MEDDELELSER OM GRØNLAND
UDGIVNE AF
KOMMISSIONEN FOR VIDENSKABELIGE UNDERSØGELSER I GRØNLAND
Bd. 164 · Nr. 5

GEOLOGICAL INVESTIGATIONS IN EAST GREENLAND

PART VII

THE BASISTOPPEN SHEET
A DIFFERENTIATED BASIC INTRUSION INTO THE UPPER PART OF THE SKAERGAARD COMPLEX, EAST GREENLAND

BY

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WITH 17 FIGURES IN THE TEXT
AND 7 PLATES

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BIANCO LUNOS BOGTRYKKERI A/S
1964

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Abstract

The Basistoppen sheet is an extensive differentiated gabbroic mass, about 400–500 m. thick, occurring within the upper border rocks of the Skaergaard intrusion. Originally, it was considered as a huge inclusion because the underlying Skaergaard rocks vein its base (Wager and Deer, 1939). It is now considered as resulting from a later injection of basic magma into the still hot, but consolidated, Skaergaard rocks. Along its lower margin there are fine grained rocks which are interpreted as partial chills. Veining of the base of the sheet by the underlying Skaergaard rocks is believed to be back-veining, due to their rheomorphism by heat from the sheet.

The sheet, much of which has been previously described by Hughes (1956), displays marked cryptic layering, both the continuous and discontinuous (phase change) types. On the basis of the phase change cryptic layering, it has been divided into a gabbro-picrite zone and successive zones of bronzite gabbro, pigeonite gabbro and pyroxene ferrodiorite. A small part of the sequence is missing because the upper contact has not been reached.

Close analogy between the sheet and the Skaergaard intrusion is found in the sequence of mineral phases, strong iron enrichment and in the behaviour of certain trace elements. Particularly slow cooling apparently allowed a high degree of fractionation to occur.

INTRODUCTION

Previous work

In their Skaergaard Memoir, WAGER and DEER (1939) (reprinted 1962) described an extensive gabbro mass situated in the upper part of the Skaergaard intrusion and clearly extraneous to the Skaergaard sequence. They observed that the mass was veined at its base by the underlying Skaergaard rocks. Outside the intrusion, within the lavas and tuffs, they noted two larger gabbro sills on Tinden and Hængefjeldet which were strikingly similar to each other and to the gabbro mass within the intrusion. The mutual contact relations between the gabbro sill on Tinden and the Skaergaard intrusion seemed to indicate that the former was earlier. From this field evidence they reasoned that the gabbro mass within the intrusion was a huge inclusion. They named it the Basistoppen raft and suggested that it was either an extension of one of the earlier sills outside the intrusion or a similar sill at another level that had remained as a large mass during the shattering which produced the intrusion because of its relatively great strength. It had then foundered some distance into the magma to form a raft-like mass roughly at the junction of the layered series and the upper border group.

During the 1953 summer expedition to the Kangerdlugssuaq area further collections of this gabbro mass were made from its main exposures. C. J. HUGHES (1956), one of the members of this expedition, examined these and earlier collections. He accepted the original view that the mass was a huge inclusion in the Skaergaard intrusion. He described in detail the mineralogy and petrography of what he believed to be the entire exposed sequence showing that it consisted of a basal zone of gabbro-picrite and overlying zones of hypersthene gabbro and pigeonite gabbro. He grouped an overlying series of pyroxene ferrodiorites with the Skaergaard layered series.

Scope of the present work

The re-examination of all the available collections[1]) has led the writer to the belief that the Basistoppen raft, here renamed the Basis-

[1]) These collections are housed in the Department of Geology and Mineralogy, Oxford. Specimen numbers given in the text should strictly be prefixed E. G., East Greenland collection.

toppen sheet, represents injection of basic magma into the upper part of the Skaergaard intrusion. Petrological evidence will be given supporting this view. Examination of the larger number of specimens allows some amplification of the zones described by Hughes and a description is given for the first time of a border division and a pyroxene ferrodiorite zone not recognized by him. Most of the optical determinations made by Hughes have been repeated but apart from minor changes his determinations have proven to be substantially correct.

Certain field observations, made by the writer during a brief visit to the area in the summer of 1962, have been added since returning but most of the work was completed before the recent visit, the field observations being interpreted from diaries and catalogues made during Professor Wager's earlier expeditions.

Acknowledgements

This paper gives some of the results of an investigation carried out on material collected by L. R. Wager and W. A. Deer during the various expeditions to East Greenland viz.:

The Scoreby Sound Committee's Second East Greenland Expedition 1932 to Kong Christian IX.'s Land, leader Ejnar Mikkelsen.
The British East Greenland Expedition 1935–36, leader L. R. Wager and The East Greenland Geological Expedition 1953, leaders L. R. Wager and W. A. Deer.

The results are part of a D. Phil. thesis (1961) of Oxford University.

The writer is much indebted to Professor Wager for the privilege of working on these collections and access to his field notes and catalogues. He wishes also to thank him for his guidance and encouragement during the course of the investigation. Grateful acknowledgements are made to Dr. G. M. Brown for his valued advice on many aspects of the work; to Dr. E. A. Vincent for instruction on chemical and ore microscopic techniques; to Dr. Vincent, Mr. B. Collett and others for chemical analyses. The writer thanks the Greenland Administration for permission to visit Greenland and especially Mr. I. Lundblad for his assistance in visiting the Skaergaard area. For financial assistance the writer is grateful to the Trustees of the Burdett Coutts Fund and the Department of Scientific and Industrial Research.

Fig. 1a.

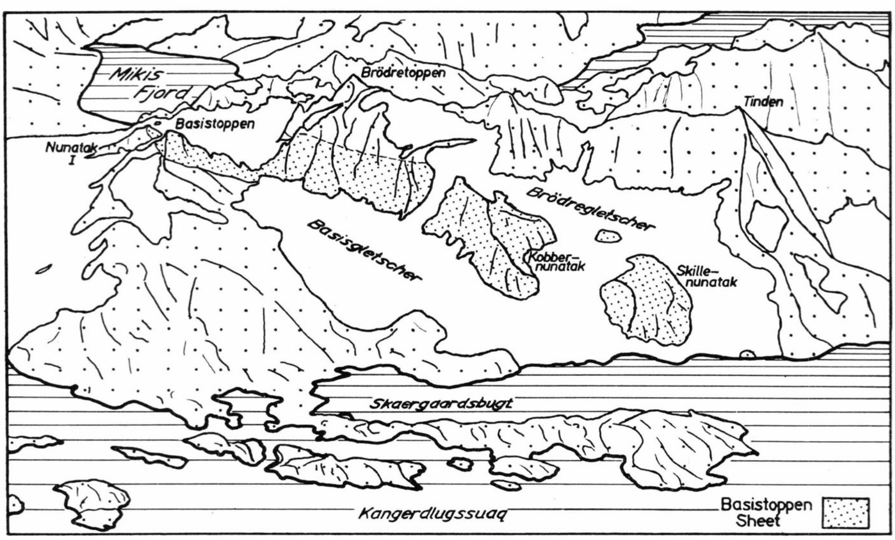

Fig. 1b.

Fig. 1a & b. S.E. aerial view of the southern part of the Skaergaard intrusion with key (H. G. Watkins, Aug. 1930).

GENERAL DESCRIPTION

Field relations

The Basistoppen sheet is an extensive differentiated layered mass of gabbroic rocks, about 400–500 m. thick, occurring within the lower upper border group rocks of the Skaergaard intrusion that form its southern part. The attitude of the sheet is roughly parallel to the layering of the enclosing Skaergaard rocks, which as a result of a crustal flexure now dips 25° to 30° south (WAGER and DEER, 1937, 1939).

The sheet is exposed longitudinally over about 4 kms. in a line of exposures trending ENE–WSW (fig. 1). It forms the top 150 m. of Basistoppen and from this prominent locality it takes its name. On the south side of Basisgletscher it forms the two nunataks, named Kobbernunatak and Skillenunatak, and also much of the steep and relatively inaccessible north face of Brödretoppen (fig. 3). These and the other smaller exposures of the sheet are shown in fig. 2.

The possible extent of the sheet (fig. 2) is open to speculation because to the south-east the sheet is below sea level and to the north-west it is mostly hidden under glacier. On the northern side of the small exposure of Nunatak I, situated to the east of Basistoppen, the sheet takes on a narrow dyke-like form. It is possible that the sheet continues under Forbindelsesgletscher and connects with the macro dyke, that extends from the Skaergaard's north-east margin into the basalts and tuffs, but there is as yet no definite evidence to support this suggestion. Some comparison of the sheet and macro dyke rocks is given in an appendix.

No complete section of the sheet has been collected. A virtually complete section must be exposed somewhere on the steep north face of Brödretoppen (fig. 3) but these rocks have not been reached.

The base of the sheet is seen on the west and part of the east faces of Basistoppen (fig. 3) but it is poorly exposed under the scree. It is highly irregular in detail and in places steps up vertically for 50 m. (WAGER and DEER, 1939, p. 58). The base of the sheet was previously thought to be exposed on the south side of Nunatak I, but from recent field work it now appears that the lower contact here turns until it is about vertical and the sheet becomes dyke-like in form. The contacts on this

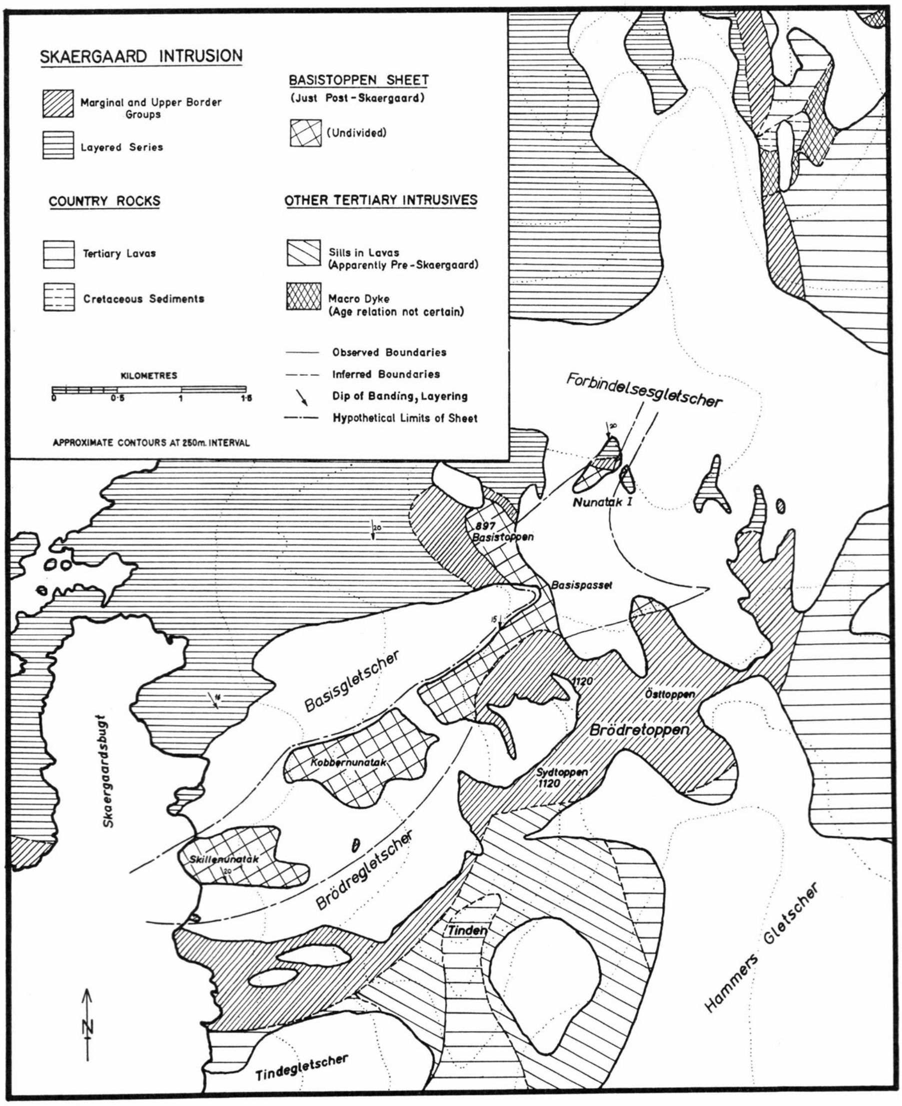

Fig. 2. Simplified geological map of the southern part of the Skaergaard intrusion.

exposure are thus better regarded as marginal. A further contact with the Skaergaard rocks must be exposed low on the north face of Östtoppen where sheet rocks have been found but it has never been examined. As the level of the glaciers is probably receding further exposures of the lower contact should, in time, be revealed on the south side of Basisgletscher.

The Skaergaard rocks, underlying the sheet on the west side of Basistoppen, are plagioclase-rich and originally described as hedenber-

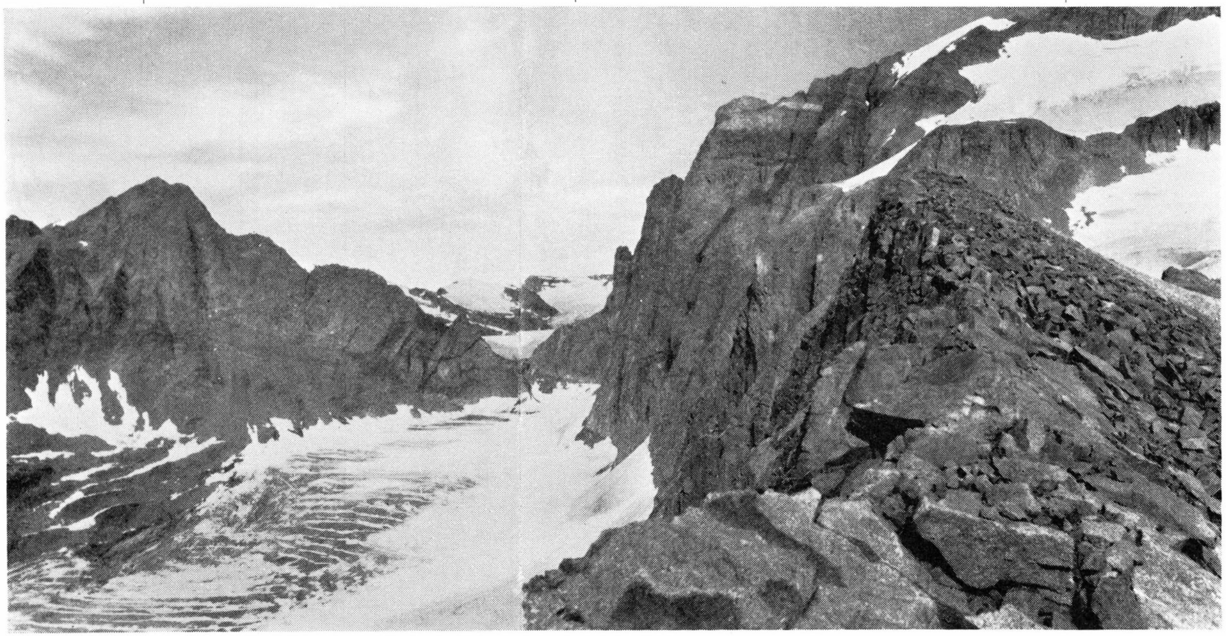

Fig. 3. Western side of Basistoppen and north face of Brödretoppen from the crest of Kobbernunatak. The lower contact of the sheet is seen on Basistoppen; the position of the upper contact on Brödretoppen is not known. Several later dykes of the swarm are seen, especially just left of the col. 1953 E. G. G. E.

c

c

Fig. 4. Net veining in the fine grained marginal gabbro along the lower contact of the sheet (c–c), south side of Nunatak I. The underlying Skaergaard pyroxene ferrodiorite is seen in lower right. Photograph taken looking N.W.

gite andesinite (Wager and Deer, 1939); they are grouped as UBG_{β} in the revised classification of the Skaergaard sequence (Wager, 1960). This material was found as veins in the basal sheet rocks, essentially a fine-grained gabbro, and blocks of this latter seemed to have been detached and enclosed in the Skaergaard material (Wager and Deer, 1939, p. 58). However, it now appears that these field observations should be interpreted as sheet gabbro surrounded by the veining Skaergaard material.

On the south side of Nunatak I rather similar contact relations are found. The Skaergaard rocks in contact with sheet are somewhat variable, but consisting mainly of a quartz-rich pyroxene ferrodiorite which is provisionally grouped as UBG_{γ} in the revised classification. Along the immediate contact the sheet gabbro, which is fine grained and similar to that found on Basistoppen, is frequently cut by small veins derived from the adjacent Skaergaard material (fig. 4).

Differing from the original view, these ambiguous relationships are here interpreted as the result of a rapid cooling of the sheet magma against the adjacent Skaergaard rocks; the veining of the sheet by Skaergaard material is now considered to be "back-veining", the result of rheomorphism of Skaergaard material by the heat gained from the sheet magma. Petrological data is given later supporting this view (pp. 35–43).

Correlation of the exposures

Although no continuous section through the sheet has been found and its top contact has never been reached, a composite and seemingly almost complete sequence is obtained by the correlation of the various partial vertical sections (fig. 5). The structural heights in any one section are only approximate, mainly because few distinct structural features exist upon which to measure an inclination in the field. In addition the thickness of the various rock types seems to vary from exposure to exposure. The composition of the samples plagioclase cores has been used extensively to position the specimens as it seems to vary systematically with height. The heights in the composite section must therefore only be taken as approximations and then only for thicker vertical portions of the sheet.

Subdivisions of the sheet based on cryptic layering

The sheet rocks show only feeble rhythmic layering. More significant changes are demonstrated by what may be generally termed cryptic layering. This is of two kinds: continuous cryptic layering, i.e. the steady change in composition of the cumulus phases, and discontinuous or phase change cryptic layering, i.e. the abrupt appearance or disappearance of a particular cumulus phase[1]).

On the basis of the phase change cryptic layering the sheet sequence has been divided into four zones: (1) gabbro-picrite (GPZ) (2) bronzite gabbro (BGZ) (3) pigeonite gabbro (PGZ) (4) pyroxene ferrodiorite (PFDZ). A mixed assemblage of rocks occurring along the base and lower margin of the sheet have been grouped as the lower border division (LBD). The first three zones were recognized by HUGHES (1956); the fourth and lower border division have been added by the writer.

Brief comments should be made on the nomenclature of the rock types. The name gabbro-picrite is applied in the same sense as was

[1]) The terminology of cryptic layering was proposed by Professor WAGER (personal communication). Terms such as cumulus, intercumulus, etc., have been defined by WAGER, BROWN and WADSWORTH (1960).

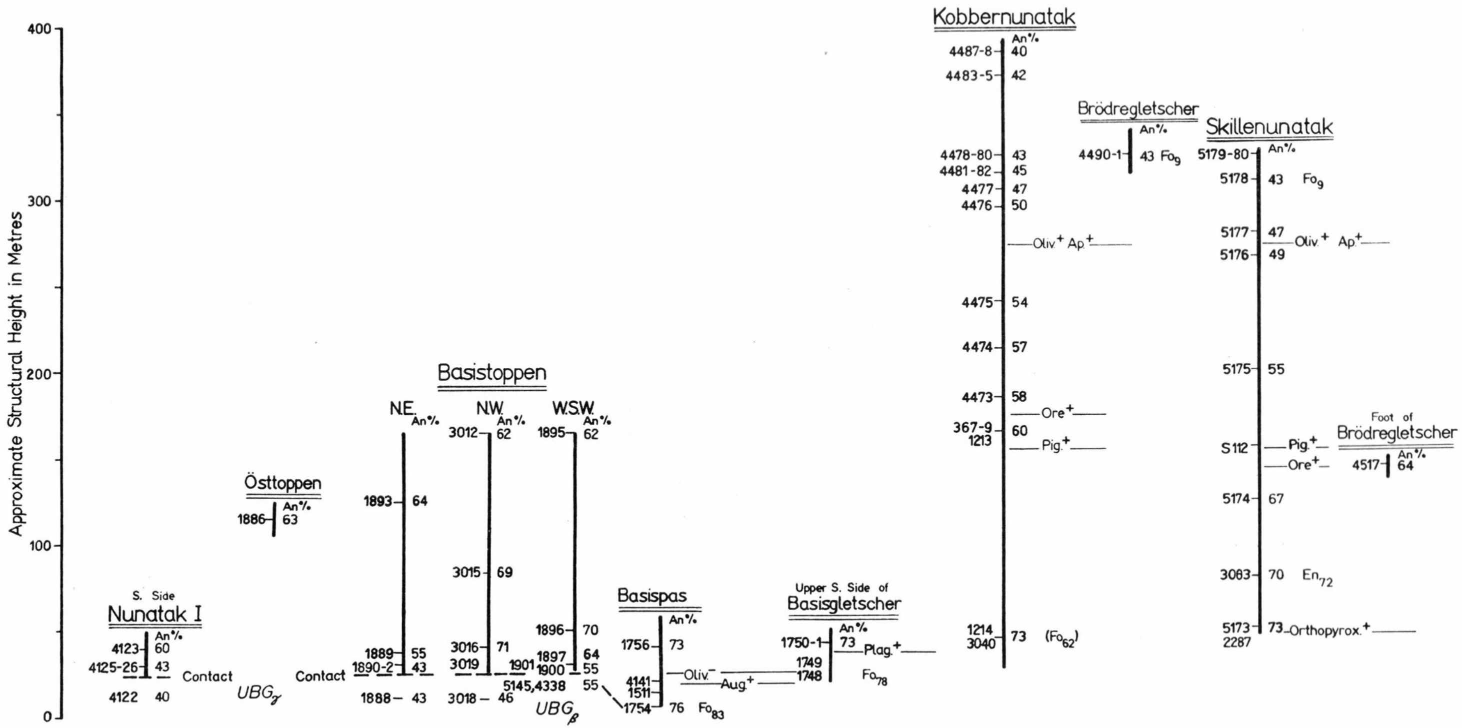

Fig. 5. Correlation of vertical sections of the various exposures of the sheet.

done originally by Wager and Deer (1939, p. 162) to distinguish olivine-enriched rocks with gabbroic affinities. Hughes (1956) described the bronzite gabbro as hypersthene gabbro but because the orthopyroxene is bronzite it seems more logical to revise the name. The name pigeonite gabbro, as used by Hughes, is retained. The pyroxene ferrodiorite would have been described as ferrogabbro in the original terminology of Wager and Deer (1939, p. 98). However, Wager and Vincent (1962) have applied the name ferrodiorite to a rock from the Tertiary igneous centre of Skye, having rather similar chemical affinities and plagioclase less basic than An_{50}. To avoid confusion with the usual conception of a diorite, the name pyroxene ferrodiorite is used tentatively here.

A generalized vertical section showing the apparent thickness of the zones is given in fig. 10, and vertical sections for each exposure are given in fig. 5. Certain features concerning the distribution and thickness of the rocks are worth separate mention. Gabbro-picrite is not present continuously along the apparent base of the sheet. Just NNW of the Basistoppen col the exposed gabbro-picrite is 20 m. thick and the zone may be thicker as the base of the sheet is below glacier level. Futher north, although access is difficult, it is evident that the gabbro-picrite thins out rapidly. On traverses across the east, west and north-west faces of Basistoppen the gabbro-picrite was not found and the border rocks are directly overlain by bronzite gabbro.

The bronzite gabbro provides the most extensive exposure. Nearly complete sections are seen on Basistoppen and Skillenunatak; the sections of bronzite gabbro on Kobbernunatak and the north face of Brödretoppen are incompletely known because of the danger from falling stones. Pigeonite gabbro is only known on Skillenunatak and Kobbernunatak. A small part of the top of the PFDZ may be missing because the upper contact of the sheet has not been reached.

Rhythmic layering

Cryptic layering is important as explained in the previous section but rhythmic layering as developed in most of the Skaergaard layered series is not strongly developed in the sheet. Rather weak large scale layering can be seen from a distance in the sheet rocks on the east face of Basistoppen. One example, 3016, from the west face of Basistoppen shows weak gravity stratification of the orthopyroxene crystals and among the rocks as a whole there is some variation in proportions of plagioclase and augite. More regular feldspathic banding is seen in the almost vertical face on the south-west side of the Basistoppen col (fig. 6). Narrow feldspathic bands are found especially on the upper parts of

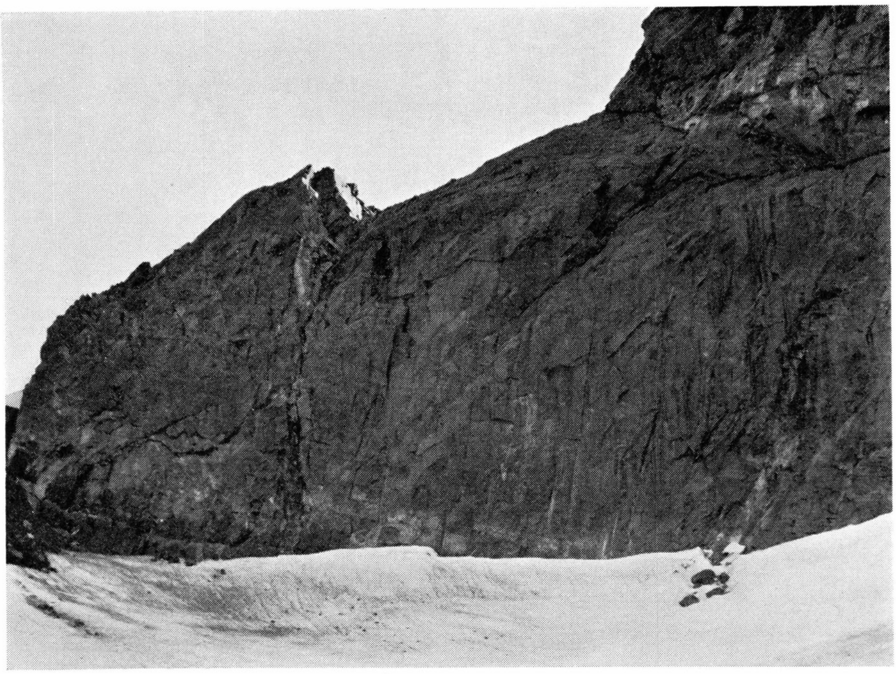

Fig. 6. Rhythmic layering in bronzite gabbro on S. side of Basistoppen col. Gabbro-picrite forms 10 m. of the face at lower left. Height of face at centre about 60 m.

Skillenunatak and Kobbernunatak (fig. 7) and the small nunatak in Brödregletscher. Sometimes sharp variations in grain size and texture also account for a certain degree of banding.

Some clear examples of banding have been collected: a pyroxene rich band about 4 m. thick overlies the gabbro-picrite at the bottom of the north face of Brödretoppen, dying out toward the col where gabbro-picrite passes directly into bronzite gabbro. Material recently collected from a moderately fine grained feldspathic band, 20 cm. thick, contains eight or so narrow (5 mm.) layers of orthopyroxene crystals (fig. 8) of the type already noted by Hughes (1956, p. 12) in a specimen containing a single layer of these crystals.

A further feature of the layering, igneous lamination is sometimes well developed although generally faint. It occurs in rocks of all the zones above the gabbro-picrite.

Pegmatitic segregations

Segregations of coarse pegmatitic gabbro are exposed on the western side of Kobbernunatak but due to the difficulties of access little is known about their size, number and relative position. Several seen on

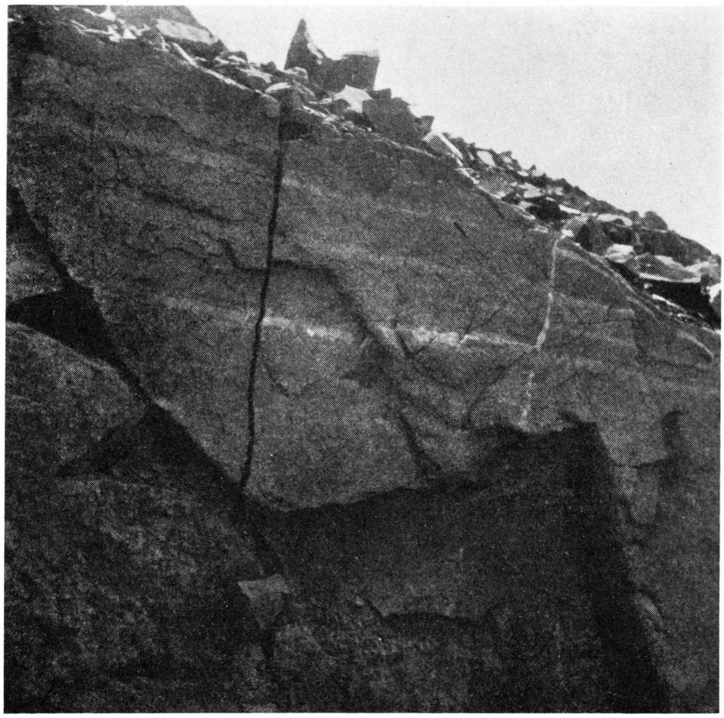

Fig. 7. Feldspathic layers and small transgressive acid vein in pyroxene ferrodiorite, crest of Kobbernunatak. 1953 E. G. G. E.

the almost vertical west face of Kobbernunatak are stated by Hughes (1956, p. 16) to form parallel sheets, averaging 2–3 m. in thickness; others, from which collections were made *in situ* during earlier expeditions, are shown in a field sketch as lensoid masses about 3 m. in length. Apparently all occur within pigeonite gabbro. On Skillenunatak small irregular veins with pegmatitic margins are found within the pyroxene ferrodiorite but the more striking type of Kobbernunatak have not been found there. Petrographic descriptions of these rocks are given later (p. 24).

Presumed acid inclusions and late-stage acid veins

Certain leucocratic rocks, collected during the early expeditions, occur as indefinite bands within bronzite gabbro near the top of Basistoppen; the writer has noted small transgressive veins of similar material lower on the east face. On the south side of the Basistoppen col there are approximately three dyke-like masses of hybrid rock about a metre thick and rising at least ten metres above the glacier (fig. 13). An acid rock from the crest of Kobbernunatak is also of hybrid character. Al-

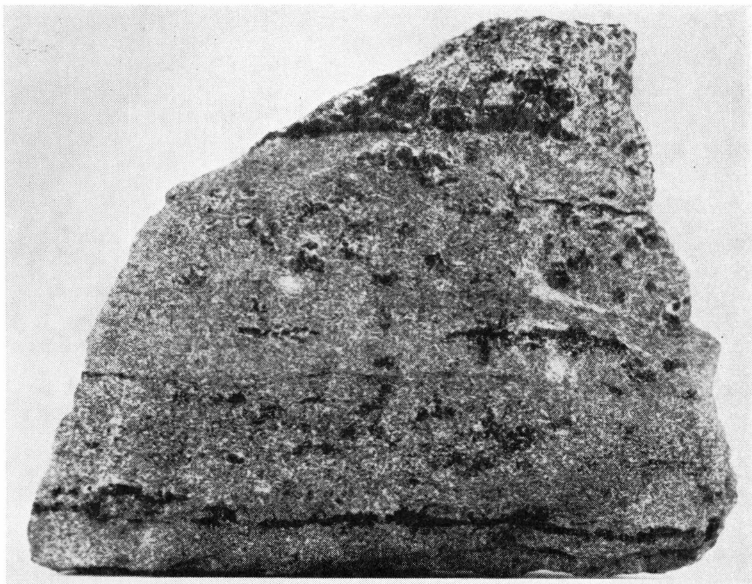

Fig. 8. Specimen from laminated feldspathic band with bronzite crystals, some forming thin layers. × 3/4 J. COOKE.

though these rocks are of varying composition and their origin is in doubt it seems probable that the sheet magma incorporated some acid material, presumably derived from the metamorphic complex. This material is now found sometimes streaked out into indefinite bands and in some instances pressed into veins. Petrographic descriptions are given on p. 44.

Small veins of granophyric composition have been noted at several horizons. The more important examples occur in pyroxene ferrodiorite in the upper parts of Kobbernunatak and Skillenunatak (fig. 7 and p. 23). Contrasting with more obvious hybrids these appear to be late segragations derived by "filter-press" action. A conspicuous microgranitic sill (about 10 m. thick) and its vertical feeder are seen on the north-west face of Kobbernunatak but this material does not appear to be a product of the differentiation of the sheet.

PETROGRAPHY OF THE SHEET SEQUENCE

Gabbro-picrite Zone (GPZ)

The gabbro-picrite zone consists of olivine rich rocks near the base of the sheet. The rocks are fresh in appearance and have a somewhat variable mineralogical composition (table I). Four specimens are described to illustrate the variation.

The lowest example, 1754, from the col of Basistoppen, is probably near the base of the zone. It is composed essentially of olivine, augite and plagioclase. The olivine (Fo_{83}) occurs as rounded, subhedral, equidimensional crystals, averaging 1 mm. in diameter. The augite forms slightly larger crystals and is subpoikilitic toward olivine but idiomorphic toward the plagioclase (An_{76}) which is seen as large poikilitic plates enclosing both olivine and augite. Small crystals of chrome-spinel are found in all the minerals, but mainly in the olivine. Other minerals include a few flakes of brown biotite, a little colourless serpentine replacing the olivine, and a pale green chlorite which is found interstitially or at the expense of the plagioclase and always as a narrow rim at plagioclase-olivine boundaries.

Another rock, 1511 (Pl. I, fig. 1), from the same locality but slightly higher, is texturally similar but contains orthopyroxene in addition to the minerals found in the previous example. The orthopyroxene (ca. En_{76}) occurs as large anhedral branching crystals. Augite is less abundant than in the previous example.

The third example, 4141, north of the col on the flanks of Basistoppen, likewise contains orthopyroxene. Olivine (Fo_{77}) is similar in habit though less abundant and extensively altered to serpentine. The orthopyroxene (En_{75}) occurs as granular to subhedral prismatic crystals, 2–4 mm. in length. The augite is granular to subpoikilitic with crystals about 1 mm. in length. The plagioclase is less abundant and much altered to chlorite. Accessory biotite is more common; a little apatite and iron ore, probably ilmenite, are also found.

The fourth example, 1748, from the top of the zone at the base of the north face of Brödretoppen differs significantly in the following: augite is the dominant phase and occurs in small granular to subhedral prismatic crystals averaging under 1 mm.; olivine (Fo_{78}) is less abundant;

Table 1. Modes of selected sheet rocks arranged in increasing order of height (Volume $^0/_0$)

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Plagioclase	53	34	30	30	57	55	52	59	60	58	42	30
Augite	42	15	22	60	30	32	28	20	13	10	20	28
Olivine	—	45	28	—	—	—	—	—	—	9	10	16
Orthopyroxene	2	—	7	8	10	10	8	—	—	—	—	—
Pigeonite	—	—	—	—	—	—	—	11	15	—	—	—
Ore	3	3	5	1	1	1	9	6	7	7	10	9
Apatite	—	—	tr	—	tr	tr	tr	tr	tr	4	3	2
Quartz and Micropegmatite	—	—		—	1	1	3	2	3	8	12	13
Chlorite	—	3	3	1	1	1	1	2	2	4	3	2
Biotite	—	tr	5	—	—	—	—	—	—	—	—	—

Note: These figures may include for: plagioclase, some sericite and chlorite; augite, a little amphibole; olivine, orthopyroxene and pigeonite, fresh and altered material; micropegmatite and quartz, a little associated chlorite.

Numbers
(1) Fine-grained marginal gabbro, 4125.
(2–3) Gabbro-picrite, 1754, 4141.
(4–7) Bronzite gabbro, 1896, 5173, 5174, 4517.
(8–9) Pigeonite gabbro, 4474, 5176.
(10–12) Pyroxene ferrodiorite, 5177, 5178, 4487.

orthopyroxene (ca. En_{78}) is found as prismatic crystals, 2–3 mm. long; plagioclase retains its poikilitic habit but is reduced in amount.

Summarizing the chief features of the zone—olivine is undoubtedly a cumulus phase, along with chrome-spinel. The texture of the lowest rock, 1754, suggests that the augite formed largely as an intercumulus phase at that early stage, but it is a definite cumulus phase by the top of the zone in the example, 1748. Orthopyroxene is probably intercumulus in origin in the examples, 1511, 4141, but it appears to have formed as a cumulus phase at the top of the zone. It is also significant that the amount of olivine decreases with the incoming orthopyroxene, and notably in the topmost rock of the zone.

Bronzite Gabbro Zone (BGZ)

The bronzite gabbro zone overlies the gabbro-picrite or, where the latter is absent, it overlies the mixed group of rocks designated as the border division. The top of the zone is taken as the level where the bronzite gabbro passes into pigeonite gabbro. The cumulus phases are plagioclase, augite, orthopyroxene and, for the first few metres, chrome spinel.

Olivine has ceased to be a cumulus mineral. A little iron ore and micropegmatite occur interstitially. In hand specimen the bronzite gabbro is medium to coarse grained and characteristically spotted in appearance as the result of the alteration of the orthopyroxene.

A pyroxene rich band, 2–4 m. thick, forms the base of the zone at the foot of the steep ridge leading to Kobbernunatak. In a typical example, 1749 (Pl. 1, fig. 2), augite composes over 80°/₀ of the rock. It is largely granular in habit, individual grains measuring 0.5 mm. across; a few larger, subhedral, prismatic crystals, up to 2 mm. in length, are also seen. The orthopyroxene, totally pseudomorphed by bastite, is subpoikilitic. The texture suggests that a part of each orthopyroxene crystal has grown from the intercumulus liquid. The plagioclase is poikilitic, filling the interspaces between augite grains. Other minerals include a few small euhedral opaque grains, probably chromite and finely disseminated iron ore.

Above the pyroxene band in such examples, as 1746, 1750, 1756, the plagioclase (An_{73}) occurs as a cumulus phase, in laths up to 3 mm. in length. The augite forms subhedral prismatic crystals generally smaller than the plagioclase. The orthopyroxene, almost totally replaced by bastite, is found in large poikilitic plates, up to 1 cm. or more across, which enclose both plagioclase and augite (Pl. 2, fig. 1). In two similar rocks, 1214 and 3040, from Kobbernunatak a few grains of olivine (ca. Fo_{62}) are found, largely replaced by iron ore and serpentine.

On Basistoppen the lowest bronzite gabbro examples, 1896, 3015, 3016, contain more augite than the bulk of the zone but less than the pyroxene rich band already mentioned. The plagioclase (An_{72}) occurs in subhedral laths. The orthopyroxene, now bastite, occurs in somewhat branching prismatic crystals, up to 3 mm. in length, and is probably largely cumulus in origin.

The analysed example from Skillenunatak, 5173, has a texture more typical of the bulk of the zone. The plagioclase (An_{73}) occurs in subhedral tabular crystals, up to 3 mm. in length, and is generally little zoned except at the margins. The augite forms granular to subhedral crystals, averaging 2 mm. across; simple twinning on (100) is common; incipient alteration to colourless uralite is seen around crystals margins. The orthopyroxene, now bastite, occurs as broad prismatic crystals, up to 5 mm. in length, which may be embayed marginally by the plagioclase or augite or enclose small crystals of both. Iron ore occurs sparingly in interstitial patches. A little micropegmatite and chlorite comprise the remainder.

A finer grained rock, 3063, (Hughes, 1956, p. 13) from a feldspathic layer and above the previous example, is remarkable in containing a thin, 5 mm. layer of orthopyroxene crystals (En_{73}) lying parallel to the well laminated plagioclase (Pl. 2, fig. 2). Higher on Skillenunatak the rocks, e.g. 5174, are texturally quite similar to the analysed example 5173; the plagioclase changes in composition upward reaching (ca. An_{64}) near the top of the zone. The orthopyroxene, although completely pseudomorphed, is seen to be mantled by another phase of different orientation which is also altered but is believed to have been pigeonite (Pl. 3, fig. 1). Iron ore occurs interstitially except in a rock, 4517, from the bottom of Brödregletscher, where iron ore is found as an abundant cumulus phase. The plagioclase composition (An_{64}) places this rock near the top of the zone.

Pigeonite Gabbro Zone (PGZ)

The pigeonite gabbro is a generally medium-grained, moderately mafic rock and lacks most of the spotting characteristic of the bronzite gabbro. The lower boundary of the zone is defined by the initial appearance of pigeonite as a cumulus phase and the upper boundary by the reappearance of olivine in the sequence. Neither transition can be described in detail because the sample interval of about 30 m. is too large and, in any case, the relationships are obscured by the alteration of these minerals. The cumulus phases of this zone are plagioclase, augite, pigeonite and iron ore; the intercumulus phases consist of alkali feldspar, quartz, chlorite and minor accessory apatite (table 1 for modes). A little sulphide is sometimes seen in hand specimen and often produces malachite staining on weathered surfaces.

A typical rock, 4474, from Kobbernunatak (Pl. 3, fig. 2) is described first. The plagioclase, with cores (An_{57}), occurs as subhedral tabular of lath shaped crystals, up to 5 mm. long. Slight to moderate normal zoning is seen in their central and outer parts but it is strong at the margins where contact is made with the interstitial micropegmatite. In this example there is extensive alteration to sericite. The augite occurs in anhedral, granular to sub-prismatic crystals; a more prismatic habit is common in other examples. It is neutral in colour and only little altered to pale uralite. The pigeonite is easily distinguished from the augite by its habit and extensive alteration. It occurs in elongate rounded grains, up to 1 mm. long, and is closely associated with the augite. The fresh pigeonite is colourless and gives biaxial interference figures of small optic axial angle. Altered pigeonite is replaced by chlorite or possibly an amphibole which is slightly pleochroic from pale yellow to pale green. The iron ore is widely interspersed as anhedral to subhedral grains, varying in size up to 1 mm. across. The crystal interspaces are filled with turbid finely intergrown quartz and alkali feldspar or a pale green chlorite containing minute crystals of apatite. Microscopic veinlets of quartz and chlorite traverse many of the larger crystals and apparently follow minute fractures.

Among other examples from Kobbernunatak, 4473, (also probably 1218, 369) collected below the example just described, has a slightly more basic plagioclase (An_{58}) and no fresh pigeonite is preserved. Above and near the top of the zone, a coarser grained rock, 4475, contains plagioclase (An_{54}) and the prismatic augite shows a dense opaque schillerization. The acid mesostasis is more abundant; the quartz-alkali feldspar intergrowth is diffuse or radiating. Some of the quartz occurs in separate grains or composite clusters and is obviously later than the quartz intergrown as micropegmatite.

Of two examples from Skillenunatak, the lower, 5175, has plagioclase (An_{54}) and is similar to the rock, 4475, described above. The higher example, 5176, has plagioclase (An_{50}), and is unique in containing more pigeonite than augite.

An important variation is found in two rocks, 367, 1213, from the north-west side of Kobbernunatak; neither contains cumulus iron ore. From the composition of the plagioclase (An_{60}) in both, these rocks are apparently the lowest examples of the zone. Cumulus iron ore has been described (p. 20) in the high bronzite gabbro, 4517, from the small exposure at the base of Brödregletscher; apparently the horizon at which iron ore appears as a cumulus phase varies slightly within the sheet.

Pyroxene Ferrodiorite Zone (PFDZ)

The pyroxene ferrodiorite zone is taken to begin at the horizon where olivine reappears in the sequence and continues to the highest rock collected which is probably near the top of the sheet. The cumulus phases of the zone are plagioclase, augite, iron-olivine, iron ore and apatite; the intercumulus phases, chiefly a quartz-alkali felspar intergrowth, are more abundant than in the pigeonite gabbro. In hand specimen the pyroxene ferrodiorite is medium to moderately coarse grained, more melanocratic than the pigeonite gabbro and distinguished by a slight to marked spotting due to the alteration of the olivine. Rusty weathering is a characteristic of the extremely iron-rich examples in the upper parts of the sheet. The modal proportion of plagioclase varies and sometimes imparts distinct banding (fig. 7). Small transgressive acid veins occur in the upper part of the zone (fig. 7).

The analysed example, 5178 (Pl. 4, fig. 1), from near the top of Skillenunatak, contains plagioclase (An_{43}) occurring mainly as well shaped tablets or laths, up to 3 mm. in length. It is little zoned except marginally where in contact with the acid mesostasis; some crystals are bent and show a resultant wavy extinction. Alteration of the plagioclase to sericite and the spread of alteration from the olivines is slight but it is often advanced in other examples. The augite occurs as subhedral prismatic crystals, about the same size as the plagioclase and is brown in colour at this horizon. The olivine (Fo_9) is light yellow, subhedral in habit but it is mostly replaced by a dark green chlorite and iron ore. The cumulus iron ore occurs in anhedral to subhedral grains of varying size. The apatite is widespread in small crystals and largely confined to the mesostasis or the outer parts of the other cumulus phases; it is usually more abundant in the other examples.

Other examples of pyroxene ferrodiorite from Skillenunatak include a more feldspathic variety, 5177, below 5178 just described and with plagioclase (An_{49}). The augite is pale brown. The olivine is completely altered to the dark green chlorite and iron ore, which are characteristic of the partial pseudomorphs found in 5178. In another example, 5179, from the top of Skillenunatak, the pseudomorphs after olivine are mainly of "iddingsite".

A rock, 4491, from the small nunatak in Brödregletscher is similar to the analysed example, 5178, and also contains a little unaltered olivine (Fo_9). The augite, however, is subpoikilitic enclosing the plagioclase, a textural relationship not found elsewhere in this zone. An adjacent rock, from a feldspathic band, contains little olivine.

On Kobbernunatak, the pyroxene ferrodiorite is generally slightly coarser grained and more altered, no fresh olivine has been found in these rocks. The lowest example, 4476, has plagioclase (An_{52}) and contains areas, measuring 5 mm. across, composed of a fibrous assemblage of brown and green hornblende, chlorite and iron ore which are apparently derived from the alteration of large olivine crystals. Apatite in this example is found in remarkably large stubby crystals, measuring up to 3 mm. long by 1 mm. wide. In ascending the sequence, 4477–4487, the augite becomes steadily darker in colour and is a purple brown in the highest example, 4487; it is frequently rimmed or partially replaced by brown or blue-green amphibole especially where a crystal is in contact with the acid mesostasis. The plagioclase (An_{40}) in the highest rock, 4487, (Pl. 4, fig. 2), is much embayed by quartz and alkali feldspar and often cloudy with alteration products. The olivine is altered to a variety of complex assemblages of hornblende, serpentine, chlorite and iron ore or "iddingsite" and these impart a marked spotting in the examples, 4482, 4483. Micropegmatite is abundant in these rocks and may occur in areas up to 5 mm. across. Some free quartz is found in small crystals, 0.5 mm., having the bipyramidal habit of its β-form.

Small acid veins, a few centimetres across and believed to be late-stage segregations, occur high on Skillenunatak and Kobbernunatak. The example, 5180, from Skillenunatak is moderately leucocratic and fine grained. In section it has a micrograntic texture and is composed mainly of interlocking granular quartz and plagioclase, having an average grain size of 0.2 mm. The plagioclase (An_{35}) shows fine, often discontinuous, twinning lending a patchy extinction to these sections. A blue-green amphibole occurs in small acicular crystals; it shows an incipient alteration to a dark reddish brown mineral, probably a biotite. A little ore, probably ilmenite, is partially altered to leucoxene. Zircon occurs sparsely in minute euhedral crystals.

The acid vein from Kobbernunatak, 4481, (fig. 7), has a granophyric texture. Lath shaped crystals of plagioclase (An_{32}) are set in a fine-grained granophyric intergrowth; the intergrown feldspar is sometimes in optical continuity with the plagioclase crystal it surrounds. A partial chemical analysis (table 5) shows this vein to be extremely poor in potash indicating that the intergrown feldspar must be nearly pure albite. A little blue-green amphibole occurs, as in the previous example, but is more altered. If the veins are late segregations, the anomalous low $K_2O:Na_2O$ ratio possibly indicates that they formed from a final water-rich fraction (cf. Walker, 1940).

Gabbro pegmatite

Segregations of coarse pegmatitic gabbro, as already mentioned (p. 15), occur within pigeonite gabbro on Kobbernunatak and although they do not constitute a separate zone, they are sufficiently different mineralogically to be considered separately. Hughes (1956, p. 16) has given an account of material collected (1953 expedition) from fallen blocks; two examples from pegmatites, *in situ*, among the earlier collections have not been previously described.

One of these, 366, illustrates the junction between the pegmatite and the host pigeonite gabbro (fig. 9). The pigeonite gabbro is similar to the previous examples 4473, 4474, but contains no cumulus iron ore (see p. 21). From the composition of the plagioclase (An_{60}) the rock is apparently representative of the base of the zone. The pegmatite is composed essentially of large crystals, up to 3 cm. long, of augite and plagioclase. The plagioclase (An_{48}) is unzoned except where marginally in contact with the acid mesostasis. Clouding from sericite and opaque specks is moderate; the latter show preferential alignment along various crystallographic directions. Certain crystals show a confusion of fractures filled with another plagioclase which, being of lower relief, seems considerably more albitic. The augite is light brown in colour and near areas of alteration heavily schillerized. Its extinction is uniform and the optic axial angles shows little variation; refractive index tests (cf. Hughes, 1956, p. 16) indicate that it is richer in iron than that of the host pigeonite gabbro. The intersticies (comprising about $20\,^0/_0$ by vol.)

consist mainly of micropegmatite, quartz, hornblende, iron ore and chlorite and in lesser amount, spherulitic clusters of a cherry brown mineral, probably a mica, epidote and apatite. Much of the quartz, intergrown as micropegmatite, occurs in acicular units, presumably

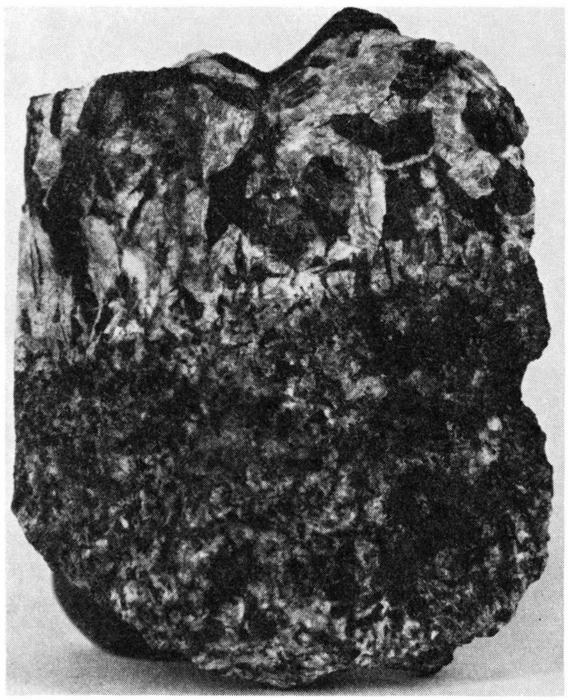

Fig. 9. A specimen (366) showing the contact between pigeonite gabbro and a pegmatitic segregation. $\times {}^3/_4$ J. COOKE.

paramorphs of tridymite. The hornblende (α = pale yellow, γ = dark blue-green) is largely a marginal development of the augite.

The large augite and plagioclase crystals, constituting the pegmatite, lie roughly at right angles to a well defined junction with the pigeonite gabbro. In section the junction is seen to be gradational; within a few millimetres of the junction, the plagioclase of the pigeonite gabbro shows strong normal zoning; the augite changes in colour from neutral to brown. Passing into the pegmatite the ends of the large plagioclase crystals enclose or grow outwards, with resultant zoning, from the smaller crystals of the wall. Late-stage alteration is less marked than in the more central parts of the pegmatite.

Another rock, 1213, collected from the centre of a lensoid mass, is remarkably coarse grained; crystals of both augite and plagioclase attain lengths up to 7 cm.; the acid interspaces are clearly visible in areas up to 2 cm. across. The augite is somewhat intergrown with the plagioclase, mainly in thin plates along the cleavages.

These gabbro-pegmatite segregations were probably derived in a manner similar to that described by WALKER (1953); intercumulus liquids migrated into areas of low pressure, possibly tension fissures, while the rocks were still only a spongy crystal structure. The size and attitude of the crystals that grew into these areas and the absence of strong zoning in the plagioclase may be related to the ease of crystallization enhanced by an enrichment of volatiles.

MINERALOGY OF THE SHEET SEQUENCE

The changing mineralogy of the Basistoppen sheet, which provides a logical basis for its classification, is summarized in fig. 10. The variation in composition of the cumulus phases with increasing height demonstrates the extent of differentiation as the result of fractional crystallization. All the compositions given have been estimated optically. Unfortunately extensive alteration makes it impossible to determine fully the range in composition of olivine, orthopyroxene and pigeonite.

Plagioclase

Plagioclase is the major constituent of the sheet rocks; the average modal proportion by volume is about 55 % through four fifth of the sequence, decreasing in the upper pyroxene ferrodiorite to under 40 %.

The poikilitic habit of the plagioclase in the gabbro-picrite and basal pyroxene bands indicates that the plagioclase crystallized initially as an intercumulus phase; throughout the overlying sequence it is a cumulus phase. The size and shape of the cumulus plagioclase crystals show little systematic variation. As a generalization most of the crystals in the early and middle stages are rectangular laths, the majority 2–3 mm. long, the longer 5 mm.; a more tabular habit is found in coarser grained variants. In the upper rocks the crystals are more tabular with an average length about 1 mm. although some, 5 mm. in length, are still found.

Zoning is always seen; it is predominantly normal and largely marginal. Infrequently, the early cumulus crystals show a single narrow, poorly defined, reversed zone near the margin. In the bronzite and pigeonite gabbro zones the central portion of crystals often shows a somewhat patchy extinction around an irregularly shaped core.

The plagioclases show little or no clouding from opaque material but sericitic alreration is often advanced, especially in the upper pyroxene ferrodiorites being associated with the more abundant acid mesostasis.

Compositions of the little zoned central parts of the plagioclase were determined optically from the maximum extinction angles measured

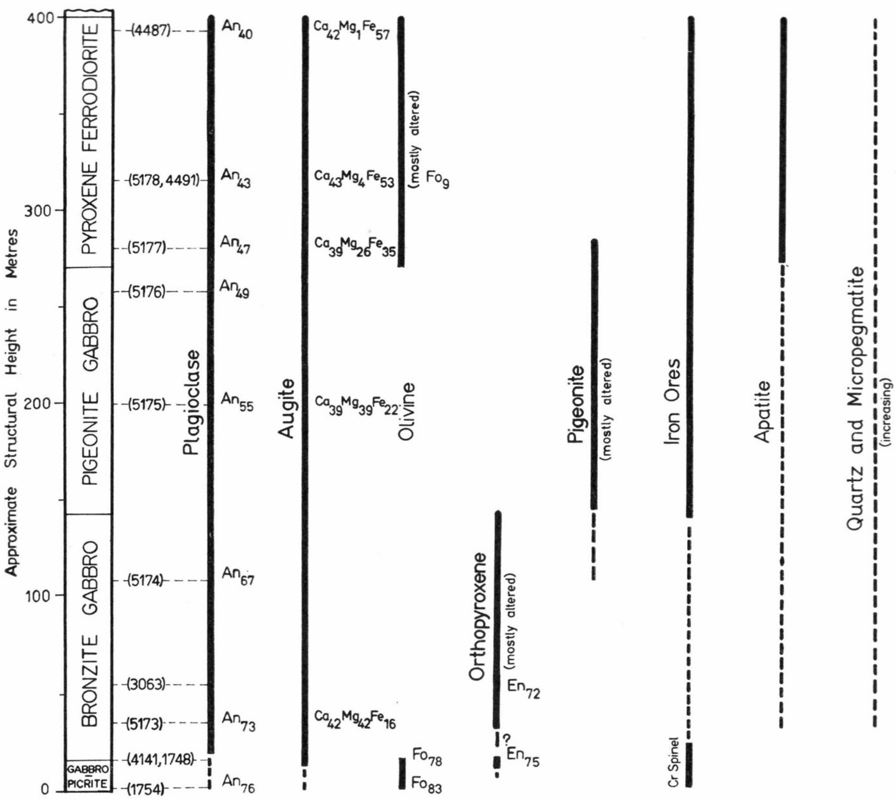

Fig. 10. General mineralogical section of the sheet. Full lines indicate cumulus minerals; broken lines, intercumulus minerals.

in the zone ⊥ to (010) and using the determinative curve from Winchell (1951, p. 262). The composition varies systematically with height from An_{76}–An_{40} (mol. $^0/_0$). It is worth noting that these determinations assume that the sheet plagioclase is in a low structural state. Rittmann and El Hinnawi (1961) have shown that the extinction angle is a function of the structural state as well as of composition. Gay and Muir (1962), finding significant departures from the low structural states in the plagioclase of the upper layered rocks of the Skaergaard intrusion, have emphasized the earlier suggestion of Smith and Gay (1958) that plagioclase in the composition range An_{40-50} achieves equilibrium with difficulty, even in slowly cooled plutonic rocks. It is quite possible that the plagioclase compositions in the upper pigeonite gabbro and the pyroxene ferrodiorite are 2–4$^0/_0$ lower than those quoted because the assumption made in deriving the composition has been that the plagioclase are in a low structural state and this may not be correct.

Pyroxenes

(1) Augite

Augite is the principal pyroxene and next to plagioclase in importance as a constituent of the sheet rocks. The texture of the lower gabbro-picrite, 1754, suggests that the augite crystallized initially mainly as an intercumulus phase; in the upper gabbro-picrite, 1748, it is obviously a cumulus phase and remains so throughout the overlying sequence. In the early stages, the cumulus augite is anhedral, granular to slightly prismatic, but as the series is ascended it becomes steadily more prismatic until the middle stages where odd crystals attain 1 cm. in length; in the later stages it occurs as moderately euhedral stubby prisms, averaging 2 mm. in length.

Gradual changes in colour are also seen in ascending the sequence; the augite of the gabbro-picrite is pale green, probably indicating a high chromium content; throughout the bronzite and pigeonite gabbros the colour is neutral to pale brown in thicker sections; in the pyroxene ferrodiorite the colour deepens gradually to a purple brown, like the colour of the ferroaugite in the upper Skaergaard layered rocks.

Simple twinning on (100) is common up to the pyroxene ferrodiorite stage where it is absent. Zoning is apparently of little importance as the

Table 2. Optical properties and estimated composition of augite in selected sheet rocks.

	1	2	3	4	5	6	7	8	9
Spec. No.	1754	5173	4474	5176	5177	4478	4483	5178	4487
Colour	pale-green	neutral	neutral	neutral	pale-brown	pale-brown	brown	brown	brown
R.I.$_\beta$ (±.001) ...	1.694	1.695	1.701	1.710	1.715	1.718	1.732	1.736	1.745
2V$_\gamma$ (± 2°)......	46°	45°	42°	44–46°	48°	47$^1/_2$°	53°	53$^1/_2$°	55$^1/_2$°
Estimated Comp. Atomic $^0/_0$									
Ca	43	42	39	38	39	40	43	43	42
Mg	42	42	39	31	26	21	6	4	1
Fe	15	16	22	31	35	39	51	53	57

(1) Gabbro-picrite
(2) Bronzite gabbro
(3,4) Pigeonite gabbro
(5–9) Pyroxene ferrodiorite

Estimated compositions are read from curves based on analysed Skaergaard augites (Brown, 1957, 1963) and plotted in fig. 11.

extinction is usually uniform and optic axial measurements on single grains show little variation.

Thin exsolution lamellae are seen in the augite except in that of the upper pyroxene ferrodiorite. The augite of the gabbro-picrite contains faint lamellae or straie on (100) and (001); these are too fine for optical identification. With increasing height the (100) lamellae disappear and (001) lamellae become more apparent; small blebs associated with these latter also appear. These exsolution textures have a patchy distribution and are mainly confined to the central parts of crystals. The exsolved material is altered, mainly to chlorite and iron ore dust and its identity cannot be determined. By analogy with the optical and x-ray study of the exsolution phenomena in the Skaergaard pyroxenes (Brown, 1957; Brown and Gay, 1960), most of the exsolved material is thought to have been pigeonite; in the more altered rocks an opaque schillerization accompanies these features.

Atomic ratios (Ca:Mg:Fe) for nine augites at representative heights in the sequence are listed in table 2 and plotted in fig. 11. The ratios were estimated from optical parameters ($2V_{\gamma}$, R.I.$_{\beta}$) using the determinative curve prepared by Brown (1957) from data on Skaergaard augites from the early and middle stages of fractionation and tentatively extended by the writer into the ferroaugite field on the basis of nine unpublished analyses of the later Skaergaard ferroaugites[1]).

The nine sheet augites define a trend similar to the trend of the Skaergaard augites shown by Brown (1957) and the nine unpublished analyses in the ferroaugite region, although a strict comparison cannot be made on the basis of optical properties because these may be influenced by minor constituent cations and other factors (Brown, 1957, p. 536). The pyroxenes from the upper ferrodiorite of the sheet plot in the ferrohedenbergite field, but unlike the Skaergaard pyroxenes of the layered series of this stage, they show no indication of having inverted from iron-wollastonite (Wager and Deer, 1939, p. 81).

(2) *Orthopyroxene*

Orthopyroxene commenced crystallization soon after the olivine and augite; it continued to crystallize until a phase change established pigeonite in its place. The early orthopyroxene in the gabbro-picrite, 1511, is subpoikilitic and like augite it crystallized initially as an intercumulus phase. In the top gabbro-picrite, 1748, it has a prismatic habit; in the overlying pyroxene band and for some distance above, the orthopyroxene occurs in large platy poikilitic crystals (Pl. 2, fig. 1). This latter

[1]) A paper on the Skaergaard augites from the later stages of fractionation has since been publised (Brown and Vincent, 1963).

texture implies an intercumulus origin; no zoning could be seen in the unaltered material in 1214, suggesting that these crystals were enlarged by adcumulus growth. On Basistoppen, where the gabbro-picrite does not appear, the orthopyroxene never shows any strong poikilitic tendencies and is essentially prismatic in habit.

Unfortunately most of the orthopyroxene is replaced by bastite but some fresh material is present in the gabbro-picrite and lower bronzite gabbro for optical study. The unaltered material is pleochroic in shades of pink. Thin exsolution lamellae, presumably of augite, are occasionally seen on (100), and this feature is preserved in the pseudomorphs.

The Mg:Fe ratio was estimated by direct measurement of 2V and using the appropriate curve from Hess (1960). The assumed cumulus orthopyroxene in the gabbro-picrite, 4141, is En_{75} ($2V_{\alpha}$ 68°). The ratio decreases to En_{73} ($2V_{\alpha}$ 65°) in a low bronzite gabbro, 3063. Above this horizon no fresh material has been found; orthopyroxene seems to have continued to crystallize until the stage of fractionation marked by the approximate plagioclase composition, An_{62}.

(3) *Pigeonite*

Pigeonite is a cumulus phase in the pigeonite gabbro. It appears to have crystallized initially as an intercumulus phase around the orthopyroxene in the upper bronzite gabbro (Pl. 3, fig. 1) but this relation is largely obscured by extensive alteration. Like the orthopyroxene the pigeonite is mostly altered and has therefore to be identified largely from the character of the pseudomorphs. Sufficient fresh material is available to allow certainty in the identification. Other features that distinguish the pigeonite pseudomorphs from those of orthopyroxene are the rounded habit and its close association with augite. No confusion exists with the augite because the latter is little altered. Hughes (1956, p. 15), however, confused altered pigeonite with altered olivine in the lower pyroxene ferrodiorite rocks. It seems that the pigeonite of the sheet did not invert to orthopyroxene before altering.

There is insufficient fresh material to separate for refractive index measurement. The optic axial angle is small ($2V_{\gamma}$ about $10° \pm 2°$).

(4) *Sequence of crystallization of the pyroxenes*

The sequence of crystallization of the sheet pyroxenes simulates the sequence outlined by Brown (1957) for the Skaergaard pyroxenes. The calcium-rich pyroxene, augite, crystallized throughout the sheet for the most part as a cumulus phase; it changed in composition during fractionation essentially by the gradual enrichment of Fe'' relative to Mg (i.e. $Ca_{43}\,Ca_{43}\,Mg_{42}\,Fe_{15}$ to $Ca_{42}\,Mg_{1}\,Fe_{57}$).

The first calcium-poor pyroxene, orthopyroxene, probably crystallized initially as an intercumulus phase having a composition of about En_{75}. The orthopyroxene composition changed with fractionation by the replacement of Mg by Fe″ until pigeonite crystallized instead. The composition at which this phase change occurred cannot be determined because both phases are altered; a reasonable estimate, by extrapolation of the fractionation rates relative to that of the plagioclase, gives a composition of En_{30} (cf. Hess, 1941, 1960).

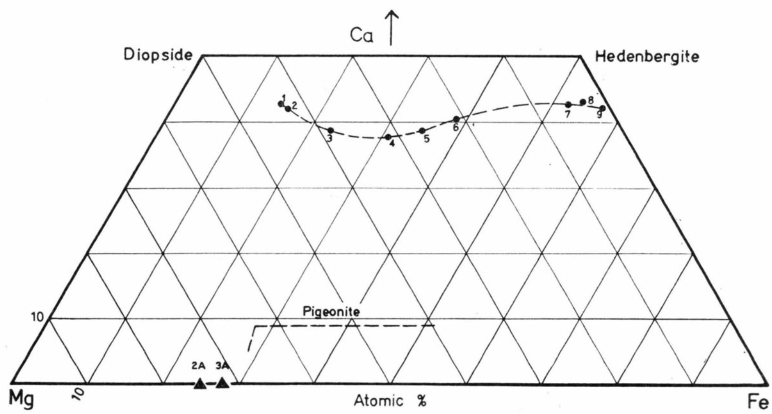

Fig. 11. Trend of the sheet pyroxenes based on optics. Augites (1–9) are listed in table 2. Orthopyroxene (triangles): (2a) gabbro-picrite, 4141; (3a) bronzite gabbro, 3063.

The enrichment of the pigeonite in Fe″ relative to Mg during the fractionation must be inferred from the bulk chemical data of the rocks and the accompanying variation found in the augite and plagioclase. The cooling interval for the sheet was probably sufficiently long for inversion to have taken place, yet there is no indication that any of the sheet pigeonite has inverted to orthopyroxene as fresh uninverted pigeonite is found in several examples. Some other factors may be involved. Poldervaart and Hess (1951, p. 487) have suggested that volatiles may increase the stability of pigeonite at lower temperatures so that inversion never occurs. Brown (1957, p. 534) has suggested that inversion is sluggish where "an appreciable interval separates the temperatures of crystallization and inversion", that is for ferriferous pigeonite.

The limit of the two pyroxene field appears to have occurred roughly where olivine reappeared in the sequence, although the lower pyroxene ferrodiorite rocks contain, in addition to pseudomorphs of olivine, diffuse alteration products which are possibly after pigeonite. Brown (1957, pp. 524–527) has discussed various factors influencing the cessation of the two pyroxene field in the later stages of fractionation.

Olivine

Olivine occurs in the gabbro-picrite and pyroxene ferrodiorite zones and also sporadically in the border rocks and in two examples, 1214, 3040, from the base of the bronzite gabbro.

In the gabbro-picrite olivine is the principal cumulus phase; the crystals have a rounded subhedral outline and average about 1 mm. across. No zoning is apparent. Iron ore, as dust or in dendritic form, occurs along cracks and crystal margins. Alteration to colourless or pale green serpentine is slight to moderate. The forsterite content, estimated optically, decreases upwards in this zone from Fo_{83}–Fo_{77}, ($2V_\alpha$ 88–86$^1/_2$°, ± 1°, compositions read from TOMKEIEFF's tables, 1939).

Iron olivine composes about 15$^0/_0$ by volume of the pyroxene ferrodiorite but it is almost entirely altered, chiefly to a mixture of ore and chlorite, less commonly to ore and "iddingsite" (GAY and LE MAITRE, 1960) or an amphibole. These alteration products have not been investigated systematically, but there is apparently some variation with changing composition. A little unaltered olivine in two rocks, 5178, 4491, is Fo_9 ($2V_\alpha$ 52° ± 1°) in both and provides the identity of the pseudomorphs in other examples. It is unfortunate that the range in composition of the olivine in the pyroxene ferrodiorite cannot be demonstrated because of the alteration.

Opaque minerals

The opaque minerals have been summarily studied by examination of six polished sections which represent the important horizons in sheet.

The gabbro-picrite, 1754, contains minute opaque euhedral crystals occurring mainly in the olivine, and on the basis of the reflectivity and high Cr content of the rock, they are identified as chromite. A few discrete grains of ilmenite are seen interstitially.

A typical lower bronzite gabbro, 3062, contains a few discrete interstitial grains of ilmenite and magnetite in roughly equal amounts. The magnetite, in a spongy state, contains bar lamellae of ilmenite. The separate ilmenite grains occur in ragged skeletal crystals and have possibly exsolved from the magnetite but there is little proof of this. A few grains of chalcopyrite, mostly enclosed by the magnetite, are present.

Two typical specimens of pigeonite gabbro, 5175, 5176, are above the horizon where iron ore first occurs as a cumulus phase. Magnetite and ilmenite occur separately in a ratio of roughly 3:2 and compose about 7$^0/_0$ of these rocks. The magnetite is euhedral and contains distinct exsolved bar lamellae arranged on (111) (Pl. 7, fig. 1). The separate ilmenite occurs in elongate anhedral grains, almost all showing a relict portion that may have been intergrown with magnetite. No ulvöspinel, as found throughout much of the Skaergaard layered series (VINCENT, 1960), was seen. A little chalcopyrite and iron pyrite is present interstitially.

Two specimens of pyroxene ferrodiorite, 5178, 4488, contain about the same amounts of magnetite and ilmenite as the pigeonite gabbro. The magnetite shows a curious "grid iron" relation with the exsolved ilmenite phase (Pl. 7, fig. 2). In some cases the magnetite has apparently dissolved away under deuteric action leaving an ilmenite skeleton (cf. VINCENT and PHILLIPS, 1954). A few specks of pyrite, but no chalcopyrite, occur in both rocks. Ilvaite is abundant as an alteration product of olivine.

Apatite

Apatite appears as a cumulus phase (up to 5% by volume) in the PFDZ, roughly coincident with the reappearance of olivine in the sequence. It is found generally as slender crystals, rarely over 1 mm. in length; these are widely distributed and sometimes included within augite, olivine and the outer parts of plagioclase. Below the PFDZ apatite occurs sparingly, mainly associated with chlorite in the mesostasis. The similarity in behaviour of apatite in the sheet and Skaergaard sequences is remarkable.

Mesostasis

Quartz and alkali feldspar, largely intergrown as micropegmatite, are found early in the sequence. Neither appears as a cumulus phase but they increase in amount upwards becoming important constituents in the highest rocks (see Table I). The alkali feldspar is turbid and too finely intergrown for optical examination. Small skeletal insets of a turbid feldspar, showing vague twinning, are seen occasionally within the large areas of micropegmatite in the uppermost rocks, 4483–87. Apparently, at this stage an alkali feldspar was begining to separate slightly before it crystallized simultaneously with quartz at the cotectic boundary.

Some quartz, obviously later than that intergrown as micropegmatite, is found in separate grains, along minute fractures, and in microscopic veins which can be traced across an entire section. This quartz was probably deposited at the late hydrothermal stage during which the orthopyroxene, olivine, pigeonite and, to some extent, augite underwent extensive alteration (HUGHES, 1956, p. 24). These alteration products have not been investigated systematically. Chlorite, distinct from that derived from the alteration of pigeonite or olivine, also formed interstitially.

THE LOWER BORDER ROCKS

Introduction

Along the lower contacts of the sheet, exposed on the upper parts of Basistoppen and the south side of Nunatak I, there is a group of rocks, largely fine-grained gabbros, which are here designated as the lower border division (LBD). The thickness of the LBD is probably well under ten metres. At the better exposures, on Basistoppen and on the south side of Nunatak I, it is not known accurately because of the scree cover.

On Basistoppen the border rocks pass upwards into the basal members of the BGZ. On Nunatak I the fine-grained gabbro along the contact passes inwards, within a metre or so, into a medium-grained gabbro that persists, over a horizontal distance of about fifty metres, to the southern limits of the exposure. In view of the vague structural relations this latter will here be considered as belonging to the border division; it might equally be considered as belonging to the upper part of the BGZ as it contains pseudomorphs of orthopyroxene and plagioclase equivalent in composition to that of the upper rocks on Basistoppen.

Due to the intricate contact relationships it is necessary to consider briefly the composition of the Skaergaard rocks underlying the sheet; a detailed description of these rocks will, however, be given elsewhere. The Skaergaard rocks under the sheet on the western side of Basistoppen consists of hedenbergite andesinite and similar material has been found in veins (width not recorded) penetrating for several metres above what could be established as a fairly definite base of the sheet. (Wager and Deer, 1939, p. 58). On the eastern side of Basistoppen the underlying Skaergaard rocks consist of quartz-rich pyroxene ferrodiorite. Although no large scale veining is recorded, the field notes indicate that the sheet and Skaergaard rocks are somewhat intermingled and further evidence of this is seen later on a microscopic scale. On Nunatak I the sheet is also underlain by pyroxene ferrodiorite but here containing block-like masses and streaks, of uncertain relation, consisting of plagioclase-rich material rather similar to the hedenbergite andesinite mentioned previously. The fine-grained margins of the sheet is, in places, intricately veined (net-veined) by material easily traced to the adjacent Skaergaard rocks (fig. 4).

Nunatak I

Although essentially fine grained and light weathering, the marginal rocks along this contact vary slightly in composition. In the attempt to collect representative material free from the effects of net-veining, many of the subtle variations were overlooked and not discovered until the rocks were examined more closely in the laboratory. Two rocks from the immediate contact to be described first are believed, however, to be representative.

One of these, 4125, has been analysed (table 3, p. 47). In hand specimen the rock is fresh, compact and distinctly saccharoidal in appearance on a freshly broken surface. It is composed essentially of plagioclase and augite (mode given in table 1, p. 19) with a small amount of iron ore and chlorite. The texture is characteristically intergranular with a definite flow structure (Pl. 5, fig. 1).

The plagioclase (An_{43}) occurs mainly in small laths, averaging under 0.5 mm. in length, generally twinned and slightly zoned. In one section the laths are well aligned except for small areas where they lie randomly or in stellate patterns; in another section of the same specimen, the plagioclase forms ill defined, poorly twinned crystals but these retain a definite linear arrangement. A few larger crystals occur in different habits. Certain, as tablets up to 2 mm. across, are well twinned and their centres have about the same composition as the smaller plagioclase; most have a thin indistinct reversed zone near the margin which is a few percent richer in anorthite; they contain small granules of augite and show evidence of fracture. Other larger crystals are irregular or shard-like in form, untwinned and normally zoned from centres which seem to be more basic than the groundmass plagioclase, but whose composition cannot be determined by the extinction angle method.

The augite is neutral in colour, granular in habit and generally in smaller crystals than the plagioclase; some larger grains, up to 0.5 mm. across, are found in glomeroporphyritic aggregates. The iron ore is evenly distributed in small subhedral grains. A few grains, composed of an amphibole largely altered to chlorite, resemble most closely pseudomorphs of orthopyroxene or possibly pigeonite but their true identity is uncertain.

A second rock, 5428, is also representative of the immediate margin but, with possible significance, in a part where the net-veining is denser. On the freshly broken surface it is more melanocratic than the previous example and slightly coarser grained; a linear spotting is also found on certain weathered surfaces. In section the rock is seen to be similar to the previous example but contains, in addition, an iron-olivine, slightly more iron ore and a small acid mesostasis. The plagioclase (An_{40}) is slightly less basic and the linear arrangement of the laths more pronounced. Some larger crystals, as previously noted, occur mainly in tabular form and their composition is the same as the groundmass feldspar.

The iron-olivine ($2V_\alpha$ 67°; Fo_{24}) is confined to small lenticular-shaped areas, about 1 cm. in length, the long axis of which lies parallel to the direction of flow. Within these areas, the olivine is found in small branching crystals in sub-ophitic relation with plagioclase. It is colourless and partly replaced by iron ore along margins and cracks. A little chlorite and a brown, semi-opaque mineral accompany more extensive alteration. Augite is largely excluded from these areas; in other parts it has a similar habit and appearance to that of the previous example, 4125.

Quartz and a turbid feldspar are occasionally found in small interstitial patches, especially in the areas where olivine occurs or in places filling marginal embayments in the larger plagioclase.

Within a horizontal distance of about a metre from the contact, (probably less structurally) the sheet rocks become medium grained, more leucocratic and spotted in appearance; this type continues to the southern limits of the exposure without apparent change in composition. Thus a typical rock, 4123, is composed mainly of plagioclase, augite, pseudomorphs of orthopyroxene and iron ore. The plagioclase is strongly zoned with cores (An_{60}) and occurs mostly in broad anhedral laths, averaging 1 mm. in length, with their outer margins modified by late growth; the laths show no preferential orientation, but many are bent. The augite is neutral in colour, granular in habit, of varying size and frequently in composite clusters. The texture suggests that it crystallized contemporaneously with plagioclase. Evidently orthopyroxene crystallized later in comparatively large ophitic to sub-ophitic units but the textural relations are largely destroyed by its complete alteration to a fibrous amphibole, itself largely altered to chlorite. Iron ore is found in small irregular grains. Some grains of quartz, patches of turbid alkali feldspar and a later chlorite are unevenly distributed and near these there is extensive sericitic alteration of the plagioclase.

Among other examples, 5429, about a metre from the contact, is finer grained than 4123, just described but contains the same essential minerals with rather the same textural relations. On a sliced surface the rock gives the appearance of having been impregnated with quartz and alkali feldspar which occur in tiny stringers and in section are seen to cause local dense sericitic alteration of the plagioclase. Another rock, 5406, about twenty metres horizontally from the contact, is coarser grained but in a similar way is apparently impregnated with acid material.

Consideration must also be given to the net-veins in the fine grained margins of the sheet and the parent material, that is the adjacent Skaergaard rocks, from which they were clearly derived. The latter consist of pyroxene ferrodiorite of heterogeneous aspect due to a streaky variation in the relative proportion of plagioclase. About an average type, 4122, is medium grained and composed essentially of plagioclase (An_{40}), ferrohedenbergite, foyalite (Fo_5) and in lesser amount, iron ore, micropegmatite, free quartz and apatite; a little accessory zircon is seen in another more leucocratic example, 5431.

Net-veins, in places dense, intricate and standing out in contrast to their fine-grained host may often be traced laterally to the ferrodiorite. Most of them are composed essentially of plagioclase and iron ore. A typical example, 4126, contains a small vein, about 2 cm. at its widest part, from which it splits into attenuating branches. In a large section (fig. 12) the veining is seen to be roughly parallel to the distinct flow structure in the fine grained host, this latter being essentially similar to the two examples described earlier. About 1 cm. from the nearest part of the vein, the grain size increases slightly and ragged poikilitic aggregates of an iron-olivine are found, mostly replaced by iron ore or chlorite. Moving from this area and at right angles to the lineation the grain size is alternatively very fine to moderately fine but this variation seems to have little relation to proximity of the veining. In its widest parts the vein is composed mostly of plagioclase (An_{45}), iron ore, a remarkable concentration of zircons and a small acid mesostasis (Pl. 6, fig. 1). The plagioclase is little zoned, sometimes untwinned and occurs either in anhedral interlocking grains, up to 2 mm. across, surrounded by iron ore or in separate grains which show evidence of strain and fracture. The zircon is widely scattered in subhedral prisms (0.2 mm.), mainly within iron ore. Other parts of this vein also contain augite of neutral colour, granular to sub-ophitic in habit and in places altered to green hornblende. Augite also occurs in granular clusters, either along parts of the vein margins or strung out in thin veinlets, surrounded in iron ore containing small zircons. This augite is, with little doubt, of the same composition as that of the fine-grained host. Finally, minute cracks transgressing both veins and host are delineated by alteration of the augite to green hornblende.

North-east side of Basistoppen

The group of rocks collected from this exposures in 1935 probably reveals the main features of the apparently ambiguous relationships found along this contact. Although the field relations could not be well established sufficient analogy may be made with the Nunatak I exposure to justify brief description.

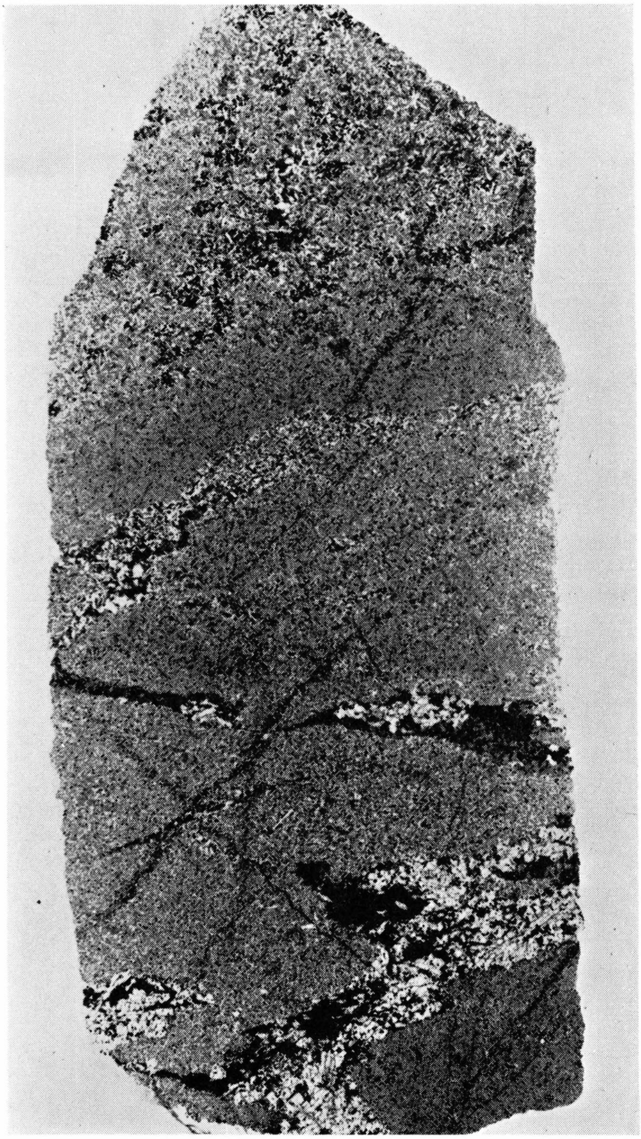

Fig. 12. Thin section of fine-grained marginal gabbro, 4126, showing detail of net-veining. Plain light. ×2.

A composite rock, 1890, shows a contact relation between the fine-grained margin to the sheet and the underlying Skaergaard pyroxene ferrodiorite. This latter, comprising most of the specimen, is streakily mafic and slightly drusy with fillings of quartz and chloritic material. In section the component minerals are found to be much altered; the plagioclase (An_{43}) is turbid with alteration products, especially sericite and much sieved by quartz; the pale green augite is little altered but has been obviously granulated and is partly recrystallized; the olivine is completely altered to felted masses of "iddingsite" and chlorite. Micropegmatite and quartz form an abundant groundmass. A small portion of 1890 is moderately fine-grained sheet gabbro composed essentially of plagioclase and augite and a little iron ore. It is impregnated with micropegmatite, clearly derived from the adjacent Skaergaard rock.

A fine-grained rock, 1892, of uncertain relation but essentially similar to those rocks described from Nunatak I, is by inference typical of the sheet margins. The texture is intergranular with slight but distinct flow structure. Plagioclase (An_{50}) occurs mainly as well formed laths, less often in irregular, anhedral grains poorly twinned and notably zoned. None of the larger tabular crystals, as found previously, are seen. Iron olivine, mostly altered to iron ore and a colourless serpentine, occurs sporadically in branching crystals. A slight streakiness is due to areas of turbid alkali feldspar and quartz which seem to be associated with a small vein of massive iron ore composed of a granular aggregate of magnetite which in reflected light is seen to contain thin exsolution lamellae of ilmenite.

Two other sheet rocks, 1889, 1891, collected nearby, are described in the field notes as the dominant material of this complex contact area. Both are medium grained and strongly resemble in appearance the neighbouring Skaergaard ferrodiorite rock, 1890, a factor over which confusion resulted in the field. In section both are seen to be composed essentially of plagioclase, augite, pigeonite and iron ore. Plagioclase (An_{53}) occurs in anhedral to tabular crystals, up to 2 mm. in length, and normally zoned in the outer parts. A neutral-coloured augite occurs as granular interlocking aggregates. Pigeonite ($2V_{\gamma}$ under 10°) occurs fairly abundantly in small rounded grains associated with augite and mostly altered to a characteristic yellowish green chlorite. Iron ore is present in anhedral grains, up to 1 mm. across. Interstitial to vein-like areas containing micropegmatite, quartz and a little apatite are believed to have been derived from the adjacent Skaergaard material. The rock, 1891, is cut at its edge by a small vein of granular iron ore and this passes out into an aggregate of small tabular plagioclase set in an acid matrix.

Western side of Basistoppen

Immediately below the sheet on this exposure and veining its base lies the Skaergaard hedenbergite andesinite. Tabular plagioclase compose at least seventy per cent by volume of this rock; the remainder consists of ophitic to sub-opthitic ferrohedenbergite, iron ore and a small amount of micropegmatite. Common only to the andesinite in the vicinity of the contact, examples 5145, 4338, 5137, show a contorted lineation and a whitened altered aspect. In thin section the plagioclase (An_{55}) is seen to be fractured, in part recrystallized and sometimes heavily sericitized or containing small "peg-board" areas filled with quartz and chlorite. The pyroxene forms extensive poikilitic crystals, many of which seem to have been granulated, these being much altered to green and brown hornblende. The acid mesostasis, mainly finely intergrown micropegmatite with quartz often acicular in habit, contains a little iron ore, apatite and epidote associated with late-stage chlorite. Other examples, 4337, 4336, either at the immediate contact or just below it, contain veins of massive iron ore which also penetrate the base of the sheet.

A junction between andesinite and fine-grained sheet gabbro is illustrated by a composite rock, 1900, collected either from the lower contact or from the edge of an andesinite vein just above (Pl. 6, fig. 2). Along the margin the andesinite is slightly drusy, streaked with iron ore and containing some weathered sulphide minerals. Some of the plagioclase crystals show evidence of strain and crushing. The junction is sharply defined but irregular veinlets of acid material, clearly derived from the andesinite, invade the fine-grained gabbro.

Within this latter, along parts of the margin and over a width of about 1 mm. there is a curious concentration of plagioclase (An_{55}) occurring mainly in stubby granular crystals (0.2 mm.) and also small grains of iron ore, some of which are enclosed in the outer parts of the adjacent large tabular plagioclase of the andesinite; augite is absent in these areas. Away from the margin the fine-grained gabbro is rather similar to that found on the other exposures. Some larger crystals of plagioclase and augite occur in clusters which impart a patchiness to the general texture. A single crystal (possibly a phenocryst) of olivine (ca. Fo_{36}), near the margin, has a corroded outline rimmed by a dendritic growth of iron ore.

Other fine-grained rocks, such as 1902, collected near to that just described, are essentially similar to those found on Nunatak I. By comparison the larger plagioclase crystals with cores (An_{55}) are more basic and more zoned; the groundmass plagioclase (An_{45}) has about the same composition. Pseudomorphs of orthopyroxene, as found in the analysed example, 4125, are more abundant in these latter.

These fine-grained rocks grade upwards into medium-grained rocks, such as 1897, containing plagioclase (An_{64}) and bastite pseudomorphs of orthopyroxene. An overlying rock, 1896, containing plagioclase (An_{72}), represents the base of the BGZ.

Origin of the lower border division

The complexity along the lower contacts of the sheet, especially the veining of its basal rocks by Skaergaard material, led to the original suggestion that the Skaergaard rocks were later than a raft-like inclusion; the fine-grained rocks of its lower contact were interpreted as granulites formed as a result of thermal metamorphism by the Skaergaard intrusion (WAGER and DEER, 1939, p. 200; HUGHES, 1956, p. 7). These views are no longer held for several reasons:

(1) From a recent field examination (p. 8) a dyke-like extension of the sheet was found in transgressive relation with the Skaergaard upper layered rocks on Nunatak I. In this light the relations along the lower contact, referred to above, obviously become ambiguous.

(2) Because the marginal sheet rocks are less basic than the overlying bronzite gabbro they are not its metamorphosed equivalent, nor are they likely products of some metasomatic process.

(3) Textural features of the fine-grained marginal rocks, especially the relation of microphenocrysts of plagioclase and augite to the groundmass, are better explained on the view that these rocks crystallized directly from a magma.

The present view (p. 4) with regard to the origin of the LBD rocks is based on the following argument. Some degree of chilling accounts for the transition inwards from fine-to medium-grain size. The lack of real chilling, as when a dolerite invades cold country rocks, indicates that the Skaergaard rocks were still hot at the time of the injection of the sheet magma yet cool enough to produce fine-grained rocks along the margins. The LBD is thin and transition to overlying zones is apparently abrupt indicating that the initial rapid heat loss was confined to the outer skin of the sheet; thereafter crystallization proceeded more slowly and the effects of the sinking crystals became apparent.

The complex veining of the basal sheet rocks by Skaergaard material is considered to be the result of rheomorphism of the latter by heat from the sheet. The Skaergaard rocks in contact with the sheet were nearly the last to crystallize (low temperature end-members) and would therefore have remelted again most readily. In the larger veins on the west side of Basistoppen the overall composition is similar to the underlying hedenbergite andesinite (UBG_β) but the component minerals are sometimes altered or partially recrystallized. Smaller veins on

Nunatak I, derived from the Skaergaard pyroxene ferrodiorite (UBG_{γ}), apparently formed by partial fusion and squeezing out of the more acid matrix. The massive iron ore, occurring generally as terminations or as marginal segregations of both types of veins, was probably concentrated by the same process but was perhaps in part derived from a hydrous iron-rich residue, such as that suggested by SHAND (1947) as an explanation of the origin of intrusive magnetite.

PRESUMED ACID INCLUSIONS

Certain indefinite bands of leucocratic rocks referred to earlier (p. 16), are thought to be hybridized inclusions of acid material incorporated from the metamorphic complex. The two examples, 1894, 3014, from near the summit of Basistoppen, are described first: both rocks are moderately leucocratic, medium grained and contain small druses filled with quartz and a brown micaceous mineral, probably stilpnomelane. The mafic minerals, notably small acicular pyroxenes up to 1 cm. long, are unevenly distributed in 1894, promoting a slight streaky appearance, whereas in 3014 the distribution is more even. Under the microscope, the rock, 1894, is found to be composed mainly of plagioclase, augite, micropegmatite and iron ore. The plagioclase (An_{50}) occurs in irregular tablets, a few up to 1 cm. in length; these are strongly zoned on the margins and largely sericitized. The augite has a subhedral prismatic to granular habit; it is of neutral colour, finely schillerized and partially altered to brown hornblende. A few small altered grains of another pyroxene, probably pigeonite, are also found. Iron ore is found abundantly in small irregular grains. Coarse micropegmatite, free quartz and chlorite form the groundmass. The rock, 3014, has much the same assemblage but is richer in micropegmatite and contains, in addition, considerable calcite and accessory zircon, apatite and epidote.

The highest rock in position on Kobbernunatak, 4486, is remarkably similar in appearance to those just described from Basistoppen. In section, the plagioclase (ca. An_{35}) is seen as spongy, much sericitized, lath-shaped crystals, some of which appear perthitic. The augite is acicular in habit, heavily schillerized and, in places, marginally altered to brown hornblende and chlorite. The groundmass is predominantly granophyric, in parts microgranite. The intergrown quartz occurs mainly in fine-acicular units (presumably paramorphs of tridymite) producing a "criss-cross" texture (cf. Wager, Weedon, and Vincent, 1956). A little iron ore, partially altered to leucoxene is present. Apatite, in skeletal needles up 1 cm. length, epidote and zircon are also present. From its position above the pyroxene ferrodiorite it might be argued that this rock represents a final differentiate of the sheet. The mineralogy and chemistry (tables 4 and 5) suggest, however, that the rock is a hybrid and related to those rocks lower in the sheet whose origins are also in doubt.

Rocks, which can with more certainty be considered as remelts of acid gneiss or hybrids of the gabbro-picrite and bronzite gabbro, occur near the Basistoppen col as coarse "cumulose" patches or in the dyke-like masses (fig. 13) referred to earlier. One example, 1873, will be described. This rock contains remarkable bladed prismatic augite crystals, some at least 10 cm. long, growing roughly at right angles to the junction with the enclosing bronzite gabbro. These are set in a medium-grained groundmass which resembles the inclusions of refused gneiss in the Skaergaard marginal border group (Wager and Deer, 1939, p. 187). Small pockets of stilpnomelane are common. In section plagioclase, like augite, is seen in long prismatic crystals, heavily sericitized and sometimes including many small apatites. The groundmass is mainly a microgranitic aggregate of quartz and turbed alkali feldspar. Some large crystals of quartz show resorption. Sphene is a fairly abundant accessory.

Fig. 13. Dyke-like mass within gabbro-picrite of hybridized gneiss containing bladed augite crystals. About 100 m. S. of Basistoppen col at base of face seen in fig. 6.

VARIATION AND TRENDS IN CHEMICAL COMPOSITION

Chemical data

Chemical analyses of four sheet rocks are given in table 3. Analysis I of a fine-grained border rock is believed to give approximately the composition of the initial sheet magma and is discussed later, p. 54. The three other analyses, arranged in order of height, include an example of gabbro-picrite, bronzite gabbro, and pyroxene ferrodiorite respectively; unfortunately no example of pigeonite gabbro has been fully analysed. Partial analyses, by wet chemical or spectrophotometric methods of seven other sheet rocks, are also available (table 4). The optical spectrographic determinations, also given in the table, are considered to be only approximate (± 15%). Although the analyses are few there are sufficient data to show the general differentiation trends in the sheet and to allow for some discussion.

Table 3a gives comparisons for the analysed gabbro-picrite, bronzite gabbro and pyroxene ferrodiorite. The sheet gabbro-picrite is seen to have a composition quite similar to the gabbro-picrite of Skaergaard intrusion (Wager and Deer, 1939). Rocks with compositions comparable to the sheet bronzite gabbro are found in the Kærven intrusion, East Greenland (Ojha, 1960) and the Stillwater Complex, Montana (Hess, 1960). The pyroxene ferrodiorite of the sheet is remarkably similar in composition to a newly analysed pyroxene ferrodiorite belonging to the Skaergaard upper border group; a further comparison is made with an example from the uppermost Skaergaard layered series. The extensive alteration of certain mafic minerals in the sheet rocks is reflected in the relatively high water content of the rocks analysed but apart from this the alteration has probably not greatly effected the overall composition (cf. Oliver, 1951).

Optical spectrographic analyses for thirteen trace elements in the analysed and partially analysed rocks are given in table 5. These analyses were carried out by a D. C. arc method employing the natural silicate standards, G-1, W-1 and internal standardization for each sample[1]).

[1]) Details of the spectrographic method may be obtained from the writer's D. Phil. Thesis, Radcliffe Science Library, Oxford, 1961.

Table 3. Analyses of sheet rocks

	I	II	III	IV
SiO_2	53.43	43.00	51.32	49.17
Al_2O_3	15.86	8.16	15.82	11.33
Fe_2O_3	1.00	1.73	1.52	4.19
FeO	10.16	11.32	5.86	17.28
MgO	3.87	24.16	7.97	1.28
CaO	9.29	6.17	12.42	7.62
Na_2O	3.86	0.97	2.62	3.62
K_2O	0.29	0.49	0.30	0.81
H_2O^+	0.34	1.81 (H₂O⁺ and H₂O⁻)	1.06	1.47
H_2O^-	0.10		0.15	0.11
TiO_2	1.50	0.22	0.78	2.20
P_2O_5	0.09	N.D.	0.10	0.78
MnO	0.16	0.19	0.10	0.33
Total	99.95	99.53	100.02	100.19
Atomic ratios:				
Iron ratio $\frac{100\,(Fe''+Mn)}{Fe''+Mn+Mg}$	59.9	21.1	29.6	88.5
Albite ratio $(100)\frac{2\,Na}{Na+Al-K}$	57.8	35.5	43.5	72.7

C. I. P. W. Norms

	I		II		III		IV	
Q		1.98		—		—		1.86
Or	1.67	59.17	2.78	27.56	1.67	54.26	5.00	47.34
Ab	32.50		8.38		22.01		30.39	
An	25.00		16.40		30.58		11.95	
Di Wo	8.12	16.70	5.92	11.34	12.64	24.37	9.05	18.99
Di En	3.30		4.10		8.30		1.10	
Di Fs	5.28		1.32		3.43		8.84	
Hy En	6.40	16.70	3.80	5.12	10.80	15.29	2.10	18.46
Hy Fs	10.30		1.32		4.49		16.36	
Ol Fo	—		36.40	49.25	0.56	0.76	—	
Ol Fa	—		12.85		0.20		—	
Mt		1.39		2.55		2.32		6.03
Ilm		2.89		0.46		1.52		4.27
Ap		0.34		—		0.34		1.68
Water		0.44		1.81		1.21		1.58

Key to analysed rocks (Table 3).

I. Fine-grained marginal gabbro, 4125. S. side of Nunatak I. (Anal. E. A. VINCENT and B. A. COLLETT.).

II. Gabbro-picrite, 1754. Col, head of Basisgletscher. (Anal. H. HEGEDUS and J. ESSON.)

III. Bronzite gabbro, 5173. W. end of Skillenunatak. 30 m. above sea-level. (Anal. E. A. VINCENT and B. A. COLLETT).

IV. Pyroxene ferrodiorite, 5178. Near top of Skillenunatak, above 400 m. above sea-level. (Anal. E. A. VINCENT and B. A. COLLETT).

Table 3a. Certain analysed sheet rocks with comparisons

	II	A	III	B	C	IV	D	E
SiO_2	43.00	41.27	51.32	53.18	51.12	49.17	48.90	48.27
Al_2O_3	8.16	8.71	15.82	15.69	16.34	11.23	11.97	8.58
Fe_2O_3	1.73	2.69	1.53	1.81	1.09	41.19	4.12	4.06
FeO	11.32	10.52	5.86	6.20	5.84	17.28	17.18	22.89
MgO	24.16	27.09	7.97	7.50	8.49	1.28	1.46	1.21
CaO	6.17	6.59	12.42	10.71	13.63	7.62	8.24	7.42
Na_2O	0.97	0.69	2.62	2.78	2.18	3.62	3.18	2.65
K_2O	0.49	0.13	0.30	0.39	0.06	0.81	0.62	0.34
H_2O+ ...	1.81 (})	0.87	1.06	0.22	0.49	1.47	0.67	1.13
H_2O^- ...		0.07	0.15	0.19	0.07	0.11	0.09	0.37
TiO_2.....	0.22	1.54	0.78	0.68	0.19	2.20	2.40	2.20
P_2O_5	N.D.	0.02	0.10	0.07	0.03	0.78	0.81	0.65
MnO	0.19	0.16	0.10	0.13	0.15	0.33	0.33	0.26
Total: ...	99.53	100.35	100.02	99.55	99.68	100.19	100.06	100.03
Iron Ratio:	21.1	18.0	29.6	32.0	29.6	88.5	87.1	91.5
Albite Ratio:	35.5	24.1	43.5	45.8	36.5	72.7	63.4	64.2

II. Gabbro-picrite, 1754. Table 3.
A. Gabbro-picrite, 1682. Northern border, Skaergaard intrusion. (Anal. W. A. DEER) WAGER and DEER, 1939, p. 162, table 23.
III. Bronzite gabbro, 5173. Table 3.
B. Hypersthene gabbro, 4817. Kærven intrusion, Kangerdlugssuaq, E. Greenland. (Anal. D. N. OJHA). OJHA, 1960.
C. Hypersthene gabbro, EB 40. Upper gabbro zone, Stillwater complex, Montana. (Anal. A. H. PHILLIPS). HESS, 1960, p. 94, table 29.
IV. Pyroxene ferrodiorite, 5178. Table 3.
D. Pyroxene ferrodiorite, 4122. Upper border group of Skaergaard intrusion. (Anal. E. A. VINCENT and B. A. COLLETT) Unpublished analysis.
E. Ferrogabbro, 1881. Top of layered series, Skaergaard intrusion. (Anal. W. A. DEER). WAGER and DEER, 1939, p. 106, table 14.

Variation of the major oxides with height

From the petrographic and mineralogical data already given it is evident that the sheet sequence, with the possible exception of the highest rocks which have not been reached, formed mainly by deposition of the cumulus minerals on the floor. Thus the structural height in the sequence, so far it is known, is a useful measure of the stage of fractionation. The weight percentages of each major oxide for the analysed and partially analysed rocks (tables 3 and 4) are plotted against

Table 4. Analysed and partially analysed sheet rocks

	1	2	3	4	5	6	7	8	9	10	11
SiO_2 ..	53.43	43.00	51.32	50.71	—	50.83	51.26	49.17	—	—	—
Al_2O_3 .	15.86	8.16	15.82	—	—	—	—	11.23	—	—	—
Fe_2O_3 .	1.00	1.73	1.52	0.90	3.96	4.25	0.94	4.19			
FeO ..	10.16	11.32	5.86	8.79	11.27	9.63	10.76	17.28	(22.8)	(10.7)	(5.2)
MgO .	3.87	24.16	7.97	6.77	(4.4)	3.07	(2.1)	1.28	(0.5)	(2.1)	(0.5)
CaO ..	9.29	6.17	12.42	12.08	(8.4)	7.11	6.84	7.62	(7.4)	(4.9)	(1.7)
Na_2O .	3.86	0.97	2.62	2.31	3.08	3.91	4.19	3.62	3.69	3.41	6.71
K_2O ..	0.29	0.49	0.30	0.29	0.56	0.56	0.90	0.81	0.91	2.61	0.22
H_2O^+	0.34	1.81	1.06	—	—	—	—	1.47	—	—	—
H_2O^-	0.10	0.22 (H_2O^- + TiO_2)	0.15	—	—	—	—	0.11	—	—	—
TiO_2 ..	1.50		0.78	0.85	3.52	3.04	2.37	2.20	(2.4)	(1.7)	(0.3)
P_2O_5 .	0.09	—	0.10	—	—	—	—	0.78		—	—
MnO .	0.16	0.19	0.10	0.18	0.18	0.19	0.13	0.33	(0.3)	(0.17)	(0.10)

Notes: No. 1. gives approximate composition of initial magma.
Nos. 2–9 are representative of sheet sequence in increasing order of height.
Nos. 10, 11 are acid rocks associated with pyroxene ferrodiorite.

Figures in ( ) are approximate values by optical spectrographic method. Total iron by this method is expressed as FeO. Excluding analysed rocks, alkalis and spectrographic determinations by J. A. V. Douglas. Other values: (4) K. Brooks (5, 6) J. Esson (7) J. Bartle.

Table 5. Certain trace elements in the analysed and partially analysed sheet rocks (in ppm)

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
Ga ...	35	16	25	23	34	35	36	45	30	30	33
Cr....	35	1500	180	68	10	—	—	—	—	8	—
V	150	83	160	130	215	42	16	23	?	?	9
Li....	10	5	4	5	10	8	11	17	14	17	7
Ni ...	45	770	100	94	(3)	(2)	(2)	(3)	(3)	15	(3)
Co ...	35	150	43	34	65	30	23	15	14	22	10
Cu ...	80	170	175	190	80	25	35	45	25	90	12
Sc....	24	15	12	35	33	24	22	63	64	10	12
Zr....	135	38	95	80	215	195	260	280	420	490	915
La ...	—	—	—	—	—	(30)	50	62	70	105	50
Sr....	300	140	205	205	320	325	320	260	255	230	145
Ba ...	280	105	145	145	220	310	330	310	280	450	130
Rb ...	—	16	10	(5)	10	12	18	16	28	68	(5)

Analyst — J. A. V. Douglas.

Note: ( ) indicates figures near limits of sensivity; — below sensitivity; ? value unknown.

Key to Tables 4 and 5.

	Number	Height[1])	Description	Locality
1.	4125	—	Fine-grained marginal gabbro	S. side of Nunatak I
2.	1754	5	Gabbro-picrite. (Olivine, chrome-spinel cumulate)	Col, head of Basisgletscher.
3.	5173	50	Bronzite gabbro. (Plagioclase, augite, orthopyroxene cumulate)	W. end of Skillenunatak.
4.	5174	110	Same	S. side of Skillenunatak.
5.	5175	200	Pigeonite gabbro. (Plagioclase, augite, pigeonite, iron ore, cumulate)	S. side of Skillenunatak.
6.	5176	260	Same	S. side of Skillenunatak.
7.	5177	280	Pyroxene ferrodiorite. (Plagioclase, augite, iron-olivine, iron ore, apatite cumulate)	S. side of Skillenunatak.
8.	5178	310	Same	Near top of Skillenunatak.
9.	4487	390	Same	Crest of Kobbernunatak.
10.	4486	395	Acid granophyre, probably hybridized inclusion	Crest of Kobbernunatak.
11.	4480	—	Small transgressive acid vein in pyroxene ferrodiorite	Crest of Kobbernunatak.

[1]) Estimated structural heights in metres are given above base of sheet.

the approximate structural height in fig. 14. The following are brief comments on their variation:

SiO_2 The data are incomplete but the variation is slight. A slight drop is shown in the PFDZ due to a decrease in the amount of plagioclase. Part of this effect is offset by a general increase with height in the amount of quartz and micropegmatite.

Al_2O_3 Again the data are scarce. A decrease shown in the PFDZ reflects the smaller amount of plagioclase contained in these rocks.

Fe_2O_3 The amount is largely dependent upon the proportion of magnetite; thus an abrupt increase is shown at the base of the PGZ where magnetite first enters as an abundant cumulus phase.

FeO A sharp increase is also expected, as for ferric iron, where magnetite and also ilmenite first appear as cumulus phases. Apart from this factor, there is an overall enrichment as in the Skaergaard layered series.

MgO The steady decrease reflects the extreme fractionation of the ferromagnesian minerals.

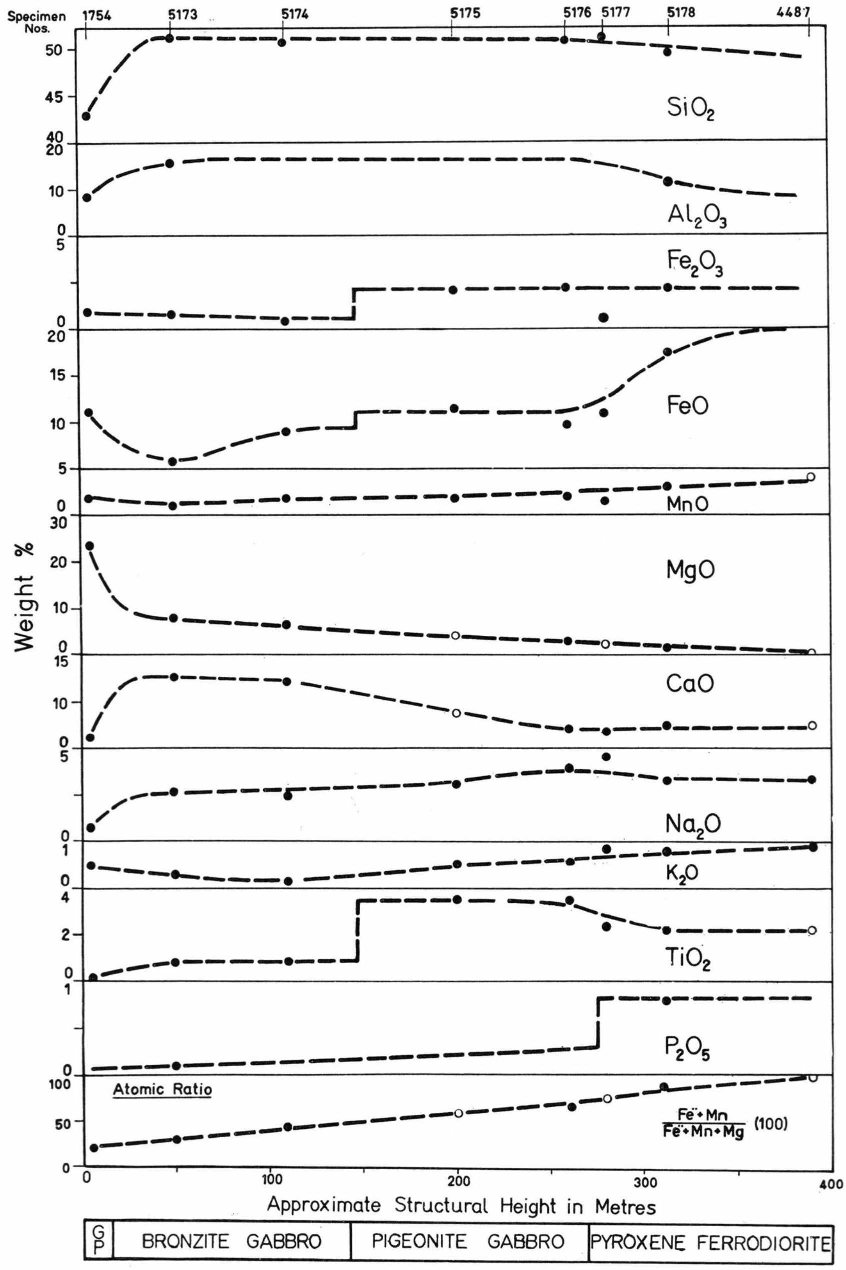

Fig. 14. Variation of the major oxides in the sheet rocks with approximate structural height. Open circles indicate approximate values by spectrographic method.

CaO A gradual decrease in amount is accounted for by impoverishment of the anorthite molecule in the plagioclase linked with a decrease in the modal proportion of plagioclase.

Na_2O The albite content of the plagioclase increases, yet an overall increase in the amount of soda is partially offset by the decrease in the amount of plagioclase.

K_2O Fluctuations in amount correspond to the irregular variation in the proportion of micropegmatite. There is, however, an overall increase with height.

TiO_2 An abrupt increase is shown at the base of the PGZ where ilmenite and titaneferous magnetite first appear as cumulus phases.

P_2O_5 The data are insufficient but a sudden jump in the amount is shown as the base of the PFDZ where apatite first appears as an abundant cumulus phase.

MnO The variation is similar to ferrous iron and shows greatest enrichment in the upper PFDZ.

Variation of certain trace elements with height

The variation with height of thirteen trace elements in the sheet rocks (table 5), illustrated in fig. 15, follows the excepted geochemical behaviour (Goldschmidt, 1954, Ringwood, 1955) and parallels the variation displayed by the Skaergaard rocks (Wager and Mitchell, 1951). Brief comments for each element determined are given in the following:

Ga Following aluminium the content is thus dependent largely on the amount of plagioclase present. There is evidently slight enrichment with fractionation.

Cr A rapid decrease above the gabbro-picrite (> 1500 ppm) to below sensivity in the PGZ indicates that the magma was rapidly depleted in chromium by its early removal in chromite and the ferromagnesian minerals, essentially augite.

V Most of the vanadium was apparently removed from the magma in the early magnetite. The maximum content (ca. 225 ppm) is thus reached in the PGZ where magnetite appears as a cumulus phase; thereafter the amount drops off rapidly in the PFDZ (< 20 ppm).

Li An increase (5–20 ppm) occurs with fractionation.

Ni Mostly concentrated in the GPZ (770 ppm) and to a lesser extent in the lower BGZ (100 ppm) the amount thereafter drops to the

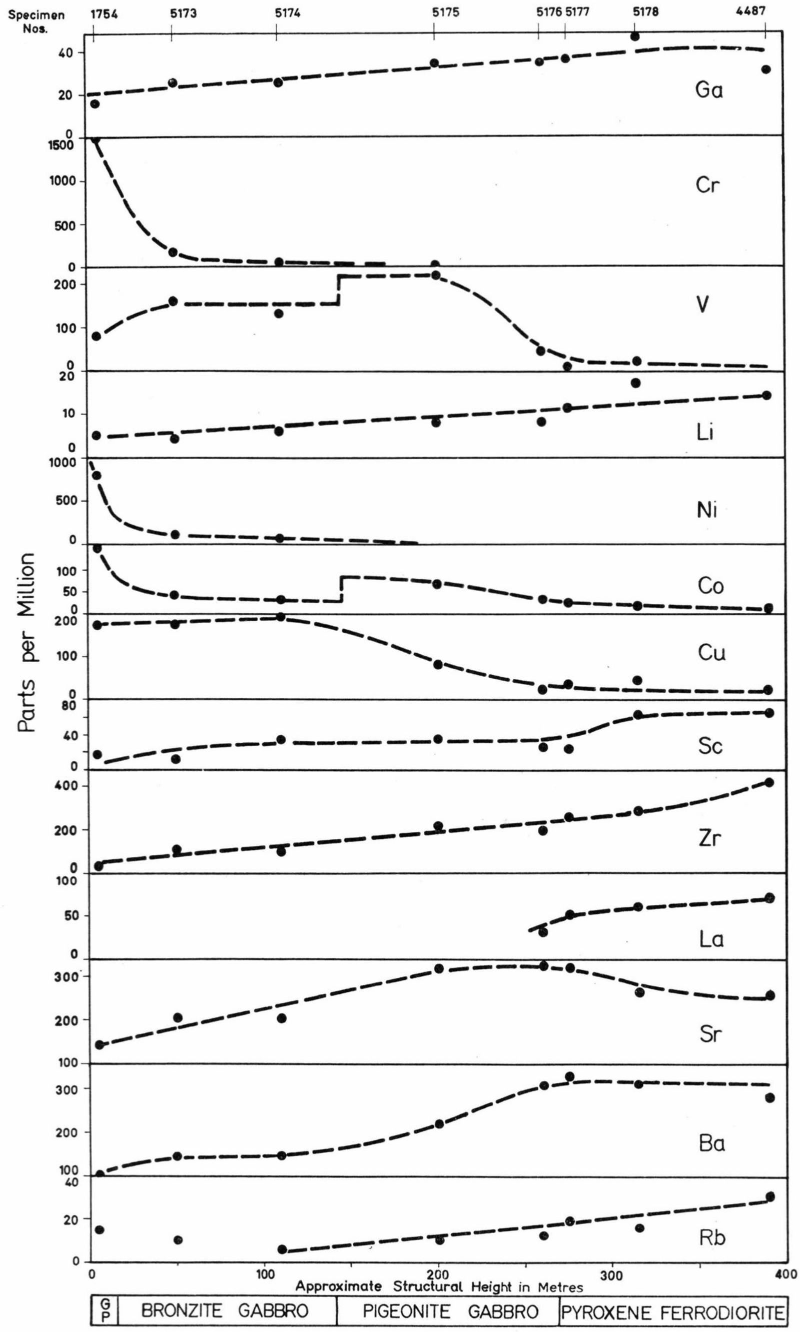

Fig. 15. Variation of certain trace elements in the sheet rocks with approximate structural height.

limits of sensitivity (< 5 ppm). The magma evidently became depleted in nickel by its early removal in the olivine and the pyroxene where it is camouflaged largely by ferrous iron (Ringwood, 1955).

Co Apparently slightly less abundant than nickel in the initial sheet magma, cobalt is largely concentrated in the GPZ (150 ppm), presumably in the olivine. A rise occurs in the PGZ (50 ppm), like vanadium, in sympathy with the appearance of magnetite as a cumulus phase. After this stage the amount drops in the PFDZ (15 ppm). Thus the Co/Ni ratio, initially low, must rise to a maximum in the PGZ and decline in the PFDZ.

Cu The higher copper content of the lower rocks (180 ppm) is confirmed by the presence of minute specks of chalcopyrite (p. 34). The initial magma seems to have been steadily depleted in copper by its removal in this early sulphide.

Sc The amount only increases appreciably in the PFDZ (60 ppm). Scandium is expected to follow ferrous iron and is presumably contained mainly in the later pyroxene (Wager and Mitchell, 1951, p. 192).

Zr A progressive increase occurs with height and fractionation (40 to 500 ppm). Zircon is only seen in the small late-stage acid veins (900 ppm) in the PFDZ.

La The amount rises above sensitivity (30 ppm) in the PFDZ coinciding with the coming-in of apatite as a cumulus phase. Lanthanum is believed to replace calcium in apatite and less so in the pyroxene (Wager and Mitchell, 1951, p. 194).

Sr Fluctuations in amount seem to bear relation to the variation in the proportion of plagioclase and alkali feldspar in the upper rocks. Apparently strontium, as predicted, is substituting for either calcium or potassium.

Ba The content increases up to the PGZ and remains thereafter mainly constant. This differs from the Skaergaard intrusion where it continues to increase.

Rb Following potassium an overall increase occurs with fractionation (10–30 ppm). The rubidium content of the gabbro-picrite (16 ppm) is unexpectedly high but it is possibly explained by the small amount of biotite present.

Composition of the initial sheet magma and certain successive residual liquids

The composition of an initial magma is ideally obtained from a chilled marginal facies. Unfortunately in the case of the sheet the complicated contact relations with the underlying Skaergaard rocks and the hetero-

Table 6. Estimated average rock compositions of the sheet zones from which are calculated the initial magma and two successive residual magmas.

Zones	*Rocks*				*Liquids*		
	GPZ	BGZ	PGZ	PFDZ	1.	2.	3.
% Total ...	(2.5)	(32.5)	(32.5)	(32.5)			
SiO_2	44.0	51.0	50.5	49.5	50.0	50.0	49.5
Al_2O_3	10.0	16.0	15.0	12.0	14.5	13.5	12.0
Fe_2O_3	1.7	1.3	4.0	4.0	3.0	4.0	4.0
FeO	11.0	8.0	10.5	16.5	11.7	13.5	16.5
MgO	22.0	7.0	3.5	1.0	4.3	2.2	1.0
CaO	7.5	12.0	8.0	7.5	9.0	7.8	7.5
Na_2O	1.5	2.5	3.5	3.7	3.2	3.6	3.7
K_2O	0.45	0.3	0.6	0.9	0.6	0.8	0.9
TiO_2	0.22	0.9	3.0	2.5	2.1	2.8	2.5
P_2O_5	—	0.15	0.2	0.8	0.4	0.5	0.8
MnO	0.15	0.15	0.2	0.3	0.2	0.3	0.3

Note: Liquid (1) is average of rocks, i.e. the initial sheet and to be compared with the fine-grained marginal gabbro, 4125, (Table 3).
(2) Residual sheet magma after formation of GPZ and BGZ.
(3) Residual sheet magma after formation of PGZ; this equals average composition PFDZ.

geneity of the border rocks themselves make it difficult to select material which can be regarded with much certainty as representative of the initial sheet magma. A fine-grained rock, 4125, (p. 28) from the contact on Nunatak I was, however, selected as the best approximation to an uncontaminated chilled facies; the analysis is given in table 3.

The composition of the initial sheet magma has also been estimated by summing the approximate overall compositions of each zone (table 6) on the assumption that their relative volumes are proportional to the thicknesses shown in fig. 14. Since the relative volumes are not known accurately and the chemical data are scarce, the composition obtained by this method must be considered only as a rough approximation. Comparison between the estimated composition and the analysed border rock, 4125, shows, despite the limitations, an essential degree of similarity. The analysed border rock, 4125, is obviously deficient in K_2O and P_2O_5 and therefore cannot represent the initial sheet magma for these oxides. Differences in the amount of the other oxides, such as SiO_2, Al_2O_3, Fe_2O_3, FeO, cannot be evaluated with the data at present available.

Of significance is the relatively low MgO content in both the analysed rock, 4125, and the estimated initial amount. At the start of cooling the sheet magma was able to precipitate an olivine of Fo_{73}

(wt. $^0/_0$); the normative olivine composition of 4125 is Fo_{36} (converting hypersthene in the norm to olivine). According to the experimental evidence (Bowen and Schairer, 1935) a liquid of this composition would initially crystallize olivine about Fo_{70}. A further test may be made with the normative plagioclase composition, An_{44}, which as a liquid would be capable of precipitating a plagioclase of about An_{76} (Bowen, 1913); the earliest cumulus plagioclase in the sheet is An_{72} (wt. $^0/_0$). These relations thus give further reason to believe that a magma having a composition approximately that of the analysed border rock, could by extreme differentiation be parent to the sheet sequence.

It is helpful when considering next the stages and trend of fractionation to calculate the composition of the residual sheet magma at certain arbitrary stages of fractionation, being taken for the purpose at the end bronzite gabbro (35$^0/_0$ solidified) and pigeonite gabbro (68$^0/_0$ solidified) stages respectively. The composition of the residual magma (table 6) at the end of the bronzite gabbro stage was thus about equal to the average of the overall compositions of the PGZ and PFDZ, and at the end of the pigeonite gabbro stage it was about equal to the overall composition of the PFDZ. It is again emphasized that these compositions are only considered as rough approximations.

Trend of differentiation

The stages of fractionation in the sheet are best shown by plotting the albite $\left(\frac{Ab}{Ab + An}\right)$ and iron $\left(\frac{Fe'' + Mn}{Fe'' + Mn + Mg}\right)$ ratios (cf. Wager, 1956). A plot of these ratios for the four analysed rocks, the estimated initial sheet magma and the two successive residual liquids is given in fig. 16 with the revised Skaergaard liquid trend (Wager, 1960, fig. 9, p. 392) shown for comparison. These ratios for the fine-grained border rock, i.e. the "chill", and the estimated initial sheet magma are in fair agreement and thus it appears that the initial sheet magma must have been at a fractionation stage corresponding to about the middle of the late stage-α as defined by Wager (1956, fig. 7). The two approximate successive sheet liquids define a trend roughly parallel to that of the Skaergaard liquid but their albite ratios are correspondingly higher. In the later stages during the crystallization of the pyroxene ferrodiorite the trend cannot be properly evaluated but probably turns upwards, as shown, as the iron ratio approaches its maximum value. Tie-lines are shown between the approximate liquids and the three other analysed rocks, which as crystal fractions are richer in the more refractory components than the liquids from which they formed.

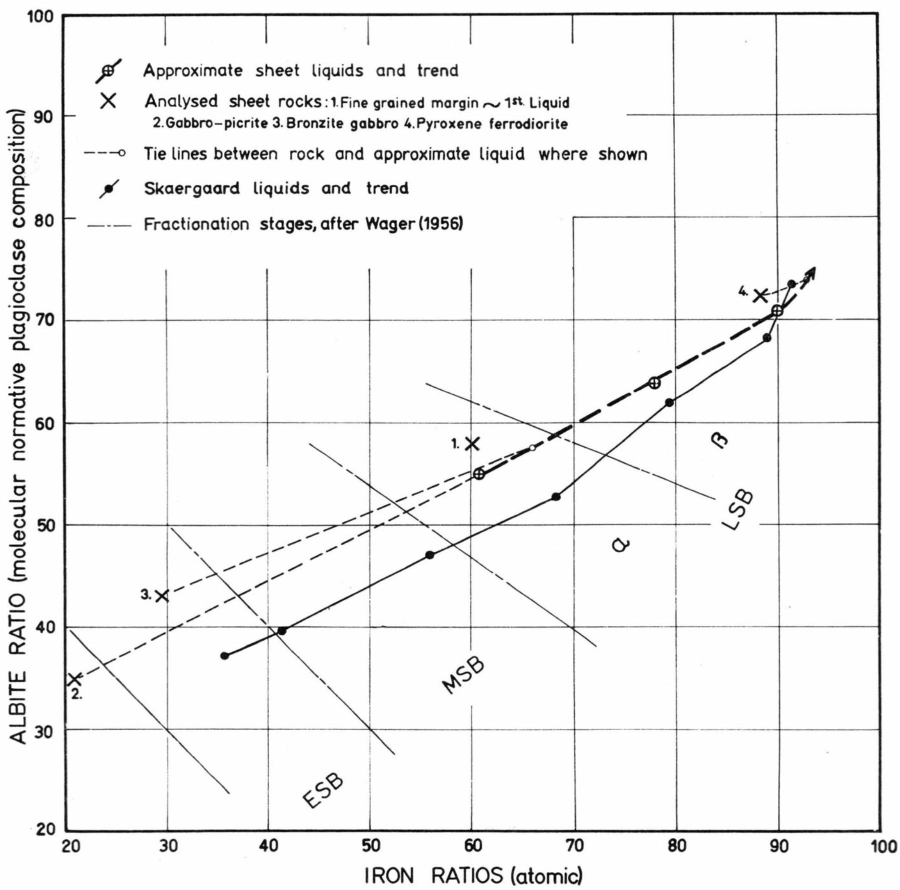

Fig. 16. Albite and iron ratios for the analysed rocks and approximate liquid trend of the sheet compared with the Skaergaard liquid trend.

The essential trend in composition shown by the analysed and partially analysed sheet rocks and the estimated liquids is well seen in a triangular diagram (fig. 17) with the apices representing the atomic proportions of Mg, Fe'' + Mn, Na + K (cf. Wager, 1960, p. 394, fig. 10). The Skaergaard liquid trend is again given for comparison. The fractionation trend in the sheet is essentially towards enrichment in ferrous iron but the estimated successive liquids and rocks, the latter with a few exceptions, are richer in the Na + K component than any corresponding Skaergaard liquid, which in fact reflects the higher proportion of plagioclase in the sheet as a whole. Since the uppermost sheet rocks have never been reached the trend shown, apart from being slightly

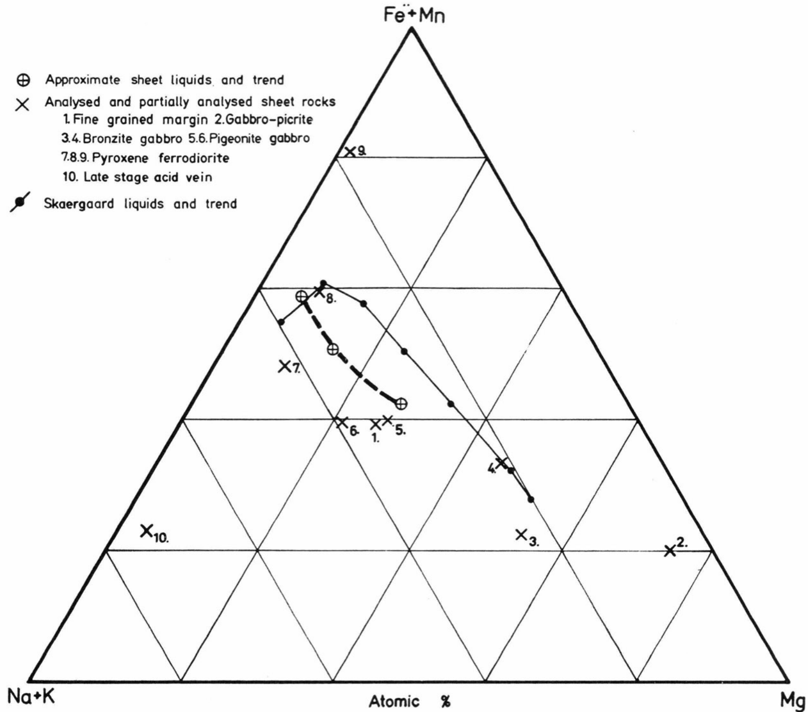

Fig. 17. Triangular diagram showing the essential trend in composition of the sheet rocks and approximate liquids compared with the Skaergaard liquid trend.

incorrect on this account, is incomplete. Its final direction must, however, be toward Na+K enrichment, and this is indicated by the composition of the partially analysed acid vein from within the pyroxene ferrodiorite which is considered to have been derived by "filter-press" action but the amount of this final fraction can only have been relatively small.

EMPLACEMENT AND DIFFERENTIATION OF THE SHEET

Probable conditions existing at the time of emplacement of the sheet magma

Detailed consideration of the relationships at the lower contact of the Basistoppen sheet has led to the view that the sheet is the result of a single injection of basic magma into the upper part of the Skaergaard intrusion (p. 42). The fine-grained marginal sheet rocks are believed to have formed as the result of partial chilling of the initial magma against the Skaergaard rocks which themselves were rheomorphosed to vein the base of the sheet. A lack of true chilling and the degree to which the underlying Skaergaard material is intermingled with border rocks of the sheet suggests that the sheet magma intruded just after the last Skaergaard rocks had solidified and while they were still hot. Significantly, the sheet magma cuts through a part of the Skaergaard complex which was a late part to solidify. Searching for the cause of the intrusion it is suggested that it took place in connection with the early stages of the powerful crustal flexuring which eventually tipped the whole Skaergaard intrusion 30° to the south (Wager and Deer, 1938, 1939).

Origin of the initial magma of the sheet

Assuming that the fine-grained marginal rocks preserve the character of the initial sheet magma, their texture and mineralogy suggest that it was probably almost completely liquid at the time of intrusion except for an apparently small amount of material which is believed to have been derived from the metamorphic complex and is now seen as acid inclusions at various levels in the sheet (p. 44). The influence of this material on the course of crystallization was probably small, except possibly in the final stages.

From this time sequence it appears that the sheet magma was brought from some source beneath the Skaergaard intrusion. Comparison of the composition and mineralogy of their "chilled" facies indicates that the initial sheet magma was less basic or at a more advanced stage of fractionation than the initial Skaergaard magma; nor does it lie on the Skaergaard liquid trend (fig. 16).

Sequence of crystallization

From the petrography and mineralogy of the cryptically layered sheet it is possible to reconstruct the general course of crystallization of the sheet magma, assuming that there was a single period of injection followed by the gradual accumulation of the various sinking crystal phases.

At the start of cooling the sheet magma deposited olivine (Fo_{83}) and a chrome-spinel; the intercumulus phases at this stage were augite, plagioclase and later, orthopyroxene. Within a short interval diopsidic augite and orthopyroxene (ca. En_{75}) appeared as cumulus phases; olivine diminished in amount. These phases compose the gabbro-picrite layer.

After an interval of time represented by the gabbro-picrite, olivine ceased to crystallize, its disappearance being analogous to the sequence of phases separating in the course of strong fractionation of certain liquids in the system MgO-FeO-SiO_2 (BOWEN and SCHAIRER, 1935). Augite continued as an abundant cumulus phase, accumulating in pyroxene rich bands. Soon plagioclase (An_{73}) joined as a cumulus phase. In the formation of the overlying sequence augite and plagioclase continued to separate as cumulus phases in fairly constant proportion and were progressively enriched in their low temperature end-members (ca. $Ca_{42}\,Mg_{42}\,Fe_{16}$ to $Ca_{42}\,Mg_1\,Fe_{57}$; An_{73} to An_{40}). Orthopyroxene, having been a cumulus mineral at the top of gabbro-picrite, is poikilitic in many of the lower bronzite gabbro rocks, indicating that in these it is an intercumulus mineral again. Above it seems to have been a cumulus phase until, with fractionation, the temperature conditions were reached where pigeonite crystallized instead.

At roughly the horizon of pigeonite development the cumulus iron ores first occur and these persist to the highest known part of the sequence. On further fractionation the magma reached the condition where pigeonite ceased to crystallize (the two pyroxene boundary). Thereafter only augite crystallized. About this stage and coinciding roughly with the initial precipitation of cumulus apatite, the residual magma moved into a field where iron-olivine crystallized, throughout the formation of the pyroxene ferrodiorite zone. Any later rocks have not been collected but they can only form a small fraction of those known.

After crystallization of the mesostasis widespread alteration of orthopyroxene, pigeonite, olivine, incipient uralitization of augite and sausuritization of the plagioclase is attributed to deuteric action by the final hydrous residues.

Factors relating to the fractionation of the sheet

The sequence upward from gabbro-picrite to pyroxene ferrodiorite is seen as resulting from particularly strong fractionation of the initial sheet magma. Most significantly early precipitation of forsteritic olivine and magnesian pyroxenes led to the rapid depletion of magnesium in the magma with the result that the ferromagnesian phases are progressively enriched in iron. Fractionation of the plagioclase led to their enrichment in sodium but the extent of these changes is less than in the ferromagnesian minerals.

Such effective fractionation is perhaps related to the cooling rate of the sheet. Earlier (p. 42) it has been suggested that the sheet magma invaded the Skaergaard intrusion while its rocks were still at elevated temperatures. Cooling in this environment must have proceeded slowly allowing more time for the growth and separation of the various cumulus phases than in a sill of comparative thickness intruding cold country rocks.

Criteria respecting the cumulate origin (WAGER et al, 1960) of the sheet rocks include, beside cryptic layering, the minor layering and feeble igneous lamination developed throughout most of the sequence (p. 14). Whether deposition of the cumulus phases took place by direct sinking or whether currents were involved (cf. WAGER and DEER, 1939; HESS, 1960) is not clear.

Various ways of completing crystallization after the accumulation of the crystal precipitate leading to differences in the rocks finally produced have been discussed in detail by WAGER and others (1960). Following their nomenclature the majority of the sheet rocks are probably best described as orthocumulates. Some degree of adcumulus growth may, however, have occurred accounting for certain textural features such as, the small degree of zoning in the large poikilitic plagioclase of the gabbro-picrite.

The sheet, although comparatively thin, is remarkable in showing the results of strong fractionation. The sequence of mineral phases shows a close analogy with the Skaergaard intrusion. The main difference is in the bronzite gabbro zone and it is possible that bronzite is a mineral of the Skaergaard hidden layered series. The pyroxene ferrodiorites of the upper part of the sheet, as already stated, resemble those of the Skaergaard upper layered series (UZc) so closely in the field that they were not previously distinguished (cf. WAGER and DEER, 1939, p. 58; HUGHES, 1956, p. 10).

The Basistoppen sheet is not very different in thickness from some of the better known dolerite sheets such as, the Palisades (WALKER, 1940), Tasmanian (EDWARDS, 1942; McDOUGALL, 1962), Dillsburg (HOTZ, 1953) and Karroo (WALKER and POLDERVAART, 1949). There are close similarities in the mineralogy between the lower and middle parts of the Basistoppen sheet and these latter, especially the Palisades sill as noted by Hughes (1956, p. 12). None of these sills, however, shows the extreme iron enrichment as displayed by the pyroxene ferrodiorite of the Basistoppen sheet. Probably particularly slow cooling of the Basistoppen sheet was the most important single factor allowing such a degree of fractionation to occur.

APPENDIX

Notes on the dyke-like extension of the sheet on Nunatak I and its possible relation to the northern macro dyke lying outside the Skaergaard intrusion

On the northern side of Nunatak I the sheet takes on a narrow dyke-like form which suggests that it may continue under Forbindelses-gletscher and connect with a macro dyke, extending from the Skaer-gaard's north-east margin (fig. 2). A small collection from the macro dyke shows that it is less fractionated than the sheet. Although they may be associated with the same injection of magma, the sheet would have cooled more slowly than the macro dyke, being enclosed in hot Skaergaard rocks, resulting in differences in the rocks produced.

Nunatak I The dyke-like extension of the sheet on this exposure is about 100 m. wide; the western contact, with rocks of the Skaergaard layered series, is nearly vertical; the eastern contact is hidden under scree. At the margin the rocks are fine grained and within half a metre they grade inwards to a gabbro containing irregular stringers of peg-matitic gabbro a few centimetres in length.

The fine-grained marginal rocks, such as 5417, are similar to those occurring along the base of the sheet on Basistoppen and on the south side of Nunatak I (pp. 36–42). Plagioclase (An_{45}) and augite are the chief constituents and accompanied by a later crystallizing sub-ophitic olivine (ca. Fo_{26}) and a small amount of iron ore. The medium-to coarse-grained gabbro away from the margins, such as 5413, 4133–35, is characterized by plagioclase (average comp. An_{60}) occurring as tablets (up to 5 mm.) and small laths (1 mm.) enclosed by augite and an ophitic texture. Other constituents consist of remarkable skeletal platy crystals of ilmenite and chloritic pseudomorphs, probably after orthopyroxene. Patches and small veins, containing quartz, micropeg-matite, chlorite and apatite, are unevenly distributed. Severe alteration of plagioclase and augite occurs in their vicinity.

Northern macro dyke The exposures extend over 3 kms. from the Skaergaard's margin; the average width is about 300 m. and at its northern and southern contacts inward dips near 80° have been observed (Wager and Deer, 1939, Map I). Contacts against the basalts and tuffs are apparently chilled but unfortunately no material was collected from these. Relations between the macro dyke and the Skaergaard have not been well established and in particular the relative age is not known. The rocks of the northern macro dyke are gabbroic. Those from its western end are fairly coarse and resemble, in hand specimen, the rocks described above from Nunatak I. They contain mainly plagioclase (average comp. An_{52}) and augite in prismatic crystals. Quartz, micropegmatite and chlorite are abundant and associated with extensive alteration of the plagioclase.

Horizontal layering has been observed on the eastern exposures and certain rocks among those collected show moderate igneous lamination. The lowest rocks stratigraphically are olivine gabbros and in the single example available, 1789, the olivine is about Fo_{70}; plagioclase (An_{64}) and augite have ophitic relationship. Rocks, 1790–93, about 300 m. above, from the eastern end of the exposure, contain bastite pseudomorphs, presumably after orthopyroxene, plagioclase (An_{59}) and prismatic augite, which refractive index tests indicate is slightly richer (ca. 4 %) in iron than that in the olivine gabbro, 1789. Some degree of cryptic variation in the macro dyke is thus apparent which has, in general, similarities to that of the Basistoppen sheet but not so extensive so far as known.

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Færdig fra trykkeriet den 15. juli 1964.

PLATES

Plate 1

1. Gabbro-picrite, 1511, Basistoppen col (p. 18). Cumulus olivine and small chrome-spinels. Intercumulus minerals: subpoikilitic orthopyroxene (Op) and augite (A), single poikilitic plagioclase crystal. Plain light. x 20.

2. Pyroxene rich band, 1749, upper S. side of Basisgletcher (p. 20). Cumulus minerals: mainly granular to prismatic augite, partially schillerized, and chrome-spinel. Intercumulus minerals: bastite pseudomorphs after orthopyroxene (Op), poikilitic plagioclase (P), in some places cloudy with decomposition. Plain light. x 20.

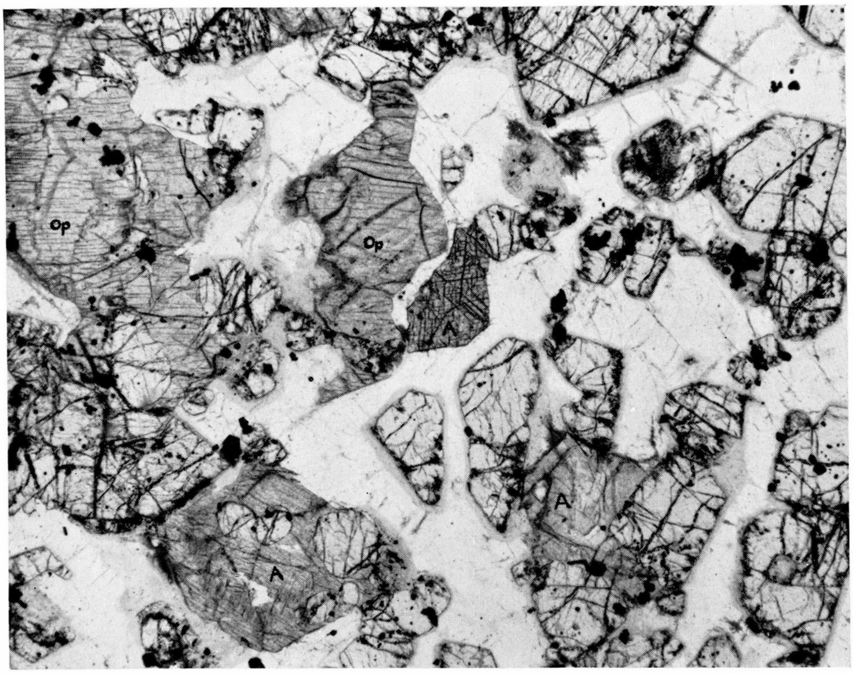

Fig. 1

Fig. 2

Plate 2

1. Low bronzite gabbro, 1214, W. side of Kobbernunatak at the base (p. 20). Poikilitic crystal of orthopyroxene (left half), partially replaced by bastite. Cumulus minerals; plagioclase, augite (mainly right). Plain light. x 20.

2. Bronzite gabbro, 3063, near base on W. side of Skillenunatak (p. 20). Single layer of cumulus bronzite crystals lying parallel to good lamination in a more feldspathic band. Plain light. x 20.

Fig. 1

Fig. 2

Plate 3

1. Bronzite gabbro, 5174, S. side of Skillenunatak, (p. 21). Cumulus minerals: plagioclase, augite and orthopyroxene. Prismatic bastite pseudomorph of orthopyroxene (lower left) is mantled by another altered phase, possibly pigeonite originally. Iron ore is intercumulus. Plain light. x 20.

2. Pigeonite gabbro, 4474, S. side of Kobbernunatak, (p. 21). Cumulus minerals: plagioclase, augite, pigeonite (e.g. just left of centre), largely altered to chlorite and iron ore. Mesostasis (mainly upper left centre) of cloudy micropegmatite and chlorite with small apatites. Plain light. x 20.

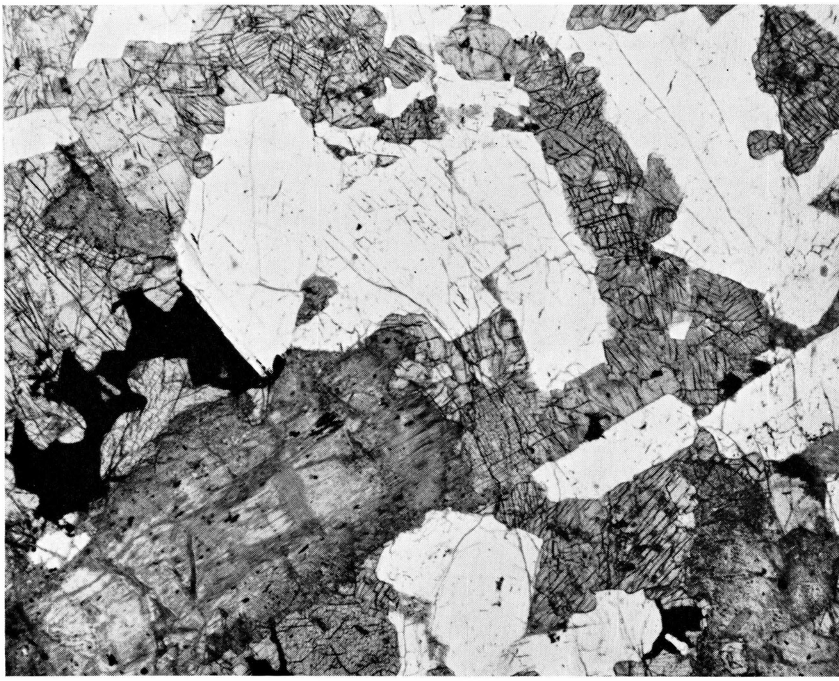

Fig. 1

Fig. 2

Plate 4

1. Pyroxene ferrodiorite, 5178, near top of Skillenunatak (p. 23). Cumulus minerals: plagioclase augite, iron-olivine (e.g. lower centre), largely altered to chlorite and iron ore, iron ore and small euhedral apatites. Interstitial micropegmatite cloudy with decomposition. Plain light. x 20.

2. Pyroxene ferrodiorite, 4487, crest of Kobbernunatak (p. 23). Cumulus minerals as above. Plagioclase is cloudy with decomposition and rimmed by alkali feldspar. Iron-olivine (e.g. centre and upper right) replaced by "iddingsite" and iron ore. Plain light. x 20.

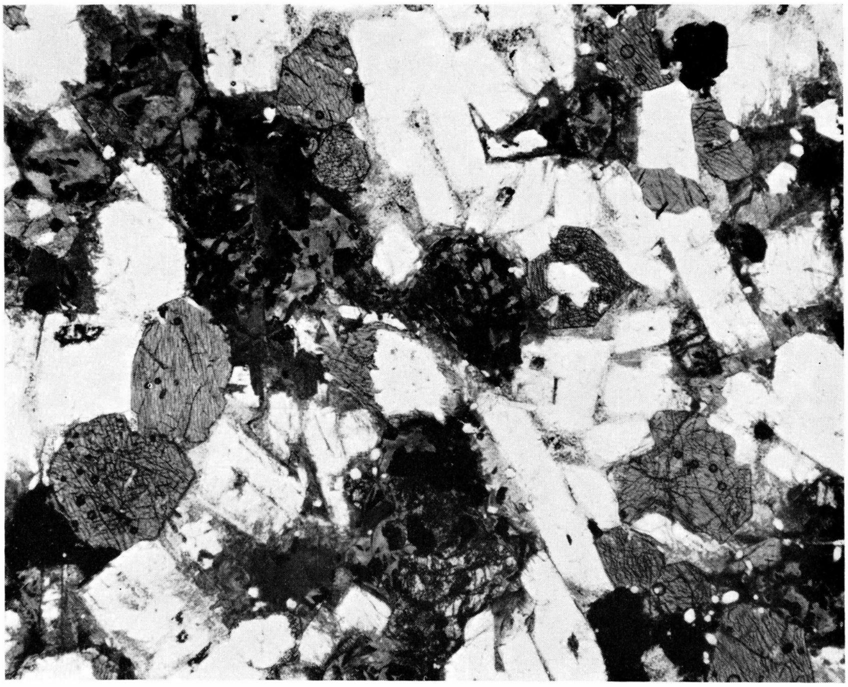

Fig. 1

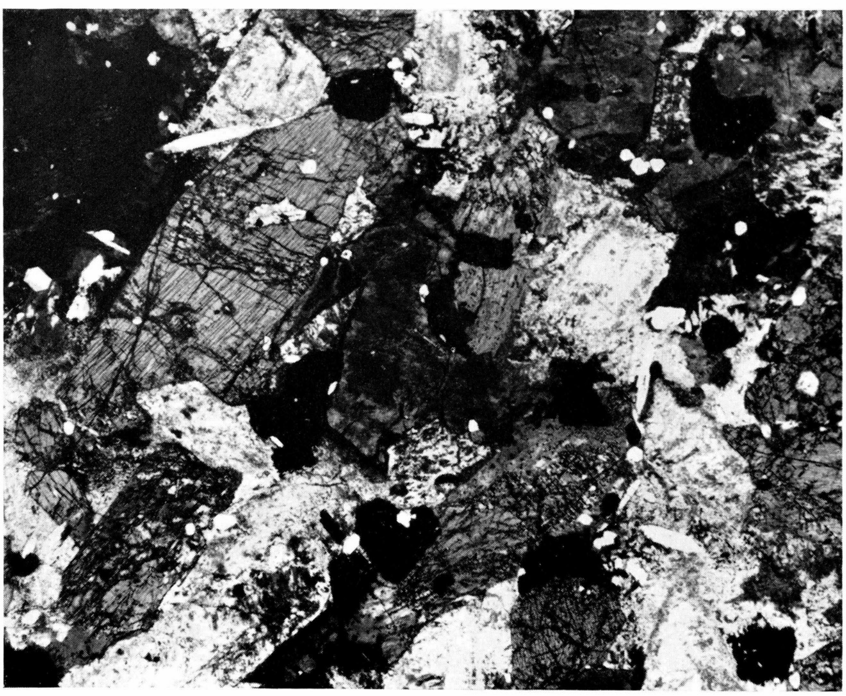

Fig. 2

Plate 5

1. Fine-grained marginal gabbro, 4125, S. side of Nunatak I (p. 36) Plagioclase augite, iron ore and pseudomorphed orthopyroxene (right centre). Note flow texture. Plain light. x 20.

2. Fine-grained marginal gabbro, 5428, as above (p. 36). Subpoikilitic olivine partially replaced by ore (central). Plain light. x 20.

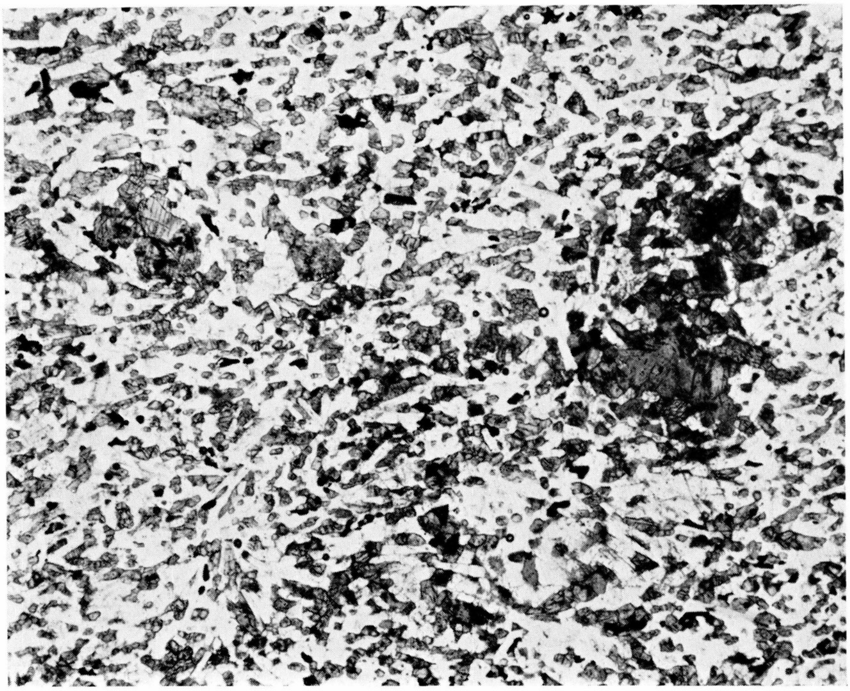

Fig. 1

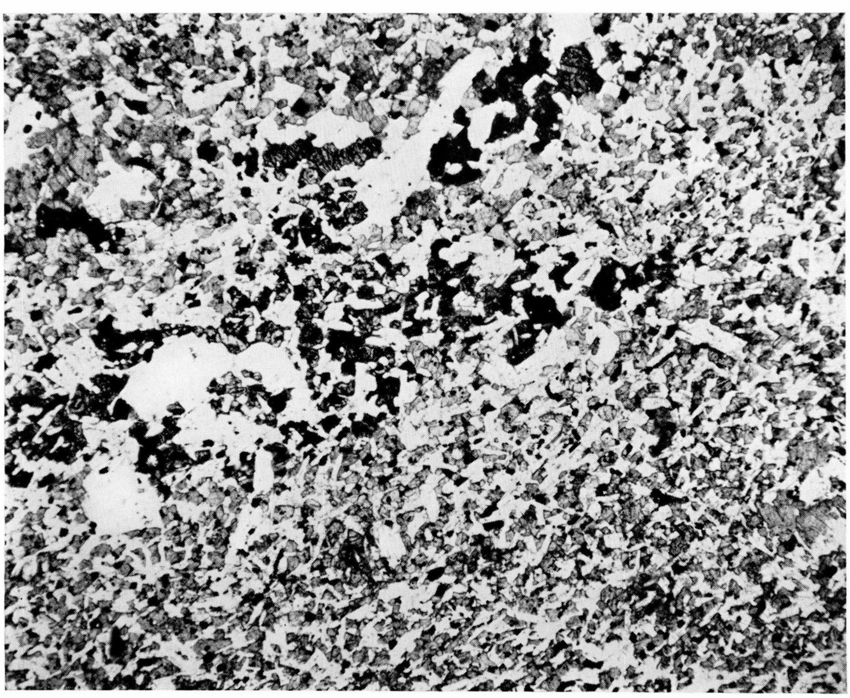

Fig. 2

Plate 6

1. Net-vein in fine-grained marginal gabbro, 4126. S. side of Nunatak I (p. 38). Vein (right half) consists mainly of plagioclase and iron ore, containing small zircons. Plain light. x 20.

2. Hedenbergite andesinite (left) veining fine-grained gabbro, 1900. W. face of Basistoppen (p. 41). Note absence of augite at contact. Olivine phenocryst in lower right. Plain light. x 20.

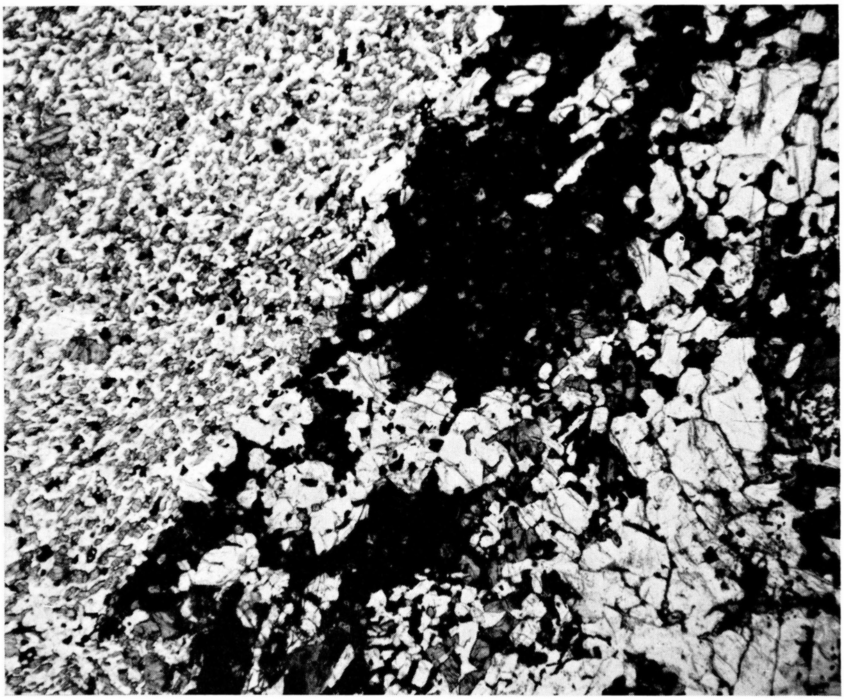

Fig. 1

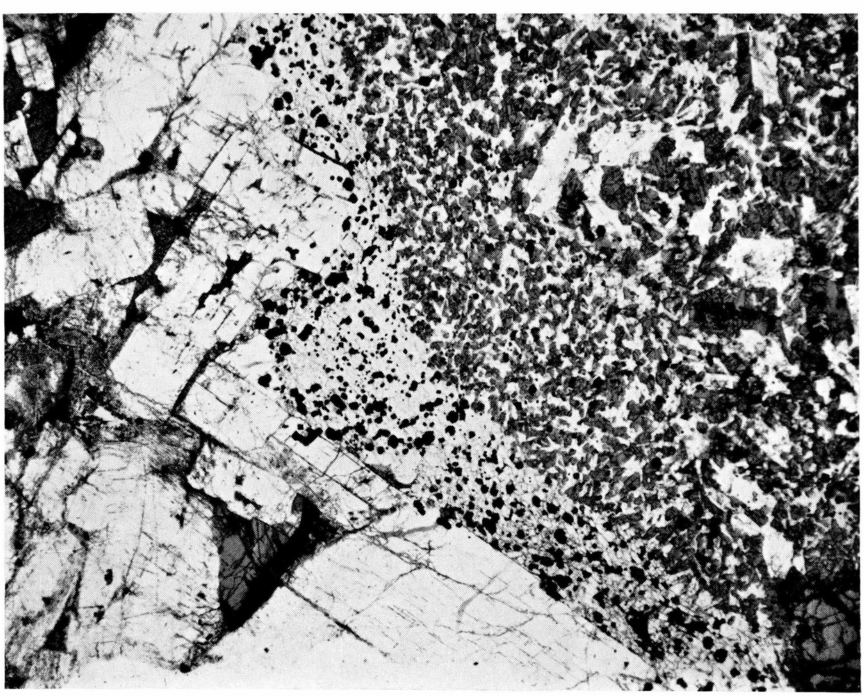

Fig. 2

Plate 7

1. Cumulus iron ores in pigeonite gabbro, 5175, Skillenunatak (p. 34). Euhedral titaniferous magnetite with exsolved ilmenite (III), and discrete elongate ilmenite crystals. Reflected light, crossed polarizers. x 56.

2. Magnetite-ilmentite intergrowth in pyroxene ferrodiorite, 5178, Skillenunatak (p. 34). Partial dissolution of magnetite (lighter) results in "grid-iron" texture. Reflected light, crossed polarizers, oil immersion. x 600.

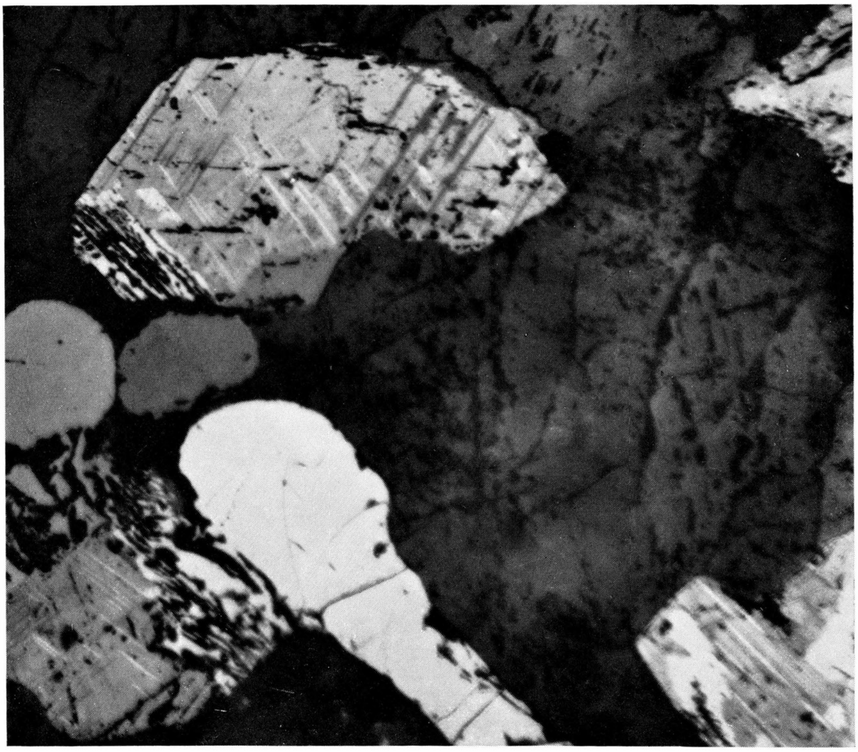

Fig. 1

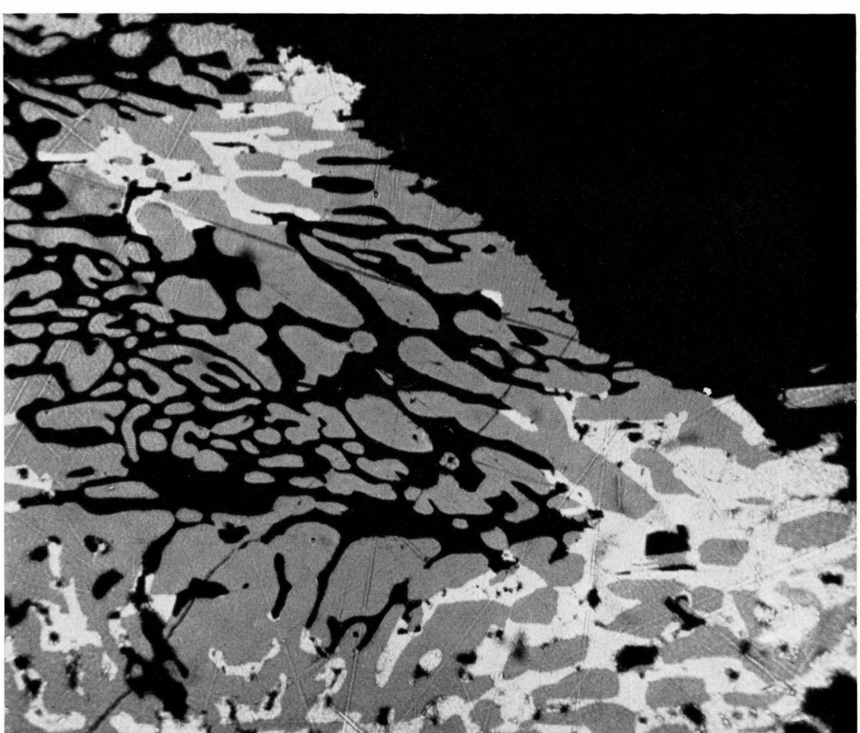

Fig. 2