggests a mobilization of the syenite material. Between the two rocks there is a thin reaction-rim. In thin-sections, rounded clusters of strongly undulose quartz, in amounts of up to 20 per cent, and porphyroclastic plagioclase crystals are found in a perthositic rock which otherwise is similar to the one just described.

In the amphibolite of northern Stjernöy small dykes of medium to relatively coarse grained, syenite are very common, being even more abundant in the neighbourhood of the syenite gneiss layers. These dykes have the same reddish weathering colour as the syenite of the gneissic layers and consist of 95 per cent perthitic alkali-feldspar.

In the northern part of Smalfjordfjell and East of Kjerringfjordnes large bodies of syenite occur, consisting of the same purely feldspathic rock. In the centre of these bodies the syenite is massive, but towards the borders there is more or less obvious foliation, parallel to that in the neighbouring rocks.

As already stated, it seems reasonable to explain the perthosite dykes near the syenite layers as the product of a mobilization of alkaline material. However, it is more difficult to explain the generation of massive bodies of syenite in this way.

No undersaturated nepheline-bearing alkaline rocks have been found in this area nor has an association with carbonatitic rocks been established. It is unlikely that the syenite rocks in northern Stjernöy have anything to do with the rocks of the latter association.

Mangerite

Some of the reddish-stained feldspathic layers are identifiable as plagioclase gneiss rather than perthosite gneiss layers since oligoclase-andesine is the main mineral component. Orthoclase or perthitic feldspar can even be reduced to subordinate amounts. The same mafic minerals, such as diopside and hypersthene, occur in both types of rocks, as do the accessory minerals apatite, rutile, and zircon. A sample of such mangeritic gneiss was taken from one of the layers at Udsiktfjell. The layer across summit 570, South of Kjerringfjordnes, is a garnet-bearing feldspathic gneiss with more plagioclase than orthoclase.

From Hysingjord's work in the western part of Stjernöy it can be concluded that such plagioclase-rich gneisses, consisting of 60 to 75 per cent andesine, 15 per cent hypersthene, 15 to 5 per cent garnet, and usually 10 to 2 per cent quartz, are abundant in the gabbro gneiss unit, which also incorporates quartz-rich garnet-plagioclase gneisses, syenite gneisses, and amphibolite zones [1]). Some of Hysingjord's rocks are clearly transitional between plagioclase-gneiss and the granulitic garnet-bearing gneisses described below.

ACID GRANULITES

The concept granulite facies was referred to in the beginning of the chapter on the metamorphic rocks in connection with the mafic gneissic rocks. Granulites [2]) in the petrographical sense of the word occur in this region also.

[1]) Krauskopf's gabbro gneiss III.

[2]) According to a definition by Eskola (1954), granulite is a banded garnetiferous quartz-feldspar rock with usually intercalated bands of more basic, mostly garnet-free, hypersthene-bearing materials.

In the NE area of Stjernöy garnet-plagioclase-quartz granulite is not an abundant rock; only one continuous layer stretches from the slope of Middagsfjell to Nordmandsnes. This is a light grey, fine to medium grained rock of gneissic texture, which has red garnet-porphyro-crystalloblasts and bluish streaks of quartz as conspicuous constituents set in a matrix of finer grained quartz and feldspar.

Foliation is indicated by the quartz streaks and by biotite and other mafic constituents.

The feldspar in this layer consists mainly of andesine, but oligoclase is also an important constituent. Garnet is usually present in amounts varying from 15 to 5 per cent; hypersthene and ore-minerals are less important constituents. Biotite occurs in some samples in amounts of up to 5 per cent. As accessory minerals zircon, sillimanite, rutile, and apatite have been found. A peculiarity to be mentioned is that flakes of graphite have been noticed in some places in this granulite.

The granulitic layer is inhomogeneous in composition. South of Lille Kvalfjord, intercalations of hypersthene-plagioclase gneiss occur in the garnet-gneiss; at Nordmandsnes also streaks of syenite gneiss have been observed.

At Kjerringsfjordnes porphyroblastic garnet is found in a wedge-shaped occurrence of coarse grained gneiss, which consists of 50 per cent perthitic orthoclase and 45 per cent quartz; the balance being made up of the above-mentioned garnet and fibrolitic sillimanite. This rock is transitional between the garnet-gneiss and the syenite gneiss (perthosite). As a matter of fact, streaks of such perthositic syenite, sub-parallel to the foliation, do occur in the rock at this place.

Hysingjord describes the abundant occurrence of garnet-bearing, quartz-rich gneisses in the metamorphic rocks of the western part of Stjernöy. According to his investigations, the gneisses there contain 70 to 80 per cent quartz and 25 to 20 per cent feldspar, mainly orthoclase. Garnet is present in amounts of from 5 to 1 per cent; accessory minerals are zircon and rutile. Layers of plagioclase gneiss and syenite gneiss also occur in these quartz-rich gneisses.

On Seiland, banded garnetiferous quartz-feldspar rocks occur as an independent rock unit over great expanses of the southwestern parts of the island. A sedimentary origin has been ascribed to this rock by Barth (1927). During the present author's survey at Lille Kufjord (Seiland) intercalations of biotite-bearing hypersthene-plagioclase gneisses (e.g. sample P 24) were identified in this acid granulite.

Eskola (1954) maintains that acid garnet-bearing granulites agree reasonably well in chemical composition with aluminium-rich sediments. He further mentions, that the occurrence of graphite- and sulfide-bearing aluminous granulitic rocks can be related in all probability to bituminous sediments.

Graphite has been found in the granulite bordering on the Lille Kufjord layered gabbro occurrence on Seiland (Oosterom 1955). It also occurs in the granulitic band across the peninsula between Store Kvalfjord and Lille Kvalfjord.

Sulfide-rich zones have not been found in the granulite layer of northeastern Stjernöy. However, such zones frequently occur in the metamorphic rocks (mainly gabbro gneisses with intercalated syenite bands) of the western part of the Öksfjord peninsula.

It appears to be a reasonable assumption that the granulites on Stjernöy, Seiland, and the Öksfjord peninsula are indeed rocks of sedimentary origin.

CALC-SILICATE ROCKS

Both calcite-bearing and calcite-free calc-silicate rocks have been detected as layers and lenses at numerous places in the Öksfjord-Stjernöy-Seiland area. Krauskopf (1954) was the first to report the occurrence of such layers in the gabbro gneisses along the western coast of the Öksfjord peninsula, in the Lokkerfjord region, and in the southern slope of Småholmfjell. If these layers consist for a considerable part of calcite, as they do in some cases, we may well apply the name impure metalimestone (or diopside-garnet bearing marble) for such rocks. According to Krauskopf, at several places on the Öksfjord peninsula calc-silicate rocks and syenite in adjacent layers are intimately mixed, for instance at the contact the syenite appears to intrude the metalimestone in small tongues and irregular masses.

At the southeastern tip of Stjernöy (Stjernodden), several outcrops are found in the gabbro gneiss. Here bands of calc-silicate rock, 5 to 10 metres in width, show well-developed, centimetre-scale layering and intricate small-scale folding (plate B, fig. 2). The layering is caused by alternating bands of calcite-rich and calc-silicate composition. The calc-silicates comprise such minerals as diopside, scapolite, wollastonite, and garnet. Other minerals present in the sections are orthoclase, andesine, biotite, and ore minerals. The calcite content in the few investigated samples ranges from 30 (impure metalimestone) to less than 2 per cent. Here, too, a syenite layer occurs in juxtaposition with one of the calc-silicate bands.

The calc-silicate rock in the layers is of moderate grain-size (less than 5 mm) but there are also layers with a fine grained hornfelsic appearance. Because the various layers have different resistance against erosion, the surface of the metalimestone is furrowed.

Hysingjord describes the occurrence of lenses of calc-silicate rock (without calcite) in the gabbro gneiss. He was able to demonstrate, that the dominant mineral garnet consists of grossularite with about 20 per cent andradite. The garnet in the acid granulite and in the plagioclase-gneisses could be determined as a magnesium-rich garnet, intermediate in composition between almandine and pyrope.

A few calc-silicate layers, about 10 to 20 centimetres wide, are intercalated in the gabbro gneiss at the southeastern side of Lille Kvalfjord.

At Bumannsfjord on the western coast of Seiland in a layered series composed predominantly of gabbroic rock types, several concordant bands of diopside-garnet bearing marble and calc-silicate rock occur. In one place a most unusual spinel-sillimanite rock forming a composite band, is reported by Barth (1961), in whose opinion the layered series, together with the various layers of calc-silicate rocks, are largely metasediments.

The calc-silicate layers or lenses are often sheared and may show intense microfolding as seen at Stjernodden, indicating that this material acted as a lubricant during tectonic movements. The banding in these layers is most probably an inherited structure and may be considered as an indication of the original sedimentary origin of the limestone.

In the neighbourhood of the Stjernodden calc-silicate layers, coarse grained garnet- and diopside-bearing calcite-pegmatites are found. It is believed that these dykes are the result of local mobilization and not a differentiation product of the carbonatite dykes found elsewhere on the island.

HORNBLENDITE AND THE CARBONATITE-NEPHELINE SYENITE SUITE

In the course of a field investigation on Stjernöy the attention of the geologist is inevitably drawn to the outcrops of intriguing rocks such as hornblendite on the one side and carbonatite and nepheline-syenite on the other. No survey in the Stjernöy-Seiland-Öksfjord area could be complete without a brief description of these rocks, which with respect to both space and time seem to be closely related, e.g.

in the occurrences of Ytre Pollen and around Gammevann. From the field relations it is evident that they are the youngest rock-units in the area.

At the hornblendite occurrences, transitional borders are found frequently towards the surrounding ultramafic rocks or gabbro gneisses. In several places pocket-like inclusions of various sizes consisting of peridotite, gabbro, or gneiss are enclosed by the hornblendite. There can be little doubt that these pockets are remnants of larger bodies of the said rocks, the greater part of which have been replaced metasomatically by the hornblendite (fig. 3 gives an impression of this hornblenditization process).

Another feature in the field relations common to the hornblendite occurrences is their emplacement in more or less structurally-defined zones, e.g. the zone from Smalfjord to Lillebukt (see also page 211). It may be pointed out here that hornblendite is a particularly abundant rock in a zone of the southern part of the island along the Stjernsund.

A glance at the geological map of the Smalfjord-Lillebukt zone across the western part of Stjernöy is sufficient to reveal the genetic relation between the sizable, lense-shaped body of carbonatite and the boss-like outcrop of nepheline-syenite. These rocks exhibit field relations which indicate that they could have been deposited from fluids. Whether these fluids were hot aqueous solutions or actual silicate melts cannot be stated definitely, although the author is inclined to assume a process of formation by hot solutions. It is concluded here that the occurrences on Stjernöy agree with Brögger's opinion, according to which these rocks should originate by the crystallization from subsilicic and alkaline liquids (Brögger 1921). This may justify speaking of a fenitic suite of rocks. The abundant nepheline-syenite pegmatite-dykes in the area were probably formed from similar alkaline fluids emplaced more or less simultaneously with the carbonatite and nepheline-syenite at Gammevann.

Within most of the hornblendite occurrences, numerous small and medium sized dykes of albite-nepheline pegmatite occur, and carbonatite dykes have also been found within the hornblendite. The existence of hornblendite surrounding the carbonatite and nepheline-syenite occurrences in central Stjernöy suggests likewise a kind of genetic relationship between the mentioned rocks.

HORNBLENDITE

In the western part of Stjernöy and also along the Stjernsund, extensive bodies of a black, coarse grained rock occur which consists mainly of hornblende. As a matter of fact, several types of hornblende rocks have been mapped under the name hornblendite because there is considerable variety in texture and also in mineral composition.

The hornblendite occurrences of Indre Simavik and Skarvberg are deposits of massive and almost monomineralic rock, of a particular coarse grained texture with crystal sizes of up to one centimetre; in the abundant pegmatitic spots, crystals up to 20 centimetres in size have even been found.

The hornblendite outcrop at Ytre Pollen is more variable in composition and has a moderately coarse grained texture. Hornblende-crystals of the extreme sizes mentioned above have not been found here. A thin-section study has revealed that this hornblendite, like the occurrence at Indre Lokkerfjord (Öksfjord peninsula), contains diopsidic pyroxene [1]); in the latter occurrence as much as 30 per cent pyroxene has been observed.

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[1]) In some cases rounded grains of pyroxene are poikiloblastically enclosed by the hornblende crystals. Johanssen (1939) describes a poikilitic hornblendite with inclusions of olivine and pyroxene as cordtlandtite.

Locally in these occurrences the hornblendite contains considerable plagioclase and the rock should then be termed a hornblende-melagabbro.

As accessory constituents ore minerals, biotite, and calcite occur; more rarely, spinel and grains of sulphides. Under the microscope, apatite and diopsidic pyroxene have also been observed.

In the hornblendite of Sörfjordvalley (West-Stjernöy) the presence of magnetite and ilmenite as principal ore minerals has been demonstrated by Hysingjord (1960). He reports that the ore occurs at the boundaries of the hornblende crystals. Irregular streaks also occur; in some cases as much as 50 per cent of the total rock consists of ore. The impression is gained that the ore mineralization is mainly connected with the hornblendite of moderate grain-size; in any case, the coarse grained occurrences of Indre Simavik and Skarvberg do not contain more than a few per cent of ore.

The coarse grained hornblendite weathers relatively easily; this is evident from a lower topographical relief and from the apparent ease with which rivers and brooks carve almost canyon-like valleys in this rock. An example of such a canyon can be found at Store Bekkarfjord on Seiland, where the glacier-brooks have carved almost vertical walls in the hornblendite. The rock debris of the hornblendite falls apart into loose and weathered fragments of hornblende crystals in sizes of up to 5 centimetres, in appearance somewhat reminiscent of heaps of charcoal.

The hornblendite occurrences along the Stjernsund mainly have sharp contacts with the bordering rocks, but a dense network of hornblendite dykes penetrates the adjacent rock in some places along the contact zone, which creates the impression of an intrusive breccia. This is the case with the hornblendite at the western side of the Indre Simavik-occurrence, for instance.

In the valley of Sökmyr on the island of Seiland an interesting and sizable outcrop of coarse grained hornblendite is encountered; microscopical investigation revealed that in several thin-sections up to 50 per cent of the rock consists of pyroxene or olivine (Oosterom 1954). The microscopic evidence suggests that the often poikiloblastically enclosed, olivine- or pyroxene-grains were in the process of being replaced by growing hornblende crystals. There is also macroscopic evidence for such a process, since remnants of peridotite in the hornblendite-zone on Seiland are densely dissected by hornblendite veinlets; see e.g. the photograph of such an almost-digested remnant of ultramafic rock (fig. 3). At the borders of this hornblendite occurrence with the surrounding ultramafic rocks, more or less transitional rock also occurs.

A metasomatic process of replacement, such as can be deduced from the abovementioned textural relations, agrees reasonably well with the suggestion that the oblong shape, in an EW-direction, of the hornblendite occurrence on Seiland might be interpreted as a zone of structural weakness. By the same reasoning an acceptable explanation may be given for the EW striking dykes of nepheline-syenite pegmatite in its vicinity (see basement map).

An interesting outcrop of hornblendite is found in an occurrence of low relief in a coastal section along Rognsund, West of Ytre Pollen. Here the coarse grained hornblendite, macroscopically similar to the other occurrences on Stjernöy, shows an intimate relationship to the included patches of carbonatite which grade into the hornblendite without a clean contact. As a matter of fact, nearly all the hornblendite at Ytre Pollen is calcite -bearing and has as accessories biotite and apatite, minerals which are also abundant in the carbonatite. The latter, in its turn, is hornblende-bearing.

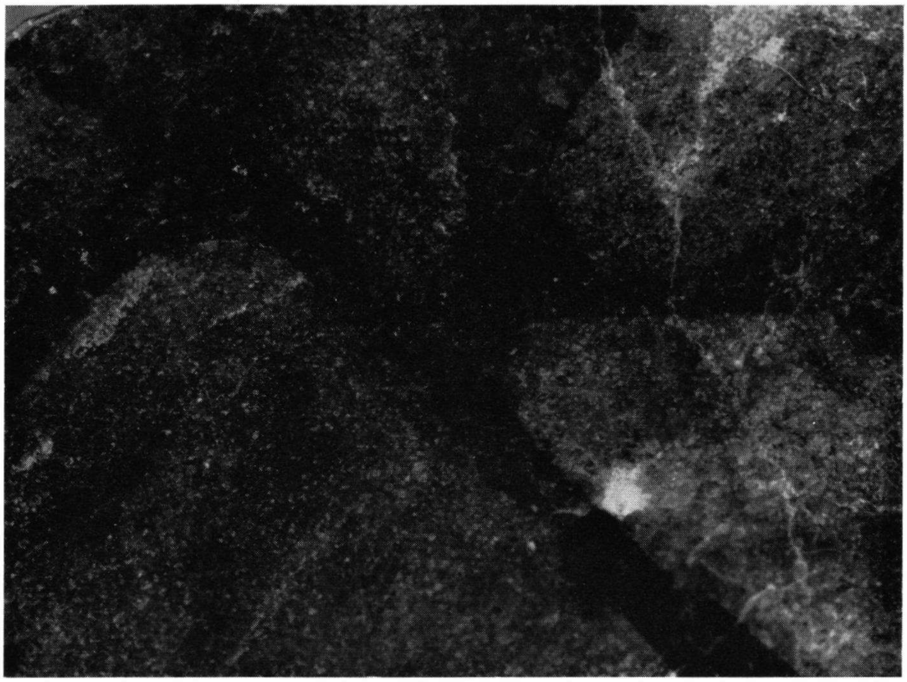

Fig. 3. Peridotite dissected by veinlets of hornblendite, the textural relations indicating replacement along fractures. Note the incipient alteration into hornblende of the peridotite remnants at left. Sökmyr valley, Seiland.

Lin. magn. 2.5 x, vertical illumination.

CARBONATITES

The occurrence of calc-silicate rocks on Stjernöy has been known since its discovery by Kvale in 1938. The first publication about the occurrence of these rocks at Gammevann was by Strand (1952), who established a mineralogical and chemical similarity with occurrences in the Fen district of southern Norway and in Alnö in central Sweden. For this reason he named the calc-silicate rock at Gammevann a biotite-sövite. Heier (1961) refrains from using this modified local name and prefers the general term of carbonatite.

In the hornblendite occurrence of Ytre Pollen patches of carbonate-rich rock are found, very similar in appearance to the carbonatite at Gammevann. The surface area of these patches varies from a few to several hundreds of square metres. It is a rather coarse grained, massive rock with well-developed crystals of calcite, hornblende, apatite, and biotite as main constituents; the distribution of green diopsidic pyroxene, perthitic feldspar, and ore minerals is less regular.

The mafic component in the Gammevann-carbonatite consists of biotite, whereas hornblende is a very subordinate constituent. In the Ytre Pollen occurrence the mafic constituents exhibit a greater variety, hornblende being in most cases the principal mineral, with biotite occurring as the second mafic mineral. Diopside is also present, in still lower percentages.

Another type of carbonatite is met with in an apatite-rich pyroxene-bearing dyke of sizable dimensions in the southern slope of Udsiktfjell, which as far as mineral composition is concerned, is quite different from the other carbonatite outcrops. The main mafic mineral here is a green aegiritic pyroxene, whereas only minor amounts of hornblende and biotite are found in this rock. According to Brögger (1921), a carbonatite with alkali-pyroxene and feldspar should be named a ringite.

Dykes of carbonatite are found in several places on Stjernöy and on the Öksfjord peninsula. They are, however, less frequent than the dykes of albite-nepheline pegmatite. These dykes do not exhibit particularly coarse grain sizes; in most cases the rock is very similar in composition and texture to the average carbonatite rock.

On Seiland carbonatite occurs much more rarely than on Stjernöy. Barth (1927) describes the occurrence of a so-called albite-ringite pegmatite dyke. From his mineralogical description it is clear that this dyke consists of a carbonatite rock of pegmatitic texture. During the survey on Seiland an apatite-bearing hornblendite dyke (the apatite amounting to about 25 per cent), containing a few per cent of calcite, was found by the author in the Sökmyr hornblendite occurrence. This dyke, obviously representing a later stage in the process of emplacement of the hornblendite, shows similarities in mineralogical respect to the hornblendite-carbonatite transition rocks found in the occurrences on Stjernöy.

In the Ytre Pollen occurrence the carbonatite contains about equal amounts of mafic and felsic minerals, which by an increase of the content of mafic minerals grades into the surrounding hornblendite. It has already been stated in the preceding chapter that the hornblendite from this locality contains a few per cent of calcite.

The weathered surface of the carbonatite, which has a brownish-stained crust, is crumbly and peels off at the surface. This explains the typical rounded and hummocky topography of the carbonatite rock in the landscape. Just as in the lower parts of the slopes around Gammevann, at Ytre Pollen there is luxuriant growth of grass and herbs on the apatite-bearing carbonatite.

The carbonaceous hornblendite of Ytre Pollen has a wedge-shaped outcrop between the coarse grained olivine gabbro of Oterfjell and the amphibolite with intercalated syenite layers of Vailas Goppe. To the SW it tapers off to a sheet-like body of carbonatite between the two rock units just mentioned. The poorly exposed border against the coarse grained gabbro seems to run along a fairly distinct line, although locally the actual contact might be somewhat diffuse.

Towards the contact with the amphibolitic rocks of Vailas Goppe, the carbonaceous hornblendite grades first into melanocratic carbonatite which in its turn changes into a layer of very leucocratic carbonatite-limestone layer, about 20 metres thick (fig. 4). This layer persists along the length of the contact and exhibits only faint indications of melanocratic schlieren. This contact-carbonatite does, however, contain about 12 per cent apatite ¹), whereas the normal carbonatite only yields about 6 per cent. The latter mineral is also found frequently as an accessory constituent in the hornblendite.

The apatite-rich leucocratic carbonatite borders along a well-defined straight line on a reddish gneissic rock of syenitic composition. This syenite might, of course, be considered as a rim of fenitized amphibolite. However, with regard to the abundant occurrence of such syenitic layers in the amphibolite, it is more likely that the syenite layer at the contact already existed when the hornblendite and

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¹) From the economic point of view this apatite occurrence is very poor compared with the amounts of up to 50 per cent found in the carbonatite associated with the syenite intrusions on the Kola Peninsula.

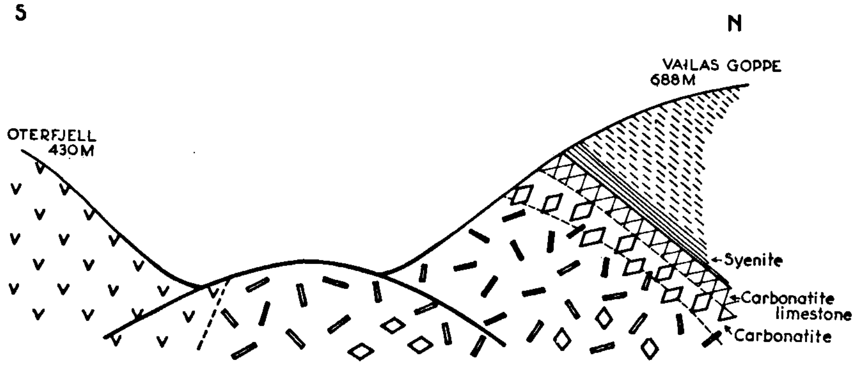

Fig. 4. Diagrammatic section with contours after a photograph of the hornblendite-carbonatite occurrence in the valley between Oterfjell and Vailas Goppe, Ytre Pollen. Stjernöy. For symbols see sketch map in insert.

carbonatite were formed. As already stated in the introduction to this paragraph, the author is inclined to believe in a metasomatic genesis of the hornblendite and carbonatite. It is compatible with this view that the coarse grained gabbro would yield to such replacement more easily than the fine-grained rocks of the metamorphic complex.

The occurrence of strips of carbonatite-bearing hornblendite along the coast further North at Hammeren, at the northern tip of Pollen island, and further West at Nordmandsnes indicates a much larger extension of these rocks, the greater part of which must have been eroded away. At the western side of Kjerringfjordklubben there is also a thin strip of carbonatite-bearing hornblendite along the coast. No doubt several more of these hornblendite patches escaped discovery during the present survey.

For the occurrence at Ytre Pollen a metasomatic emplacement in a structurally-defined location seems to be obvious, but also for the occurrence of carbonatite at Gammevann, within the hornblendite zone extending from Smalfjord to Lillebukt a metasomatic mode of emplacement from subsilicic and alkali-bearing liquids may be deemed likely. Heier (1961) points out that the emplacement may also have resulted from a metasomatic action of gases.

NEPHELINE-SYENITE

In the area investigated by the author, nepheline-syenite mainly occurs as coarse grained albite-nepheline (canadite) dykes; the occurrence of massive nepheline-syenite at Store Nabberen was visited only cursorily. In his thesis Barth (1927) has dealt extensively with these canadite dykes in the southern part of Seiland. Here the treatment of this highly interesting rock type on Stjernöy will of necessity be kept short.

The discovery of a massive occurrence of nepheline-syenite in the steep sloping peak of Store Nabberenfjell by Ramberg c.s. in 1953 is of considerable genetic importance for the whole area since this coarse grained, light coloured rock contains the same minerals as the dykes of albite-nepheline pegmatite which are so abundant in the Öksfjord-Stjernöy-Seiland area. This massive albite-nepheline is a granitic-looking granular rock, handsomely spotted red and black by more or less idiomorphic reddish stained nepheline in amounts of up to 25 per cent, and 5 to 15 per cent biotite and hornblende. These minerals are embedded in saccharoidal perthitic feldspar with grain-sizes of up to half a centimetre. As accessory minerals magnetite, titanite, and apatite occur. In thin-sections of samples of the eastern slope of the Store Nabberen, calcite has been found by the author in amounts of up to 3 per cent.

The nepheline-syenite protrudes into the carbonatite; nepheline-syenite pegmatite dykes and small bosses of the same composition also occur within the carbonatite. Obviously, the nepheline-syenite is the youngest rock in this suite, South of Gammevann.

In detail the structure of the Store Nabberen outcrop is rather complicated (Heier, 1961); it will suffice to mention here that in the northeastern slope of summit 720 the nepheline-syenite exhibits a kind of crude and faint banding, roughly concentrical with the boundary of the occurrence. In the southwestern slope the syenite has a much more fine grained texture and gneissic structure and does not contain nepheline.

The proportions of the constituing minerals in the nepheline-syenite boss of Store Nabberen are roughly the same as in the many nepheline-syenite pegmatite dykes, which consist of albite, nepheline, and minor amounts of biotite. These dykes have been described comprehensively under the name canadite-pegmatites by Barth (1927). Many of these dykes are particularly coarse grained. Crystals of albite and nepheline up to ten or twenty centimetres across have been frequently observed on Stjernöy. The dykes often exhibit a kind of mylonitization at the contacts with the surrounding rock, together with intense crushing of the minerals.

Swarms of sub-horizontal canadite-dykes are frequent in the steep eastern slopes of Rottenhaller- and Simavik-fjell. The reason for their parallel outcrops must be sought in the pegmatitic material preferentially following the basal joint-system of the gabbroic hostrock. Most of these dykes are from 0.5 to 2 metres in thickness, a few may be as thick as 10 to 20 metres. Their length varies from several tens to several hundreds of metres.

Southwest of summit 622 of Antonfjell is a boss-like occurrence of such nepheline-syenite pegmatite several hundreds of metres long and about fifty metres in thickness, consisting of albite and nepheline crystals up to 10 centimetres in size. This nepheline-syenite boss contains a few per cent of a blue scapolite [1]).

In the southern part of the island of Seiland, North of the valley of Sökmyr, there are a number of these albite-nepheline dykes of considerable dimensions. These vertical and continuous dykes are oriented in an approximate EW-direction. This is parallel to the general orientation of the oblong body of hornblendite in this part of Seiland (see page 208). It is tentatively suggested that the materials for these albite-nepheline dykes were emplaced in predestined places of structural weakness by vertical master jointing or in cavities caused by tectonic drag.

In and near the hornblendite occurrences on Stjernöy, moreover, the albite-nepheline pegmatites are particularly abundant, e.g. at Ytre Pollen. In the hornblendite occurrence of Indre Simavik many of these alkaline dykes are also noticed. In the hornblendite West of Indre Lokkerfjord (Öksfjord-peninsula), there are several dykes with approximately horizontal outcrops, dipping slightly to the South (apparently also a case of joint-filling).

There appear to be reasons for a certain local differentiation of the albite-nepheline syenite pegmatites. It has been noticed that these dykes in central and

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[1]) According to an analysis by Norges Geologiske Undersökelse of a blue scapolite from Hakjerringselv (Öksfjord) this mineral is a calcium-scapolite, rich in the meionite molecule.

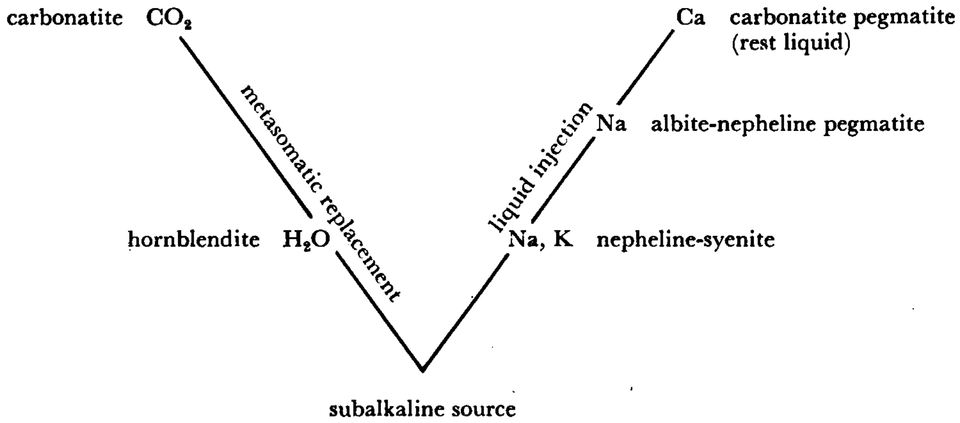
eastern Stjernöy, which are predominantly emplaced in gabbroic rocks, generally are scapolite-bearing (see footnote page 212). The dykes in the southern part of Seiland, mainly occurring in ultramafic rocks, do not contain this mineral. Krauskopf (1954) also reported dykes with the blue scapolite in the gabbroic rocks of the NE-corner of the Öksfjord-peninsula. Other alkali-feldspar pegmatites in the western part of the same peninsula contain pyroxene and ilmenite or magnetite; a peculiar dyke of this type also contains molybdenite and apatite.

Barth (1927) stresses the influence of the host rock on the mineral composition of the silica-undersaturated alkaline dykes. Thus the pegmatite dykes in the acid granulite gneiss along the southern coast of Seiland are feldspar pegmatites. Possibly due to the desilicating influence of the peridotite or gabbro, the same dykes in the latter host rocks are nepheline-bearing.

In the amphibolitic rocks of northern Stjernöy many medium to small sized dykes are encountered which consist mainly of perthitic feldspar. These medium-grained dykes are especially abundant near the layers of syenitic gneiss intercalated in the amphibolite. The similarity in mineral composition and texture between dykes and syenite-gneiss makes it plausible that these dykes are the result of mobilization of potassium-rich alkaline material from the syenite gneiss layers and not a product of differentiation of nepheline-syenite liquid (see also page 204). However, the position of outcrops of massive syenite such as the occurrence E of Kjerringfjordnes remains uncertain.

Very interesting from the genetic point of view is a discovery that lenses or schlieren of coarse grained calcite, biotite, and apatite occur in several of the canadite pegmatites on Stjernöy as the product of final crystallization in the dyke. Thus a lense of coarse grained carbonatite, about 30 centimetres in thickness, with large flakes of biotite up to 20 centimetres in diametre and idiomorphic crystals of green apatite up to 10 centimetres in length, is found in the southern slope of Simavikfjell, North of Skarvberg, in the middle of a canadite dyke about 20 metres thick. In the northern slope of Rottenhallerfjell carbonatite-bearing canadite dykes are also found; in one case the wedging end of an outcrop consists completely of carbonatite. This differentiation process in the canadite dykes is in agreement with the Daly-Shand hypothesis about the appearance of calcium-rich minerals in rest liquids during the course of crystallization in an alkaline magma. Among such calcium-rich minerals, in this case primary calcite and apatite can be mentioned; no melilite and melanite have been found on Stjernöy. The latter minerals are frequent accessories in the rocks of the later stages of crystallization in other fenitic suites, e.g. the turjaite and alnoïte rocks of the Turja-occurrence, Kola peninsula (Kranck 1928).

In the Store Nabberen-Gammevann region the whole constellation is more in favour of a close succession in space and time of nepheline-syenite and carbonatite in which the nepheline-syenite is the younger rock. It may be pointed out that large dyke-like bodies of the latter rock are found in the carbonatite near Gammevann. It is likely that in depth a separation of carbonaceous and alkaline liquids took place in the order mentioned above, which ultimately resulted in the emplacement of hornblendite-carbonatite and nepheline-syenite at their present sites. The emplacement into higher levels of the crust could be schematically represented as follows:



Thus ample field evidence has been found on Stjernöy for a close relationship between hornblendite, carbonatite, and nepheline-syenite, an association which appears to be only indirectly related to the gabbroic rocks of the ultramafic suite. Apart from this, the geological situation pleads for a younger age of these rocks. It is evident that the region between Gammevann and Store Nabberen was the main channel for carbonaceous and alkaline liquids of deep-seated origin. The field evidence in the preceding chapters suggests a metasomatic manner of emplacement for the hornblendite and carbonatite. Heier (1961) defines this metasomatic emplacement as an intrusion of a potassic carbonatite liquid. He further states: "its emplacement was accompanied by gas metasomatism of the surrounding rocks, mainly by H_2O and CO_2".

Whether the nepheline-syenite was emplaced metasomatically is questionable. There are arguments for the injection of the nepheline-syenite material in the liquid state. The albite-nepheline dykes exhibit cleancut and sharp contacts against the bordering rocks, however, with only slight indications of contact-metamorphism. Barth (1927) describes the fluidal texture in a protaclastic border zone in some of the pegmatite dykes, which also exhibit albite and nepheline crystals of a peculiar roundness, probably due to mechanical deformation.

CHAPTER III

PETROLOGY AND MINERALOGY OF THE ULTRAMAFIC AND METAMORPHIC ROCK SEQUENCES

The preceding chapter presented the general lithology and the macroscopical characteristics of the various types of rocks occurring in the central and eastern regions on Stjernöy. In this chapter an account of the microscopical investigations of the most important rocks will be given.

The two groups referred to in the heading of this chapter are the sequences of ultramafic igneous rocks and the metamorphic rocks of mafic composition. As outlined in Chapter II, the description of the rocks of the ultramafic sequence refers to dunite, pyroxene-peridotite, and olivine-melagabbro, but it also includes the gabbro and anorthosite of the layered complexes on Rottenhallerfjell and Simavikfjell. The textural and mineralogical properties of gabbro gneiss, amphibolite, and syenite gneiss will be described in the section on the metamorphic rocks.

Thin-section study of rocks such as garnet-bearing granulites, calc-silicate layers, hornblendite, carbonatite, and nepheline-syenite was also made; the information gathered from these observations has already been used in their general description in Chapter II. For the other rocks the same order of discussion is followed as in the preceding chapter.

ULTRAMAFIC SEQUENCE INCLUDING THE LAYERED GABBRO

DUNITE

It has been explained (see page 187) that within the dunite outcrops on Stjernöy there also occur rocks with up to 75 or 95 per cent olivine (dunitic peridotite). It may be recalled here too that the dunitic rock also occurs in pockets or schlieren, their surface measuring only a few square metres, within the predominantly pyroxenic ultramafite. In Storelve valley and on the western side of Kjerringfjord there are also outcrops of dunite of considerable dimensions.

As can be seen in table 2, the sole constituents of fresh specimens of dunite are olivine and augitic pyroxene. The latter occurs as crystals which have grown interstitially between the olivine. Orthopyroxene is absent or is at most only a very rare constituent. As constituents of very minor importance a few grains of iron ore and green spinel occur.

Hornblende, largely secondary after pyroxene, occurs in some of the thin-sections. A few per cent saussuritized plagioclase have also been observed in one of the sections.

Description of some of the samples

Among the samples of olivine-rich rocks from Stjernöy the almost monomineralic specimen T 4.2a is well-suited to optical investigation. A photograph of this dunite sample is given in plate B, fig. 3. The rock of sample T 4.2a has a hypidiomorphic, slightly porphyritic texture; otherwise it is of moderate grain size, in the range of 2 to 5 millimetres.

TABLE 2 *Modal compositions of the dunitic rocks.*

	T 4.2[a]	T4.135[a]	T 4.88[a]	P 23	T 4.56	T 3.76	T 4.78
olivine	90.5	95.0	75.0	83.0	60.9	79.0	85.0
pyroxene	9.3	4.0	23.0	16.0	30.4	12.0	10.0
spinel-pyroxene symplectite	—	—	—	—	0.3	1.5	2.0
spinel	0.1	0.5	0.2	1.0	—	—	—
hornblende	—	—	1.2	—	8.4	4.0	3.0
plagioclase	—	—	—	—	—	1.0	tr.
ore	0.1	0.5	0.6	—	—	2.5	—

Olivine. The olivine in sample T 4.2a is only moderately serpentinized. From optic axial angle 2 Vα — determinations of 89°, 89°, and 91° (average 90°) by means of the universal stage, a Fo-content of 88 per cent [1]) was estimated using a graph published by Poldervaart (1950).

The olivine crystals in section T 4.2a exhibit only a very slight serpentinization along cracks and cleavages in the well-known mesh pattern. The serpentine is feebly yellow-greenish pleochroitic and has low birefringe and negative sign; obviously it is a Mg-rich crysotile.

Although fibrous by habit, in none of the sections does the crysotile exhibit the characteristics of economic-grade crysotile-asbestos. There is only slight pigmentation by iron-ore (probably magnetite) in the serpentine. In some of the other sections (e.g. T 4.88a), where the serpentinization has proceeded further, more iron-ore has segregated. It is noteworthy that in some samples the small veinlets of serpentine which cross the grain-boundaries between the crystals are oriented in about the same direction.

Pronounced zones with undulose extinction in the olivine crystals of specimen T 4.2a, as well as in those of most of the other samples, bear witness to severe mechanical deformation; some crystals even extinguish in more or less parallel strain-lamellae. In most of the other olivine crystals the extinction is in any case undulose.

Clinopyroxene. The augite in section T 4.2a has suffered only very slightly from secondary alteration. In some of the other sections the pyroxene has been altered partly to secondary hornblende (uralite).

No accurate optical determinations of clinopyroxene have been made in thin-sections of dunitic rocks, but the average values of the extinction angles $c \wedge \gamma =$ approx. 42° and the optic axial angles $2 V\gamma =$ approx. 52° agrees with the corresponding values of clinopyroxenes in peridotite. It seems likely that pyroxene of about the same composition occurs in both rock types.

The samples P 23 and T 4.56 from the massive outcrop of dunitic peridotite in Storelve valley consist of the same olivine and pyroxene as those in sample T 4.2a, the only difference being that the alteration of the dunite has progressed to a higher degree in the samples from Storelve valley. The alteration products are serpentine, magnetite dust, and carbonate. The alteration apparently made progress along

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[1]) By X-ray diffraction a Fo-content of 92 per cent is found in olivine (table 17).

fractures in the rock and along grain-boundaries between cracks within the olivine.

Also the samples T 4.78 and T 4.79 from the dunitic outcrop at the western side of Store Kjerringfjord contain high volumetric percentages of olivine (90 per cent and more). Not only hornblende but also biotite occur as accessory mineral in these samples. As can be seen in plate B, fig. 4, rounded grains of olivine occur in a granulated matrix which also consists of olivine. A cataclastic fracturing of the rock in these samples is prominent. The larger crystals of olivine also exhibit perfect strain-lamellae. In sample T 4.82 from the same locality, porphyroclastic grains of olivine showing pronounced strain-lamellae occur in a more or less mylonitized ground-mass. The textures described from the Store Kjerringfjord locality can only be explained by a severe mechanical deformation of the rock.

PYROXENE-PERIDOTITE

The components of the olivine-rich peridotite do not deviate much in their mineralogical characteristics from those in the dunite. However, most of the rock mapped as peridotite consists of a type of ultramafite with pyroxene as the predominant mineral. The pyroxene in the Stjernöy peridotite is augite; in most other cases, e.g., in the ultramafic zones of stratified gabbro occurrences, orthopyroxene is the predominant mineral in the peridotite (harzburgite, bronzitite).

The next important minerals are olivine and hornblende; the accessory minerals are ore, spinel and plagioclase. The modes of a number of pyroxene-peridotite samples are given in table 3. A characteristic phenomenon is the occurrence of a symplectitic intergrowth of spinel and pyroxene in the plagioclase-bearing samples. In the samples free of plagioclase the symplectite is absent and in these rocks spinel is of minor importance. Therefore, it may be concluded that the latter mineral is mainly of secondary origin.

TABLE 3 *Modal compositions of the pyroxene-peridotite samples.*

	T 4.2bI	T 4.2bII	T 4.88b	T4.135b	T 4.50	T 4.51	T 4.53	T 4.45
olivine	9.6	23.3	37.9	22.7	33.1	33.8	49.8	44.7
pyroxene	63.3	73.7	39.7	61.0	63.5	63.6	40.0	54.0
spinel-pyroxene symplectite	6.9	—	4.1	4.7	—	—	3.8	—
spinel	5.6	1.4	3.7	3.1	0.7	1.1	2.6	0.2
hornblende	10.9	1.5	6.6	2.3	2.1	1.6	2.4	1.2
plagioclase	3.4	—	7.8	5.9	—	—	1.4	—
ore	0.2	0.4	0.3	0.4	0.6	—	—	—

Description of some of the samples

Sample T 4.2b is a typical representative of a pyroxene-rich peridotite. The rock of this sample is of a very coarse grain-size and has furthermore a sub-porphyritic texture. Large subhedral crystals of augitic pyroxene measuring from 0.3 up to 1 centimetre in diameter predominate over olivine, the crystals of which are of smaller dimensions and generally occur in oblong or even lenticular shapes between the pyroxene (plate C, fig. 1). It should be mentioned here that this sample was taken from closely adjacent spots in the same locality as the preceding sample, T 4.2a.

It is apparent that pyroxene is the younger mineral and has grown larger than the olivine. Lense-shaped remnants of olivine between the large subhedral pyroxene crystals in some of the thin-sections indicate that the olivine may have been replaced metasomatically by the augite. The latter mineral in section T 4.2b is remarkably fresh; in some other sections the pyroxene has undergone an alteration into brown hornblende (uralite) along the cleavage planes or along the margin of the crystal.

In section T 4.2b hornblende also occupies the interstices between the augite crystals and is probably of primary crystallization. Thus, the order of crystallization of the principal minerals is: olivine first, then pyroxene and hornblende.

In pyroxenic rocks of this type, clinopyroxenes of pigeonitic composition may be found apart from augite (see Hess, 1941, p. 520). However, pyroxene showing the characteristics of pigeonite, with an optic axial angle of 2 $V\alpha \leqslant 32°$, has not been found in the Stjernöy-samples. It is therefore concluded that a two-phase clinopyroxene system did not exist on Stjernöy. According to Barth (1927), however, small amounts of a titaniferous augite occur in the peridotitic rocks on Seiland; this augite is recognizable by its strong dispersion.

In subordinate amounts orthopyroxene also occurs in the pyroxene-peridotite, most of it being found in symplectitic intergrowths with spinel occurring where olivine borders upon plagioclase. In some cases these reaction rims can be composite with first a rim of orthopyroxene around olivine and then spinel-symplectite between orthopyroxene and plagioclase. However, independent grains of orthopyroxene are absent or very rare.

In sample T 4.88b rims of orthopyroxene and also rims of spinel-orthopyroxene symplectites occur in abundance around grains of plagioclase, which gives a peculiar texture to these samples (plate C, fig. 2).

Pyroxene-spinel symplectites are sometimes developed in cases where the olivine is completely enclosed by augite; the symplectite in this case being less typically vermicular, consisting rather of a rim with small droplets of spinel around the olivine. The spinel droplets can in such cases also be embedded in clinopyroxene. It must be added here that no spinel is developed between olivine and augite if the rock is completely free of plagioclase (see table 3).

Mineralogy

Clinopyroxene. The augite in the peridotite samples most often shows well-developed cleavages which can be accentuated by ironoxide-staining or by segregated ore particles. It also exhibits a slight violet colour with occasionally visible reddish pleochroism. Most grains are weakly zoned, which is supported by the optic axial angle 2 $V\gamma$ — determinations, giving as the average of a few measurements in sample T 4.2b a value of 49° for the rim and 53° for the core of the crystals. The average extinction angle $c \wedge \gamma$ is about 45° and refractive index-determinations gave $n\gamma = 1.709$. On the basis of these data the pyroxene is a calcium-rich salitic augite [1]) (Winchell 1951). Optical data on clinopyroxenes in other peridotite samples are given in table 7.

In the augite from the ultramafic rocks many inclusions of various natures occur. The most striking are angular inclusions of a green mineral; spinel according to Barth (1927). These inclusions are oriented with their long dimensions at right angles to the {110}-cleavage (plate C, fig. 1); however, they may also be inclined at various angles to this cleavage. Small oblong plates or thin needles of a brownish

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[1]) For the pyroxene-peridotite somple T 4.88b a composition of $Wo_{47.8}En_{41.2}Fs_{11.0}$ has been determined by spectrochemical analysis. See table 15.

black mineral are also seen to occur within or also at small angles to these cleavage planes. The dark mineral inclusions probably consist of ilmenite or rutile.

Exsolution lamellae of orthopyroxene parallel to the plane {100}, which generally occur in clinopyroxenes (Hess 1941), do also occur in the augite of the ultramafic rocks on Stjernöy, although they are not abundant. Irregularly distributed tiny blebs of a mineral with high birefringence which occur frequently in the pyroxene, are believed to be calcite or perhaps sphene.

Olivine. In sample T 4.2bɪ the average result of the optic axial angle 2 Vα - observations in olivine is 88°, which corresponds with a Fo-content of 83 per cent. The olivine in this specimen, just as in most of the other samples, is moderately serpentinized; occasionally a few grains are altered into dark yellow serpentine (xylotile) with many ore-segregations. Data on the composition of the olivine in other samples of pyroxene-peridotite are given in table 17 (Chapter IV).

Hornblende occurring as well-defined crystals in the samples has a moderate birefringe and a strong pleochroism with yellowish brown α, reddish brown β, and greenish brown γ. According to crude measurements the optic axial angle 2 Vα is nearly 90° with strong axial dispersion $r > v$ and an extinction-angle $c \Lambda \gamma$ varying between 12° and 15°. In its optical characteristics this mineral could be regarded as a common hornblende, although the small angle $c \Lambda \gamma$ could also indicate basaltic hornblende. The hornblende shows little or no alteration to chlorite and calcite.

Green spinel occurs both as rather large anhedral grains up to 1 or 2 millimetres in size and as smaller irregular blebs along the grain boundaries. In some of the sections subhedral grains of spinel occur within olivine or pyroxene, which suggests an early crystallization of the spinel. But most of the spinel is clearly interstitial and crystallized later than olivine and pyroxene. Grains of spinel, together with iron-ore minerals, are frequently found within the hornblende crystals. Spinel-orthopyroxene symplectite is a noteworthy constituent in those sections containing spinel and, significantly, also plagioclase (see table 3).

Plagioclase in the ultramafic specimens is present in small clusters (about 2 or 3 millimetres in diameter) or in subhedral single grains. Some of the subhedral plagioclase grains are completely enclosed by a single pyroxene crystal; apparently this plagioclase is of early crystallization. Mostly the crystals are slightly clouded and small patches of calcite occur within them. By approximate $X' \Lambda$ trace {010} determinations on sections $\perp$ crystallographic a, an An content of about 78 per cent was determined in section T 4.2bɪ; by the zone-method of Rittmann, An contents of 79 and 80 per cent have been established for the albite-twins. This is a rather low value for an ultramafic rock, and it is suggested here that a decalcination of the plagioclase took place. The same applies to the plagioclase found in sample T 4.88b (see table 6).

The accessory ore mineral in the ultramafic specimens is probably magnetite. Sulphides have been detected in some of the other samples as tiny interstitial blebs; occasionally, somewhat bigger grains also occur, e.g. in sample T 4.88b.

OLIVINE MELAGABBRO

Olivine melagabbro is a typical transition rock between the pyroxene-peridotite and the gabbro in the layered suite of Rottenhallerfjell. Compared with the former

TABLE 4 *Modal compositions of the olivine melagabbro samples.*

	T 4.27	T 4.18	T 4.121	T 4.122	T 4.64	T 4.65	T 4.73	T 4.126
pyroxene	48.6	60.3	43.0	69.9	56.3	40.9	59.7	56.0
plagioclase	31.2	27.8	35.3	17.2	10.5	42.1	17.2	24.3
olivine	3.5	4.0	4.8	8.4	16.0	0.9	8.2	1.0
spinel-pyroxene symplectite	9.4	3.8	7.9	1.9	13.5	4.3	7.9	8.1
spinel	0.8	0.4	1.7	0.7	0.6	1.6	2.7	3.3
hornblende	6.1	3.8	7.2	1.9	2.9	10.1	4.3	7.3
ore	0.4	0.3	0.1	0.1	0.2	0.2	0.2	0.1

the augite content is about the same, but the olivine content has decreased considerably to the increment of plagioclase (compare tables 3 and 4).

The rock has a very coarse grained hypidiomorphic texture, consisting of clusters of plagioclase up to 2 centimetres in size, embedded in a network of interlocking clusters of pyroxene crystals.

The average grain-size of pyroxene and plagioclase is 1 or 2 millimetres. There are, however, porphyritic grains, especially of augite, measuring up to 1 centimetre. Compared with the pyroxene, the olivine grains are moderate in size but usually occur in small aggregates which may be of porphyroclastic origin.

There is no obvious foliation visible in most samples, but in some olivine-melagabbro specimens (e.g. T 4.64) there is coarse lineation in the rock due to oblong clusters of plagioclase.

The variation in the quantitative mineralogical composition of the olivine melagabbro can be found in table 4, where the results of a number of modal analyses are given.

Mineralogy

Clinopyroxene. Specimen T 4.27 can be considered to have yielded a representative section of the olivine melagabbro. The clinopyroxene in this sample is slightly zoned, as is indicated by different values for the optic axial angle 2 Vγ measured for rim and core of a crystal, such as 47½—51½, 47—51, 48½—51½, 48—52, and 49—53½ respectively. The extinction-angle c Λ γ is approximately 44°. Other optical data for clinopyroxenes in olivine melagabbro sections are given in table 7. From these results it might be concluded that the mineral is an augite [1]) not much different from the one occurring in the pyroxene-peridotite. In some of the augite-grains small ore-needles are met with in great numbers; green spinel-inclusions within the crystals and orthopyroxene lamellae are less abundant than in the pyroxene of the peridotite.

Olivine in this specimen is only slightly serpentinized; in the other olivine melagabbro samples it is usually much more altered. The only property measured was the optic axial angle 2 Vα, with values of 89° and 87° respectively, which correspond with a Fo-content of 84 and 80 per cent (see also table 17).

[1]) Spectrochemical analysis demonstrated a composition of $Wo_{53}En_{39}Fs_8$ (table 15).

Plagioclase will be dealt with briefly here because that mineral will be treated in the description of the gabbro. By means of universal stage methods (Rittmann's zone method), 85 and 84 per cent An were determined. Calcite also occurs in the plagioclase of the olivine melagabbro, which points to a certain degree of redistribution of lime by autometasomatism.

Spinel-pyroxene symplectites

As mentioned in the paragraph on pyroxene peridotite, a symplectitic intergrowth of spinel and orthopyroxene, already described by Barth (1927, pp. 14—19), occurs frequently as a reaction corona around olivine. The best-developed reaction coronas occur where olivine borders on plagioclase (plate C, fig. 3). It is probable that the plagioclase provided the aluminium and the olivine the necessary magnesium for the formation of the green spinel pleonast ($MgAl_2O_4$). This symplectite resembles in appearance the myrmekitic intergrowth of quartz and plagioclase bordering on potash feldspar. In the ideal case there is first a zone of orthopyroxene around the olivine and then a zone of finely-divided vermicular intergrowths of spinel in orthopyroxene. In some cases (e.g. sample T 4.124) the reaction rims can be even more complex due to an intricate subzoning in the symplectitic rim.

However, it rarely occurs that a reaction-corona surrounds an olivine grain completely. Furthermore, in many cases no intermediate rim of pure orthopyroxene is present and the symplectitic intergrowth borders immediately on the olivine.

The orthopyroxene in the rims around the olivine and in the spinel-poor parts of the symplectitic intergrowths is a pinkish-green pleochroitic bronzite with an optic axial angle 2 $V\gamma$ of about 90°. In sample T 4.27 distinct rims of spinel-free orthopyroxene occur. Independent grains of orthopyroxene in this sample, as in most of the others, either do not occur or are very rare.

In the symplectitic rims anhedral grains of spinel measuring up to 0.5 millimetre are also developed. It is likely that these irregularly shaped spinel grains also originated from the interaction of mobilized material from the plagioclase and the olivine. It even seems plausible that spinel grains of that size could be formed in places where no symplectitic borders are developed.

In the olivine-bearing melagabbro sample, T 4.126 (see table 4) very abundant rims of symplectitic intergrowth, with intercalated spinel grains, occur around more or less cataclastic cores of pyroxene which are free of spinel inclusions or are poor in that mineral (plate C, fig. 4). The pyroxene consists mostly of a pinkish-green pleochroitic orthopyroxene with a value for 2 $V\alpha$ of about 85° (corresponding with En 80). However, clinopyroxene is also found in the pyroxene core and in the symplectitic rims around it; in a few cases intergrowth of hornblende with spinel is seen. This type of spinel-pyroxene intergrowth is less vermicular than the one in the rims around olivine, the whole pyroxene-aggregate being riddled by more or less rounded droplets of spinel (sizes up to 0.05 millimetre).

In another gabbro sample, T 4.67 (see table 5), which has the same abundant rims of symplectite around orthopyroxene, only a few tiny grains of intensely serpentinized olivine occur. In sample T 4.126 some serpentinized blebs in amounts of up to 1 per cent occur, but no positive indication of the presence of olivine has been found.

The over-all impression gained from the occurrence of spinel-pyroxene symplectite in the last-mentioned samples is that of an arrested process of readjustment of equilibrium in the mineral compounds. It would not seem too improbable to assume that olivine was present in sections T 4.67 and T 4.126 in amounts in agreement with the occurrence of the symplectite.

TABLE 5 *Modal compositions of gabbro samples from layered suite.*

	T 4.93	T 4.46	T 4.47	T 4.24	T 4.19[a]	T 4.20	T 4.118	T 3.93	T 4.66	T 4.61	T 4.60	T 4.59	T 4.68	T 4.67	T 4.123[a]
plagioclase	60.7	61.3	57.9	49.3	60.8	68.6	60.6	47.7	58.6	66.7	61.5	56.2	65.5	60.4	56.0
olivine	4.0	1.2	—	—	—	0.5	—	—	0.7	—	—	0.5	—	0.1	—
pyroxene	31.3	31.7	27.8	42.1	22.1	23.7	29.0	34.6	28.8	24.8	27.5	24.6	23.1	15.3	33.8
spinel-pyroxene symplectite	2.2	1.2	6.9	—	1.4	2.3	6.1	3.7	5.6	2.5	1.4	5.1	0.8	17.7	1.4
spinel	—	—	—	0.2	—	0.3	0.2	0.8	0.9	0.3	0.7	1.2	1.4	2.7	0.2
hornblende	1.8	4.6	7.1	5.2	13.2	4.0	4.0	9.7	5.4	5.5	7.6	12.2	8.7	3.7	7.6
ore	—	—	0.4	3.2	2.5	0.6	0.1	3.5	0.1	0.2	1.2	0.2	0.5	0.2	1.1

GABBRO

In the specimens of the layered gabbro suite, plagioclase is the principal mineral; estimated roughly, it is twice as abundant as augite. All the other minerals are of minor importance, with the exception of hornblende which in some cases attains a percentage of more than 10 per cent.

The quantitative mineralogical composition of the layered gabbro rocks is not constant, as can be seen in table 5 in which the results of a number of modal analyses are given. Especially the amounts of spinel-pyroxene symplectite and hornblende vary; on the other hand the amount of plagioclase is fairly constant.

In the foregoing chapter the foliation of the gabbro was described as one of its main characteristics. An example of an excellently foliated melagabbro (sample T 4.98) from the middle, well-differentiated part of the layered suite of Rottenhallerfjell, is given in fig. 1, plate D. At this location, anorthosite layers alternate with gabbro and melagabbro in rapid succession.

The pronounced foliation of the rock is caused by the planar orientation of clusters of mafic minerals. These clusters are more or less elongated in the plane of the foliation; they vary from 1 to 2 centimetres in size. Granular plagioclase forms the matrix in which the mafic clusters are embedded. It may be noted that small grains of plagioclase do occur in the mafic clusters, although not abundantly, whereas single grains of pyroxene are not found in the monomineralic plagioclase matrix. Apparently the plagioclase is of early crystallization, but its velocity of crystallization seems to have been much lower than that of augite.

Another type of foliation is found in sample T 4.123a (plate D, fig. 2); a leucocratic gabbro taken from the northern contact of the layered suite which is here less well-differentiated. It is a granular rock of medium grain-size which exhibits an irregular foliation formed by more or less parallel orientation of mafic clusters up to 1 or 2 centimetres in size. In some of the mafic clusters porphyritic cores of augite measuring up to 5 millimetres occur in such a way that one tends to believe in their porphyroclastic origin. Similar indications have been found in other samples, too. However, in most cases it is impossible to tell whether the clusters of augite are crushed single crystals or igneous cumulates.

Other samples show plagioclase-phenocrysts measuring up to 1.5 centimetres. It is even more difficult to judge whether these may be considered crystals which resisted fragmentation. This is not apparent because the plagioclase matrix has a perfect mosaic texture and no fractured rims are found around the larger plagioclase cores.

Mineralogy

Plagioclase. In the samples of the layered gabbro the plagioclase has very few inclusions and is unusually fresh. Here and there a slight clouding of the plagioclase is found but saussuritization, so common in basic plagioclase, is totally absent. In many sections, however, a little calcite can be observed along the grain-boundaries or as inclusions in the plagioclase itself. In a few cases this "decalcination" of the plagioclase has gone so far that calcite makes up about 1 per cent of the total rock by volume. Scapolite occurs as secondary mineral in the plagioclase of some specimens, apparently formed at the expense of the plagioclase.

The plagioclase in the gabbro of the layered suite is generally twinned. The twinning laws most frequently met with are the albite and the pericline law, but acline and complex twinning have also been observed.

The plagioclase is very little zoned; only in a few cases has a difference for rim and core been observed in 2 Vα-determinations, e.g. 80°—85° in sample T 4.66 and 75°—79° in sample T 4.61.

Undulose extinction of the plagioclase was seen frequently in sections of the layered gabbro; the porphyritic plagioclase grains especially exhibit this phenomenon. In the latter crystals, bent twin-lamellae have also been found.

The An content of the plagioclase of the gabbro samples was established by various methods. The most exact results were obtained with the universal stage, using Rittmann's zone-method as improved by Van der Kaaden (1951). With the universal stage also determinations of the optic axial angle 2 Vα were made. The microscopical survey of the thin-sections included approximate $x' \wedge$ trace $\{010\}$ determinations made on sections normal to crystallographic a.

Table 6 contains the optical data mentioned above. This table also includes the data from the plagioclase-bearing ultramafites and the olivine melagabbro. The notation gives the order of sequence, going from the most ultramafic to the more leucocratic gabbro members of the rocks on Rottenhallerfjell.

From the results of the plagioclase determinations it can be concluded that the highest An percentages occur in the olivine melagabbro and in the anorthosite (85 to 90 per cent); the layers towards the contact of the layered sequence with the gabbro gneiss (samples T 4.59—T 4.123a) yield lower An percentages (72 to 78 per cent).

The feldspar in the ultramafic rocks, contrary to the expectations, also does not consist of plagioclase extremely high in An but instead has a rather moderate An content of about 80 per cent.

Clinopyroxene. In the gabbro this mineral is represented by a very weakly violet-coloured variety of diopsidic augite, which sometimes also exhibits a slight pleochroism. The crystals are usually fresh and free of staining, but inclusions do occur in most of the grains.

Inclusions in the pyroxene of the gabbro specimens are less abundant than in the pyroxene of peridotite or olivine melagabbro. The angular green inclusions are observed only rarely, and lamellae of orthopyroxene in the augite are not abundant either. Small patches of calcite in the augite are very common in most of the samples.

Rather frequently seen is a type with brownish-black needles and oblong plates of ore. In sample T 4.19a these needles occur in almost every pyroxene grain, usually parallel to the most prominent cleavage but also at various angles to the latter.

Table 7 gives such optical data for the augite, as the extinction angle $c \wedge \gamma$ and the optic axial angle 2 Vγ. Here again, the samples are arranged in the order of their emplacement at Rottenhallerfjell.

The optical properties of the various samples do not differ greatly. Both the value of the extinction angle $c \wedge \gamma$ and the optic axial angle 2 Vγ of the augite from the anorthositic samples seem to be somewhat higher than for the augite from the gabbro samples. In table 7 some chemically-determined values of the WoEnFs-composition have been given for comparison. The different optical data for samples T 4.88b and T 4.19a seem to be confirmed by the chemical analyses.

Orthopyroxene is a very subordinate component of the gabbro samples. In most of the spinel-pyroxene symplectite-bearing thin-sections pinkish-green pleochroitic orthopyroxene can be found. Independent grains of orthopyroxene are also found occasionally. In only a few of the samples (e.g. T 4.66 and T 4.123a) is the

TABLE 6 *Optical data on plagioclase and interpretation in anorthite-content for the rocks of the ultramafic sequence on Rottenhallerfjell.*

	sample no.	average of x′Λ tr {010} on sections ⊥ a	average of 2Vα	universal stage zone-method as interpreted by Van der Kaaden		average of inter-pretations
				albite law	other laws	
ultra-mafite	T 4.2b	39° (s) 78 % An		79 %, 80 %		79 % An
	T 4.88b	39° (s) 78 % ,,	80 °? 74 % An	78 %	78 % per	78 % ,,
olivine melagabbro	T 4.16	40° 80 % ,,		69 %, 73 %	70 % karl	70? % ,,
	T 4.27	40° 80 % ,,	82° 81 % ,,	ca. 85 %	84 % per	84 % ,,
	T 4.64	40° 80 % ,,	90° 83 % ,,	90 %, ca. 90 %	ca. 95 %, 93 % per	90 % ,,
	T 4.65	40½° 81 % ,,		85 %		85 % ,,
	T 4.98	35° 70 % ,,		80 %		app. 75 % ,,
anortho-site	T 4.97	40½° 81 % ,,	84° 78 % ,,	81 %, 80 %		80 % ,,
	T 4.62b	39½° 79 % ,,	80½°? 75 % ,,	83 %, 88 %	85 %, 83 % per	84 % ,,
	T 4.63b	40° 80 % ,,	82° 78 % ,,	78 %, 80 %		79 % ,,
layered gabbro	T 4.66	38° 76 % ,,	83° 79 % ,,	83 %, ca. 80 %		80 % ,,
	T 4.61	38° 76 % ,,	79° 72 % ,,	ca. 80 %, 80 %		80 % ,,
	T 4.60	34°? 67 % ,,	80° (s) 74 % ,,	ca. 75 %		75 % ,,
	T 4.126	39½° 79 % ,,	80° (s) 74 % ,,	84 %, ca. 85 %		84 % ,,
	T 4.59	36° 72 % ,,	84° 78 % ,,	72 %		72 % ,,
	T 4.67	38½° 77 % ,,	85° 80 % ,,	80 %, 77 %		78 % ,,
	T 4.123a	39° 78 % ,,	81° 76 % ,,	77 %		77 % ,,

s = single observation

total amount of orthopyroxene more than 3 per cent. X-ray diffraction showed that the composition of the orthopyroxene varies from about En 85 to En 92 in the gabbro samples (see table 16).

Olivine was found only as a minor constituent in a few of the gabbro specimens investigated. Corroded remnants of olivine occur in samples T 4.59 and T 4.66 within the patches of serpentine of greenish-yellow colour. In the serpentine much segregation of magnetite is found. This serpentine is probably xylotile, in which mineral the iron is partly oxidized to the ferric state. The 2 $V\alpha$-determinations of the olivine remnants in the serpentine gave an average value of 85° for T 4.66 and 84° for T 4.59; this corresponds with Fo-contents of 75 and 73 respectively (Poldervaart 1950).

Hornblende in the gabbro is a strongly pleochroic mineral with yellowish brown for α, reddish brown for β, and dark brown with a greenish tinge for γ. The optic axial angle has a negative sign and varies from 86° to 88°; this angle exhibits a strong axial dispersion. Measurement of the angle of $c \Lambda \gamma$ gave values varying between 10° and 14°. As regards optical properties this mineral lies midway between common hornblende and basaltic oxyhornblende (Winchell 1951).

Secondary hornblende (uralite) with the same optical properties frequently forms irregular blebs along cleavages and grain-boundaries in the pyroxene. A predominant site for this uralitization process is at the contacts of the pyroxene clusters with the plagioclase. This explains the occurrence of narrow fringes of hornblende around the pyroxene clusters (plate C, fig. 4 and plate D, fig. 2) which are found especially in the gabbro.

Interstitial grains of hornblende frequently include more or less rounded grains of green spinel and ore. It is assumed that these minerals were formed during secondary processes in which both the pyroxene and the plagioclase supplied the necessary elements for the formation of hornblende. A surplus of magnesium and aluminium could then crystallize as spinel, the surplus of iron resulting in ore-formation, probably magnetite.

In the hornblende of sample T 4.19a complex grains occur, consisting half of spinel and half of ore. Peculiar vermicular aggregations of ore-minerals are also found in this sample, very similar in appearance to the ore-segregations in serpentinized olivine.

ANORTHOSITE

In the layered gabbro complexes of Rottenhallerfjell and Simavikfjell, anorthosite ¹) or anorthositic gabbro (if more than 5 per cent of the rock consists of mafic minerals) is an important rock unit. A representative specimen of anorthositic gabbro is sample T 4.62b (plate D, fig. 3). In the thin-section of this sample, which contains 78 per cent plagioclase, this mineral forms a mosaic of fairly equal grain-size (0.2 to about 1.0 millimetre). The texture could best be described as hypidiomorphic granular. Small and rather thin clusters of pyroxene, small single grains of pyroxene or hornblende, and a few porphyritic crystals of plagioclase up to 7 millimetres in size, are embedded in the plagioclase matrix.

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¹) The term anorthosite is derived from the word anorthose, which is the French equivalent for the mineral anorthoclase. Strictly speaking, names like bytownitite or anorthitite would be better descriptively but they do not find general acceptance (See Johannsen 1939 p. 197).

TABLE 7 *Optical data for the augites, compared to chemically determined WoEnFs-compositions in the rocks of the ultramafic sequence on Rottenhallerfjell.*

	sample no.	value of extinction angle cΛγ	approx. results	optic axial angle 2Vγ-measurements for rim and core	approx. results	chemical determination of		
						Wo	En	Fs
ultramafite	T 4.2^a	38, 44, 42, 42, 44	42	52				
	T 4.88^a	35, 40, 38	40	52—54, 52—56, 54—58, 51—54, 49—52	51—54			
	T 4.2^b	41, 45, 46	45	49—52, 50—53, 49—53	49—53			
	T 4.88^b	43, 48, 47, 46	46	52—54, 54—58, 53—58, 56—58	54—58	47.8	41.2	11.0
olivine melagabbro	T 4.27	44, 45	44	48—52, 47—51, 49—52, 48—52, 49—54	48—52	49.7	36.0	14.3
	T 4.64	41, 41, 45, 44	44	48—51, 46—49, 48—53, 47—53, 52—57	48—53			
	T 4.65	41, 44, 43, 42, 45	44	52—55, 51—54, 52—55	52—55	51.0	38.4	10.6
	T 4.98	42, 43, 44, 45, 43	43					
anor-thosite	T 4.97	47, 43, 47, 50, 45, 48	47	54—58, 54—59	54—58			
	T 4.62^b	48, 46, 48, 43, 46, 45	47	55—57				
	T 4.63^b	50?		57—64, 55—64	56—64			
layered gabbro	T 4.62^a	47, 45, 41, 41, 45, 46	45	48—52				
	T 4.63^a	41, 41, 46, 42, 44, 43	43	52—57, 51—56	52—57			
	T 4.66	43, 44, 44, 46	44	50—57, 48—56, 48—57	49—57	51.2	34.0	14.8
	T 4.61	44, 43, 45	44	48—54, 51—54, 50—54	50—54			
	T 4.60	44, 45, 43	44	52—56, 51—56	52—56			
	T 4.126	42, 44, 45, 46	44	50—54, 53—57		51.4	37.8	10.8
	T 4.59	44, 43, 44	44	50—54, 51—56, 49—55	50—55			
	T 4.67	46, 44, 45	45	53—58, 52—56	52—57			
	T 4.123^a	42, 45, 45, 44	45	48—56, 51—56, 50—57, 53—57, 48—53, 49—53	50—57	49.3	35.9	14.8

For chemical data see chemical analyses of augite, page 255.

There is a fairly good foliation owing to parallel orientation of the mafic components. It is more difficult to decide whether the plagioclase also exhibits parallel orientation; locally this seems indeed to be the case.

It may be recalled here that the modes of a number of these anorthosite samples have already been given in table 1 (page 193).

Plagioclase. This mineral in the anorthositic gabbro from Stjernöy is unusually fresh and free of inclusions. Anorthosite from other locations is often rather dark in colour due to innumerable inclusions within the plagioclase grains (see Johannsen 1939 p. 199). According to this author, white plagioclase, such as found in the Stjernöy samples, is much less common and occurs only in the fine-grained rocks.

In specimen T 4.63b, almost an anorthosite in view of its plagioclase content of 90 per cent, rather clouded crystals of that mineral occur together with very fresh crystals, which indicates a crystallization of the plagioclase in two generations. In addition, it has been noticed that the pyroxene in the small mafic clusters of this sample is very corroded. After its crystallization the pyroxene apparently reacted with the plagioclase under formation of a green hornblende and the separation of spinel droplets.

An accurate universal stage determination of the An content of the plagioclase in sample T 4.62b, using Rittmann's zone-method on albite- and pericline-twins, gave An percentages of 83, 88, 85 and 83 respectively (see table 6). This suffices to show that the plagioclase in this anorthosite sample is a bytownite of approximately 85 per cent anorthite.

The data for samples T 4.97 and T 4.63b, including optic axial angle 2 $V\alpha$-determinations and approximate $x' \wedge$ trace {010}-determinations, also point to bytownitic plagioclase with 79 to 80 per cent anorthite molecule (see table 6).

In the plagioclase of the anorthosite samples there is strongly undulose extinction; in sample T 4.63b the twin-lamellae are bent and in some cases even distorted. Zoned structures occur in the plagioclase of sample T 4.63b but are very weak in the plagioclase of sample T 4.62b.

The augite in the anorthosite layers does not deviate much from that found in the surrounding gabbro (see table 7). The average extinction angle $c \wedge \gamma$ in sample T 4.62b is about 47°. The value for 2 $V\gamma$ in the augite of the anorthosite is somewhat greater than that in the pyroxene of the gabbro. However, in sample T 4.63b, 56° was found for the rim and 64° for the core of the augite.

Compared with the gabbro, the pyroxene in the anorthosite exhibits a greater amount of uralitization; in sample T 4.63b the pyroxene is even rather corroded. Orthopyroxene is rare in the anorthosite and olivine is completely absent.

The hornblende in the anorthosite samples has a definitely more greenish tinge with pleochroism in greenish-brown and greenish-yellow colours. The extinction angle $c \wedge \gamma$ is of a low value, varying between 8° and 12°. In sample T 4.62b an intergrowth of hornblende and spinel occurs within the small mafic clusters, intercalated within the plagioclase matrix.

Small, more or less idiomorphic, grains of ore minerals occur in minor amounts in the anorthosite sections; in sample T 4.97 sphene is also found as an accessory mineral.

Concerning the order of crystallization, it has been concluded (see page 242) that the augite precipitated first or in any case had a more rapid rate of crystallization. This view is confirmed by an observation in thin-section T 4.120, thin veins of plagioclase dissecting the mafic streaks and the anorthositic intercalations in that sample as well.

ROCKS OF THE METAMORPHIC COMPLEX

GABBRO GNEISS

As has been explained in Chapter II, recognition of the gabbro gneiss in the field depends upon a few characteristics such as foliation formed by mafic clusters and upon the rather monotonous gneissic appearance. These are rather general criteria and it may be said that the recognition hinges even more on the association of gabbro gneiss with layers of rocks such as amphibolite, garnet-bearing granulite, syenite gneiss and, last but not least, layers of calc-silicate rock.

The ratio of plagioclase to mafic minerals in the samples of the gabbro gneiss varies considerably; this is expressed by the modes of a number of samples from different regions of Stjernöy (see table 8). It ranges from as low as about 35 per cent to as high as about 75 per cent. Gabbro gneisses with still higher percentages of plagioclase, in other words samples of anorthositic composition, have not been found in the regions of Stjernöy investigated by the author ¹).

The gabbro gneisses exhibit a higher content of hornblende and ore than the layered gabbro rocks related to the ultramafic sequence (compare the modes in tables 5 and 8). Apatite and to a lesser degree biotite occur as accessory minerals in the samples of gabbro gneiss; they are absent in the layered gabbro. As can be seen in table 8, a local variation in the amounts of apatite is evident; the areas of Udsiktfjell and Sundfjell being richer in that mineral than, for instance, the areas around Store Kjerringfjord.

In the following paragraphs an attempt will be made to find out in how far microscopic evidence concerning textural and mineralogical features can add to the diagnostic characteristics of the gabbro gneiss.

Textural types of gabbro gneisses

Concerning the textural relations in the gabbro gneiss, the most common type is a gabbro gneiss with flat clusters of mafic minerals oriented more or less parallelly so as to constitute a foliation. A photograph of a good specimen (T 4.41) of this type is given in plate D (fig. 4). The rock in this sample is of medium grain-size and has a hypidiomorphic equigranular texture. The degree of perfection of the foliation is obviously determined by the shape of the clusters. In sample T 4.41 a perfect foliation is developed by the parallel orientation of lenticular mafic clusters which in this case are free of plagioclase inclusions. Within the mafic clusters of other samples of foliated gabbro gneiss, small plagioclase grains occur, indicating that these clusters are not purely fractured pyroxene crystals.

An excellent example of preferred orientation is also found in sample T 4.111, forming a thin and well-defined gneissosity, on a 1 to 3 millimetre-scale, caused by alternating laminae of leucocratic and melanocratic composition (plate E, fig. 1). In this sample porphyritic grains of pyroxene of about 5 to 10 millimetres in size occur in a normal ground-mass of 0.1 up to 1 millimetre. Such phenocrysts (sometimes altered to a porphyroclastic aggregate) are found in some other samples of the gabbro gneiss as well.

A very thinly laminated gneiss of a fine grained texture (diameters in the order of 0.05 to 0.2 millimetre) is found, for instance, in sample T 4.112a. This latter sample consists of alternating laminae of plagioclase-rich and plagioclase-poor composition, 0.2 to 1.0 millimetre in thickness. It is noteworthy that the dominant mineral in this sample is diopside.

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¹) Barth (1961) records the occurrence of anorthositic and ultramafic intercalations in a complex of mafic gneisses at Bumannsfjord (Seiland).

TABLE 8 *Modal compositions of the gabbro gneiss samples from the Store Kjerringfjord area.*

	T 4.123^{b}	T 4.75	T 4.76 1)	T 4.58	T 4.129	T 3.48	T 3.49	T 3.66^{a}	T 3.66^{b}
plagioclase	48.4	50.4	33.8	38.3	67.8	46.6	68.2	61.0	48.4
pyroxene	34.8	38.3	37.2	46.2	20.1	34.7	26.6	37.4	45.5
spinel-pyroxene symplectite	—	5.4	22.4	4.9	—	—	—	—	—
spinel	—	1.8	3.9	5.0	—	0.4	0.5	—	1.1
hornblende	12.1	4.0	1.1	5.7	4.6	14.6	4.7	—	4.8
ore	4.6	0.2	0.1	0.1	6.5	3.8	0.1	0.8	0.2
biotite	—	—	—	—	—	—	—	0.8	—
apatite	—	—	—	—	0.9	—	—	—	—

Modal compositions of the gabbro gneiss samples from Udsiktfjell and Sundfjell.

	T 4.111	T 4.112^{a}	T 4.80	T 4.69	T 4.71	T 4.41	T 4.38	T 4.37
plagioclase	63.6	42.4	42.7	36.2	44.3	43.5	55.6	72.6
pyroxene	19.8	54.4	37.2	20.7	28.1	33.0	22.1	7.2
spinel-pyroxene symplectite	—	—	—	—	—	—	—	—
spinel	—	—	—	—	—	—	0.3	—
hornblende	10.8	—	17.0	40.0	24.8	23.0	14.1	16.5
ore	5.7	0.1	3.2	1.7	2.4	0.4	7.7	2.6
biotite	—	2.8	—	—	—	—	—	—
apatite	—	0.2	—	1.4	0.4	0.2	0.3	1.2

Modal compositions of the gabbro gneiss samples from the Store Kvalfjord-Sternodden area.

	T 4.4	T 4.130^{a}	T 4.130^{c}	T 4.89^{a}	T 4.11
plagioclase	33.8	60.7	44.6	72.5	62.4
pyroxene	52.5	16.5	27.7	9.1	18.3
spinel-pyroxene symplectite	0.9	—	—	—	—
spinel	0.6	—	—	—	—
hornblende	9.4	16.1	18.4	13.7	10.7
ore	1.9	6.7	9.3	4.7	3.6
biotite	0.6	—	—	0.1	4.8
apatite	0.2	0.1	—	0.1	—

1) Sample T 4.76 is taken from the contact of gabbro gneiss with the layered complex at Rottenhallerfjell. This sample contains 1.4 per cent olivine and probably is a remnant of an olivine-bearing gabbro dyke which resisted the metamorphosis of the country rocks in its surroundings.

Gabbro gneiss with single grains of pyroxene well aligned in the plane of the foliation is found in sample T 4.130a (plate E, fig. 2). The grain-size in this rock is slightly unequal (0.2 to 3 millimetres) and the texture can best be described as subidiomorphic with lathshaped plagioclase and prismatic augite crystals. The augite exhibits a definite lineation of the crystallographic c axes for most crystals. Not only the pyroxene but also many of the laths of plagioclase show a marked preferred lattice orientation visible by virtue of their extinction positions.

A hypersthene-bearing leucocratic type of gabbro gneiss (e.g., sample T 3.62) also shows a crude linear orientation of the pyroxene owing to parallel orientation not only of single grains but also of small stringers of pyroxene. The main mafic component in this case is hypersthene, the sample being noritic rather than gabbroic in composition. It is the experience of the present author that the intercalations of hypersthene-plagioclase gneiss within the metamorphic complex are usually more leucocratic than the average type of gabbro gneiss.

Between a foliation formed by preferred orientation of single grains of pyroxene (plate E, fig. 2) and one caused by clusters of parallel orientation (plate D, fig. 4) transitions are possible, such as lineation of fractured grains of pyroxene, of large porphyroclastic mafic aggregates, or oblong mafic clusters, all oriented parallel with their long axes in the plane of foliation.

It may be added that in the gabbro gneiss areas rock with coarse mafic clusters, unoriented or very poorly oriented, is found at several locations. At Mjånes and Lille Kvalfjordnes such coarse grained rock occurs in the gabbro gneiss where it resembles average igneous gabbro in appearance; large pyroxene crystals up to 1 centimetre in size exhibit a clearly poikilitic growth and consequently indicate a late crystallization of the pyroxene. There are no objections from either the textural or the structural point of view to considering these samples as truly igneous gabbros.

A rock of monzonitic rather than gabbroic composition exists where the content of mafic minerals in such leucocratic gneisses has decreased further and orthoclase has eventually entered into the mineral composition. Such rocks, also named mangerites, with both diopside and hypersthene as mafic constituents, are intermediate between the average gabbro gneiss and the syenite gneisses. In the northern and western part of Stjernöy, where syenitic intercalations are abundant, such mangeritic rocks may also be found (see page 204).

Mineralogy

Plagioclase. In most cases the anhedral plagioclase in the gabbro gneiss specimens is fresh and devoid of inclusions. If a slight alteration has occurred, sericite, scapolite, and calcite are found in minor amounts as the products of alteration.

Commonly the plagioclase is twinned, usually exhibiting twins with narrow lamellae according to the albite-law, but complex twinning and twins with irregular and twisted lamellae also occur. In still other samples a considerable percentage of the plagioclase, although undulose and slightly cataclastic, is not twinned at all.

This undulose extinction is a very frequent phenomenon in many samples. Further evidence of the severe mechanical strain suffered by the gabbro gneiss is found in the presence of bent twin-lamellae and, more rarely, also in the occurrence of a slight mortar texture along the edges of the plagioclase crystals (e.g. sample T 3.62).

In most specimens a zoned structure in the plagioclase can be found. It is possible that only a few crystals in a sample exhibit this feature, while the general mass of the plagioclase shows hardly any zoning. In some cases the plagioclase is zoned such that there is a narrow rim of clearly different extinction around nearly all the crystals. The difference in An content between core and rim can amount to 10 per cent. In all investigated cases the core of the plagioclase crystal contains the higher An percentage.

The anorthite content of the plagioclase in the gabbro gneiss samples was determined by the same methods as applied to the plagioclase of the layered gabbro (see page 224): Rittmann zone-method determinations on albite-twins, measurements of optic axial angle 2 $V\alpha$ with the universal stage, and approximate $x' \wedge$ trace {010} determinations in sections normal to crystallographic a carried out during the survey of the thin-sections with the standard microscope. The results of these observations are given in table 9.

With the exception of a number of samples, for instance T 4.123b (at the contact with the layered gabbro complex) and T 4.41 (at considerable distance from the contact), the An content of the bytownitic plagioclase varies between 67 and 80 per cent. These exceptions are within the range of an andesine composition of the plagioclase. For the moment, no explanation can be given for these highly deviating values of the An content, nor can the question be answered whether the much lower An content is persistent in certain zones or bands.

Is is to be recalled here that in all cases the measured values are taken from the cores of plagioclase crystals.

Clinopyroxene

The clinopyroxene in the gabbro gneiss samples occurs as anhedral,somewhat rounded grains or small clusters; short prismatic crystals are rarely met with in the average type of gabbro gneiss. In the thin-sections of the gabbro gneiss it mostly has a very weak violet colour; in some cases the pyroxene has a slight greenish tinge. This may or may not be accompanied by a reddish pleochroism.

In clinopyroxenes of the gabbro gneiss samples the extinction angle $c \wedge \gamma$ and the optic axial angle 2 $V\gamma$ were also determined. These optical data can be found in table 10.

It appears that the clinopyroxene in the samples of gabbro gneiss is an augite with a positive elongation and with the extinction angle, $c \wedge \gamma$, varying between 42° and 44°. The results of the optic axial angle and 2 $V\gamma$-determinations show a remarkable uniformity. For most of the pyroxenes, which are slightly zoned, the values for the rim lie between 52° and 54°; for the cores, values between 56° and 60° are found.

On the basis of these optical observations a rather uniform chemical composition of the augite might be expected. This is confirmed by the results of the chemical analyses of these pyroxenes, which show only small variations in their WoEnFs-composition.

Within the augite of the gabbro gneiss samples, small needles or oblong plates of ore are oriented parallel to the crystallographic c axis, but are also inclined at 30° or perpendicular to that direction. In most augites these needles occur sparsely, with a tendency towards a higher concentration in the phenocrysts. Such phenocrysts are scarce, but they are found, for instance, in sample T 4.111 (plate E, fig. 1).

In specimens T 4.71 and T 4.130a these ore-needles occur in great abundance. In sample T 4.123b very small needles of ore occur in the core of the augite crystals, which also may be stained dark brown by very finely distributed dust of ore-particles.

Other inclusions met with in the augite of certain samples are well-oriented flakes of a brown colour (goethite or brookite?); only in sample T 4.11 do they

TABLE 9 *Optical data on plagioclase and interpretation in anorthite content for the gabbro gneisses of the metamorphic complex.*

sample no.	Average of x'Λ tr. {010} in sections ⊥ a	Average measurements of optic axial angle 2 Vα	Universal stage zone method on albite twins	Average of interpretations
T 4.123b	27½° 52 % An	95° 43 % An	43 %, 42 %, 48 % An	43 % An
T 4.57	38° 76 % „		71 %, 72 % „	72 % „
T 4.75	37° 73 % „			approx. 73 % „
T 4.71	34° 67 % „			approx. 67 % „
T 3.48	39° (s) 78 % „		79 % „	79 % „
T 3.49	39° (s) 78 % „	87° 72 % „	80 % „	80 % „
T 4.111	34° 67 % „			approx. 67 % „
T 4.112a	37° 74 % „		75 %, 75 % „	75 % „
T 4.129	21° 38 % „	85° 33 % „	33 %, 33 % „	33 % „
T 4.41	27°? 51 % „			approx. 51 % „
T 4.4	34° 67 % „	88° (s) 70 % „	70 % „	70 % „
T 4.66a	37½° 74 % „	87° (s) 72 % „	71 %, 70 % „	71 % „
T 4.66b	34° 67 % „	85° (s) 75 % „	70 % „	70 % „
T 3.62	24° 44 % „			approx. 45 % „
T 3.69	29° 54 % „			approx. 55 % „
P 24	31° 58 % „	97° (s) 63 % „	60 % „	60 % „

s = single observation.

TABLE 10 *Optical data for the augites in the rocks of the metamorphic complex compared to chemically determined WoEnFs-compositions.*

sample no.	value of extinction angle $c \wedge \gamma$	approx. results	optic axial angle $2V\gamma$-measurements for rim and core	approx. results	chemical determination of		
					Wo	En	Fs
T 4.123^{b}	44, 44, 40, 44	44	58—62, 58—60, 57—60	58—60	46.6	36.6	17.2
T 4.57	43	43	53—57, 55—59, 54—58	54—58	45.5	38.0	16.5
T 4.75	43, 43, 42, 43	43	54—59, 54—58, 54—58	54—58	45.6	40.8	13.6
T 4.71	41, 43, 41, 43	42					
T 3.48	44	44	54—58, 53—58, 54—60	54—58			
T 3.49	42, 43, 44	43	53—56, 50—56, 49—55, 53—59	52—56			
T 4.111	43, 42, 42, 40, 44	43	54—58, 54—59, 55—59	54—59	46.6	38.9	14.5
T 4.112^{a}	43, 41, 43, 40, 42	42					
T 4.4	42, 42, 41	42			47.3	37.2	15.5
T 3.66^{a}	40, 42, 45, 40	43	54—58, 54—58, 54—59	54—58			
T 3.80	40, 43, 44, 42, 45, 44	44	54—58, 55—59, 53—59	54—59			
T 3.62					46.1	36.3	17.6
T 3.69	41, 42, 40, 43	41	55, 58, 57, 59	57	48.7	36.4	14.9
P 24	app. 39, 40		55	55	46.3	40.9	12.8

For chemical data see chemical analyses of augite, page 255.

occur in sufficient numbers to cause the characteristic metallic lustre "Schiller" of the pyroxenes. The angular spinel inclusions which are so characteristic of pyroxene from the ultramafic sequence do not occur in the augite of the gabbro gneiss samples.

Spinel. In general, spinel and spinel-symplectite are far less abundant constituents in the samples of the gabbro gneiss than in those of the ultramafic sequence, with the exception of a few samples [1]) taken from the gabbro gneiss North of the layered gabbro suite on Rottenhallerfjell. The gabbro gneiss samples taken directly at the contact with the Store Kjerringfjord ultramafic outcrop are also very rich in spinel, and here too a kind of symplectitic intergrowth of spinel and pyroxene occurs [2]). The latter shows a great resemblance to the symplectite in the rocks of the ultramafic sequence, except that here the spinel-symplectites are less vermicular. It has already been suggested (p. 221), that the spinel originated from a reaction between a magnesium-rich mineral (hypersthene) and its aluminium-rich surrounding (plagioclase). Exsolution of magnesium and aluminium from hypersthene under decreasing P and T conditions could be an alternative explanation.

Orthopyroxene. In samples of the normal gabbro gneiss, orthopyroxene is a rather frequent associate of augite, for example in samples T 4.4 and T 4.111 in which up to 10 per cent of the mafic constituent consists of orthopyroxene [3]). In most of the other samples orthopyroxene occurs either in amounts of up to a few per cent or only as a few, more or less independent grains. However, in sample T 4.123b this mineral is not found at all.

Orthopyroxene can easily be distinguished in thin-section by its virtually straight extinction, its lower refractive index (compared to augite), and its marked brownish red-green pleochroism. The optic sign in this mineral is positive; the optic axial angle (2 Vγ) values lie between 75° and 90°. This corresponds to an approximate chemical composition of about En_{90} to En_{80}; the orthopyroxene, therefore, is a bronzite. Concerning the composition of orthopyroxenes, further information will be given in Chapter IV (see table 16).

In samples T 3.62 and T 4.137 (also in sample P 24 from Lille Kufjord, Seiland) orthopyroxene occurs in great abundance and is the dominant mafic mineral. In thin-section this orthopyroxene is distinguished by a fine lamellar, diallage-like structure, caused by exsolution-lamellae parallel to {100}. It also shows much less pleochroism than the above-mentioned orthopyroxene and has a negative optic sign. By means of X-ray diffraction a composition of En_{60} to En_{70} was determined. It is important to note that these samples, which occur as intercalations in the amphibolite and gabbro gneiss respectively, are leucocratic rocks (the ratio plagioclase : pyroxene is about 70 : 30) and are also free of spinel or are in any case very poor in that mineral.

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[1]) Specimen T 4.76, taken from the region mentioned, apparently must be a sample of an olivine melagabbro sill, interstratified with the gabbro gneiss.

[2]) In gabbro gneiss samples T 4.57 and T 4.75 taken near the contact with the layered gabbro sequence North of Rottenhallerfjell, very abundant symplectitic intergrowths of spinel and pyroxene also occur.

[3]) Spinel occurs in both samples, also in appreciable amounts (see table 8). In sample T 4.4 most of the orthopyroxene grains are relatively devoid of spinel inclusions, although in others a crude type of intergrowth between spinel and orthopyroxene is found. In T 4.111 a few elongate droplets of spinel occur in nearly every orthopyroxene grain; in some cases the spinel is even more abundant and a crudely vermicular intergrowth results.

Hornblende. This mineral is more abundant in the samples of the gabbro gneiss than in those of the gabbro of the ultramafic sequence (compare tables 5 and 8). It occurs incorporated in the mafic clusters or dispersed as small grains. In some samples the hornblende shows a tendency to poikiloblastic growth around plagioclase and pyroxene crystals. However, the mineral is less obviously secondary to pyroxene than in the rocks of the ultramafic suite.

Its optical properties point to a similarity with the hornblende from the layered gabbro described on page 226. It also has strong pleochroism in greenish brown and brownish-yellow. In most of the investigated samples the optic axial angle has a negative sign and varies between 78° and 86°, which is somewhat lower than in the hornblende of the ultramafic sequence. The extinction angle $c \wedge \gamma$ has values varying from 10° to 13°, which is also somewhat smaller. This would mean that the hornblende has a composition, which lies nearer to oxyhornblende than to common hornblende (Winchell 1951, pp. 437—439).

In some samples, e.g. T 3.48, rather large anhedral grains of spinel (up to 1 millimetre) are surrounded by hornblende. The co-existence and the mode of occurrence of these minerals clearly suggests a secondary or at any rate a late crystallization of both minerals.

An important rock constituent of the gabbro gneiss is formed by the ore minerals, which make up 5 to 10 per cent in many samples. The grains of ore usually occur interstitially within the mafic clusters, but small grains of ore are also found in the plagioclase-ground-mass. Just as is the case with the grains of spinel, ore minerals are frequently surrounded by a rim of hornblende. In some cases the ore mineral is somewhat corroded and a mineral with a red internal reflection can be found within or near the opaque grain. The minerals in question are probably magnetite and hematite. From the chemical analyses it is concluded that some ilmenite must be present, either independently or as solid solution in magnetite, to account for the TiO_2 content found in the analyses.

Of other accessory minerals apatite and biotite are met with in noticeable amounts in some of the sections (see table 8); these minerals are rare or absent in the gabbro of the layered sequence. Apatite is the most widespread mineral occurring as a minor accessory in nearly all samples.

The apatite is recognized by its moderate relief and low birefringence; in addition, it seems to be biaxial with a small optic axial angle of about 10°.

Biotite occurs in minor amounts in samples T 4.112a, T 4.11, and T 4.102a as flakes oriented parallel to the foliation (in the latter case with bent cleavage in sections $\perp \beta$). In the other sections it is absent or occurs only as a trace. In the first two sections the biotite has a strong pleochroism in reddish-brown for γ and β and a light cream colour for α; in sample T 4.102a an almost opaque brown is characteristic for γ and a light yellowish colour for α. The former mineral is apparently a normal biotite, the latter an iron-rich variety approaching lepidomelane in composition.

Rutile and titanite (sample T 4.102a) are found in very subordinate amounts in a few thin-sections.

AMPHIBOLITE

On the northern peninsulas of Stjernöy, the amphibolite, in principle a rock consisting of about equal amounts of hornblende and andesine, exhibits variability due to the amount of additional minerals and to various textural relations. Amphibolite with well-developed small-scale banding alternates with a fairly homogeneous rock. The variation in the quantitative mineralogical composition of the amphibolitic rocks can be found in table 11 which gives the results of a number of modal analyses.

TABLE 11 *Modal compositions of a number of samples of amphibolite.*

	T 3.43	T 3.43^C	T 3.40	T 3.55	T 3.57	T 3.87	T 3.96	T 3.100
hornblende	40	30	50	40	30	10	27	20
plagioclase	40	55	42	51	56	48	45	45
pyroxene	15	3	5	2	6	18	10	10
ore	5	2	1	1	2	4	1	7
apatite	x	2	1	1	2	5	tr.	5
biotite	—	—	1	5	4	—	17	3
garnet	x	8	—	—	—	15	—	10

N.B. Samples T 3.43 and T 3.43^C are taken from adjacent bands.

It is to be noted here that the amphibolite is a melanocratic rock which generally is also pyroxene-bearing. Sample T 3.87 of a garnet-rich intercalation, for example, is not an amphibolite in the strict sense of the term but rather a hornblende-bearing granulite of mafic bulk composition.

The variable nature of the amphibolite is demonstrated by sample T 3.43 (see table 11), in which bands consisting of plagioclase and hornblende alternate with bands, a few centimetres wide, containing considerable amounts of garnet. The rock of this sample has a hypidiomorphic granular texture which is of a fairly equal grain-size in the range from 0.5 to 2.5 millimetres. In addition, it exhibits a crude foliation owing to a more or less parallel orientation of irregular clusters of mafic minerals. Other sections, however, show an excellent foliation which may be accompanied by a linear parallelism of the hornblende crystals. Such lineation is found, e.g. in specimen T 3.40.

In other samples the amphibolite is a massive rock resembling a diorite in appearance. In these samples the rock has a hypidiomorphic, slightly porphyritic texture with grains in sizes from 0.5 up to 5 millimetres. It also has a simple mineral composition consisting of about equal amounts of plagioclase and pyroxene with about 5 per cent of iron ore as the only accessory mineral. This sample shows no indications of either foliation or lineation.

A moderate mortar texture exists along the grain-boundaries of plagioclase and hornblende crystals, a feature indicative of the amount of mechanical deformation suffered by the rock. Further indications of strain in this, as well as in other samples, are found in strongly undulose extinctions and irregular or even bent twin-lamellae in the plagioclase crystals. These phenomena are more manifest in the samples of the amphibolite than in those of the gabbro gneiss.

Mineralogy

Hornblende. In the amphibolite this mineral has a very strong pleochroism with a reddish-brown for α, light yellowish-brown for β, and greenish-dark brown for γ. The impression is gained that the greenish tinge for γ in the hornblende of the amphibolite is somewhat stronger than in the hornblende of the gabbro gneiss.

The optic axial angle (with strong axial dispersion) has a negative sign and a value of about 80°, but values as low as 76° are also encountered. For the extinction angle $c \Lambda \gamma$ the values lie between 11° and 14°. Compared to the values for $c \Lambda \gamma$ of about 15° to 25° and with an optic axial angle of about 90° for the common hornblende, the optical properties of this hornblende indicate that at least part of the iron is oxidized to the ferric state. According to Winchell (1951), the values for $c \Lambda \gamma$ in basaltic hornblende, rich in trivalent iron, vary between 0° and 10° and the optic axial angle $2\,V\alpha$ is smaller than in common hornblende.

The hornblende in the amphibolite samples does not exhibit either alteration to chlorite or inclusions such as ore-needles or exsolution lamellae. However, small grains of ore and apatite are frequently enclosed by the hornblende crystals.

Plagioclase. The fresh and clear-cut plagioclase of the amphibolite has a much more zoned character and exhibits much less twinning than the plagioclase of the gabbro gneiss. It is quite common to find untwinned crystals with a considerable difference in extinction between the narrow rim and the core. The albite twinning, if present, is of a type with narrow lamellae; often these lamellae are slightly bent or irregular.

Determinations of $x' \Lambda$ trace {010} in sections normal to crystallographic a give an average value of 24° (corresponding to about 45 per cent An) in the core of the plagioclase crystals of sample T 3.43c. The rim of the plagioclase in this same sample is more sodic, and for the same run of determinations in sections $\perp$a gives values of about 20° (about 37 per cent An). In samples T 3.55 and T 3.57, also with moderate to strong zoning, the values found in the core for $x' \Lambda$ trace {010} in sections $\perp$a are 18°; the corresponding values found in the rim are 16°. This corresponds with An contents of 34 per cent for the core and of 32 per cent for the rim.

Determinations of $x' \Lambda$ trace {010} in sections normal to crystallographic a and zone method-determinations on albite-twins yielded the data for the plagioclase in the amphibolite samples shown in table 12. A few measurements of $2\,V\alpha$ were also made. In zoned plagioclase such measurements were carried out on the cores of the crystals.

TABLE 12 *Optical data on plagioclase and interpretation in terms of the anorthite content for the amphibolite samples.*

sample no.	Average of $x' \Lambda$ tr. {010} in sections $\perp$ a	Average measurements of optic axial angle $2V\alpha$	Universal stage zone method on albite twins	Average of interpretations
T 3.43	24° 45 % An	80° ($2V\gamma$) 46 % An	48 % An	47 % An
T 3.40	25° 47 % „			approx. 47 % „
T 3.55	18° 35 % „	88° ?	33 % „	34 % „
T 3.87	22° 40 % „	86° ($2V\gamma$) 42 % „		approx. 40 % „
T 3.96	10° 26 % „	83° 27 % „	26 %, 27 % „	27 % „
T 3.100	20° 38 % „	90° 38 % „	35 %, 40 % „	38 % „

It is concluded that the plagioclase in the amphibolite is an andesine varying from about 30 to about 50 per cent An. It may be added that in sample T 3.55 an exsolution of orthoclase is found in some of the plagioclase grains. Such exsolution structures in the plagioclase, especially if hair-like, are typical for the granulite facies of metamorphism.

Clinopyroxene. This mineral occurs in all the amphibolite samples but is especially abundant in samples T 3.40 and T 3.57. The mineral has a slightly greenish tinge but it is not pleochroitic. In sample T 3.43c the following optical properties were found: an extinction angle $c \wedge \gamma$ varying between 42° and 47° and an optic axial angle $2\ V\gamma$ with values of 56°—62° and 59°—61° for rim and core respectively; the same properties for the pyroxene in sample T 3.87 showed values of 54°—60°, 53°—58°, and 47°—52°, respectively. Compared to the values for the normal augite found, for instance, in the gabbro gneiss, these optical proporties may be attributed to a slightly higher content of alkalis in the pyroxene.

Garnet. Garnet is an important constituent in specimen T 3.43c as well as in some of the other samples (e.g. T 3.87). It occurs as small, irregularly shaped, independent grains but also as more or less porphyroblastic crystals up to 3 or 4 millimetres in size. In thin-section it is apparent that the garnet and ore occur in a close relation and it also appears that the garnet has a tendency to form as reaction rims around grains of ore or hornblende.

In thin-section the garnet has a pale pink colour; however, in the hand-specimen it is dark red. Hysingjord (1960) determined its index of refraction and found values of 1.788 and 1.779, with 3.97 and 3.95 for its specific gravity. The garnet can thus be identified as an almandine with considerable admixtures of pyrope and grossularite [1]). A garnet of this composition occurs in amphibolite as well as in granulite facies rocks (see also fig. 9).

Biotite occurs in some of the amphibolite samples in amounts of up to 5 per cent; in others only a trace of biotite is found. According to its pleochroism with almost opaque brown for γ, it is similar to the iron-rich variety of biotite found in the gabbro gneiss.

Apatite is rather abundant in the amphibolite. In most samples up to 2 per cent is found as small subhedral grains within the hornblende aggregates, but also as single grains between the plagioclase.

Ore minerals in amounts varying from 1 to 5 per cent occur in the same way as in the gabbro gneiss. However, spinel is a rare accessory mineral in the amphibolite and occurs only as a mere trace. In sample T 3.43c it is more abundant; here spinel grains are found in close association with the ore minerals.

The name amphibolite has been applied somewhat loosely in agreement with the usage of that term for foliated rocks consisting of hornblende and andesine. In respect of the theory of metamorphic facies it may be recalled that the appearance of a pyrope- and grossularite-rich almandine, of anti-perthitic feldspar, and rutile, e.g., in the samples points to a high grade of metamorphism for the amphibolite on Stjernöy, approaching the granulite facies of Eskola (1939). This would indicate high temperatures and pressures such as would exist at great depth in major orogenic zones of the earth's crust.

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[1]) By chemical analysis Hysingjord determined the following composition for the garnet of a leucocratic garnetiferous layer within the gabbro gneiss complex of western Stjernöy: almandine 57.48 per cent, pyrope 22.87 per cent, grossularite 18.70 per cent, and spessartine 0.95 per cent.

SYENITE GNEISS

Layers of syenite gneiss are such an integral part of the amphibolite region of northern Stjernöy that some sort of mineral relationship and a similar genetic history may be anticipated for both rocks.

In most samples the peculiar syenitic rocks consist of from 80 per cent to more than 95 per cent anti-perthitic feldspar (plate E, fig. 3), and it is furthermore a fairly equigranular rock of fine to medium grain-size (0.1 to 1.0 millimetre). Not only in the hand-specimen does this rock exhibit a definite gneissic texture but also in the thin-section where a pronounced foliation owing to the parallel arrangement of the lenticular grains of perthitic feldspar is perceptible. Even a certain lineation of the feldspar crystals is apparent from the more or less parallel extinction of the crystals (plate E, fig. 3). This foliation is accentuated by the occurrence of small, oriented clusters or single grains of pyroxene and hornblende in the plane of the foliation; in sample T 3.91 a rough lineation of the pyroxene can also be observed.

A characteristic feature found in some of the thin-sections of the syenite layers is a pronounced mortar structure in the sense of a finely-granulated crystal aggregate along the boundaries of the perthitic crystals (plate E, fig. 4). The grain-size in this ground-mass is not more than a few hundredths of a millimetre. In one sample (T 3.38) the fracturing and granulation along the grain-boundaries has proceeded to such a degree that one might even speak of thin mylonite-zones in the section. Undulose plagioclase and fractured pyroxene crystals constitute further evidence of severe mechanical deformation suffered by the syenite. Apparently the syenite layers are more liable to plastic deformation by the nature of their feldspar minerals than the surrounding mafic rocks (about the plastic deformation in feldspathic rocks versus the rigid behaviour of amphibolitic layers see also plate A, fig. 4).

As already mentioned, the main component in the syenite samples is a peculiar intergrowth of plagioclase and orthoclase, consisting of about equal amounts of both minerals. In general, the intergrowth exhibits slightly crinkling lamellae, but exsolutions of orthoclase in the shape of droplets also occur; in sample T 3.38 a tendency to flame exsolutions can be found. The lamellae are densely spaced within distances of about 0.01 millimetre and in most cases are continuous throughout a crystal (sized about 1 millimetre); so one may rightly speak of hair-perthite or hair-antiperthite (plate E, fig. 4).

In most cases it is difficult to tell whether the plagioclase or the orthoclase is the host-crystal; thus it could be mesoperthitic feldspar. However, from a few less perthitic grains found in the sample it appears that most often orthoclase occurs as inclusion in plagioclase; in fact, the intergrowth should then be called antiperthite. In sample T 3.84 the opposite situation is observed, with plagioclase droplets in orthoclase (perthitic intergrowth).

In the few grains of plagioclase with no, or at any rate only a few exsolution lamellae, a narrow albite-twinning may be found; from the values of $x' \wedge$ trace $\{010\}$ in sections $\perp$ a between 6° and 10° (2 V neg.) it can be concluded that the An content of the oligoclase varies from 15 to 20 per cent. Sample T 3.84 gave values of 5° (2 V pos.) which points to an oligoclase containing about 15 per cent An. In addition, a few grains of clearly recognizable orthoclase occur in most samples.

The next important mineral in the perthitic syenite is a distinctly greenish pyroxene, sometimes with slightly blue-green pleochroism. The optic axial angle is positive and has a moderate value, and the extinction angle $c \wedge \gamma$ is about 50°. Probably the mineral is an aegirine-augite, which from the paragenetic point of view is quite understandable. The pyroxene is often fractured and decomposed.

Secondary ore minerals usually occur within or near the mafic constituents, which besides diopside also comprise hornblende, biotite, and hypersthene (probably all of secondary origin). In sample T 3.84 peculiar rims of this orthopyroxene occur around grains of ore but also around the diopside.

As accessory minerals in the syenite, apatite, rutile, and zircon can be mentioned, the latter being rather abundant in the syenite gneiss, whereas it is rare or non-existent in the mafic rocks.

From the investigation of thin-sections from syenite layers in the gabbro gneiss regions of the metamorphic complex it is known that syenite, consisting of perthitic feldspar, also occurs in the latter rock association (e.g. sample T 4.12 from Stjernodden); however, in most cases these layers in the gabbro gneiss are rather plagioclase-rich gneisses with amounts of anti-perthite varying between 10 and 30 per cent (e.g. sample T 4.128a from Stjernodden, sample T 4.70 from Lassefjordfjell, and sample T 4.112b from Udsiktfjell). Containing up to 25 per cent diopside and hypersthene, these layers are more or less transitional between syenite gneiss and gabbro gneiss (mangeritic gneisses, see page 204). Sample T 4.95 from Lassefjordfjell contains 20 per cent quartz and may be considered as a transitional rock between syenite gneiss and the garnet-bearing acid granulites.

The mineral paragenesis in the syenite gneiss points to a very high grade of metamorphism. Especially the occurrence of hair-anti-perthite and the association diopside-hypersthene-garnet is critical for the granulite facies (Eskola 1954). In view of the very close field relations between syenite gneiss and amphibolite the grade of metamorphism of the latter rock cannot have been much lower. In addition, it may be said that the subordinate and accessory mineral constituents in both rocks are practically the same.

SUMMARY AND CONCLUSIONS

Concluding, it may be said that several important differences between the rocks of the ultramafic suite and those of the metamorphic complex have emerged. The comparison of those differences is based on the mineral composition and the textural and structural relations within the most widespread members of both groups of rocks: the gabbro of the layered sequence and the gabbro gneiss, respectively.

It may be recalled here first that in the field survey the layered gabbro was identified by its generally igneous appearance and its intercalations with anorthositic gabbro, similar to the well-known occurrences of Stillwater and Bushveld, etc. From the genetic point of view it is no less important to recall the gradual transition of peridotite through olivine melagabbro into the gabbro of the layered sequence.

The rocks of the metamorphic complex exhibit a more pronounced schistose texture and a more variable mineral composition, including rocks of effusive and possibly of sedimentary descent which have undergone a rather complex metamorphic history. The outstanding genetic implication of the main rock unit, the gabbro gneiss, seems to lie in the abrupt interlayering with such strongly contrasting rocks as garnet-bearing acid granulite, syenite gneiss, and metalimestone-layers. In the following synopsis the characteristic features of both rock types are recapitulated:

GABBRO OF THE LAYERED SEQUENCE

Mineral composition:

a. The An content of the plagioclase varies from about 90 to about 70 per cent in the olivine melagabbro - gabbro sequence (see table 6). The plagioclase in the ultramafic rocks, however, has a lower An content than that in the olivine melagabbro. Zoning in the plagioclase is absent or very weak in most samples.

b. The chief pyroxene mineral in the gabbro of the layered sequence is a calcium-rich augite, which is not very much different for ultramafic or gabbroic samples (see table 7). A slight zoning in the augite has been observed. Orthopyroxene occurs only in subordinate amounts (see also d).

c. Olivine is abundant in the melagabbroic samples and occurs as a minor constituent in the gabbro of average composition.

d. Spinel is a frequent minor constituent in the rocks of the ultramafic sequence. Most of the spinel is incorporated in a symplectitic intergrowth of spinel and orthopyroxene characteristic of the samples of the layered gabbro.

e. Other accessory minerals in the layered gabbro rocks comprise iron oxide minerals and sulphides in minor amounts.

Order of crystallization:

The rocks of the ultramafic sequence show a clear crystallization sequence which took place in the following order: olivine - plagioclase - augite - hornblende - spinel - ore.

Alteration of minerals:

As most of the samples show only very slight alterations the pyroxene has suffered moderate alteration into secondary hornblende (uralitization) and some of the samples show a slight decalcination of the plagioclase. However, the olivine grains are usually moderately to severely altered into serpentinite.

Grain-size:

The layered gabbro consists mainly of hypidiomorphic, roughly equigranular crystals varying in size from 0.1 to 2.0 millimetres. Several samples contain subporphyritic crystals measuring up to 1 centimetre.

Mechanical deformation:

Undulose extinction is common in the plagioclase and translation-lamellae are found in the olivine grains. In some samples clasto-porphyritic pyroxene occurs, which may explain the origin of the mafic clusters by fracturing of larger individual crystals.

Fabric:

Pronounced layering (with individual band widths usually varying from a few decimetres up to several metres), in most cases accompanied by a coarse foliation of more or less aligned, flattened clusters of mafic minerals; in size these clusters vary from about 0.5 to about 2 centimetres.

GABBRO GNEISS AND ALLIED ROCKS

Mineral composition:

a. In the average type of gabbro gneiss the An content of the plagioclase remains rather constant between 60 and 80 per cent (table 9). Decidedly lower values, between 35 and 50 per cent An, occur erratically in zones within the metamorphic complex; the samples of amphibolite also contain plagioclase of andesine composition (table 12).

b. The augite in the gabbro gneiss samples is of uniform composition (table 10); in bulk composition it is only slightly different from the augite in the gabbro of the layered sequence. Orthopyroxene is a rather frequent associate; in some samples up to 10 per cent of the mafic constituent consists of orthopyroxene.

c. Olivine is completely absent in the samples of the metamorphic rock complex.

d. Spinel is absent in most of the samples or is at most a rare constituent. In a few samples it is somewhat more abundant, and a type of intergrowth with pyroxene can even be found. However, the latter is not the typical vermicular intergrowth such as is found in the layered gabbro.

e. Apatite is a frequent accessory mineral, but rutile, titanite, and zircon are also found. Garnet and biotite are frequently associated minerals, especially in the amphibolitic rocks.

Order of crystallization:

No definite order of crystallization seems apparent in the gabbro gneiss; the main components augite and plagioclase obviously have been recrystallized. Exceptions are the clastoporphyritic mafic clusters and the mortar rims in some of the samples. In addition, the hornblende is less obviously secondary, being rather an integral component of the rock, and seems to have been recrystallized.

Alteration of minerals:

Most of the samples show only very slight alterations in the composing minerals.

Grain-size:

Within the gabbro gneiss it varies considerably; in general sizes are somewhat smaller than in the layered sequence.

Mechanical deformation:

Strongly undulose extinction is common, but bent twin-lamellae also occur frequently in the plagioclase crystals. Clastoporphyritic pyroxene occurs only rarely. In the gabbro gneiss, and especially in the amphibolite and syenite gneiss, mortar textures along the grain-boundaries testify to a high degree of clastic deformation.

Fabric:

Different textural types occur, for instance with mafic clusters but also with smaller aggregates or single elongated minerals, which may exhibit lineation. In general, the foliation found in the gabbro gneiss is somewhat more regular and well-defined than that found in the layered gabbro.

Reviewing the petrographical observations, the conclusion seems warranted that in many respects the layered gabbro exhibits truly igneous phenomena, although its postmagmatic history was certainly also eventful. In the first place, there are indications of strain (undulose extinction and translation lamellae in olivine and pyroxene). Further, evidence of an incipient plastic deformation is found in the protoclastic fracturing of pyroxene-grains. The rocks of the ultramafic sequence have been subjected to attack not only mechanically but also chemically. The rims of orthopyroxene and spinel-pyroxene symplectite around olivine point to a tentative and possibly late-magmatic adaptation of these rocks to new conditions of temperature and pressure, under which the existing olivine was no longer in equilibrium with its surroundings. It is the opinion of the author that the reaction:

$$\text{bytownite} + \text{olivine} \rightarrow \text{diopside} + \text{spinel} + \text{hypersthene}$$

is the consequence of pressure metamorphism. Evidently this adaptation was arrested and no final equilibrium was established. Concerning the abruptness of the alterations, it is important to note that both the chemical inequilibrium of the olivine and the mechanical breakdown of the pyroxene have left unaltered remnants.

From the textural and structural point of view the metamorphic gabbro gneiss is certainly a rock whose origin and tectonic history have been obscured by the effects of crystallization. Apparently, considerable clastic and plastic deformation occurred, since oriented, elongate crystals and lenticular clusters of mafic minerals can be observed frequently in the plane of foliation. In addition, a pronounced mortar-texture is found along the grain-boundaries in many samples, especially in the amphibolite and syenite gneiss.

From the mineralogical point of view the difference between the two groups of rocks is less obvious: the dominant minerals in the gabbro gneiss, plagioclase and augite, differ only slightly from the same minerals in the layered gabbro. This suggests that the gabbro gneiss is a rather schistose differentiate of the layered gabbro sequence.

On the other hand, the mineral paragenesis in the gabbro gneiss, with its abrupt intercalations of peculiar rocks, points to a high grade of metamorphism near or within the granulite facies of Eskola (1954).

In the recent petrological literature considerable attention has been paid to the study of pyroxenes in igneous and metamorphic rocks. In the next chapter a detailed study of the pyroxenes in the Stjernöy rocks is presented in an effort to reconcile the contrasting lines of evidence favouring igneous and metamorphic features. It is hoped that new light can thus be shed on other genetic problems as well.

CHAPTER IV

SPECIAL MINERALOGICAL INVESTIGATIONS OF PYROXENE AND OLIVINE

INTRODUCTION

A study of the variation in composition of the minerals in a layered series of igneous rocks is of considerable importance for a better understanding of a possible process of crystal-fractionation and for the tracing of an eventual pattern of cryptic layering. In the case of the rocks on Stjernöy it is also useful as a means of ascertaining whether or not the gabbroic rocks have undergone metamorphosis. Wager and Deer (1939) have defined cryptic layering as the steady change in composition of the essential mineral constituents in a sequence of magmatic rocks, including the pyroxenes. The abrupt appearance or disappearance of a particular crystalline phase in the course of crystallization is also termed cryptic layering.

In the preceding chapter the variation in composition of the plagioclase was tentatively established by optical means in the rocks of the layered gabbro and in those of the metamorphic complex (see tables 6 and 9).

In this chapter a similar study of the compositional variation of clinopyroxene as essential constituent of the different types of gabbroic rocks from the Stjernöy-area will be made. The variation in composition of olivine and orthopyroxene will be discussed in a later paragraph.

Since Hess (1941) published an observation about the Mg/Fe ratio in hypersthene and augite, Muir and Tilley (1958), O'Hara (1960), Wilson (1960), and Kretz (1961) have studied co-existing clinopyroxenes and orthopyroxenes with a view to obtaining criteria by which to distinguish between igneous and metamorphic basic rocks. The different types of gabbroic rocks in the Stjernöy-area unquestionably provide an interesting field for this type of investigation.

Recent petrological literature contains many new data on the compositional variation of pyroxenes from basaltic magmas.The urgent need for reliable chemical analyses, especially in the case of augite, as a check on the standard optical methods of determination, has been stressed by most authors, e.g. Wilson (1960) and McDougall (1961).

In mafic rocks of hypabyssal or plutonic character such as diabases, dolerites, gabbros, and norites, the first mineral to appear in the cooling magma is usually olivine. Commonly pyroxenes proper to such mafic magmas appear somewhat later in the course of crystallization of the magma.

In most cases the first pyroxene to appear is augite, shortly afterwards joined by a calcium-poor orthopyroxene, and for the greater part of the crystallization period these two pyroxenes separate out in cotectic equilibrium. This second pyroxene is either a pigeonite or a very typical hypersthene with exsolution-lamellae of augite in the crystal-lattice, commonly oriented in twinned sets with an irrational composition plane and making an angle of approximately 74° with the crystallographic c axis (Hess 1941). It is the opinion of Hess that the host mineral was pigeonite, which inverted to orthopyroxene by slow cooling subsequent to exsolution, and that uninverted metastable pigeonite is characteristic of rapidly cooled magma.

Pigeonite and augite are difficult to distinguish in thin-section; the most practical means of optical identification is a determination of the optic axial angle with the aid of the universal stage. Since no pyroxenes with low values for the optic axial angle were found (see tables 7 and 10), pigeonite is apparently absent in the samples from Stjernöy. On the other hand, hypersthene with exsolution-lamellae of augite oriented parallel to an irrational lattice plane in twinned sets were not met with in thin-sections from Stjernöy pyroxenes either.

The olivine in the layered gabbro from Stjernöy was the earliest mineral to crystallize, but it is doubtful whether the rims of orthopyroxene around olivine and the orthopyroxene in the intergrowths with spinel are also of early crystallization. The same applies to most of the samples taken from the gabbro gneiss in which orthopyroxene is usually present in some type of intergrowth with spinel. Orthopyroxene occurs in only a few samples as clearly independent grains in considerable amounts, e.g. in the sample of hypersthene-bearing granulite P 24 from Lille Kufjord (Seiland).

From the paragenetic point of view it seems clear that the gabbroic rocks from Stjernöy have not been subjected to crystallization in cotectic equilibrium of two pyroxenes, such as has been described for normal basaltic magmas (Hess 1941).

Mineral separation technique

Clean samples of the mafic minerals were obtained by using the Frantz Isodynamic Magnetic Separator. Although this piece of apparatus is widely used and the general technique is well-known, each separation problem is different and it is deemed useful to describe the procedure followed with the rocks from Stjernöy.

To separate the minerals for chemical analysis the samples are first crushed in a mortar and then passed through a 60 mesh ASTM-sieve with recycling. After crushing, the samples are washed and decanted because removal of dust is essential for a good magnetic separation. The magnetite is taken out with a permanent magnet. The samples are then split into fractions of 60—100 mesh and 100—200 mesh (ASTM-sieves).

With this procedure the greater part of the crushed feed goes into these two fractions; grains coarser than 60 mesh and finer than 200 mesh were not used for analysis.

The two fractions (60—100 mesh and 100—200 mesh) are separated by centrifuge in a heavy liquid medium into fractions lighter and heavier than a specific gravity of 3.3. The fraction < 3.3 contains the plagioclase and most of the hornblende and biotite; some of the other minerals found in the light fraction are apatite and serpentine. The fraction > 3.3 contains augite, olivine, ore, spinel, orthopyroxene, and occasionally also a rather large amount of hornblende with ore- or spinel-inclusions.

Samples of gabbro gneiss yielded minerals which must have been overlooked in the thin-section study, e.g. kyanite in the non-magnetic fraction at 0.8 amp. in the hypersthene-bearing granulite of sample P 24.

Electromagnetic separation depends on a delicate balance between gravity (controlled by the side slope) and field strength (controlled by the current). Factors such as forward slope and rate of feed are less critical (Flinter 1959). A more or less uniform grain-size of the feed is critical for good separation. It was found that with the samples from Stjernöy good results could be obtained with fractions in the range of 200—100 mesh, the 60—100 mesh fractions containing too many interlocking grains.

Further, it was found that effective separation of the samples from Stjernöy could be achieved with a constant forward slope of 15°, a side slope varying between 15° and 25° and a variable field strength (currents between 0.1 and 1.0 amp.).

As an illustration of the distribution of the minerals over the different magnetic fractions the following examples can be given:

Sample T 4.88b, sp.gr. > 3.3:

fraction 60-100 mesh

magnetic 0.1 amp.: olivine with much magnetite in serpentine $> 95\%$, some grains of spinel and ore.

magnetic 0.2 amp.: olivine with less magnetite in serpentine $> 95\%$, some grains of spinel-symplectite, some grains of augite with ore-inclusions, a few grains of orthopyroxene.

magnetic 0.5 amp.: olivine fresh or slightly stained $> 90\%$, spinel or spinel-rich symplectite $> 5\%$, orthopyroxene $< 5\%$, some grains of augite and ore.

non-magnetic 0.5 amp.: augite with angular green inclusions and oriented ore-needles $> 90\%$, spinel and spinel-symplectite $> 5\%$, orthopyroxene $> 1\%$, some grains of olivine.

fraction 100-200 mesh

magnetic 0.5 amp.: olivine sometimes with ore-inclusions $< 90\%$, spinel $< 10\%$, spinel-rich symplectite $< 5\%$, orthopyroxene $> 1\%$, a few grains of augite and ore.

magnetic 0.8 amp.: augite frequently with angular green inclusions $> 90\%$, augite grains with spinel- symplectite inclusions $> 5\%$, augite grains with hornblende inclusions $< 5\%$.

non-magnetic 0.8 amp.: augite with a smaller amount of angular green inclusions $> 95\%$, augite grains with spinel or hornblende inclusions $< 5\%$, some grains of ore (sulphides) and a few interlocking grains with plagioclase.

N.B. The bulk of the material goes into the magnetic fractions 0.2 amp. and 0.8 amp. (augite concentrate).

Sample T 4.4, sp.gr. > 3.3:

fraction 60-100 mesh

magnetic 0.2 amp.: augite with interlocking ore or with abundant ore-needles $> 95\%$, orthopyroxene most often with spinel inclusions $< 5\%$.

magnetic 0.5 amp.: augite with ore-needles or with small ore or spinel inclusions $> 70\%$, spinel symplectite $< 20\%$, orthopyroxene most often with spinel inclusions $> 10\%$.

non-magnetic 0.5 amp.: augite fresh or moderately weathered also slight amount of ore-needles $> 80\%$, some augite with inclusions of hornblende or spinel (less frequent) $< 20\%$, a few grains of ore and only traces of orthopyroxene.

fraction 100-200 mesh

magnetic 0.5 amp.: augite with a moderate amount of ore-needles or small ore-patches $> 60\%$, augite with sizable hornblende inclusions $< 20\%$, spinel-grains $< 10\%$, crude spinel symplectites $< 5\%$, orthopyroxene most often with some intergrowth of spinel $< 5\%$, a few grains of free hornblende and ore.

magnetic 0.7 amp.: augite, a number of grains slightly weathered but most minerals almost free of ore-needles $> 90\%$, augite with hornblende inclusions $> 5\%$, augite with spinel inclusions $< 5\%$, a few grains of ore.

non-magnetic 0.7 amp.: augite fresh and almost without ore-needles $> 95\%$, augite with small hornblende inclusions $< 5\%$, a few augite grains have small ore-inclusions but spinel is as good as absent.

N.B. The bulk of the material goes into the fractions: magnetic 0.7 amp. and non-magnetic 0.7 amp.

Sample P 24, sp.gr. > 3.3:

fraction 60-100 mesh

magnetic 0.2 amp.: orthopyroxene most often slightly weathered $> 60\%$, grains of ore $< 25\%$, augite with ore-needles or small ore-inclusions $> 5\%$, grains of biotite, usually intergrown with ore or pyroxene $< 5\%$.

magnetic 0.5 amp.: orthopyroxene in part slightly weathered $< 90\%$, augite with ore-needles $> 5\%$, biotite $< 5\%$, grains of ore $< 1\%$.

non-magnetic 0.5 amp.: augite $> 80\%$, augite with small ore-inclusions $> 10\%$, grains of rutile, titanite, and zircon $< 5\%$, a few grains of ore.

fraction 100-200 mesh

magnetic 0.2 amp.: orthopyroxene in part weathered or intergrown with small grains of ore or bitotite $> 50\%$, grains of ore also intergrown with small amounts of pyroxene or biotite $< 40\%$, biotite $< 5\%$, traces of augite.

magnetic 0.5 amp.: orthopyroxene only slightly weathered $> 70\%$, orthopyroxene rather weathered $< 15\%$, orthopyroxene intergrown with biotite $< 10\%$, grains of ore $< 5\%$, a few grains of augite.

magnetic 0.8 amp.: augite slightly to moderately weathered $> 90\%$, augite rather severely weathered $< 10\%$, augite with biotite or ore-inclusions $> 1\%$, rutile and titanite $> 1\%$, only a few grains of orthopyroxene.

non-magnetic 0.8 amp.: rutile and titanite $< 55\%$, kyanite $< 40\%$, plagioclase $< 5\%$, zircon $> 1\%$, some grains of ore (sulphides).

N.B. The bulk of the material goes into the magnetic fraction 0.5 amp. The augite fraction (magnetic 0.8 amp.) is comparatively small.

It appears that the clinopyroxene (augite) is concentrated in the less magnetic fractions (0.7 and 0.8 amp.); the orthopyroxene is concentrated in the more magnetic 0.2—0.5 amp.-fractions and the olivine (if free of magnetite dust) in the magnetic 0.5 amp.-fraction. When the two latter minerals occur in the same sample, no sharp separation can be achieved.

A fair concentration of the augite can be obtained even in the first run. By repeated re-running of the material (five times or even more) such an augite concentrate can be upgraded to a purity of more than 99 per cent. By increasing or decreasing the current by 0.05 amp. in the case of a 0.8 amp. augite fraction, small amounts of impurities of slightly higher or lower magnetic susceptibility can be

TABLE 14A *Analyses of clinopyroxenes separated from rocks of the ultramafic sequence.*

	T 4.88b	T 4.121	T 4.27	T 4.73	T 4.65	T 4.126	T 4.66	T 4.123a	T 4.19a
SiO_2	46.5	48.4	cal. 47.7	cal. 47.6	cal. 48.7	48.4	cal. 46.7	49.0	cal. 45.5
TiO_2	1.25	1.0	0.96	av. 1.0	1.02 1)	0.67	1.12 1)	0.87	1.05
Al_2O_3	7.5	5.5	8.0	av. 6.0	5.96 1)	6.0	6.95 1)	6.9	8.3
Fe_2O_3 } total	est. 1.6 } 5.8	2.7 } 6.9	2.4 } 7.3	2.3 } 6.7	1.5 } 5.8	2.0 } 5.9	2.6 } 8.9	est. 1.0 } 7.6	est. 2.5 } 9.0
FeO } Fe_2O_3	est. 3.8	3.8	4.4	4.0	3.9	3.5	5.6 1)	est. 5.9	est. 5.8
MnO	0.12	0.09	av. 0.1	av. 0.1	0.11 1)	0.07	0.12 1)	0.12 1)	av. 0.1
MgO	14.0	13.7	11.7	13.4	12.9	12.8	11.3	11.2	9.4
CaO	23.5	23.8	23.8	24.6	24.6	24.6	24.5	23.0	26.2
Na_2O	est. 0.5	0.77	av. 0.8	av. 0.8	0.78 1)	av. 0.8	0.72 1)	0.85 1)	av. 0.9
K_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
H_2O	n.d.	0.08?	0.1?	0.24	0.51	0.98	0.37 1)	0.7 1)	0.27
Total	98.8	99.8	100.0	100.0	100.0	99.8	100.0	99.5	100.0

TABLE 14B *Analyses of clinopyroxenes separated from gabbro gneiss and other metamorphic rocks.*

	T 4.111	T 4.75	T 4.57	T 4.123b	T 3.69	T 3.82	T 4.4	T 3.62	P 24
SiO_2	47.4	cal. 49.1	cal. 48.7	49.25	49.4	cal. 49.4	cal. 50.3	48.7	cal. 50.3
TiO_2	0.76	0.64	av. 0.8	0.87	0.79	av. 0.8	0.59	0.41	1.05
Al_2O_3	6.3	av. 6.0	av. 6.0	5.35	7.7	av. 6.0	5.0	3.1	3.0
Fe_2O_3 } total	1.2 } 8.8	0.4? } 7.9	2.6 } 10.2	2.77	1.8 } 6.8	est. 2.0 } 7.3	1.9 } 9.5	est. 2.3 } 12.7	est. 1.5 } 8.4
FeO } Fe_2O_3	6.8	6.7	6.8	6.82	4.5	est. 4.7	6.8	est. 9.3	est. 6.2
MnO	0.42	av. 0.2	av. 0.2	0.18	0.08	av. 0.2	av. 0.2	av. 0.2	av. 0.2
MgO	13.5	13.9	12.7	12.33	12.7	13.9	12.4	12.6	14.5
CaO	22.5	21.6	21.2	21.13	22.5	21.5	21.8	21.0	21.8
Na_2O	0.89	av. 1.0	av. 1.0	1.09	0.76	av. 1.0	av. 1.0	av. 1.0	av. 1.0
K_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
H_2O	0.1?	0.47	n.d.	0.24	0.12	0.51	0.09	n.d.	0.47
Total	99.9	100.0	100.0	100.03	100.4	100.0	100.0	98.6	100.0

N.B. Components determined by other than spectrographic methods are loss on ignition (mainly H_2O) by weight, alkalis by flame photometer, bivalent iron by titrimetric methods (total iron is determined spectrographically). Sample T 4.123b however, has been determined by gravimetric analysis.

av. value of minor elements is constituted of a reasonable average.
cal. in several samples the SiO_2 value is obtained by adding up to 100%.
est. in some samples the FeO/Fe_2O_3 ratio is estimated as no bivalent iron could be determined owing to shortage of material.
1) values obtained by non-spectrographic analysis on a duplicate augite concentrate from the same sample.

extracted until the augite concentrate is of the desired degree of purity. To effect a subtle separation, the side slope may also be increased to 25°.

It may be noted here that a shift in the amperage at which the maximum amount of augite enters the magnetic fraction is indicative of a change in the mineral composition of the augite. For instance, in sample T 4.88b it enters the magnetic fraction at 0.9 amp., in sample T 4.66 at 0.8 amp., and in sample T 4.19a at 0.7 amp. (for the chemical analyses of these samples see tables 14A and 14B).

The same technique of upgrading a mineral concentrate has been applied to the 70 per cent orthopyroxene in the 0.5 amp. magnetic fraction of sample P24. In principle it is also possible to separate an orthopyroxene concentrate of better than 90 per cent in those cases in which this mineral amounts to only 5 or 10 per cent in the first magnetic fraction. Actually such a result was achieved for the gabbro gneiss samples T 3.62 and T 4.111.

Since in orthopyroxene a fairly accurate determination of the Mg/Fe ratio can be made by X-ray diffraction methods, it is much less time-consuming to handpick 20 to 40 grains of the orthopyroxene under the binocular than to use the electro-magnetic separation technique. The same applies to the separation of an olivine concentrate for the determination of the Mg/Fe ratio of that mineral. The samples of orthopyroxene and olivine thus prepared by handpicking are reported in tables 16 and 17.

In all, 20 concentrates of pyroxene of a sufficient degree of purity for chemical analyses were prepared with the described separation technique using the Frantz Isodynamic Magnetic Separator.

Samples of rocks of the ultramafic suite yielded 9 augite concentrates, ranging paragenetically from pyroxene-peridotite (T 4.88b) via melanocratic olivinegabbro to augite of the layered gabbro in Simavikfjell (T 4.19a).

From the gabbro gneiss of northern Stjernöy, 9 samples were chosen for the separation of augite. Most of these samples consist of the average type of gabbro gneiss from locations distributed more or less at random over the metamorphic region in northern Stjernöy. However, augite sample T 3.62 is from a hypersthene-bearing granulitic intercalation South of Kjerringfjordnes and sample P 24 is from a hypersthene-rich metamorphic rock of Lille Kufjord (Seiland).

From the last two samples orthopyroxene concentrates for chemical analysis were also prepared with the magnetic separation technique.

Chemical analyses of clinopyroxene

The purpose of the chemical investigation was to locate the differentiation trend in the WoEnFs diagram of the pyroxene minerals from Stjernöy rather than to make complete mineral analyses.

The elements to be analysed were chosen to suit the requirements of these calculations within the silicate system mentioned. However, a determination of only Ca, Mg, and Fe is inadequate. The determination of such elements as Al, Ti, and Na is also important. Furthermore, the distribution of bivalent and trivalent iron over the total amount of iron must be known.

It was decided to use the spectrographical method 1) for the determinations

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1) The analyses were made by the spectro-analytical laboratory of the Billiton Co. in Arnhem, under the supervision of Mr. A. Rijkeboer. No account of the spectrographical assay technique will be given here; it will suffice to mention that the components are determined as elements by means of an internal standard and recalculated to oxides.

wherever applicable, this method offering the advantages that it is rapid and employs small amounts of material.

The spectrographical technique cannot be employed for the determination of alkali metals. Only the total amount of iron can be determined spectrographically; the determination of bivalent iron requires a complementary gravimetric analysis. It is also difficult to determine Si in amounts of up to 50 per cent spectrographically. In most analyses the amount of SiO_2 is established by adding up to obtain a sum total of 100 per cent.

As a check on the spectrographic results a few rapid method silicate analyses (Shapiro and Brannock, 1956) were made of identical material from three samples, the results of which can be seen in table 13.

The results for the major constituent oxides in these parallel analyses do not deviate from each other by more than 0.5 to 1.3 per cent absolute or 4.0 to 5.5 per cent relative of, for instance, MgO and CaO respectively. The percentages of total iron are also in fair agreement with each other. The value for the rapid method analysis of ferric oxide in sample P 24 (orthopyroxene) seems far too high and will be disregarded in later discussions.

Chemically speaking a slight, but in the author's view significant, differentiation trend is noticeable in the clinopyroxenes of the samples of the ultramafic sequence from the most ultramafic members towards the more gabbroic rocks (table 14A). This trend is expressed by an increase in total iron oxide ($FeO + Fe_2O_3$) accompanied by a decrease in magnesium oxide; the behaviour of SiO_2 and Al_2O_3 being more erratic. The order of magnitude of the differentiation from a peridotitic rock (sample T 4.88b) to anorthositic gabbro (sample T 4.19a) is illustrated by the values for these components in the following table (the values in sample T 4.121 represent a very mafic olivine melagabbro):

	T 4.88b	T 4.121	T 4.19a
SiO_2	46.5 %	48.4 %	45.5 %
MgO	14.0 %	13.7 %	9.4 %
Al_2O_3	7.5 %	5.5 %	8.3 %
total iron as Fe_2O_3	5.8 %	6.9 %	9.0 %

The question of trends of differentiation, however, will be discussed in detail in the paragraph on formula calculations of pyroxenes.

The clinopyroxenes of the metamorphic complex are more silicic in comparison with those of the ultramafic sequence; otherwise these samples exhibit fairly uniform chemical compositions in which no differentiation trend is perceptible (table 14B).

The Fe_2O_3/FeO ratio in the analyses (see tables 14A and 14B) also shows fairly constant results. ¹) In the ultramafic augites (with the exception of T 4.121) this ratio is slightly less than 1 : 2; for the gabbroic members of the same sequence the ratio is about 1 : 2.5. In the augite samples of the metamorphic complex a value of

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¹) In some of the samples total iron could only be determined as Fe_2O_3; in these samples the ratio FeO/Fe_2O_3 has been estimated in agreement with the ratio found in the other samples.

TABLE 13 *Comparison of results of spectrochemical and rapid method silicate analyses in weight percentages.*

	spectrochemical analysis			rapid method analysis [1]	
Sample T 4.121	SiO_2	48.4 %		49.42 %	
	TiO_2	1.0 %		1.04 %	
	Al_2O_3	5.5 %		5.32 %	
	Fe_2O_3	2.7 %	total Fe as Fe_2O_3 is 6.9 %	2.89 %	total Fe as Fe_2O_3 is 6.2 %
	FeO	3.8 %		2.94 %	
	MnO	0.09 %		0.14 %	
	MgO	13.7 %		14.06 %	
	CaO	23.8 %		22.48 %	
	Na_2O	0.77 %		0.83 %	
	K_2O	n.d.		tr.	
	H_2O	0.08 %		0.44 %	
		99.8 %		99.56 %	
Sample T 3.69	SiO_2	49.4 %		49.46 %	
	TiO_2	0.79 %		0.78 %	
	Al_2O_3	7.7 %		6.40 %	
	Fe_2O_3	1.8 %	total Fe as Fe_2O_3 is 6.8 %	2.50 %	total Fe as Fe_2O_3 is 6.7 %
	FeO	4.5 %		3.74 %	
	MnO	0.08 %		0.15 %	
	MgO	12.7 %		13.22 %	
	CaO	22.5 %		22.10 %	
	Na_2O	0.76 %		0.95 %	
	K_2O	n.d.		tr.	
	H_2O	0.12 %		0.24 %	
		100.5 %		99.54 %	
Sample P 24 (orthopyroxene)	SiO_2 cal.	53.0 %		52.98 %	
	TiO_2	0.22 %		0.19 %	
	Al_2O_3	1.6 %		1.86 %	
	Fe_2O_3	1.1 %	total Fe as Fe_2O_3 is 21.3 %	6.05 %?	total Fe as Fe_2O_3 is 21.9 %
	FeO	18.2 %		14.26 %	
	MnO	0.28 %		0.37 %	
	MgO	24.3 %		23.37 %	
	CaO	0.85 %		0.78 %	
	Na_2O	n.d.		tr.	
	K_2O	n.d.		tr.	
	H_2O	n.d.		0.41 %	
		100.0 %		100.27 %	

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[1] The quantitative silicate analyses were carried out by the petrochemical laboratory of the Department of Petrology, Mineralogy, and Crystallography of the University of Leyden (Miss H. M. I. Bik, analyst).

about 1 : 2.7 is found in most analyses, with the exception of samples T 4.75 and T 4.111. The systematic distribution of bivalent and trivalent iron is important with respect to the following mineral calculations.

FORMULA CALCULATIONS OF CLINOPYROXENES

From the chemical analysis of augite a specified mineral formula can be calculated, which can be used as a check on the accuracy of the chemical analyses.

The generalized formula of clinopyroxene given by Hess (1949) is:

$W_{1-p}(XY)_{1+p}Z_2O_6$ in which formula

- W is the group of the large cations in hexahedral co-ordination such as: Ca^{2+}, Na^{+}, and K^{+};
- X is the group of the medium-sized bivalent cations in octahedral co-ordination: Mg^{2+}, Mn^{2+}, and Fe^{2+};
- Y is the group of the smaller trivalent cations Al^{3+}, Fe^{3+} and the quadrivalent Ti^{4+}, also in octahedral co-ordination;
- Z is the group of the small trivalent and quadrivalent cations in tetrahedral co-ordination, Si^{4+} and Al^{3+}.

In the X-group Ni^{2+} and in the Y-group Cr^{3+} may be added as possible constituents. In layered gabbro from Lille Kufjord (Seiland) the order of magnitude of weight percentages for these elements is 0.1 per cent or less (Oosterom, 1954). Elements occurring in such minor amounts can be excluded from the calculations.

Al^{3+} can replace Si^{4+} in tetrahedral co-ordination to a maximum ratio of 1 in 8. To adjust the electrostatic balance an equally large amount of trivalent ions should then replace Mg^{2+} or Fe^{2+}. Also, Ca^{2+} can be replaced by Na^{+} or K^{+} if the changes in electrical charge are again counterbalanced in the X-position.

The analyses in tables 14A and 14B were recalculated on the basis of six oxygen atoms, according to the method of Hess (1949), first calculating molecular proportions (weight percentages divided by molecular weights) and from these the cationic and oxygen atom proportions. An example of such a calculation is given in the augite analysis of sample T 4.121.

	percentages by weight	molecular proportions	cationic proportions	oxygen atom proportions	cations on 6 oxygen atoms
SiO_2	48.4	807	807	1614	1.80
TiO_2	1.0	12	12	24	0.03
Al_2O_3	5.5	54	108	162	0.24
Fe_2O_3	2.7	17	34	51	0.08
FeO	3.8	53	53	53	0.12
MnO	0.09	1	1	1	tr.
MgO	13.7	343	343	343	0.77
CaO	23.8	425	425	425	0.95
Na_2O	0.77	13	26	13	0.06
H_2O	0.08				
	99.8			2686	4.05

N.B. The number of Si-ions on 6 oxygen atoms is $x = \frac{6 \times 807}{2686} = 1.80$.

In this example 0.20 cations of aluminium are needed in addition to the 1.80 cations of silicium to bring the Z-group to the stoechiometrically required value of 2.00. The remainder of the aluminium together with all the trivalent iron and quadrivalent titanium goes into the Y-group. The combination of the nearly equal-sized magnesium- and ferrous-ions in the X-group, and the combination of calcium- and sodium-ions in the W-group, is self-evident.

	degree of electrostatic adjustment
2.00 Z = Si 1.80 + Al 0.20	— 0.20
0.15 Y = Al 0.04 + Ti 0.03 + Fe^{3+} 0.08	+ 0.18
0.89 X = Mg 0.77 + Fe^{2+} 0.12	
1.01 W = Ca 0.95 + Na 0.06	— 0.06
2.05 total Y + X + W	— 0.08 balance

The present method of pyroxene calculation makes a check on the reliability of the analysis possible; according to Hess (1949) in high-quality analyses the total number of cations to six oxygen atoms in the WXY-group should be 2.00 (± 0.02), granted that for the Z-group this number has been put at the required value of 2.00. Table 15 gives the WXY: Z ratios of the analysed augites of both groups of rocks. The degree of electrostatic adjustment caused by the ionic interchanges (see page 254) is also calculated. For sample T 4.121, and all the other samples a systematically negative value was found, indicating that the electrostatic balance is not completely obtained.

The molecular fractions of the clinopyroxene can now be calculated in terms of WoEnFs-composition in the manner mentioned below. Since it is assumed that the small aluminium- and titanium-ions in the Y-group have no preferred affinity for either the Fs- or the En-molecule, they are equally divided between Ferrosilite and Enstatite.

For sample T 4.121 the calculation of the WoEnFs-composition is as follows:

Fs = 0.12 Fe^{2+} + 0.08 Fe^{3+} + 0.02 Al + 0.01^5 Ti = 0.23^5 is 11.4 per cent
En = 0.77 Mg + 0.02 Al + 0.01^5 Ti = 0.80^5 is 39.3 per cent
Wo = 0.95 Ca + 0.06 Na = 1.01 is 49.3 per cent

2.05

Table 15 shows the WoEnFs-compositions derived from the chemical analyses of augites of both the ultramafic and the metamorphic groups (see tables 14A and 14B). It may be concluded that most of the analyses carried out on the pyroxenes from Stjernöy are fairly satisfactory; some of them meet Hess's requirements for high-quality analyses.

In the augites of the ultramafic sequence a slight differentiation trend is found in which the percentage of the Wo-component increases from 47.8 (in sample T 4.88b) to 55.0 (in sample T 4.19a), whereas the En-component decreases from 41.2 to 29.3 in the same samples. The augite richest in magnesium is found in the pyroxene-peridotite (sample T 4.88b). The Fs-component in the same augite samples increases moderately from 11.0 to 15.7 per cent; the specimens richer in iron are found in the gabbro members of the sequence. The projection points of the ultramafic augites are represented graphically in fig. 6a.

Compared with those of the ultramafic group, the clinopyroxenes from the gabbro gneisses exhibit a lower Wo content in all but one sample (T 3.69). In the augites of the latter group of rocks the percentages of En and Fs vary within the narrow limits of 36.5 to 40.5 per cent and 12.5 to 16.5, respectively; but no systematic variation is perceptible. There is thus no support for the suggestion that the augites of the gabbro gneisses might be the products of a further differentiation of the gabbro of the ultramafic sequence. The projection points of the metamorphic augites are found in fig. 6b.

Into fig. 6a the trend of differentiation in augites of normal basaltic magmas is drawn; the augites in the Stjernöy samples do not follow this trend and also in composition differ from basaltic augites by a higher wollastonite content.

DETERMINATION OF THE CHEMICAL COMPOSITION OF ORTHOPYROXENE AND OLIVINE

Orthopyroxene. As described in Chapter III orthopyroxene is not an important rock-forming mineral in the Stjernöy region. However, to determine the trends of differentiation in two-pyroxene systems it is necessary to analyse the Mg/Fe ratio in the orthopyroxene.

The orthopyroxene grains in the rims around olivine and in the spinel-symplectites are crystallographically ill-defined, which makes precise determination by optical methods unpracticable. For this reason it was decided to employ the X-ray powder diffraction technique, which gives accurate results with even small amounts of relatively impure material when it is used for the determination of the Mg/Fe ratio in orthopyroxene. A good X-ray powder analysis requires no more than 30 to 40 small grains (size fraction 100—200 mesh). Because these grains are fragments of various crystals, a better average result is obtained than by the determination of the optical characteristics of a few crystals only.

The technical details of X-ray powder diffraction methods [1] will not be discussed here. It may suffice to mention that the mineral-determination is based on the measurement of:

1. the relative distance between specific reflections of quartz and orthopyroxene;
2. the relative distance between orthopyroxene reflections.

The method of using relative distances between reflections for pyroxene determination was investigated by Zwaan (1954), whose publication gives graphs for the relation between this parameter and the En and Fs molecular proportions. The accuracy of the method is estimated by Zwaan at plus or minus 2 per cent.

The results of the relative distance measurements in terms of Enstatite-Ferrosilite composition are given in table 16. The orthopyroxene in the rocks of both the ultramafic sequence and the metamorphic series exhibits a high En content in the range of 95 to 80 per cent and is, therefore, either a bronzite or an enstatite.

Orthopyroxene of hypersthene composition (70 to 50 En) is only found in a few samples of the metamorphic gneisses T 4.11, T 3.62 and T 4.137 [2]. Hypersthene is the dominant mafic mineral in these samples, which have been taken from leucocratic intercalations in the metamorphic complex (see p. 231). A hypersthene concentrate of sample P 24 could also be analysed chemically (see table 13). In the duplicate analyses Al_2O_3 contents of 1.6 and 1.86 per cent respectively were

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[1] Mr. A. Verhoorn made the exposures and Mr. C. F. Woensdrecht carried out the measurements with the aid of a Cambridge Universal Measuring Machine.

[2] In samples T 4.11 and T 4.137 no clinopyroxene is found and for these samples tie-lines could not be constructed.

TABLE 15 *Composition of augites from rocks of the ultramafic sequence in molecular percentages of Wo, En, and Fs.*

	Wo	En	Fs	WXY : Z	Degree of electrostatic adjustment
T 4.88^{b}	47.8	41.2	11.0	2.05 : 2	— 0.10
T 4.121	49.3	39.3	11.4	2.05 : 2	— 0.08
T 4.27	49.7	36.0	14.3	2.03 : 2	— 0.02
T 4.73	50.8	38.1	11.1	2.07 : 2	— 0.11
T 4.126	51.4	37.8	10.8	2.04 : 2	— 0.07
T 4.65	51.0	38.4	10.6	2.02 : 2	— 0.05
T 4.66	51.2	34.0	14.8	2.02 : 2	— 0.09
T 4.123^{a}	49.3	35.9	14.8	1.99 : 2	0.00
T 4.19^{a}	55.0	29.3	15.7	2.05 : 2	— 0.10

N.B. Samples T 4.88^{b} to T 4.123^{a} were taken across Rottenhallerfjell approximately in a line from the 907 summit to St. Kjerringfjord; this direction is more or less perpendicular to the layering in the gabbro. Sample T 4.19^{a} was taken from the summit of Simavikfjell and probably represents a further differentiation product of the gabbro.

Composition of augites from rocks of the metamorphic complex in molecular percentages of Wo, En, and Fs.

	Wo	En	Fs	WXY : Z	Degree of electrostatic adjustment
T 4.111	46.6	38.9	14.5	2.06 : 2	— 0.14
T 4.75	45.6	40.8	13.6	2.04 : 2	— 0.10
T 4.57	45.5	38.0	16.5	2.00 : 2	— 0.06
T 4.123^{b}	46.2	36.6	17.2	2.01 : 2	— 0.05
T 3.69	48.7	36.4	14.9	1.95 : 2	— 0.02
T 3.82	43.8	41.2	15.0	1.99 : 2	— 0.02
T 4.4	47.3	37.2	15.5	2.03 : 2	— 0.02
T 3.62	46.1	36.3	17.6	2.04 : 2	— 0.11
P 24	46.3	40.9	12.8	2.03 : 2	— 0.09

N.B. The locations of samples T 4.111 to T 3.62 are more or less distributed at random over the metamorphic region of northern and north-western Stjernöy. Sample P 24 originates from an intercalation of hypersthene-bearing granulite in the region around Lille Kufjord, Seiland.

found, whereas augite from Stjernöy contains Al_2O_3 contents of between 3 and 8 per cent.

Boyd and England (1961) could prove that up to 14 per cent Al_2O_3 can be dissolved in enstatite crystallized at high pressures and to a lesser degree also at high temperatures. Ranges of 2.0 to 5.5 per cent Al_2O_3 for enstatites in ultramafic inclusions in basalt and of up to about 9.5 per cent Al_2O_3 for enstatites in granulitic rocks are given by these authors. Orthopyroxenes from normal mafic magmas generally contain only small amounts of Al_2O_3.

It is concluded that the pyroxenes in both the ultramafic and metamorphic samples show relatively high Al_2O_3 contents.

TABLE 16 *Composition of orthopyroxenes from rocks of the ultramafic sequence in molecular percentages of En and Fs as derived from X-ray powder diffraction data.*

			optical determination of 2 V	
	En	Fs	En	Fs
T 4.88[b]	91	9		
T 4.121	85.5	14.5		
T 4.27	90.5	9.5	87	13
T 4.73	86.5	13.5	86	14
T 4.126	84	16	83	17
T 4.65	84	16		
T 4.66	93	7		
T 4.123[a]	92	8		

Composition of orthopyroxenes from rocks of the metamorphic complex in molecular percentages of En and Fs as derived from X-ray powder diffraction data.

			optical determination of 2 V	
	En	Fs	En	Fs
T 4.111	80	20	83	17
T 4.75	85	15		
T 4.57	83	17		
T 3.69	90	10		
T 3.82	87	13		
T 4.4	78	22		
T 4.11	71	29		
T 3.62	61.5	38.5	57	43*
T 4.137	60.5	39.5		
P 24	72	28	70	30*

N.B. The En-Fs compositions of the samples marked with an asterisk are determined chemically.

By X-ray measurements Zwaan (1955) could distinguish between high aluminous orthopyroxenes (atomic proportion 0.050) and low aluminous orthopyroxenes (atomic proportion 0.010). The orthopyroxenes in the Stjernöy samples correspond with the low aluminous range; this compares well with the content of aluminium found in the orthopyroxene of sample P 24 (table 13).

Olivine. The investigation of the chemical composition of olivine was restricted in principle to those samples of the ultramafic sequence in which orthopyroxenes were also determined. Only a few additional samples of olivine were investigated.

In the case of olivine no difficulties are encountered in the magnetic separation of a concentrate from the olivine-rich peridotites and melagabbros; in the ordinary gabbro of the layered sequence olivine is only a minor constituent (and often corroded at that), and the same difficulties with regard to optical determination are met with as in the case of orthopyroxene.

The chemical composition of the olivine was also determined by X-ray powder diffraction. The technique of X-ray diffraction measurements on olivine was described by Yoder and Sahama (1954), who determined the absolute position of the (130) reflection of olivine by measuring the angular separation between this olivine reflection and the reflection of an admixed standard substance (silica powder), whose parameters are known. In their article these authors published a graph in which this spacing of reflections is plotted against the chemical composition.

The outcome of the X-ray determinations of olivine from rocks of the ultramafic sequence, together with a few values derived from available optical data, are listed in terms of Forsterite — Fayalite percentages in table 17.

TABLE 17 *Composition of olivines from ultramafic rocks in molecular percentages of Fo and Fa as derived from X-ray powder diffraction data.*

			optical determination of 2 V	
	Fo	Fa	Fo	Fa
T 4.2^{a}	92	8	88	12
T 4.2^{b}	89.5	10.5	85	15
T 4.88^{b}	85	15		
T 4.121	85	15		
T 4.27	80.5	19.5	82	18
T 4.73	83	17	75	25?
T 4.65	81.5	18.5		
T 4.66	n.d.		77	23
T 4.123^{a}	n.d.		73	27

By chemical analysis a Fo composition of 90 per cent was found for sample T 4.2^{a}.

Yoder and Sahama estimate the limit of error for X-ray determinations of olivine to be approximately 4 per cent for pure forsterite or fayalite and about 3 per cent in the vicinity of the mean of the system.

Only in the dunite rock (sample T 4.2a) does the forsterite variety of olivine occur; in the pyroxene-peridotite and the gabbro of the ultramafic sequence there is a gradation in the olivine composition from Fo_{88} to Fo_{73} (the chrysolite variety of olivine).

Lastly, it may be noted again that olivine is not a constituent of the gabbro gneiss series except for its presence in small intrusions or dykes of ultramafic rock.

TRENDS IN THE COMPOSITION OF CO-EXISTENT MAFIC MINERALS ON STJERNÖY

Clinopyroxenes and Orthopyroxenes

In his remarkable study on the pyroxenes of common mafic magmas Hess (1941) observed that tie-lines ¹) of co-existing pyroxenes, when plotted in the ternary Wo-EnFs-system, tend to intersect at the En-Wo side at or near the locus $En_{25}Wo_{75}$. For his observation Hess mainly applied carefully determined optical data of pyroxenes from the Stillwater and the Bushveld occurrences of layered mafic rocks, together with some chemical data. In presenting his data Hess probably did not wish to attach too much significance to his observation in relation to the crystal-chemistry of pyroxenes in mafic magmas.

However, in the recent petrological literature the intersection of the tie-lines at the locus $En_{25}Wo_{75}$ is accepted by several authors as a valid criterium for igneous pyroxene assemblages. In a re-evaluation of the existing data on tie-line orientations, Brown (1961) rightly remarks that the real contribution made by Hess was to prove that the intersection point of tie-lines was on the En-Wo side rather than on the Fs-Wo side of the ternary diagram. To stress his point Brown plotted the tie-lines of twelve pairs of co-existing pyroxenes from igneous rocks (all chemically analysed). Fom fig. 5a it can be concluded that all but one of the tie-lines intersect at the En-Wo side but that the assumption of a common point of intersection seems hardly justifiable. The locus $En_{25}Wo_{75}$ cannot be accepted either as the average of intersections; if such an average is sought for, then the value $En_{18}Wo_{82}$ (as calculated by Brown) should be used. The latter author rightly concludes that no special significance should be attached to this value, comparable to the significance so far attached to the composition $En_{25}Wo_{75}$.

In fig. 5a the sheaf of tie-lines of eight pairs of pyroxenes from nodules in basaltic lavas from widely distributed occurrences are also constructed. The chemical data are taken from a publication by Ross, Foster and Myers (1954). It appears that the tie-lines of the pyroxenes in the nodules intersect at the Fs-Wo side of the diagram. As pointed out by Brown (1961) and O'Hara (1960), this result is completely different from the trend found in the pyroxenes of well-known gabbro occurrences and clearly suggests different circumstances of crystallization between the two groups of pyroxene-bearing mafic rocks.

Wilson (1960) measured optical properties of pyroxenes in metamorphic two-pyroxene-bearing mafic rocks (charnockites) from SW. Australia and made comparisons with pyroxene assemblages from other metamorphic suites. He constructed the tie-lines of the co-existing pyroxenes in the metamorphic rocks and distinguished between charnockitic rocks of high granulite facies, which intersect the En-Wo side close to the apex of the triangle or even the Fs-Wo side, and two-pyroxene-bearing granites closer to the hornblende-granulite subfacies whose tie-lines intersect the En-Wo side at values nearer to the locus $En_{25}Wo_{75}$. Wilson proposed that the

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¹) A tie-line may be defined as the connection between the projection points of the compositions of co-existing calcium-rich (clinopyroxene) and calcium-poor (orthopyroxene) phases from mafic magmas in the triangular diagram $CaSiO_3$-$MgSiO_3$-$FeSiO_3$ (WoEnFs).

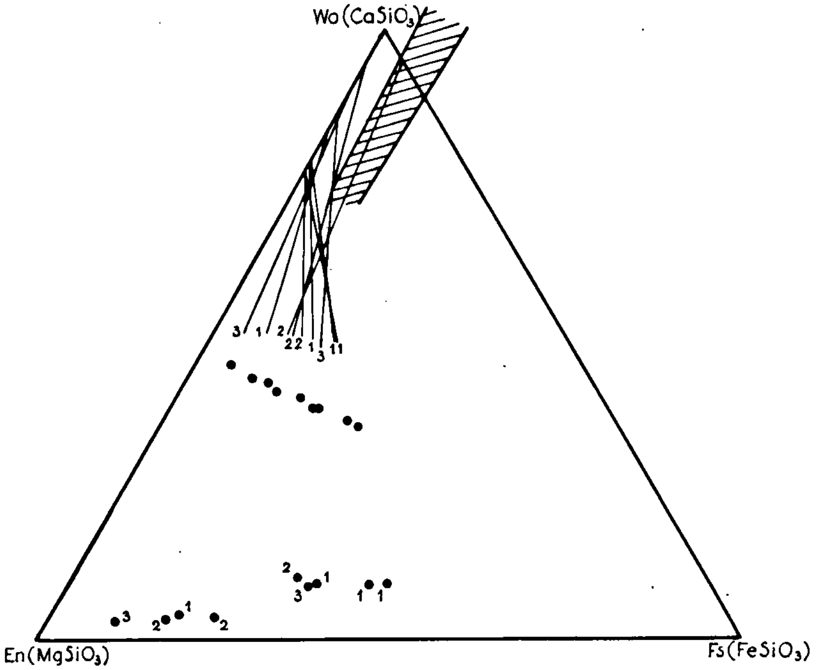

Fig. 5*a*. Tie-lines joining co-existing orthopyroxene and clinopyroxene in gabbro from Skaergaard (1), Stillwater (2), and Bushveld (3) in the WoEnFs diagram (Brown 1961). The hatched field at right side of Wo apex indicates the sheaf of tie-lines from ultramafic inclusions in basalts.

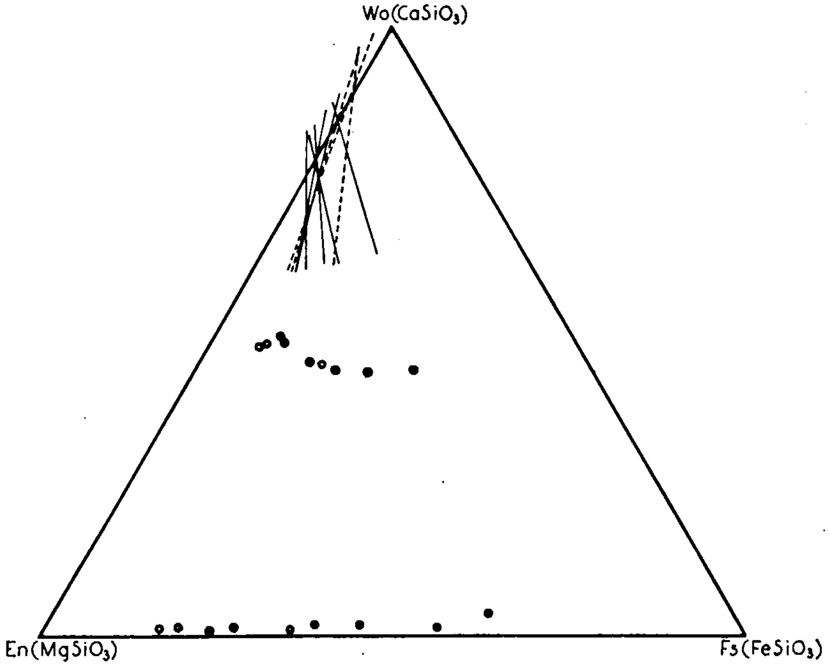

Fig. 5*b*. Tie-lines joining co-existing orthopyroxene and clinopyroxene from Madras charnockites (dots) and granulite facies rocks from Scourie, Scotland (open circles) in the WoEnFs diagram (O'Hara 1960).

tie-line trend might be an aid in distinguishing between magmatic and metamorphic two-pyroxene-bearing rocks and that the locus of intersection of the tie-lines might reflect their grade of metamorphism.

However, the data collected in fig. 5b(O 'Hara 1960), confirming earlier investigations by Muir and Tilley (1958) are contradictory to Wilson's views. These authors argued that chemically determined tie-lines in the WoEnFs-system of metamorphic two-pyroxene assemblages do not depart significantly from those derived from igneous assemblages, and found that the spread of values for igneous and metamorphic assemblages is equally great (compare fig. 5a and 5b). They showed that chemical analyses of clinopyroxenes are more reliable than optical and X-ray powder diffraction determinations of the mineral composition. However, orthopyroxenes have crystallographic constants which are more nearly linear functions of the chemical composition and the X-ray determination of the Mg/Fe ratio is equally reliable.

Lastly, Brown (1961) calculated that the average intersection value for metamorphic two-pyroxene assemblages also plots at $En_{18}Wo_{82}$.

In the WoEnFs diagrams of figs. 6a and 6b the tie-lines are drawn between chemically-analysed clinopyroxenes (see table 15) and orthopyroxenes (see table 16) as determined by X-ray powder diffraction, from co-existing pairs of these minerals in the rocks from Stjernöy. In the graph pertaining to the pyroxene pairs of the ultramafic sequence (fig. 6a) all the tie-lines intersect at the Wo-Fs side of the diagram between Fs_7Wo_{93} and $Fs_{20}Wo_{80}$. Just as is the case with the tie-lines of co-existing pairs of pyroxenes from the ultramafic inclusions in basalts (fig. 5a), the reason for their intersection at the Wo-Fs side must be sought in the high En/Fs ratio in the orthopyroxenes. It will be noticed that the pyroxene-pairs in gabbro samples T 4.66 and T 4.123 have intersections near the locus $Fs_{20}Wo_{80}$, whereas the tie-lines of the other samples (olivine melagabbro and peridotite) have intersections nearer to the Wo-apex between Fs_7Wo_{93} and $Fs_{13}Wo_{87}$.

In fig. 6b the tie-lines of the pyroxene pairs found in the samples of the metamorphic rocks are represented graphically. The loci of intersection lie within the same range as is found for the pyroxenes of the ultramafic sequence. Samples T 3.62 and P 24 are the notable exceptions, with intersections at the Wo-En side of the diagram near the locus $En_{20}Wo_{80}$. The latter samples have En/Fs ratios in the orthopyroxene-component which are considerably lower than those found in the average gabbro gneiss. In these samples orthopyroxene is a main mafic constituent, whereas in the other samples of the gabbro gneiss and in the samples of the ultramafic sequence the orthopyroxene is a minor constituent representing about 5 or at best 10 per cent of the total amount of mafic minerals. From the textural relations it emerges that the orthopyroxene in the latter samples is either a later interprecipitate phase or is possibly of secondary crystallization (see page 121 in the petrographical chapter).

One of the first conclusions to be drawn from the tie-line trends of the coexisting pyroxenes in the WoEnFs-system of the Stjernöy rocks is that the conditions of their crystallization in the ultramafic sequence and those in the metamorphic area can not have differed greatly since both are characterized by primary crystallization of calcium-rich augite and further by very high En/Fs ratios in the accompanying orthopyroxene.

A second conclusion seems to be that the crystallization process in the Stjernöy rocks differs considerably from that in layered igneous rocks of basaltic bulk com-

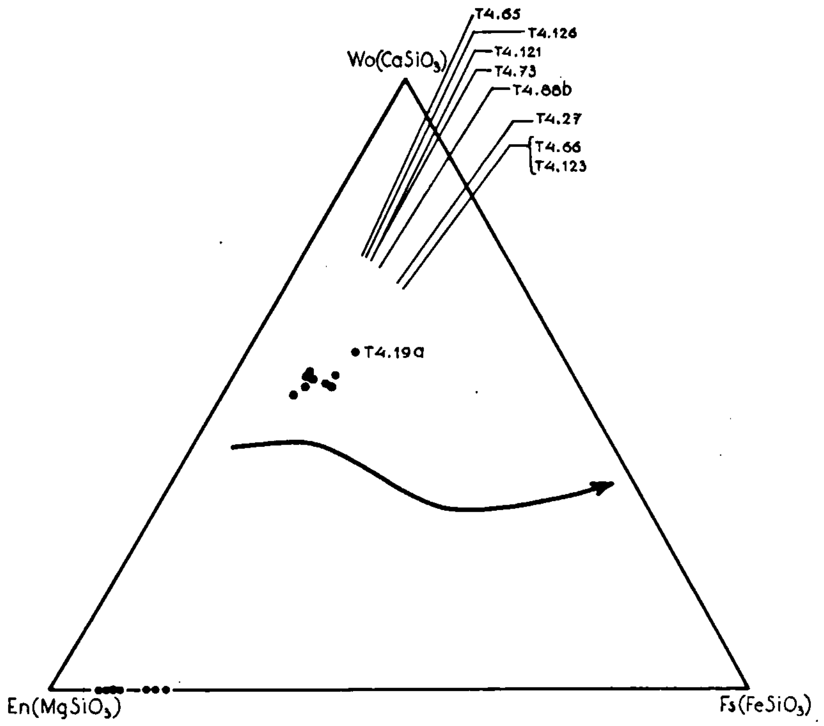

Fig. 6*a*. Tie-lines joining co-existing orthopyroxene and clinopyroxene from peridotite and layered gabbro of the ultramafic sequence on Stjernöy. Arrow indicates trend of augite differentiation in common basaltic magmas after Hess (1941).

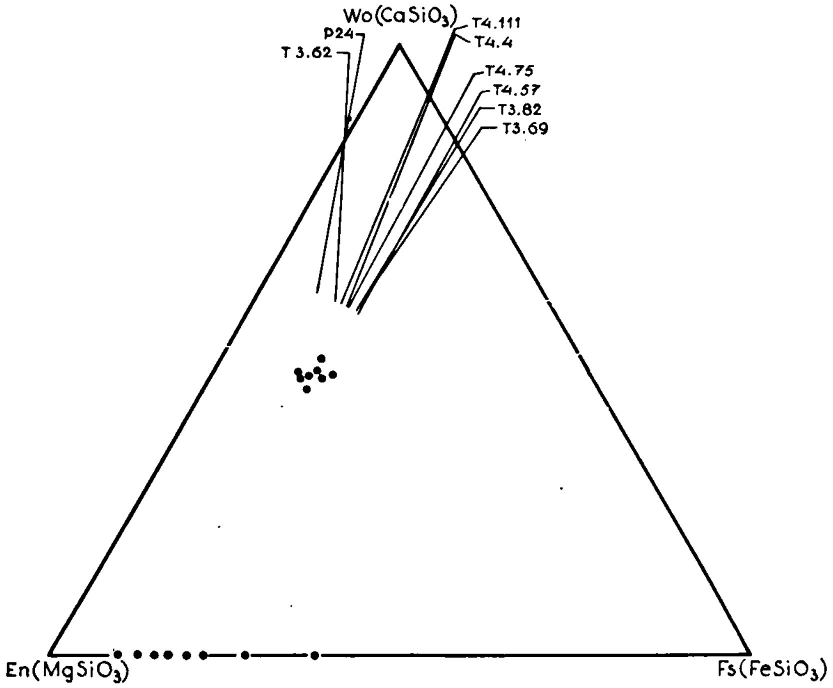

Fig. 6*b*. Tie-lines joining co-existing orthopyroxene and clinopyroxene from gabbro gneisses and hypersthene-bearing granulites (samples T 3.62 and P 24) of the metamorphic complex on Stjernöy.

position such as the Skaergaard, Bushveld and Stillwater complexes; in the latter magmas the abundant orthopyroxene of the primary precipitate and its cotectic augite have tie-lines intersecting at the En-Wo side of the diagram. The tie-lines of the pyroxenes in the Stjernöy rocks, however, show the same trend as the tie-lines in the ultramafic nodules in basalts with intersections at the En-Fs side of the diagram; this is largely due to the high Mg/Fe ratio in the orthopyroxene. The geological implications of this highly interesting case will be dealt with later on.

In the opinion of the present author it is reasonable to expect that tie-lines of co-existing pairs of pyroxenes will intersect the En-Wo side *grosso modo* at $En_{25}Wo_{75}$, or for that matter at $En_{18}Wo_{82}$ (Brown 1961), if abundant orthopyroxene crystallizes first or in any case simultaneously and in cotectic equilibrium with clinopyroxene. As Muir and Tilley (1960) have proved, metamorphic assemblages of two pyroxenes generally also have tie-lines with intersection at the loci just mentioned.

However, tie-line trends with intersections other than at the Wo-En side do exist too, as can be seen from the pyroxenes in the Stjernöy samples and in the ultramafic nodules. Wilson (1960) also found intersections different from the range at the Wo-En side, but his optically derived WoEnFs-values for the clinopyroxenes are necessarily less accurate.

In the foregoing, the distribution of magnesium and iron in pyroxene pairs has been treated empirically in terms of molecular percentages in the ternary WoEnFs diagram. However, the subject of the distribution of these elements can also be considered from the theoretical point of view in the equilibrium reaction:

$$CaFeSi_2O_6 + MgSiO_3 \rightleftarrows CaMgSi_2O_6 + FeSiO_3$$

Independently Kretz (1961) and Bartholomé (1961) calculated the chemical equilibrium [1]) between the calcium-rich (clinopyroxene) and the calcium-poor (orthopyroxene) phase in the above-mentioned reaction for the case of ideal solid solutions:

$$K(T) = \left[\frac{Fe^{2+}}{Mg}\right]_o \times \left[\frac{Mg}{Fe^{2+}}\right]_c \qquad \begin{array}{l} o = \text{orthopyroxene} \\ c = \text{clinopyroxene} \end{array}$$

Whether this equation is completely applicable to silicate reactions and whether conditions of ideal solid solution are attained by natural two-pyroxene systems is beyond the scope of this thesis.

According to Bartholomé, K(T) values of about 1.8 are obtained in the case of co-existing pairs of pyroxenes in metamorphic rock assemblages. In igneous gabbros such as from the Skaergaard, Stillwater and Bushveld occurrences the K(T) values for the pyroxene pairs average at 1.4. For the K(T) values of pairs in ultramafic inclusions (olivine nodules) in basalts Bartholomé obtained values around 1.2. As a check on Bartholomé's results analyses of such olivine nodules taken from a publication by Ross, Foster and Myers (1954) were recalculated to cation proportions, resulting in K(T) values for the said equation as follows:

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[1]) Kretz calculated the distribution coefficient $K_d = \frac{x^o}{1-x^o} \cdot \frac{1-x^c}{x^c}$ in which x^o represents the $\frac{Mg}{Mg + Fe^{2+}}$ ratio in orthopyroxene and x^c the same ratio in clinopyroxene. It appears that equilibrium constant K_d is the reverse of the equilibrium constant K(T) (Collee 1962).

Camargo, Chihuahua	Mexico	K(T) = 1.58
Ludlow	California	,, = 1.33
Peridot Cove, Globe	Arizona	,, = 1.25
Dreiser Weiher, Eifel	Germany	,, = 1.17
Kapfenstein, Styria	Austria	,, = 1.16
Ichinomegata, Akita	Japan	,, = 1.34
Salt Lake Crater, Oahu	Hawaiian Islands	,, = 1.25

Thus a range from 1.16 to 1.58 is found for these samples averaging at 1.29 approximately [1]).

In the case of the analysed pairs of pyroxenes from Stjernöy the following K(T) values can be calculated (see Appendix):

ultramafic sequence:	metamorphic complex:
T 4.88^a = 0.65	T 4.111 = 0.91
T 4.121 = 1.09	T 4.75 = 0.65
T 4.27 = 0.49	T 4.57 = 0.69
T 4.73 = 0.90	T 3.69 = 0.53
T 4.65 = 1.14	T 4.4 = 0.94
T 4.66 = 0.27	T 3.62 = 1.58
T 4.126 = 1.25	P 24 = 1.58
T 4.123^b = 0.31	

In both the samples of the ultramafic sequence and those of the metamorphic gneisses the calculated values of K(T) are rather erratic but a trend to very low values is apparent, comparable to those found in the samples of the olivine nodules in basaltic lavas. The exceptionally low values for samples T 4.66 and T 4.123a must be considered with some caution; the high En/Fs ratio causes also the tie-lines of the pyroxenes found in these samples to intersect the Wo-Fs side at the greatest distance from the Wo-apex (see fig. 6a).

The K(T) values of the clinopyroxene-orthopyroxene system in the samples T 3.62 and P 24 are distinctly higher than those of the other samples of gabbro gneisses, in fact they nearly fall within the range given by Bartholomé for pyroxenes in metamorphic rocks. The tie-lines of the former samples also intersect at the Wo-En side of the diagram at $En_{20}Wo_{80}$.

There then appears to be a relation between the value of K(T) and the locus of tie-line intersection, with lower values the tie-lines shift towards the Wo-apex. This observation is at variance with the opinion of Kretz, who supports abandoning the plotting of tie-lines.

Bartholomé (1961) has calculated the theoretical tie-line trends of co-existing pyroxenes of different ranges in composition for K(T) values of 1.8 and 1.4; he proved that tie-lines corresponding to the same temperature intersect outside the triangle and not at a point on its side as Hess suggested (1941). The sheaf of tie-lines for K(T) = 1.4, corresponding to igneous conditions at approximately 1100°, intersects the Wo-En side nearer to the apex than does the sheaf of tie-lines for K(T) = 1.8, corresponding to metamorphic conditions.

As shown in fig. 5a, the sheaf of tie-lines for olivine nodules (K(T) = 1.2) has shifted to the other side of the apex. To the present author this would mean that with more extreme conditions of temperature, and possibly also of pressure, the

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[1]) Bartholomé's lower average can be explained by the low K(T)-value from an erroneous analysis taken from Ross, Foster and Myers (1954). Personal communication Prof. Dr. W. P. de Roever, Municipal University of Amsterdam.

tie-lines will shift towards the Wo-apex or even beyond that point. Wilson (1960) argues that tie-lines may shift towards the Wo-corner with a higher grade of metamorphism; his point needs further investigation, but on chemically-analysed pyroxenes. It should be remembered that the location of the upper part of a tie-line is very sensitive to errors in the determination of the calcium-rich pyroxene. Ultimately, conditions of temperature and pressure, and possibly also the over-all composition of the rock or its magma, will decide the trend of both igneous and metamorphic tie-lines.

Kretz (1961) has calculated the temperature dependence of the distribution coefficient and concluded on theoretical grounds that a change in the slope of a particular tie-line towards the En-Fs side of the triangle can occur with a change of temperature, but he also states that formulation of a definite trend is of a speculative nature with the data available at present. On the other hand, he found that the pressure dependence of the distribution coefficient is small and concluded that an increase of pressure from 1 atm. to 5000 atm. only slightly influences the distribution of magnesium and iron over the two pyroxenes and thus can not cause a considerable shift in the tie-line trends.

Because there is still considerable controversy concerning co-existing pyroxenes in mafic rocks, in this study of the pyroxene pairs in the gabbroic rocks on Stjernöy the accent has been laid on the comparison of empirically obtained equilibrium-data and tie-line trends. These afford, remarkably enough, a parallel with the data and trends found in olivine nodules in basaltic lavas and not with those found in the pyroxenes of the layered gabbro occurrences such as Stillwater, Bushveld, or Skaergaard.

In the light of the foregoing discussion, the low K(T) values and the unusual tie-line trends for the pyroxene pairs found in samples from Stjernöy could perhaps be explained by formation at very high temperatures as, for instance, the suggested temperature of 1300°—1400 °C for the olivine nodules in basalts. At such extremely high temperatures incipient igneous conditions should be expected in all rocks other than the ultramafites, and the metamorphic rocks could not have escaped a general anatexis unless the pressure was high enough to cause the necessary rise of the melting points for the minerals of these anhydrous rocks. The results of the field investigation do not support the concept of general melting, however. In view of the presence of acid granulite layers and metalimestone bands in the complex of metamorphic rocks, the most likely conclusion would seem to be that of extreme conditions of dry metamorphism with high temperatures, made possible by equally high rock pressures allowing local anatexis and palingenesis to cause the genesis of the suite of ultramafic and layered gabbro rocks within the complex of metamorphic rocks on Stjernöy.

Olivines and Orthopyroxenes

In addition to the orthopyroxene-clinopyroxene pair, the investigation of co-existing orthopyroxenes and olivines may throw light on the conditions of formation of mafic and ultramafic rocks. For this reason determinations of olivine were made from the samples of the ultramafic sequence containing the latter mineral.

As pioneers in this sphere of investigation, Bowen and Schairer (1935) made an experimental study of the system MgO-FeO-SiO_2. They came to the conclusion that, in artificially prepared olivine-orthopyroxene systems, the olivine is always poorer in magnesium than the orthopyroxene; furthermore, they found that this trend between minerals crystallized in the range of 1550°—950 °C varies hardly at all with temperature.

Ramberg and De Vore (1951) pointed out that in natural orthopyroxene-olivine systems the olivine is also the component poorer in magnesium; however, in the magnesium-rich portion of the system olivine is the component richest in that element. They added that the differences in the Mg/Fe distribution between artificial and natural systems must be due to differences in temperature and pressure; in laboratory experiments higher temperatures and lower pressures than those in nature are usual. Proper evaluation of the Mg/Fe distribution also requires, that a state of equilibrium between the two mineral phases has been reached. It may be doubted whether equilibrium is always achieved in the laboratory. In natural systems a state of inequilibrium may also exist, as shown by zoning, coronas, etc.

Bartholomé (1960) has calculated, from the theoretical point of view, the chemical compositions of the co-existing olivines and orthopyroxenes for a number of values of the equilibrium constant:

$$K(T) = \frac{Fe_2SiO_4}{Mg_2SiO_4}\left(\frac{MgSiO_3}{FeSiO_3}\right)^2 \text{ or } \frac{Fa}{Fo}\left(\frac{En}{Fs}\right)^2$$

for the reaction:

$$Mg_2SiO_4 + 2FeSiO_3 \rightleftarrows Fe_2SiO_4 + 2MgSiO_3$$

He confirmed the observations made by Ramberg and De Vore, since in his calculations for the high-temperature range (KT = 9) he finds that olivine co-exists with far more magnesian orthopyroxene in the greater part of the diagram; only near the Mg-end in the diagram, at a composition of Fo_{90}, (see fig. 7) do both minerals have equal magnesium contents. In the low-temperature range (KT = 1.5) olivine is the mineral richer in magnesium in the range from Fo_{92} to Fo_{60}. In the medium-temperature range (KT = 4) the relation of magnesium contents is comparable to that in the high-temperature range except that the olivine is slightly more magnesian than orthopyroxene from Fo_{100} to Fo_{80}.

Confronting his theory with actual mineral assemblages, Bartholomé finds values of K(T) between 9 and 11 for olivine-rich peridotite nodules in certain basaltic lava flows. It is claimed by some authors that the mother rock of these nodules is formed in the upper part of the peridotite mantle of the earth (e.g. De Roever, 1957); temperatures at this depth have been estimated to be of the order of 1300° to 1400 °C.

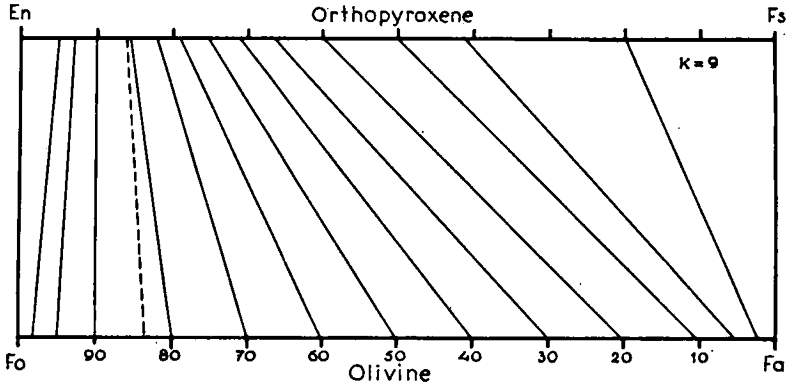

Fig. 7. Theoretical tie-line trends of co-existing olivine and orthopyroxene under high temperature conditions (KT = 9) after Bartholomé (1960). Dashed line represents tie-line in olivine-bearing rocks from Stjernöy.

For the mineral assemblages in harzburgitic rocks at the base of stratified gabbroic intrusions (e.g. Stillwater, Great Dyke of Rhodesia and Skaergaard) K(T)-values of 4.5, 4.4 and 4.1 were calculated by Bartholomé. The temperature of the initial crystallization of water-saturated basaltic magma under atmospheric pressure is commonly estimated to be 1100° to 1150 °C (Hess 1960). For the hypersthene-olivine gabbro in the border-zone of Skaergaard, a K(T)-value of 1.9 is calculated. This rock must have crystallized at a temperature below 1100 °C but above 950 °C (Wager and Deer 1939). For some olivine-hypersthene bearing metamorphic rocks (e.g. a metamorphosed picrite-basalt from Kilauea, Hawaii) K(T)-values as low as 1.7 have been found. It is difficult, however, to indicate a temperature of crystallization for such rocks. In Bartholomé's publication it is shown that low K(T)-values are compatible with temperatures in the range of the granulite facies of metamorphism (750°—1000 °C). It should be added that the attainment of equilibrium in natural associations of olivine and orthopyroxene as well as accurate analyses of the minerals concerned are prerequisites for a reasonable determination of the K(T)-values.

In applying Bartholomé's calculations to the olivine-bearing samples of the Stjernöy rocks, it may be recalled here first that this mineral occurs in the rocks of the ultramafic sequence such as dunite, pyroxene-peridotite, and olivine-melagabbro; also as dispersed grains in a few gabbro samples. In these instances orthopyroxene occurs mainly as rims around olivine grains (Chapter III, page 221 and plate C, figs. 2 and 3).

According to Boyd and England (1961) crystal-liquid reaction relations between olivine and enstatite do not exist at pressures over 6—10 kilobars (corresponding with depths of 20—30 km) which are commensurate with granulite facies conditions. Thus, if crystal-liquid relations prevailed in the rocks from Stjernöy as is indicated by the reaction rims of orthopyroxene around olivine in the rocks of the ultramafic sequence, a release of pressure from the granulite facies conditions seems to be a reasonable explanation for the phenomenon. It is likely that this release of pressure was accompanied by melting.

Co-existing olivine and orthopyroxene have been found and K(T)-values calculated in the following samples of olivine-bearing rocks from Stjernöy:

	olivine		orthopyroxene		K(T)-value
	Fo	Fa	En	Fs	
T 4.88b	85	15	91	9	18.4
T 4.121	85	15	85.5	14.5	6.3
T 4.27	80.5	19.5	90.5	9.5	21.8
T 4.73	83	17	86.5	13.5	8.6
T 4.65	81.5	18.5	84	16	6.4
T 4.66	77	23	93	7	5.0

In these samples the orthopyroxene is richer in magnesium than the co-existing olivine; a composition of Fo_{83} for the olivine and of En_{86} for the orthopyroxene may be taken as a fairly good approximation for the above-mentioned samples. This average fits in well with the theoretical trends as shown for the high K(T)-values in fig. 7. The K(T)-values show slightly erratic results; the general tendency is, however, towards values of K(T) higher than 6.

Comparing these K(T)-values with those of other rocks with co-existing olivine and orthopyroxene, the best agreement is found with the trends in olivine nodules (see page 265), which show high K(T)-values with an average of about 9. It seems plausible to expect the temperature of crystallization of dry ultramafic rocks like peridotite to be on the order of 1300° to 1400 °C especially under high pressures, although from the purely theoretical point of view low temperature associations of olivine and orthopyroxene are perhaps possible, showing equilibrium at correspondingly high K(T)-values of about 9 (Bartholomé 1960).

For a stratified basic complex such as that found on Rottenhaller- and Simavikfjell on Stjernöy one would rather have expected a trend of the co-existing olivine-orthopyroxene pair in agreement with K(T)-values of about 4, corresponding to a temperature on the order of 1100 °C.

Concluding remarks on co-existing mafic minerals

In the preceding paragraphs the equilibrium-constants and the tie-line trends in the clinopyroxene-orthopyroxene and in the olivine-orthopyroxene systems of the Stjernöy samples have been discussed. Both systems may be regarded as rather insensitive geological thermometers. The results of the discussion appears to indicate that the K(T)-values and the tie-line trends are indicative of very high temperatures of formation and indirectly of very high pressures.

Special conditions of temperature may be deduced from the aluminium content of the investigated samples from Stjernöy. It has been suggested by Hess (1941) that pyroxenes formed at high temperatures are more liable to allow aluminium to enter the crystal lattice in the tetrahedral co-ordination camouflaged by silicium. [1]) Also Boyd and England (1960) mention high contents of aluminium in pyroxenes and refer to conditions of high pressure during their formation or recrystallization. However, it might be that high pressures are indirectly responsible by increasing the melting temperatures. Brown (1961) agrees with Boyd and England about the meaning of high Al_2O_3 contents in pyroxenes: he suggests that such amounts are the consequence of crystallization or re-crystallization under high pressures.

In table 14A a higher aluminium content (varying between 5.5 and 8.3 per cent Al_2O_3) is found for the augite of the layered sequence on Stjernöy than for the augite of normal stratified gabbro occurrences, whose aluminium content averages about 3 per cent. The pyroxenes of the metamorphic rock complex (gabbro gneisses) also show a high content of aluminium in most of the samples analysed (table 14B). It is worthy of note that the amount of aluminium in the augite of the hypersthene-rich mafic gneisses [2]) is comparatively low (3 per cent) and it is just in these samples that equilibrium-constants and tie-lines are comparable to those of normal mafic igneous and metamorphic rocks (see page 260 and fig. 6b).

Significantly, the Al_2O_3 content of the chromium diopside from peridotitic nodules in basaltic lavas are also high, varying from 3.56 to 6.46 per cent (Ross, Foster and Myers, 1954). Brown points out that high aluminium contents and high

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[1]) It is assumed by Carstens (1958) that aluminium (and the other trivalent elements, e.g. iron, chromium and vanadium) divide themselves between the tetrahedral and octahedral positions in the pyroxenes according to physical and chemical conditions prevailing at the time of their formation. Furthermore, these ions are more easily accepted in the lattice structure of the clinopyroxene.

[2]) Sample T 3.62 and sample P 24.

Mg/Fe ratios in the co-existing pyroxenes are combined in the olivine-rich nodules, leading, for example, to low KT values and the intersection of tie-lines at the Wo-Fs side of the triangular diagram (fig. 5a).

In this mineralogical investigation of the layered mafic and ultramafic rocks on Stjernöy no similarities were found with the trends of differentiation in common basaltic magmas, such as Skaergaard, Bushveld, or Stillwater. In the first place, no crystallization-differentiation was found for the augites, whereas the relevant igneous occurrences exhibit a fixed pattern of differentiation in the augite (see fig. 6a). Further, in tie-line trends and in corresponding equilibrium-constants the Stjernöy rocks deviate markedly from normal stratified gabbro. In the latter respects there is a similarity with the trends found in olivine nodules, including the high aluminium contents. To interprete these phenomena solely as the consequence of extremely high temperature of formation seems unlikely; in the present author's opinion it would be more commensurate to interprete the obtained results for the Stjernöy samples as the consequence of extreme conditions of metamorphism under very high pressures and at great depths within the crust, where melting points of anhydrous rock systems are considerably higher than nearer the surface.

CHAPTER V

PETROCHEMICAL TRENDS IN THE IGNEOUS AND METAMORPHIC ROCKS ON STJERNÖY

Introduction

Chemical composition is a factor of considerable importance in a discussion of the genesis of igneous and metamorphic rocks. A chemical classification lends itself to quantitative treatment and permits the comparison of rock types of different mineral facies or different degrees of crystallinity. This certainly applies to the mafic rocks on Stjernöy, with their great variety of rock types of both igneous and metamorphic appearance.

Representative samples of the various rocks were selected for analysis according to their modal composition; for the rocks of the ultramafic sequence the choice included samples of dunite, pyroxene-peridotite, olivine-melagabbro, and samples of gabbro of the layered suite (see tables 18 and 19). Geographically, the area of sampling was confined to Rottenhallerfjell and Simavikfjell. Table 21 gives the results of the analyses of selected samples of gabbro gneiss from the northern and eastern regions of the metamorphic rock complex; a few samples of amphibolite, syenite gneiss, and granulite were also collected for chemical analysis from localities in the northern peninsulas of Stjernöy (table 22).

For the determination of the chemical composition ¹) of silicate rock samples, the methods of rapid silicate analysis given by Shapiro and Brannock (1956) were employed; these methods are based on titrimetric and spectrophotometric determinations of the component elements as expressed in terms of oxides.

Only the alkalis are determined by flame photometry. As a check, analyses of the main components SiO_2, Al_2O_3, Fe_2O_3, MgO and CaO using the orthodox gravimetric methods were carried out on a number of duplicate samples. The results of both methods agree fairly well, only the Fe_2O_3-determinations exhibiting somewhat erratic values. As can be seen from table 20, mafic rocks of basaltic bulk composition commonly contain only minor percentages of trivalent iron.

For petrochemical calculations the presentation of the analyses in weight percentages is less useful than that in molecular proportions of the composing oxides. Following the method of Burri and Niggli (1945) the weight percentages of the oxides are divided by their molecular weights. By means of the molecular equivalent numbers thus obtained, the well-known parameters al, fm, c, alk, si, mg, k, ti and p can be calculated according to Niggli's procedure. It is perhaps useful to explain here that the currently somewhat less frequently used parameter γ represents the proportion of the amount of lime in the femic minerals (pyroxenes and olivine) to the total amount of lime, magnesium, and iron in those minerals.

Finally the silica saturation index qz is recorded in tables 19 to 22; this derived quantity represents the balance between total silica and silica bound to feldspars

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¹) The analyses were made by the petrochemical laboratory of the Department of Petrology and Mineralogy in the University of Leiden. Head: Dr. C. M. de Sitter-Koomans. Analyst: Miss H. M. E. Bik.

and pyroxenes (si-si′). If this value is negative, minerals like olivine, feldspathoids and oxide ores should be expected; in the positive case free quartz should appear. It appears that the analysed samples of both the ultramafic sequence and the metamorphic complex are silica undersaturated.

The principal value of Niggli's method of petrochemical calculation lies in its simplicity and the versatility provided by the use of approximate compositions in two-dimensional variation-diagrams. The Niggli system of calculation has the further advantage that normative compositions of igneous rocks are easily recalculated to their metamorphic equivalents and vice versa, thus facilitating comparison. The values si, al, fm, c, alk, k, and mg can also be employed to define corresponding magma types. This characterization relates only to their chemical composition and should be regarded as a complement to the petrological classification on the basis of the quantitative mineralogical composition.

The calcium-rich femic rocks of the Stjernöy region obviously belong to the calc-alkali sequence, as shown by their low values of alk (as compared to that of al) and very high c and low k values. The analyses of the ultramafic specimens (table 18) including the olivine-melagabbro rocks, show affinities in their parameters with the pyroxenitic magma type (m_6) or the ariégitic magma type (m_2) in the classification formulated by Burri and Niggli (1945). The gabbro analyses (table 19) compare well with the parameters of type h_6 (pyroxene-gabbroid).

There is no difference of any real significance in the values of the main parameters between the rocks of the ultramafic sequence (including the gabbro samples) in the tables 18 and 19 and the gabbro gneiss and amphibolite of the metamorphic complex in the tables 21 and 22. The qz-indices of both the ultramafic and the metamorphic rocks have negative values of about the same order of magnitude, which shows that the rocks are all undersaturated in silica. In this respect there is agreement with the mafic rocks of Skaergaard, Sulitelma, and Grovstanäs, whereas the samples of the Stillwater and Bushveld occurrences and the samples of the Karroo sills are far less undersaturated or have a small surplus of silica.

A characteristic feature of all of the mafic Stjernöy rocks is their high value of c, which in the pyroxenite and the gabbro samples generally attains values of between 35 and 40. In the magma-type classification of Burri and Niggli (op. cit.) such a high c value is only found in anorthosite (type k_4), mineralogically a rock of much more leucocratic composition. In mafic rocks of basaltic bulk composition from the well-known occurrences (see table 20) the c parameter hardly ever exceeds a value of 25. The unusually high c values of the rocks on Stjernöy may indicate syntectic or assimilation processes of calcium-rich rocks such as limestone.

A very useful graphical representation of the petrochemistry of an igneous rock is the QLM diagram. In this graph the number of variables is reduced to three components in which Q represents the amount of silica; L the amount of feldspathoidal (felsic) molecules Kp, Ne, and Cal; and M the amount of mafic (Ca-femic) molecules Cs, Fo, Fa, Fs, and Ns. These partially hypothetical elementary molecules¹) are calculated from the chemical analyses via the molecular equivalent numbers according to Burri and Niggli (1945, pp. 74 and 622). But it is also possible to cal-

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¹) The symbols represent the following elementary molecules:

Group L : Kp = $K_2O . Al_2O_3 . 2\ SiO_2$ Ne = $Na_2O . Al_2O_3 . 2\ SiO_2$ Cal = $CaO . Al_2O_3$

Group M: Cs = $2\ CaO . SiO_2$ Fo = $2\ MgO . SiO_2$ Fa = $2\ FeO . SiO_2$
Fs = $Fe_2O_3 . SiO_2$ Ns = $Na_2O . Fe_2O_3 . 2\ SiO_2$

culate the QLM values immediately from the Niggli parameters (Burri 1959, pp. 198 and 199). Tables 18, 19, and 20 show the values of Q, L and M thus obtained.

The projection points of these values within the triangular QLM diagram give an approximation of the mineral composition of the sample; for instance, a sample with a projection point under the silica-saturation line PF ($\alpha = 1$) as shown in fig. 8a, should not contain free quartz. Various trends of magmatic differentiation can also be recognized in the QLM diagrams, for instance, the magmas of the circumpacific and atlantic provinces will show a characteristic field of projection points. A useful complement to the QLM diagram for basic rocks is found in the mg/γ diagram, which expresses the relation between the proportions of magnesia and lime to total iron, magnesia and lime not bound to alumina (Burri 1959). In the presence of sufficient SiO_2 the latter diagram is yet another version of the wollastonite-enstatite-ferrosilite system (WoEnFs). No cumbersome calculations are needed for the construction of a mg/γ diagram because the projection points follow from the intersection of the line of equal mg with the line of equal γ for given values of both (fig. 8b).

Although there are in principle no objections to calculating QLM values and constructing diagrams of the metamorphic rock samples — in figures 8a and 8b a few projections of gabbro gneiss and amphibolite samples are shown — preference has been given to the construction of ACF diagrams for the graphical representation of the latter group of analyses.

In order to find out whether or not the bulk chemical composition of a metamorphic rock allows a certain mineral paragenesis to be stable in a particular metamorphic facies, a number of simplified compositional triangular diagrams have been devised, the ACF diagram with saturated silica being the most usuful for the present purpose. The positions and joins of the minerals hypersthene, diopside, anorthite, almandine-pyrope — all minerals typomorphic of the granulite-facies — have been drawn into the ACF diagrams in fig. 9a and 9b. The approximate locus of hornblende has also been indicated in these diagrams. It should be noted that ACF diagrams may only be constructed if the degree of undersaturation of SiO_2 remains within a tolerable limit. As can be seen in table 22 the amphibolite samples T 3.57 and T 3.43 exhibit a large deficit of silica; the gabbro gneiss samples are less critical in this respect. However, a negative value of qz is acceptable as long as the deficit can be explained by the presence of the "undersaturated" minerals anorthite and aluminous pyroxene or hornblende and not by olivine or primary spinel. As can be seen in the modes of the analysed samples (see tables 8 and 11), olivine is absent and spinel occurs mainly as symplectitic intergrowths; for this reason the plotting in ACF diagrams of the metamorphic rocks on Stjernöy with a negative qz value appears to be permissible. No ACF values have been calculated for the analyses of alkali-rich syenite gneiss; owing to the high amount of alkalis the A value ($Al_2O_3 + Fe_2O_3 — (Na_2O + K_2O)$) is necessarily low or even negative. Moreover, the low content of lime and ferromagnesian elements in feldspathic rocks preclude their plotting in an ACF diagram.

CHEMICAL COMPOSITIONS AND QLM VALUES OF ULTRAMAFIC AND LAYERED GABBRO ROCKS

The results of the analyses of the different rock types of the ultramafic sequence (see table 18) show in the first place that there is a marked difference in chemical composition between dunite (sample T 4.2a) and pyroxene-peridotite (sample

T 4.2b). The main trend of chemical differentiation is found in the exchange of magnesium for calcium and aluminium.

The pyroxene-rich peridotite (sample T 4.2b) in its chemical composition resembles rather closely the samples of olivine-melagabbro in table 18, although these melagabbro samples contain up to 35 per cent plagioclase. Apparently the introduction of bytownitic plagioclase does not greatly influence the bulk chemical composition of a rock consisting mainly of calcium-rich pyroxene. As far as chemical composition is concerned, the olivine-melagabbro in its turn grades into the gabbro of the layered suite (table 19) by a decrease of MgO and FeO + Fe_2O_3 as against an increase of Al_2O_3 and a much smaller increase of Na_2O. Moreover, the rocks in question become more siliceous. The differences in composition also find expression in the Niggli values, which show as their main feature an increase of the al parameter with a concomitant decrease of the fm parameter.

A common characteristic of all the samples of the ultramafic sequence, including those of the gabbro, is the high amount of CaO demonstrated by the analyses. This feature becomes apparent when comparing the c value of the Stjernöy rocks (average value about 35) with the c values of other occurrences of mafic rocks (see table 20).

In its chemical composition the anorthosite sample in table 18 deviates from the other samples by a much higher value for al, which is compensated for by a correspondingly lower content of fm. The average of the anorthosite sample (sample T. 4.63b) and the adjacent olivine-melagabbro layer (sample T 4.63a) corresponds well with the values of the analysed gabbro samples. Thus from the chemical point of view it seems clear that anorthosite and melagabbro are complementary rocks, which may have originated from a normal gabbroïc parent magma.

As has already been said, the QLM variation diagrams are well suited to present the trends in normative mineralogical composition of igneous rocks graphically. These QLM values are plotted in fig. 8a, and show an approximately linear trend with the melanocratic dunite sample (T 4.2a) nearest to the M corner and the most leucocratic sample (anorthosite T 4.63b) nearest to the QL side. The other samples are arranged approximately along a straight line between these two points and pass through M upon extrapolation to the left. All the samples from Stjernöy are silica-undersaturated, since their projection points in the QLM diagram lie well below the silica-saturation line (PF). The arrangement of the projection points along a nearly straight line suggests a simple process of differentiation, such as liquation, or hybridization of magmas, or the sinking or filter pressing of the femic minerals olivine and possibly pyroxene in the magmatic liquid. Through sinking or filter-pressing of the latter minerals the magma becomes relatively enriched in silica, alumina, and alkalis, and upon fractionation of much olivine and pyroxene anorthosite may result. (Note the gently descending curve between 6 and 11 in fig. 8a and its extrapolation to point P).

What has been established for samples T 4.63a and T 4.63b may well be valid for the rocks of the layered sequence as a whole. It also seems to be significant that the arithmetic mean [1]) of the projection points in fig. 8a, including those of the anorthosite and the pyroxene-peridotite, will yield a point in the centre of the diagram near sample T 4.66 (projection point no. 6) in close proximity to the field of gabbro gneiss projections. This indicates that the apparent parent of the layered

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[1]) The dunite is excluded because its position in the differentiation sequence on Stjernöy is uncertain; nowhere in the field can its occurrence be explained as the first precipitate; the dunite in some places also gives the effect of having been digested by the pyroxene-peridotite.

TABLE 18 *Analyses of peridotite, olivine-melagabbro, and anorthosite in weight percentages*

No. of sample	T 4.2^{a}	T 4.2^{b}	T 4.27	T 4.121	T 4.63^{a}	T 4.63^{b}
SiO_2	39.60 (39.20) 1)	43.45 (43.42)	44.65 (44.78)	45.80	45.45	45.10
TiO_2	0.26	1.05 (1.08)	0.98 (1.02)	0.85	0.81	0.31
P_2O_5	0.07	0.08	0.10	0.10	0.06	0.11
Al_2O_3	2.38 (2.58)	9.60 (8.65)	10.40 (10.65)	13.76	13.95	30.30
Fe_2O_3	2.09 (3.06)	2.52 (3.66)	3.15 (2.93)	3.00	3.78	0.88
FeO	8.18	6.68	5.86	5.17	4.48	0.76
MnO	0.20	0.16	0.19	0.13	0.15	0.05
MgO	38.48 (38.92)	18.24 (18.53)	14.92 (15.42)	13.72	12.69	3.52
CaO	3.99 (3.45)	16.16 (15.78)	18.64 (17.45)	15.59	16.40	16.24
Na_2O	0.20	0.80	1.00	1.00	1.56	2.12
K_2O	0.10	0.10	0.10	tr.	0.10	0.10
H_2O	3.97	0.64	0.46	0.57	0.35	0.47
Total	99.52	99.48	100.45	99.69	99.78	99.96
Niggli values of the analyses						
si	55.0	74.0	78.5	88.0	86.0	102.5
al	2.0	9.5	11.0	15.5	15.5	40.5
fm	91.5	59.5	52.0	50.5	48.5	15.0
c	6.0	29.5	35.0	32.0	33.0	39.5
alk	0.5	1.5	2.0	2.0	3.0	5.0
mg	0.88	0.78	0.75	0.79	0.74	0.79
k	0.25	0.07	0.06	0.00	0.04	0.03
ti	0.28	1.30	1.27	1.22	1.13	0.54
p	0.05	0.10	0.11	0.08	0.06	0.14
qz	— 47	— 32	— 29.5	— 20	— 26	— 17.5
γ	0.04	0.26	0.34	0.27	0.29	0.19
QLM values calculated from Niggli values						
Q	3.9	16.4	18.5	23.9	22.2	33.4
L	4.7	17.6	20.2	25.4	26.9	54.9
M	91.4	66.0	61.3	50.7	50.9	11.7

Localities of samples

T 4.2a = Dunite from Store Kvalfjord valley, Stjernöy
T 4.2b = Peridotite from Store Kvalfjord valley, Stjernöy
T 4.27 = Olivine-melagabbro from Indre Simavik valley, Stjernöy
T 4.121 = Olivine-melagabbro from Simavikfjell, Stjernöy
T 4.63a = Olivine-melagabbro from Rottenhallerfjell, Stjernöy
T 4.63b = Anorthosite from Rottenhallerfjell, Stjernöy

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1) percentages in parentheses represent determinations in duplicate samples by gravimetric methods.

TABLE 19 *Analyses of gabbro in weight percentages.*

No. of sample	T 4.65	T 4.126	T 4.66	T 4.123a	T 4.19a
SiO_2	45.70	46.72	47.51	46.00	44.60
TiO_2	0.69	0.64	0.77	0.76	1.34
P_2O_5	0.04	0.03	0.06	0.10	0.09
Al_2O_3	16.77	15.03	18.00	23.08	22.30
Fe_2O_3	2.79	2.87	3.17	1.28	2.93
FeO	3.52	3.38	2.82	2.86	4.15
MnO	0.09	0.15	0.13	0.11	0.14
MgO	11.18	11.51	8.96	8.46	5.31
CaO	16.44	17.21	16.40	15.18	16.05
Na_2O	1.38	1.20	1.70	1.96	2.22
K_2O	tr.	tr.	0.10	0.10	0.08
H_2O	1.06	0.74	0.48	0.42	0.42
Total	99.66	99.48	100.10	100.31	99.63
	Niggli values of the analyses				
si	92.0	94.0	98.5	96.0	99.0
al	20.0	18.0	22.0	28.0	29.0
fm	42.0	42.5	38.0	34.0	28.0
c	35.5	37.0	36.5	34.0	38.0
alk	2.5	2.5	3.5	4.0	5.0
mg	0.80	0.81	0.73	0.78	0.63
k	0.00	0.00	0.03	0.03	0.03
ti	1.09	0.97	1.22	1.25	2.26
p	0.04	0.03	0.08	0.12	0.09
qz	— 18	— 16	— 15.5	— 16	— 21
γ	0.30	0.33^5	0.32	0.22	0.33
	QLM values calculated from Niggli values				
Q	26.4	26.4	28.2	28.9	29.0
L	33.3	31.3	34.0	41.8	43.2
M	40.3	42.3	37.8	29.3	27.8

Localities of samples

T 4.65 = Olivine-gabbro from Rottenhallerfjell, Stjernöy
T 4.126 = Gabbro (olivine-bearing) from Nordmandsnes, Stjernöy
T 4.66 = Gabbro (olivine-bearing) from Rottenhallerfjell, Stjernöy
T 4.123a = Gabbro from Store Kjerringfjordbotn, Stjernöy
T 4.19a = Gabbro from Simavikfjell, Stjernöy

sequence has strong resemblances in composition to the average type of gabbro gneiss. This fact offers very interesting perspectives for genetic deductions.

Fig. 8a includes the QLM values (see table 20) of a few other mafic magma types. They prove to be less undersaturated in silica and are more felsic than most of the gabbro samples from Stjernöy. It should be pointed out here that the analyses

TABLE 20 *Analyses of other occurrences of mafic rocks.*

	Stillwater	Bushveld	Skaergaard	Karroo	Sulitelma	Grovstanäs
SiO_2	50.68	51.45	47.92	52.5	48.57	42.00
TiO_2	0.45	0.34	1.40	1.0	0.21	0.12
P_2O_5	0.09	0.09	0.07	0.1	tr.	0.22
Al_2O_3	17.64	18.67	18.87	15.4	18.48	25.74
Fe_2O_3	0.26	0.28	1.18	1.2	0.67	1.70
FeO	9.88	9.04	8.65	9.3	6.21	4.07
MnO	0.15	0.47	0.11	0.2	0.07	0.05
MgO	7.67	6.84	7.82	7.1	9.56	8.46
CaO	10.47	10.95	10.46	10.3	12.23	14.14
Na_2O	1.87	1.58	2.44	2.1	3.22	1.06
K_2O	0.24	0.14	0.19	0.8	0.30	0.52
H_2O^+	0.42	0.34	0.41	n.d.	0.81	1.80
H_2O^-	0.06	0.03	0.10			
NiO_2	0.04					
Cr_2O_3	0.04					
Total	99.96	100.22	99.62	100.0	100.33	99.88
			Niggli values of the analyses			
si	116.0	120.0	108.0	126.0	103.5	85.5
al	24.0	25.5	25.0	21.5	23.0	31.5
fm	46.0	43.0	44.0	45.5	42.5	34.0
c	25.5	27.5	25.0	26.5	27.0	31.5
alk	4.5	4.0	6.0	6.5	7.5	3.0
mg	0.55	0.56	0.60	0.56	0.72	0.75
k	0.08	0.06	0.05	0.23	0.06	0.02
ti	0.76	0.59	2.38	1.88	0.38	0.12
p	0.08	0.08	0.07	0.09	0.00	0.12
qz	— 2	4	— 16	0	— 26.5	— 26.5
γ	0.11	0.12	0.12	0.20	0.21	0.14
			QLM values calculated from Niggli values			
Q	33.1	35.0	29.4	33.1	26.2	27.8
L	34.8	35.4	38.5	32.8	39.1	46.9
M	32.1	29.6	32.1	34.1	34.7	25.3

Stillwater Bushveld Skaergaard	Border facies rocks considered representative of these well-known occurrences of mafic magmas (Hess 1960, p. 152).
Karroo	Average of 43 chemical analyses of dolerites (Walker and Poldervaart 1949, p. 649).
Sulitelma	Analysis of olivine gabbro of average composition (Th. Vogt 1927, p. 533).
Grovstanäs	Analysis of allivalite-olivine-bytownite (Lundegårdh, 1943, p. 317).

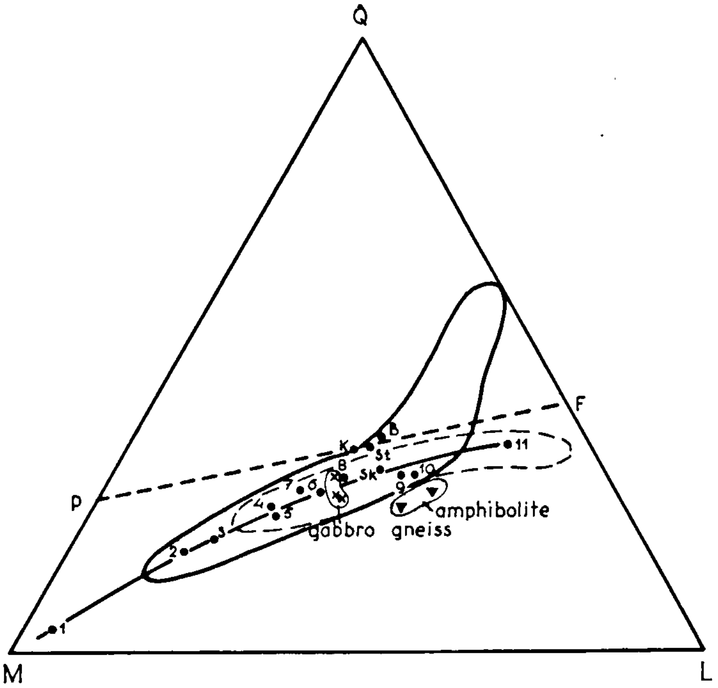

Fig. 8*a*. QLM variation diagram with projection points of samples of the ultramafic sequence: dunite (no. 1), peridotite (no. 2), olivine melagabbro (nos. 3, 4, and 5), olivine-bearing gabbro (nos. 6 and 7), gabbro (nos. 8, 9, and 10), and anorthosite (no. 11). The projection points of average samples of gabbro or norite from Skaergaard (Sk), Stillwater (St), Bushveld (B), and Karroo-sills (K) are also indicated. The fields of the circumpacific (solid) and atlantic provinces (dashed) are outlined.

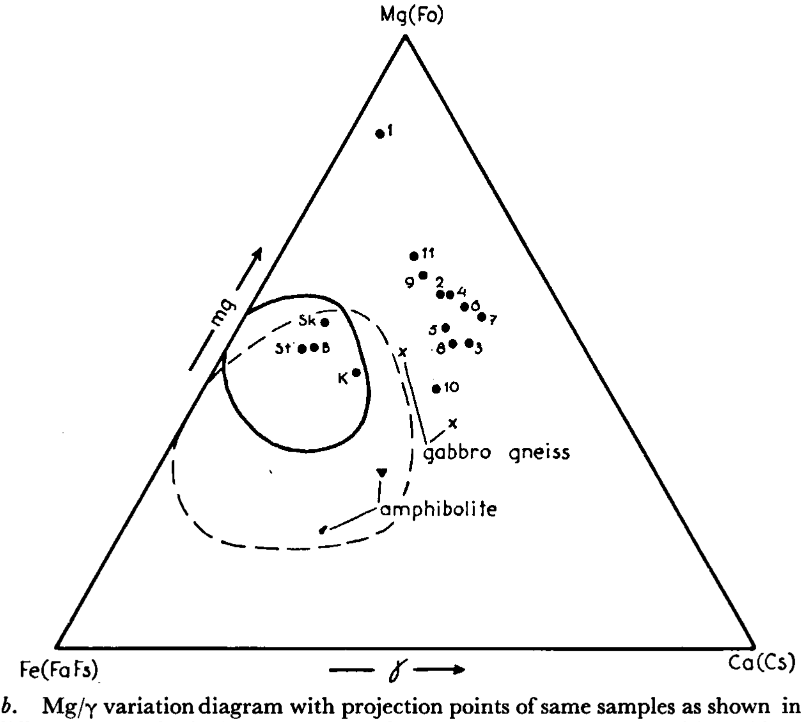

Fig. 8*b*. Mg/γ variation diagram with projection points of same samples as shown in fig. 8*a*. Note difference with field of the circumpacific province, which is outlined in solid, as well as the atlantic field with dashed outline.

of the Stillwater, Bushveld and Skaergaard magmas shown in table 20 were made from samples of the border zones, which are considered by Hess (1960) to be representative of the average undifferentiated mafic magma. The QLM values of these three analyses compare well with the average of 43 chemical analyses of the sills of Karroo dolerite (Walker and Poldervaart 1949), which average may also be considered to be representative of a mafic magma.

The rocks of the ultramafic sequence on Stjernöy seem to exhibit a fairly well-developed and simple trend of differentiation, whereas the large mafic intrusions such as Stillwater and Skaergaard exhibit a more abrupt and complex type of differentiation (Hess 1960). In fig. 8a the field of distribution of the circumpacific province is outlined, clearly indicating the tendency of this group of magmas to develop into leucocratic rocks with free silica.

In addition, the Niggli values of the Stjernöy-gabbro show a much higher c value (compare tables 19 and 20). If the analyses reported in tables 18, 19, and 20 are plotted in the mg/γ diagram (note that in this diagram Ca represents the proportion of calcium which is not bound up in plagioclase) this difference from the common magmas of the circumpacific type such as from Lassen Peak becomes manifest (fig. 8b). Even the ultramafic members of the layered sequence on Stjernöy (e.g. samples T 4.2b, T 4.121 and T 4.27) exhibit high c values and have their projection points along the MgCa side of the diagram. Few ophiolitic magmas have comparable compositions, but Burri and Niggli (1945) quote analyses from the Vaudois and the Piemont showing similar high c values in pyroxene-gabbroid and anorthosite-gabbroid rocks.

The richness in lime of the gabbro and allied rocks of Stjernöy appears to be a major chemical characteristic. It may be that this consanguineous suite is derived from a special parent magma rich in lime whose residual liquids may have give rise to carbonatitic rocks, or it may be that a lime-rich magma originated from a normal basaltic magma by the assimilation or syntexis of calcium-rich rocks such as limestone, marl, greywacke, etc.

Other literature on mafic rocks of comparable composition is rare; a representative sample of olivine-gabbro from the Sulitelma phacolith (see table 20) has comparable si, al, and fm values but also exhibits lower c and higher alk values. A sample from the Grovstanäs massif in Roslagen (Sweden) shows a fairly good chemical resemblance to the gabbro on Stjernöy (low si and alk values and a high c value), but this rock consists of olivine and bytownite and is an allivalite rather than a gabbro (Lundegårdh 1943).

CHEMICAL COMPOSITIONS AND ACF VALUES OF GABBRO GNEISS AND ALLIED METAMORPHIC ROCKS

The analyses of the gabbro gneiss samples exhibit a fairly uniform result, T 4.111 being a good average sample. In table 21 the weight percentages of oxides and the calculated Niggli values are shown. The gabbro gneiss samples are slightly to moderately undersaturated in silica and again have a high CaO content.

Compared with the analyses of the rocks of the ultramafic sequence, no differences of any appreciable importance are found in the chemical bulk compositions; in table 21 (gabbro gneisses) the al values are slightly lower and the fm values higher than in table 19 (gabbros of the layered sequence). However, in some of the analyses of gabbro gneisses the alk values are much higher than in the former rocks.

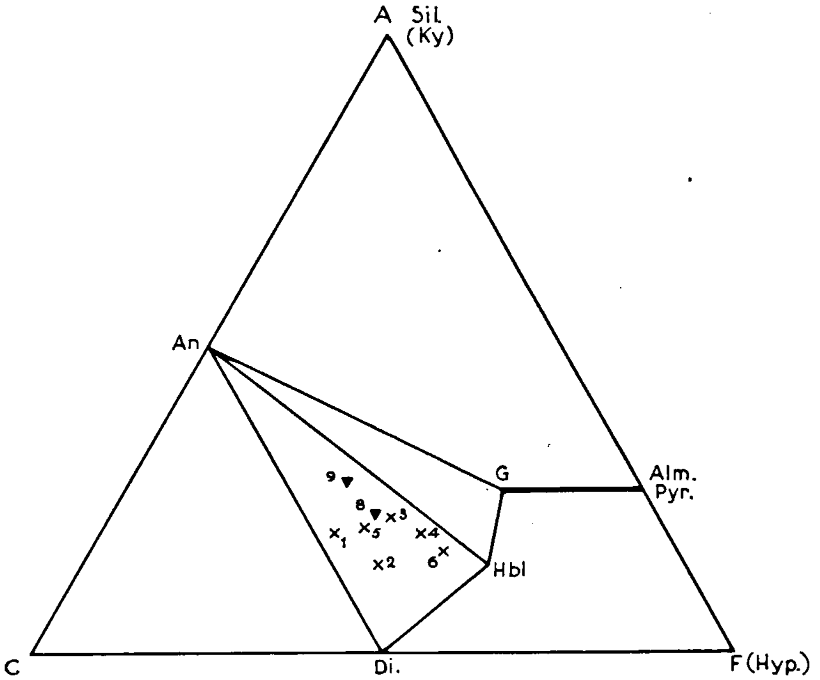

Fig. 9*a*. ACF diagram of the hornblende-granulite subfacies with projection points of gabbro gneiss (nos. 1 to 6) and amphibolite (nos. 8 and 9).

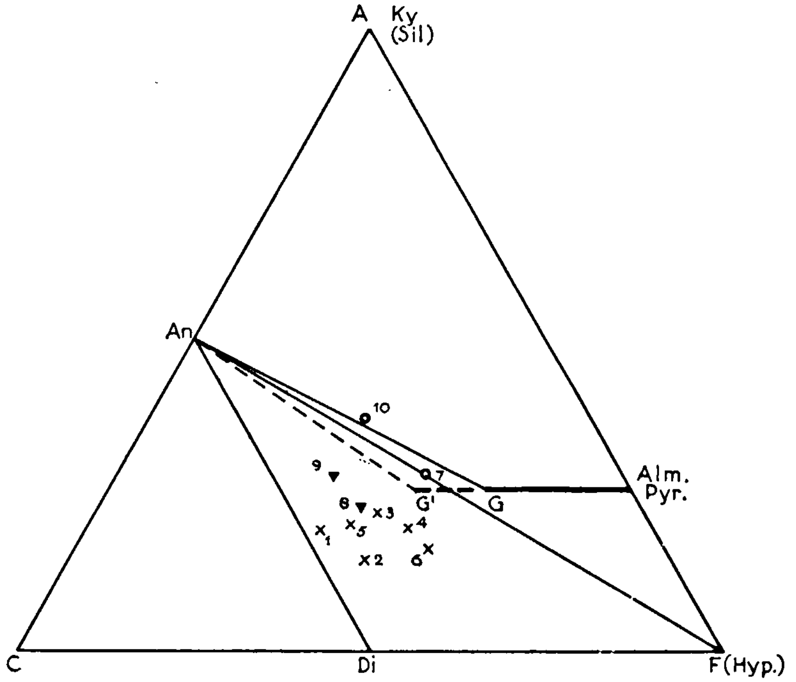

Fig. 9*b*. ACF diagram of the pyroxene-granulite subfacies with same projection points for samples as in fig. 9*a*. Hypersthene-bearing granulite is represented by nos. 7 and 10.

For an illustration of the difference, samples T 4.123a of the layered gabbro suite and T 4.123b of the gabbro gneiss should be compared [1]).

Fig. 8a contains a few projection points of gabbro gneisses in the QLM diagram. As can be seen from the Niggli values in table 21 the variability in composition of the gabbro gneisses as a whole is fairly small. The positions of these points show that the gabbro gneisses occupy a central position in the diagram and compare well with the average type of gabbro of the layered sequence (e.g. T 4.66, T 4.123a and T 4.19a). The geological implications of this central position will be discussed further in the next chapter. No apparent trends of differentiation from layered gabbro to gabbro gneiss are perceptible in the QLM (fig. 8a) and mg/γ diagram (fig. 8b); this probably means that the gabbro gneisses cannot be considered as a schistose, further differentiated product of the layered sequence.

The amphibolite samples T 3.57 and T 3.43 are shown by the chemical analyses to exhibit a lower MgO content and, remarkably enough, also a lower CaO content than is found in the gabbro gneiss samples. This is compensated for by higher amounts of alumina and alkali-oxides. The amphibolite analyses of samples T 3.57 and T 3.43 also yielded high percentages of TiO_2 and P_2O_5. In general, the Niggli values are of the same order of magnitude as those of the gabbro gneiss samples.

Generally speaking, it may be said that the metamorphic rocks of gabbroic or amphibolitic composition have higher values for the minor elements (compare for instance the alk, ti and p values) than the rocks of the ultramafic sequence, but otherwise they exhibit the same over-all trend in the values of si, al, fm, and c.

The results of the analyses of syenite gneisses (samples T 3.81 and T 3.84) and those of the garnet-bearing and garnet-free granulite (samples T 4.83 and P 24) speak for themselves. The mesoperthitic character of the syenite gneiss is confirmed by the chemical analyses, the amounts of Na_2O and K_2O found in these rocks being very similar. It may be recalled here that mesoperthite, together with antiperthite, is a feldspar critical for the granulite facies as defined by Eskola (1939). In the classification of magma types (Burri and Niggli 1945) the syenite found in the metamorphic rock complex shows affinities with the pulaskitic magma of the atlantic suite (type e_2).

In the ACF diagrams shown in figs. 9a and 9b the analytic results given in tables 21 and 22 are plotted for the hornblende-granulite and the pyroxene-granulite subfacies. The projection points of the gabbro gneiss and amphibolite samples fall within the triangle delimited by anorthite, diopside, and hornblende (fig. 9a), with the exception of sample P 24 which lies virtually on the join anorthite-hypersthene in the diagram of the pyroxene-granulite subfacies (fig. 9b). The latter sample is indeed a hypersthene-rich mafic granulite containing small amounts of biotite but, significantly, no garnet or hornblende; kyanite occurs as an accessory constituent.

Table 8 (p. 230) shows that plagioclase, diopsidic augite, and hornblende are the main mineral constituents of the gabbro gneiss samples; according to the diagram in fig. 9a, rocks with this paragenesis may be in stable equilibrium in the hornblende-granulite subfacies or in the amphibolite facies. Garnet, sillimanite, or kyanite do not occur in these samples; some of them contain minor amounts of biotite.

The projection points of the amphibolite samples T 4.43 and T 4.57 (modal composition 30 to 40 per cent hornblende, 5 to 10 per cent diopside, the remainder

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[1]) These samples derive from adjacent localities at the contact of both groups of rocks, South of Store Kjerringfjord.

TABLE 21 *Analyses of gabbro gneiss in weight percentages.*

No. of sample	T 4.123^b	T 4.57	T 4.111	T 4.112^a	T 3.66^b	T 4.4
SiO_2	46.98	44.95	45.62	49.10	48.20	46.44
TiO_2	2.34	1.86	1.71	0.56	0.45	1.67
P_2O_5	0.07	0.18	0.05	0.12	0.04	0.22
Al_2O_3	14.86	13.80	16.22	15.42	16.80	12.91
Fe_2O_3	5.08	1.00	4.95	1.01	2.71	4.13
FeO	5.59	6.97	6.71	2.53	3.53	8.36
MnO	0.20	0.09	0.18	0.12	0.12	0.19
MgO	6.16	9.12	8.56	8.72	10.09	10.85
CaO	14.32	17.12	13.29	20.16	15.12	12.81
Na_2O	3.48	2.50	2.13	1.50	2.08	1.41
K_2O	0.15	0.10	tr.	0.14	0.10	tr.
H_2O	0.43	0.47	0.63	0.59	0.41	0.54
Total	99.66	98.16	100.05	99.97	99.65	99.53
Niggli values of the analyses						
si	108.0	92.0	98.5	103.0	102.0	97.5
al	20.0	16.5	20.5	19.0	21.0	16.0
fm	37.0	40.5	44.0	33.0	40.5	52.0
c	35.0	38.0	31.0	45.0	34.0	29.0
alk	8.0	5.0	4.5	3.0	4.5	3.0
mg	0.58	0.69	0.63	0.81	0.79	0.65
k	0.03	0.02	0.00	0.07	0.03	0.00
ti	4.00	2.83	2.72	0.87	0.70	2.64
p	0.07	0.15	0.05	0.11	0.04	0.20
qz	—24	—28	— 19.5	—9	— 16	— 14.5
ACF values calculated from molecular equivalents						
A	18.5	14.2	20.8	18.4	19.5	16.1
C	46.6	43.0	37.3	48.2	38.7	32.6
F	34.9	42,8	41.9	33.4	41.8	51.3

Localities of samples

T 4.123^b = Gabbro gneiss from Store Kjerringfjordbotn, Stjernöy
T 4.57 = Gabbro gneiss from Store Kjerringfjordbotn, Stjernöy
T 4.111 = Gabbro gneiss from Udsiktfjell, Stjernöy
T 4.112^a = Gabbro gneiss from Udsiktfjell, Stjernöy
T 3.66^b = Gabbro gneiss from Store Kjerringfjord, Stjernöy
T 4.4 = Gabbro gneiss from Lille Kvalfjord, Stjernöy

TABLE 22 *Analyses of amphibolite, syenite, and garnet gneiss in weight percentages.*

No. of sample	T 3.57	T 3.43	T 3.81	T 3.84	T 4.83	P 24
SiO_2	47.60	44.99	62.10	59.63	70.75	51.14
TiO_2	2.38	2.66	0.47	0.54	0.80	0.46
P_2O_5	1.10	1.28	0.09	0.05	0.03	0.05
Al_2O_3	16.26	21.30	18.45	21.30	13.99	19.93
Fe_2O_3	3.47	0.52	1.71	1.74	1.36	2.07
FeO	7.23	7.11	2.16	1.90	3.13	5.47
MnO	0.22	0.20	0.08	0.08	0.13	0.11
MgO	3.55	3.51	0.60	0.19	1.72	8.45
CaO	10.32	12.72	2.01	2.96	4.26	8.44
Na_2O	5.10	4.40	6.20	5.12	3.00	2.78
K_2O	1.34	0.20	6.56	6.48	0.70	0.15
H_2O	0.96	0.14	0.19	0.00	0.14	0.66
Total	99.53	99.03	100.62	99.99	100.01	99.71
Niggli values of the analyses						
si	118.0	106.0	228.0	212.0	315.0	121.0
al	23.5	29.5	40.0	44.5	36.5	28.0
fm	35.0	28.0	14.5	11.5	28.0	43.0
c	27.0	32.0	8.0	11.5	20.5	22.5
alk	14.5	10.5	37.5	32.5	15.0	6.5
mg	0.38	0.45	0.22	0.09	0.41	0.70
k	0.15	0.03	0.41	0.45	0.14	0.04
ti	4.5	4.67	1.32	1.50	2.66	0.86
p	1.18	1.25	0.09	0.05	0.03	0.05
qz	—40	—36	—22	—18	155	—5
ACF values calculated from molecular equivalents						
A	21.1	28.0			36.6	26.7
C	38.8	40.0			31.7	25.6
F	40.1	32.0			31.7	47.7

Localities of samples

T 3.57 = Amphibolite from Vailas Goppe, Stjernöy
T 3.43 = Amphibolite from Kjerringfjordklubben, Stjernöy
T 3.81 = Syenite gneiss from Lille Kjerringfjord, Stjernöy
T 3.84 = Syenite gneiss (plagioclase bearing) from Lille Kjerringfjord, Stjernöy
T 4.83 = Garnet bearing granulite from Store Kvalfjord, Stjernöy
P 24 = Hypersthene gneiss from Lille Kufjord, Seiland

principally plagioclase) also fall within the field bounded by anorthite, diopside, and hornblende (fig. 9a). In other cases the amphibolite may be garnet-bearing, and in the event of a stable paragenesis its projection points should plot on the other side of the join anorthite-hornblende. Such rocks actually were found as intercalations in the amphibolite of the northern peninsulas on Stjernöy.

The grossularite content of the garnet is of great importance to the establishment of stable parageneses containing garnet in the pyroxene-granulite subfacies. Hysingjord (1960) determined the composition of this mineral in a garnet-bearing plagioclase-rich gneissic intercalation (sample T 3.250) of the gabbro gneiss complex and found the following composition: almandine 57.48 per cent, grossularite 18.70 per cent, pyrope 22.87 per cent, and spessartine 0.95 per cent. As an approximate composition in the case of the Stjernöy rocks, a garnet with 20 per cent grossularite has been plotted in the diagram; this is point G in fig. 9b. In granulite facies rocks garnet with 30 per cent of grossularite may occur (point G′ in the diagram).

When the projection point of the garnet lies close to the right of the join anorthite-hypersthene, the field of garnet-bearing orthopyroxene granulites will be very restricted; when it lies to the left of this join we may expect hypersthene, kyanite (or sillimanite), and garnet to be a stable paragenesis.

In fig. 9b samples P 24 and T 4.83 have their projection points very close to the joins anorthite-hypersthene and anorthite-garnet in the pyroxene-granulite subfacies. Sample T 4.83 is a garnet-bearing plagioclase-quartz granulite with sillimanite as accessory mineral, hence it probably lies just to the right of the join anorthite-garnet with 20 mol. % grossularite (G). In the hypersthene-rich granulite (sample P 24) no garnet but some kyanite is found. This rock should therefore plot just to the right of the join anorthite-hypersthene (see fig. 9a), the possible garnet (G′) being too rich in grossularite to be found in a rock of this bulk composition (see table 22).

The gabbro gneiss samples themselves give inconspicuous results in the ACF diagrams, but the plotting of the hypersthene-granulite and acid granulite, which rocks occur as intercalations in the gabbro gneisses, give strong support to the suppositions on granulite facies conditions made already in the chapters on petrology and mineralogy. Also the degree of metamorphism found in amphibolite samples seems to be compatible with granulite or at least hornblende-granulite subfacies conditions. There seems to be little doubt that the metamorphosis of these rocks, also characterized by very low contents of water in their chemical analyses, took place under high temperature and pressure conditions, such as would exist at great depth in major orogenetic zones of the earth's crust.

CHAPTER VI

A TENTATIVE PETROGENESIS OF THE MAFIC ROCK PROVINCE OF WESTERN FINNMARK

In the foregoing chapters the structural, mineralogical, and chemical properties of the rocks in the Seiland-Stjernöy-Öksfjord province were described in detail. In this chapter the results of these investigations will be co-ordinated in an attempt to arrive at a petrogenesis for this province, which must necessarily be of a tentative nature.

The genesis of layered mafic rock occurrences continues to be the subject of much petrological discussion. Poldervaart and Taubeneck (1960) have summarized the latest views on this matter (see p. 196). Chapter II shows that the mafic rocks on Stjernöy offer structural similarities with layered gabbro-peridotite complexes such as those found at Bushveld, Stillwater, and Skaergaard. Two types of gabbro-peridotite complexes have been distinguished (e.g. by Thayer, 1960). According to this author the stratiform type, exemplified by the Bushveld occurrence, is chiefly characterized by the systematic succession of peridotite at the base to orderly layered gabbro at the top of the occurrence. The alpine type of gabbro-peridotite complex is found along the major orogenic belts of the earth and is characterized by erratic distribution of gabbro and peridotite and also by irregularity in layering or form. However, in both cases crystallization from a primary magma is assumed.

The paragenesis of ultramafic and mafic rocks on Stjernöy has the following features in common with the alpine type of gabbro-peridotite complex (see Thayer *op. cit.*):

- Irregular structure within the layered rock complex which lacks a definite floor and signs of contact metamorphism.
  (N.B.: the stratiform type exhibits a systematic progression from peridotite to gabbroic rocks with characteristic cryptic layering).
- Interfingering of components and extreme contrast in the composition of adjacent layers; thus olivine-melagabbroic and anorthositic bands are found on Stjernöy.
- High Mg/Fe ratios in the mafic minerals (for olivine and orthopyroxene in Stjernöy samples, see p. 265). which exceed those commonly found in the stratiform type. The latter also shows a predominance of orthopyroxene over clinopyroxene.
- Due to the orolenic environment gneissic textures with signs of cataclasis are frequently found in the alpine type, whereas in the quietly crystallizing magmas of the stratiform occurrences euhedral crystals and poikilitic textural relations are found.
- Genetically related dykes of ultramafite in the gabbro or the reverse and inclusions of one rock type within the other are commonly found in the alpine sequences (see autobrecciation on Stjernöy, p. 190).

Porphyritic textures and indications of cryptic layering occur in the layered gabbro sequence on Rottenhallerfjell on Stjernöy. For instance the An content of the plagioclase (table 6) and the Fo content of the olivine (table 17) vary considerably. However, no systematic variation — so characteristic of the stratiform complexes — is found on Stjernöy; the variation being due to local changes of circumstances under which these minerals have crystallized.

From the traditional point of view the layered gabbro and peridotite occurrences on Stjernöy may be considered as the products of differentiation of a basaltic magma within the Caledonian orogenic belt. However, the main difficulty confronting a co-magmatic hypothesis for the entire western Finnmark petrographic province is the juxtaposition of mafic rocks of igneous and of highly metamorphic appearance[1]).

The main argument in favour of a metamorphic origin of the gabbro gneiss is its interlayering with granulite, syenite gneiss and meta-limestone. Krauskopf (1954) discusses the possibilities of deriving the gabbro gneiss by intrusive processes as against the more likely possibility of metamorphism of a mixed volcanic and sedimentary sequence. Barth (1961) describes a layered series of gabbroic rocks from the Bumandsfjord region with intercalations of peridotite and anorthositic gabbro laterally grading into a layered amphibolite-gabbro gneiss complex. In the layered gabbro, bands of diopside-garnet marble and spinel-sillimanite rock up to a few decimetres in width occur. Barth interprets these bands as metasediments, which form an integral part of the mafic country rock. Similar bands of metasediments as well as acid granulite intercalations have been found in the gabbro gneiss of northern Stjernöy and the Öksfjord peninsula. However, within the layered sequences of gabbro and peridotite of Rottenhallerfjell, Simavikfjell, and Lille Kufjord (Seiland) evidence of metasedimentary bands have not been found so far.

In Chapter IV the physico-chemical conditions of the clinopyroxene-orthopyroxene and the orthopyroxene-olivine systems as expressed by tie-line trends and K(T) values have been discussed. The evidence points to extreme conditions of dry metamorphism at great depths where high temperatures made possible by equally high pressures exist (pp. 267 and 268). Pressures of the order of 10 to 20 kilobars are also indicated by the high aluminium contents of the femic minerals. Davidson (1944) states that the reaction:

$$\underset{\mathrm{An}}{2\mathrm{CaAl_2Si_2O_8}} + \underset{\mathrm{Fo}}{3\mathrm{Mg_2SiO_4}} \rightarrow \underset{\mathrm{Di}}{2\mathrm{CaMgSi_2O_6}} + \underset{\mathrm{En}}{2\mathrm{MgSio_3}} + \underset{\mathrm{Sp}}{2\mathrm{MgAl_2O_4}}$$

involving a 10 % decrease in volume, proceeds to the right at high pressures. In the mafic province of western Finnmark spinel and spinel-symplectite occur abundantly.

Thus, from the physical point of view it seems quite feasible that the proper conditions for dry anatexis were attained within the metamorphic complex of mafic gneisses, resulting locally in syntexis and palingenesis of a magma of gabbroic bulk composition. It is quite possible that the degree of melting differed from place to place. In the Rottenhallerfjell region with its layering of truly igneous appearance the melting process probably was complete, whereas in the Bumandsfjord region on Seiland only incipient differential anatexis took place which left remnants of rocks having high fusion temperatures in a dry environment, such as limestone and dolomite. The melting of the mafic meta-volcanics may have been induced by a release of pressure, connected with denudation and uplift of the orogen.

Not only from the physical but also from the chemical point of view, arguments for anatexis can be drawn. The samples analysed of the various components of the layered gabbro sequence of Rottenhallerfjell, as plotted in the QLM diagram (fig. 8a), show an approximately linear trend suggesting a simple process of differentiation such as fractional melting or crystallization of olivine, pyroxene, and

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[1]) The mineralogical characteristics features of the layered gabbro and the gabbro gneiss are summarized on pp. 242 and 243.

plagioclase resulting in anorthositic gabbro and olivine melagabbro or pyroxene-peridotite as end-products.

This trend of differentiation is completely different from the trend established in the stratiform intrusions with large scale layering as in the Bushveld occurrence, which are less undersaturated in silica and tend to develop into leucocratic rocks with free silica. In this context it should be noted that granophyres, such as the Bushveld magma developed in its last stages of differentiation, do not occur in the mafic province of western Finnmark. The basaltic magmas of the alpine type of gabbro-peridotite complex show the same tendency, which in most cases is less explicitly developed.

Referring again to fig. 8a it can be seen that the approximate mean of chemical analyses of rocks of the layered sequence on Stjernöy closely approaches the centre of the field of projections of gabbro gneiss samples in a QLM diagram. This feature can be explained by assuming differential anatexis of gabbro gneisses with incongruent melting of pyroxene to yield plagioclase-rich rocks on the one hand and ultramafic rocks on the other. But it is equally possible that the gabbro gneiss underwent syntexis and that the differentiation into layers of contrasting composition was effected by sinking, or rather in this case, by filter-pressing of the early crystallization products such as olivine and pyroxene. The residual liquid, enriched in alkalis, alumina, and silica in layers adjacent to the ultramafic precipitate could then crystallize as anorthosite.

The discrepancies in the physicochemical data (tie-line trends, etc.) and in the differentiation trends between the mafic and ultramafic petrographic province in western Finnmark and the gabbro-peridotite complexes of the alpine or the stratiform type can be explained by the hypothesis of differential anatexis with local palingenesis in a deep seated zone of the crust. Krauskopf's idea of a "gabbroization" of original mafic effusives and tuffs of basaltic composition has been substantiated by the present mineralogical and chemical investigations. The absence of a prolonged crystallization differentiation may explain why a nickel-copper bearing sulphide-phase as occurring near the transition of peridotite into gabbro of the Bushveld is not found on Stjernöy. Also chromite and titaniferous magnetite horizons, characteristic of both alpine and stratiform complexes, are completely lacking on Stjernöy.

When one compares tables 19 and 20 with tables 21 and 22 it appears that the analyses of gabbro gneisses and amphibolites contain greater amounts of the minor elements sodium, potassium, titanium, and phosphorus than those of the layered gabbro sequence as is shown by the Niggli values alk, ti and p. The amounts of lime, as expressed by the c values remain about the same in the two groups of gabbros; as already stated remnants of meta-limestone bands are frequently found in the gabbro gneiss, but never in the layered gabbro suite. It is therefore suggested that during the anatectic and syntectic transformation of gabbro gneiss into layered anorthosite-melagabbro complexes the surplus of alkalis, lime and phosphorus was driven out together with H_2O or CO_2 and redeposited in fault zones and contacts. In Chapter II the role of metasomatic replacement in the formation of hornblendite, carbonatite, and nepheline-syenite has been discussed.

In contrast to common basaltic magmas of the circumpacific type the western Finnmark petrographic province is characterized by high amounts of lime; this becomes apparent when the c values in tables 18, 19, 21 and 22 are compared with those in table 20. The same trend is visible in the mg/γ variation diagram of fig. 8b. From the orogenetic point of view the gabbro gneiss could be explained as the highly metamorphic equivalent of an ophiolitic initial magmatism; however, the composition of the gabbro gneisses is too rich in lime for common basaltic lavas. Contamination caused by the intercalations of beds of impure limestone or dolomite within the volcanic series may well account for this excess of lime. Also the Stjernöy layered gabbro series exhibits higher amounts of lime than the magmas of the well-known occurrences mentioned in table 20. A very interesting mineralogical consequence is that lime-rich clinopyroxene is the dominant cafemic mineral, whereas in layered complexes of the stratiform type lime-poor orthopyroxene predominates.

Palingenesis of mafic effusives or metamorphites is not a generally accepted geological process, although it has been mentioned in connection with other parageneses of mafic igneous rocks within complexes of highly metamorphic para- and ortho-gneisses, such as pyroxene-granulites and mafic charnockites. Michot (1956) reports incipient basic anatexis of leuconoritic gneisses in the deep katazone from the well-known Egersund district in southern Norway.

As can be seen in fig. 1 the mafic petrographic province of western Finnmark is emplaced between the Precambrian, as disclosed in the Raipas- and Reparfjord-windows, and the apparently much younger Cambro-ordovician sediments of the Caledonian chain, which overly the whole region in the form of nappes. It is known that ophiolitic suites of initial magmatism are preferentially emplaced between older, highly metamorphosed basement rocks and younger unconsolidated geosynclinal sediments (e.g., Borchert 1957). The mechanism of emplacement in the case of the Seiland-Stjernöy-Öksfjord area will not be dealt with since further investigations in the field are of greater importance than lengthy discussions in this stage of knowledge about the area.

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SUMMARY

On Stjernöy, Seiland and the neighbouring peninsulas of Öksfjord and Bergsfjord ultramafic bodies of peridotite and pyroxenite with associated layered gabbro sequences occur within a complex of highly metamorphic gabbro gneisses, rocks akin to pyroxene-granulites and mafic charnockites. As is shown on the basement map in insert of backflap the layered gabbro is generally concordant with the foliation of the surrounding gneisses but locally shows transgressive features. Within this mafic province occurrences of hornblendite, carbonatite, and nepheline-syenite are also found, the latter affiliation of rocks probably being the result of metasomatic processes.

The petrography and general mineralogy of the ultramafic, gabbroic, and metamorphic types of rocks are described in detail. In the layered gabbro sequences on Stjernöy there exists no gravitational crystallization differentiation such as is found in other stratiform gabbro-peridotite complexes; the variation in the composition of the characteristic minerals is too small, and irregular at that. The textural relations point to incipient fracturing along grain-boundaries and, especially, to deuteric processes which can be inferred from the abundance of spinel-pyroxene symplectites. The characteristic rims of symplectite around olivine are clearly demonstrated in the photographs 2 and 3 on plate C.

In texture and structure the gabbro gneisses and intercalated syenitic and meta-sedimentary rocks on Stjernöy exhibit considerable clastic and plastic deformation. Their mineral association points to an intense regional metamorphism near or within the granulite facies; by means of the ACF diagrams, fig. 9a and 9b, it is shown that the plotted mineral parageneses may be stable in the hornblende-granulite and the pyroxene-granulite subfacies.

The investigation of co-existing clinopyroxene, orthopyroxene, and olivine in the layered gabbro-peridotite sequence on Stjernöy indicates that high pressures and temperatures prevailed at the time of their formation. In tie-line trends of co-existing pyroxenes the layered gabbros from Stjernöy are remarkably similar, not to the normal type of stratiform gabbro-peridotite complexes, but to peridotite nodules in certain basaltic lavas. (compare fig. 5a and 6a). As is shown in fig. 6b the tie-lines joining co-existing orthopyroxene and clinopyroxene from gabbro gneisses exhibit similar trends; these data most probably point to an extreme metamorphism of anhydrous rocks at great depth within the earth's crust.

The chemical analyses of samples of the ultramafic sequence, as plotted in the QLM diagram of fig. 8a, exhibit a linear trend of differentiation; this suggests a simple process of fractional melting or crystallization. The projection points of the gabbro gneiss occupy a central position in this differentiation trend on Stjernöy; thus the gabbro gneiss provides a suitable material for such a process. High lime content is another chemical characteristic of gabbro and related ultramafic rocks on Stjernöy (fig. 8b); hence the major femic mineral is a calcium-rich clinopyroxene, whereas magnesium-rich orthopyroxene predominates in the stratiform type of layered complex.

Clearly, then, the layered gabbro and related ultramafite within the mafic province of western Finnmark differs considerably in major features from the well-known layered gabbro-peridotite occurrences such as Bushveld, Stillwater or Skaergaard. Finally the results of the mineralogical and chemical investigations are discussed from the petrogenetic point of view. A hypothesis is offered for the emplacement of layered gabbro and ultramafite on Stjernöy involving differential anatexis with local palingenesis in a deepseated zone of the Caledonian orogen.

SAMMENDRAG

På Stjernöy, Seiland og på fastlandet ved Öksfjord og Bergsfjord finnes peridotitt, pyroksenitt og lagdelt gabbro innenfor et kompleks av höymetamorfe gabbro gneisser. Den lagdelte gabbro er i alminnelighet konkordant med parallelstrukturen i de omliggende gneisser, men viser lokalt uregelmessigheter (se kart i lommen bak i boken). Også hornblenditt, karbonatitt og nefelinsyenitt forekommer, de er sannsynligvis dannet ved metasomatiske prosesser.

En generell petrografisk og mineralogisk beskrivelse er gitt av ultramafitene, gabbroene og de metamorfe bergarter. Det er lite som tyder på en gravitativ krystallisasjons-differensiasjon i gabbro-lagene på Stjernöy slik den finnes i andre lagdelte gabbro-peridotiter; dertil er den kvantitative variasjon i sammensetningen av mineralene for liten og for uregelmessig. De teksturelle forhold viser oppknusing ved krystalgrensene og karakteristiske omdannelsesrender av spinell og pyroksensymplektitt rundt olivinkornene (se side 221 og plate C, fig. 2 eller 3).

Gabbro gneissene og tilhörende syenitiske og meta-sedimetære bergarter på Stjernöy viser betydelige klastiske og plastiske deformasjoner (plate A, fig. 4). Deres mineral parageneser svarer til granulit-facies; ACF-diagrammene i fig. 9a og 9b viser at paragenesen er stabil i hornblende-granulit eller pyroksen-granulit subfacies.

Undersökelser av ko-eksisterende klinopyroksen, orthopyroksen og olivin i de lagdelte gabbroer på Stjernöy indikerer at höye trykk og temperaturforhold hersket på den tid de ble dannet. ”Tie-line trends” hos ko-eksisterende pyroksener i utvalgte pröver på Stjernöy viser bemerkelsesverdige likhetspunkter med de ”tie-lines” som er funnet for pyroxener i peridotitt-klumper i visse basaltiske lavaer, men ikke med de som er kjent fra den normale type av stratiforme gabbro-peridotit forekomster (jfr. fig. 5a og 6a). ”Tie-lines” i fig. 6b mellom ko-eksisterende orthopyroksen og klinopyroksen i gabbro gneiss gir liknende resultater. Dette synes å tyde på höy metamorfose i törre bergartsmasser.

Resultatene av kjemiske analyser av utvalgte pröver fra den ultramafiske gabbrorekke, slik den er plottet i QLM-diagrammet i fig. 8a, viser en rett linjet differensiasjonsbane. Dette tyder på fraksjionert opsmelting eller krystallisasjon. Gabbrogneissens projeksjonspunkter faller omtrent midt på differentiasjons-kurven. Av fig. 8b fremgår det at höyt kalkinnhold er karakteristisk for gabbroen og de tilhörende ultramafiske bergarter og fölgelig er det mörke hovedmineral på Stjernöy en kalsiumrik klinopyroksen; derimot er det en magnesiumrik orthopyroksen i de stratiforme typer i peridotitt-gabbro komplekset.

Det er klart at forekomstene på Stjernöy på vesentlige punkter skiller seg betydelig ut fra de tidligere kjente forekomster av lagdelte gabbro og peridotiter, slik som Bushveld, Stillwater og Skærgaard. Til slutt er resultatene av de mineralogiske og kjemiske undersökelser diskutert fra et petrogenetiske synspunkt; hypotesen er at det har foregått en differensial anatexe med lokal palingenese av gabbro gneisser i en dyptliggende sone av det kaledonske orogen.

SAMENVATTING

Zoals aangegeven is op de bijgesloten petrologische kaart, komen op de eilanden Stjernöy en Seiland en de nabij gelegen schiereilanden Öksfjord en Bergsfjord ultramafische en gelaagde gabbro gesteenten voor, welke gelegen zijn in een grondgebergte van gneisachtige gabbroide gesteenten. In deze laatste komen ook lagen en lenzen voor van granaat-gneis, hoog metamorfe kalksteen en syeniet. Uit de kaart blijkt dat de gelaagde gabbro over het algemeen concordant is met de schistositeit in de metamorfe gesteenten. Als jongste gesteenten in het gebied komen nog voor hornblendiet, carbonatiet en nefelien-syeniet; een metasomatische ontstaanswijze van deze gesteenten wordt waarschijnlijk geacht.

Petrografische en mineralogische onderzoekingen wijzen uit, dat de gelaagde gabbro-peridotiet complexen geen gravitatieve kristallisatie-differentiatie vertonen, zoals gevonden wordt in de bekende lopolieten en trechter-plutonen van Bushveld, Stillwater en Skaergaard. Daarvoor is de aangetroffen chemische variatie-breedte in de samenstelling van de karakteristieke mineralen zoals plagioklaas, augiet en olivijn te gering; ook wordt geen regelmaat hierbij aangetroffen. Langs de kristalgrenzen heeft vergruizing en verder omzetting in andere mineralen plaats gevonden; vooral de randen van spinel-pyroxeen symplectiet (plaat C, fig. 2 en 3) rond olivijn wijzen op post-magmatische processen.

De mineraal-associatie in de metamorfe gabbro-gneisen met tussengeschakelde banden van syeniet en meta-sedimenten wijst op extreme druk en temperatuur tijdens de regionale metamorfose. Uit de ACF diagrammen van fig. 9a en 9b blijkt, dat de uit de chemische analysen berekende paragenesen stabiel zijn in de hornblende granuliet en pyroxeen granuliet subfacies.

Ook het empirische onderzoek van co-existerende clinopyroxeen, orthopyroxeen en olivijn uit de gelaagde gabbro en peridotiet van Rottenhallerfjell (Stjernöy) wijst op zeer hoge druk en temperatuur bij de vorming van deze mineralen. De z.g. "tie-lines" in de WoEnFs diagrammen tussen co-existerende clinopyroxeen en orthopyroxeen vertonen een tendens, welke overeenkomt met die van peridotiet insluitsels in sommige bazalten en niet met die van het normale type van gelaagd ultrabasisch gabbro-complex (vergelijk fig. 5a en fig. 6a). Er wordt verondersteld, dat de insluitsels in bazalt uit zeer grote diepte stammen. Ook de "tie-lines" in fig. 6b van de pyroxenen in de metamorfe gabbro gneis vertonen een dergelijke tendens; het fenomeen dient volgens de auteur verklaard te worden door ultra-metamorfose van deze "droge" gesteenten op zeer grote diepte in de korst.

De chemische analysen van gesteente-monsters van de gelaagde gabbro en de verwante anorthosiet en peridotiet, zoals uitgezet in het QLM diagram van fig. 8a, vertonen een opvallende lineaire differentiatie. Dit zou verwacht mogen worden bij een proces van gefractioneerd opsmelten of uitkristalliseren. De projecties van de analysen van gabbro gneis liggen centraal ten opzichte van deze lineaire differentiatie en zouden een geschikt uitgangsmateriaal kunnen vormen voor het opsmeltingsproces. Uit fig. 8b blijkt nog, dat een hoog calcium-gehalte karakteristiek is voor de gabbro en ultramafische gesteenten van Stjernöy. Het donkere bestanddeel in dit gesteente bestaat daarom voornamelijk uit calcium-rijke clinopyroxeen en niet uit magnesium-rijke orthopyroxeen, zoals gevonden wordt in het stratiforme type van gelaagde gabbro-peridotiet complex.

Het is duidelijk, dat de basische gesteente-provincie in West Finnmark in essentiële opzichten verschilt van de bekende vindplaatsen van gelaagde gabbro zoals de Bushveld, enz.; deze verschillen dienen verklaard te worden uit een verschillende ontstaanswijze. Differentiële anatexis van gabbro gneis met plaatselijk palingenese in een diepliggende zone van het Caledonische orogeen wordt aannemelijk geacht voor de vorming van de ultramafische en gelaagde gabbro gesteenten op Stjernöy.

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APPENDIX

For the sake of comparison values of $K(T) = \left[\frac{Fe^{2+}}{Mg}\right]_o \times \left[\frac{Mg}{Fe^{2+}}\right]_c$ have been calculated according to the principles laid down by Bartholomé (1961). For instance, in the clinopyroxene of sample T 4.121 the ratio Mg/Fe^{2+} is 0.77 : 0.12 (see p. 253); for the orthopyroxene the same ratio is $0.85^5 : 0.14^5$ (see table 15). The equilibrium constant can thus be calculated in the following way: $\frac{0.14^5}{0.85^5} \times \frac{0.77}{0.12} = 1.09$. However it seems more appropriate to add Fe^{3+} to Fe^{2+} in the calculation of compositions or equilibrium-constants since the relation magnesium/total iron gives a better approximation to the bulk chemical relations. K(T) values[1] of Mg/Fe^{2+} and Mg/total Fe ratios are compared in the following table:

Ultramafic sequence on Stjernöy

	Mg/Fe^{2+}	Mg/total Fe
T 4.88b	0.65	0.46
T 4.121	1.09	0.65
T 4.27	0.49	0.33
T 4.73	0.90	0.62
T 4.65	1.14	0.85
T 4.66	0.27	0.20
T 4.126	1.25	0.80
T 4.123a	0.31	0.26

Metamorphic complex on Stjernöy

	Mg/Fe^{2+}	Mg/total Fe
T 4.111	0.91	0.76
T 4.75	0.65	0.63
T 4.57	0.69	0.52
T 3.69	0.53	0.39
T 4.4	0.94	0.76
T 3.62	1.58	1.31
P 24	1.58	1.32

Peridotite nodules in basalt (see also page 263)

	Mg/Fe^{2+}	Mg/total Fe
sample no. 1	1.55	0.87
sample no. 2	1.33	0.88
sample no. 3	1.25	0.84
sample no. 4	1.17	0.99
sample no. 5	1.16	0.84
sample no. 7	1.34	1.08
sample no. 8	1.25	0.96

Stratiform gabbro-peridotite complexes

Mg/Fe^{2+}		Mg/total Fe
Bushveld 7666	1.54	1.33
Bushveld 7493	1.31	1.25
Stillwater EB 31	1.38	1.29
Skaergaard 1a	1.38	1.17
Shaergaard 4a	1.35	1.27
Skaergaard 6a	1.33	1.25
Skaergaard 7a	1.42	1.31

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[1] Miss J. Veraart kindly made the cumbersome calculations.

The average K(T) values of co-existing pyroxenes in peridotite nodules and in stratiform complexes are respectively 1.29 and 1.39 in the case of Mg/Fe^{2+} ratios; in the case of Mg/total Fe ratios these values are 0.92 and 1.27 respectively. It is apparent that a more distinct difference between the average K(T) of the two groups of ultramafic rocks is discernible in the latter case. Moreover, the spread in values within each group of ultramafic rocks is somewhat less.

Therefore the graphical representation of Mg/total Fe in the diagrams of fig. 6a and 6b is justified. Not considered the erratic values of samples T 4.66 and T 4.123a and the values of samples T 3.62 and P 23 (hypersthene-granulite, see p. 263) the K(T) values of pyroxenes in Stjernöy samples—based on Mg/total Fe ratios—compare reasonably well to those found in peridotite nodules. However, the general trend is towards lower values.