A preliminary account of the geochemistry and ore mineral parageneses of some Caledonian basic igneous rocks from Sørøy, northern Norway.

By

EUGEN F. STUMPFL AND BRIAN A. STURT

Abstract.

The intrusion of the Storelv and Breivikbotn gabbros into metasediments on the island of Sørøy took place during the late stages of the first phase of Caledonian folding (F 1). Both gabbros were then affected by almandine amphibolite facies regional metamorphism and accompanying granitization, the latter being especially pronounced in the Storelv area. These events were followed by a second phase of folding (F 2). Geochemical and ore-microscopic evidence shows certain characteristic differences between the two gabbroic masses. The Storelv gabbro contains higher amounts of TiO_2, Rb, Zr and Ba. It is rich in ilmenite, sphene and biotite. In the Breivikbotn gabbro, higher values for Cu, Cr and Ni have been measured, corresponding to widespread occurence of chalcopyrite and pentlandite. These differences partly reflect compositional variations of the respective local magmas, partly they can be ascribed to granitization.

Introduction.

Sørøy is an island situated off the coast of West Finnmark, near the town of Hammerfest (lat. 70°30′ N., long. 23°80′ E.). The island is mainly made up of a highly folded and metamorphosed series of sedimentary rocks (Ramsay and Sturt, 1963), and large masses of basic, ultrabasic and dioritic rocks which have varying relationships in the complex of structural and metamorphic events that occurred during the Caledonian orogeny. The object of the present account is to give, in a preliminary form, a comparison between two of the gabbro masses that occur on the island in terms of their field relationships, geochemistry and ore mineral parageneses.

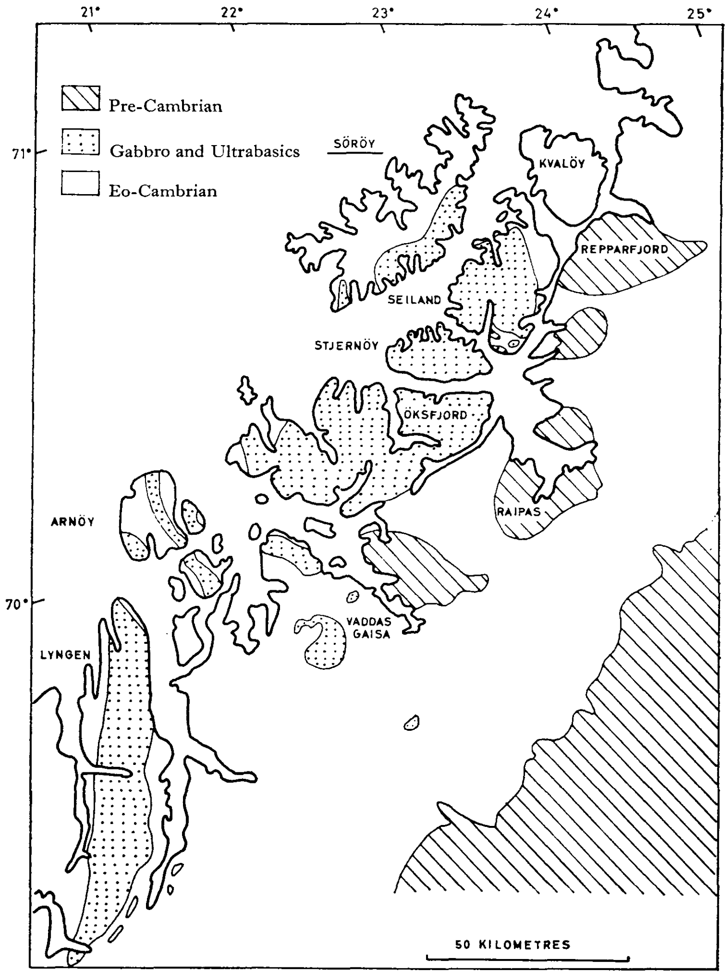

Fig. 1. General distribution of basic rocks in Northern Norway (after N.G.U. 1 : 1000,000 Berggrunnskart over Norge 1953).

The Regional Setting.

The island of Sørøy forms part of the northern margin of the great West Finnmark – North Troms basic and ultrabasic petrographic province (Fig. 1), which extends from the Lyngen peninsular in the south and includes the Oksfjord area and the islands of Seiland and Stjernøy.

The basic and ultrabasic rocks of this area contain many features which

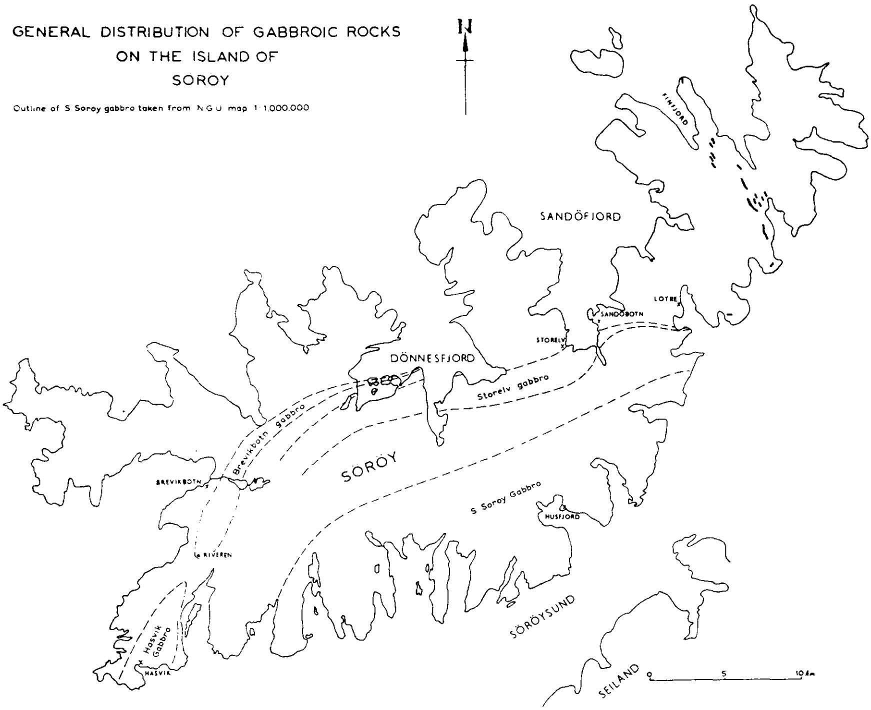

Fig. 2. General distribution of gabbroic rocks in Sørøy.

contribute to the unique character of the province. They are frequently banded and indeed their layered nature bears many resemblences to such well-documented occurrences as the Skaergaard, Stillwater and Bushveld intrusions. These latter are considered to have developed under stable tectonic conditions. The northern Norwegian examples, however, not only occupy a central position in the Caledonian orogenic belt but were emplaced during the course of the orogeny. Some of the complexities of the basic and ultrabasic rocks of the province have been described in a series of papers (Barth, 1953, 1961; Krauskopf, 1954; Heier, 1961; and Oosteroom, 1963). Barth (1953), for example, gives an account of a layered gabbro/ultrabasic complex at Søndre Bummansfjord, Seiland, which is apparently of very similar appearance to the metamorphic banded gneisses which form the country rocks. These layered gabbroic rocks, according to Barth, grade without a break into an equally well layered amphibolite/gneiss complex. Within the layered gabbro, bands of diopside-garnet-spinel and corundum-spinel-sillimanite occur as relicts of metasedimentary material (Barth 1961). He concludes that the "metamorphic rocks exhibit successively higher stages of metamorphic-anatectic transformation; with uniform westerly strike they grade into the layered gabbro series north of Nordmannsfjord-jøkel."

Krauskopf (1953) describes layered gabbros and ultrabasic rocks from the mainland at Oksfjord, and considers the layered gabbros to represent a volcanic-sedimentary sequence metamorphosed under granulite facies conditions. Oosteroom (op. cit.) in his detailed account of the basic and ultrabasic rocks of Stjernøy supports the thesis of a metamorphic origin under granulite facies conditions for the layered gabbros and associated rock types. Oosteroom also draws attention to the abnormally high lime content of the Stjernøy gabbros and concludes that this indicates assimilation of limestones.

Thus the consensus of opinion concerning the origin of the layered gabbros of parts of the province is that a variable suite of metasediments, basic lavas and tuffs were subjected to granulite facies metamorphic conditions. Under these conditions palingenesis and contamination is concluded to have occurred, eventually producing mobile magmas of gabbroic composition. The authors feel, however, that it is not yet possible to draw valid comparisons between these examples and the gabbroic rocks described in the present account.

II. Gabbroic and associated ultrabasic rocks on Sørøy.

Basic and ultrabasic rocks are abundant on Sørøy, as is indicated on the N. G. U. 1:1 000 000 map of Norway. Further large basic masses have been discovered during the regional survey begun by one of us (B.A.S.) and D. M. Ramsay in 1959 (Fig. 2). It would appear likely, that a major fault occurs along the Sørøysund, separating Sørøy from the other two islands and bringing down rocks of a higher structural level and lower metamorphic grade on Sørøy. Amphibolite facies assemblages are the rule and no granulite facies rocks have yet been discovered. The gabbroic rocks are intrusive bodies with many examples of well-defined cross-cutting contacts, and with the development of variably preserved contact aureoles in the marginal metasediments. The gabbroic and ultrabasic rocks have been emplaced at a number of stages during the structural and metamorphic development of the area.

Geological relationships of the Sørøy basic and ultrabasic rocks.

The metasedimentary rocks have been involved in at least two major phases of folding (Ramsay and Sturt 1963). The earliest phase (F1) produced overturned asymmetric to recumbent folds which, on the regional scale, may be of considerable dimensions. The prominent schistosity of the metasedimentary rocks was produced during this period of deformation. The axes of the early folds are highly variable, though their general trend appears to be between NW–SE and NNE–SSW. These early folds are refolded by a second generation of structures (F2) which vary in trend between N–S in the Breivikbotn and Finfjord areas and E–W in the Storelv area. This major swing of the strike may be influenced by later fold structures (F3) which have an approximately NW–SE trend, but only locally developed minor folds of this generation have so far been observed. It is also possible that the change in strike may be an inherent property of one of the earlier fold systems, but this will form the subject of a further investigation.

The metasedimentary rocks are mainly in the almandine amphibolite facies of regional metamorphism, though several distinct phases in the metamorphic history of the area can be distinguished. The conditions of highest grade metamorphism were established during the interval between the two major folding episodes. The almandine amphibolite assemblages of these rocks are characterized by the development of almandine garnet, staurolite, kyanite and sillimanite in the pelitic mica-schists, together with plagioclase feldspar (An_{25}–$_{35}$). Calciferous amphiboles and diopsidic pyroxenes are the dominant silicates in the impure metamorphosed limestones. Widespread granitization accompanied this metamorphism. Although irregular in occurrence, large areas of quartzo-feldspathic gneisses have developed locally and apparently at the expense of metasediments. In most localities there are patchy developments of migmatitic gneisses and pegmatites.

Although the intrusion history of the basic and ultrabasic rocks is complex in detail, it can be simplified as comprising two major episodes of emplacement as follows: –

(a) At the close of the early (F1) fold movements, but earlier than the main almandine amphibolite facies metamorphism.

and (b) After the main almandine amphibolite facies metamorphism, and probably during the complex of movements which characterize the second (F2) phase of folding.

The Storelv and Breivikbotn gabbros with their associated ultrabasic rocks were both emplaced during the earlier of these two episodes. Nonetheless, they exhibit considerable differences in their contact relationships with the country rocks and in their subsequent modifications during the regional metamorphism of the area.

The Storelv Gabbro.

This is a mass of dominantly gabbroic rocks of sheet-like form. The sheet has a general northerly dip, and shows a considerable degree of conformity to the country rocks in those areas so far studied. The mapping to date indicates that it begins as a narrow tongue near Lotre in the east, where it is highly sheared into hornblende-schists, and hornblende-biotite schists which are involved in complex fold structures with the marginal metasediments (personal communication D. M. Ramsay). Tectonic lenses of sheared gabbro have been reported by D. Roberts from the Finfjord area further to the north-east (Fig. 2). The width of the outcrop of the gabbroic rocks increases considerably to the west, reaching almost three kilometres west of Storelv. The gabbro continues westwards into the Donnesfjord area (E. C. Appleyard, personal communication), and reconnaisance by the authors reveals its extension for a considerable distance to the west towards Breivikbotn.

The Storelv gabbro is typically a melagabbro but has suffered considerable modification both in texture and composition during metamorphism. Peridotitic and troctolitic horizons are quite prominent and are concentrated near the base of the sheet. The ultrabasic horizons are in the form of disconnected lenses, sometimes of quite large dimensions, also of fairly thin sheet-like bodies. A relict igneous banded structure can be observed in some of the ultrabasic rocks which is sensibly parallel to the layering of the marginal metasediments, though the complex fold patterns of the latter are not found in the basic rocks. The margins of the gabbro are strongly sheared with the development of a schistosity parallel to the dominant schistosity of the country rocks. The schistosity extends for considerable distances into the basic rocks which are metamorphosed into hornblende-schists and hornblende-biotite schists. The ultrabasic rocks are on the whole relatively unsheared, though near the southern contact at Sandøbotn peridotites are strongly sheared into hornblende-biotite schists. As the central part of the basic mass is traced westwards beyond Storelv the effects of deformation are less pronounced and the gabbroic rocks have a more massive texture. Here more isolated shear zones are developed, which are locally quite thick.

There is a lack of contact metamorphism in the country rocks surrounding the gabbro. This is perhaps a consequence of the intense movements parallel to the gabbro margin and to the pervasive effects of the subsequent almandine amphibolite facies metamorphism. However, Dr. Ramsay has discovered concentrations of sillimanite discs locally along the southern contact, and these may perhaps represent relicts of a former contact metamorphic aureole. It seems probable from several lines of evidence that the gabbro was emplaced during the late stages of the F1 movements when strong shearing of the rocks was still prevalent. The early shear zones and the primary igneous banding were themselves folded into fairly open structures during the second (F2) deformation.

The massive facies of the gabbro has been metamorphosed to gabbro-amphibolite, although relict augite containing schiller inclusions of ilmenite is frequently observed in the process of conversion into greenish-brown hornblende. Relict ophitic texture is common in these rocks. The original igneous plagioclase (calcic andesine-labradorite) persists in the massive gabbro-amphibolites though it is often strained and corroded. It is frequently broken-down into epidotic minerals and saussurite and rimmed by later oligoclase-andesine, which is the normal feldspar of the schistose varieties. The Storelv gabbro has also been affected by the considerable influx of granitic material, and the schistose varieties in particular show well-developed granitization features with the ultimate production of quartz-monzonitic and trondhjemitic gneisses. The gneisses pass into massive types in which the schistose texture has been obliterated. The massive gabbroic rocks were also extensively granitized and developed porphyroblasts of micro-perthitic microcline and of oligoclase-andesine. Biotite after amphibole is extensively developed. Such rocks acquire a patchy dioritic aspect and eventually grade into massive bodies of quartz-diorite and quartz-monzonite.

The basic rocks are prominently jointed, many of the joints being the result of the F2 movements, and three types of activity associcted with the jointing have been noted:

(i) The development of sugary textured aplite veins

(ii) Late K-metasomatism along the joint surfaces.

and (iii) Hydrothermal alteration along some joints particularly in the neighbourhood of Stein Vann, with the development of zeolite, chlorite, albite and pyrite.

The Breivikbotn Gabbro.

This also is a sheet-like intrusion which extends from the hill of Riveren, between Breivikbotn and Hasvik, northwards to Holmvikdalen and thence swings with the strike eastwards to Donnesfjord where according to Dr. E. C. Appleyard (personal communication) the eastern extremity of the gabbro is highly deformed and sheared. From its southern extremity on Riveren to Breivikbotn the gabbro has clearly defined intrusive relationships to the metasedimentary rocks, and at many exposures along the south-western contact the gabbro cuts abruptly through the early (F1) structures in the metasediments. In this part of the area a well preserved contact aureole is developed in the marginal country rocks, with the production of the typical mineral assemblage corundum, spinel, hypersthene and sillimanite in the pelitic hornfelses closest to the contact. The gabbro has been metamorphosed into a gabbro-amphibolite and the regional almandine amphibolite facies assemblage has been overprinted on the minerals and textures of the aureole (Sturt, 1962). North of Breivikbotn the margin of the gabbro is increasingly sheared parallel to its contact (D. M. Ramsay personal communication), and here the contact is sensibly parallel to the strong schistosity in the country rocks. With the increased shearing at the gabbro margin, contact metamorphism of the metasediments becomes progressively less pronounced and its effects are no longer detectable a short distance north of Breivikbotn. This is also the case at Dønnesfjord. The intense shearing along the gabbro margin appears to have been associated with the final stages of the F1 movements. The eastern contact is also highly sheared along most of its course, and further complicated by later dioritic rocks, so that few contact metamorphic effects of the gabbro can be observed.

The gabbroic rocks at Breivikbotn are a little more variable in composition than those at Storelv and vary from melagabbro through gabbro to leucogabbro and contain rare bands of anorthosite. Peridotite and troctolite are extensively developed as lenses and sheets but are not concentrated towards the base, as was the case in the part of the Storelv intrusion described. Banding can occasionally be seen in the gabbroic and ultrabasic rocks. It shows a steep dip, as do the contacts of the mass, a consequence of large F2 folds. The gabbro is xenolithic in places and particularly obvious are large rafts of limestone which are converted into skarn. An analysis of one such calc-silicate inclusion is given in Table 4. Within the massive portions of the metagabbro relict grains of augite and orthopyroxene occur containing characteristic schiller inclusions of ilmenite. Relicts of the ophitic texture of the gabbro are abundant. The gabbroic rocks are again metamorphosed into gabbro-amphibolites and the sheared portions into hornblende-schists, hornblende-biotite schists and biotite schists. There are, however, significant differences between the metamorphic modifications of this gabbro and the Storelv mass:

(i) Granitization features, so characteristic of the Storelv mass, are rarely associated with the Breivikbotn gabbro.

(ii) The metamorphism of the Breivikbotn gabbro is typified by the widespread though irregular development of hornblende-plagioclase-scapolite pegmatite, in which individual hornblende crystals may be over a foot in length. The development of this pegmatite facies indicates a greater role of volatiles during metamorphism.

(iii) The most obvious difference in the subsequent history of the Breivikbotn gabbro is the development of nepheline syenite gneisses and pegmatites and various other syenitic rocks. These alkali rocks were emplaced during the course of the F2 deformation. They are mainly metasomatic and developed along shear zones in the gabbro.

Late K-metasomatism and hydrothermal alteration along joint surfaces similar to that described from Storelv (p. 202) also occur.

A series of later basic igneous rocks varying from norites through pyroxene-mica diorites to fairly acid diorites are intruded along the margins of the Breivikbotn gabbro. The emplacement of these rocks post-dates the main almandine amphibolite facies metamorphism, and occurred during the F2 movements. These rocks are less intensively metamorphosed than the Breivikbotn gabbro and are characterized by the abundance of primary orthopyroxene.

III. Geochemistry

1. *Major Elements.*

The analyses relating to both gabbro masses (Tables 1–3) show very similar ranges of values for SiO_2, the alkalies and for Al_2O_3, MgO and Fe_2O_3. On the other hand, the values of TiO_2 in the Storelv gabbro are more variable but consistently higher. The one exception SD5, comes

Table 1: *Analyses of Storelv gabbro.*

	1	2	3	4	5	6	7	8	9
	S2055[1]	S164[2]	S58[2]	S75[2]	S91[2]	S118[2]	S865[2]	S61[2]	S9015[1]
SiO_2	41.76	42.80	45.30	46.90	47.80	43.60	47.89	60.70	71.69
Al_2O_3	8.41	9.80	13.60	15.40	13.00	15.50	18.07	14.80	14.07
Fe_2O_3	2.58	4.62	4.62	4.02	3.90	4.73	1.59	2.68	0.62
FeO	10.22	9.91	8.92	9.20	9.50	8.94	9.05	3.37	2.05
MgO	24.63	20.16	7.71	5.27	5.81	6.84	3.74	3.69	0.57
CaO	5.74	6.68	12.95	10.70	11.27	11.87	8.77	2.13	1.27
Na_2O	1.23	1.87	2.20	2.85	2.86	2.61	3.88	6.30	3.30
K_2O	0.49	0.71	0.76	1.30	0.47	0.62	1.64	2.98	5.35
TiO_2	1.28	1.43	3.02	3.43	4.79	3.83	3.32	0.86	0.48
MnO	0.19	0.16	0.16	0.21	0.23	0.16	0.18	0.06	0.05
P_2O_5	0.16	0.16	0.21	0.31	0.19	0.38	0.64	0.26	0.14
H_2O^+	2.91	1.18	0.68	0.83	0.57	0.57	1.16	1.35	0.50
H_2O^-	0.27	0.09	0.17	0.09	0.09	0.30	0.18	0.53	0.08
CO_2	0.14	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00
Total	100.06	98.98	100.30	100.51	100.48	99.95	100.11	99.71	100.17

[1] Analyst R. Solli, Grethe Holseth, N.G.U. (Classical Methods).
[2] Analyst R. Thomas, University College London (Rapid Methods).

1. S 2055 Peridotite 3 km SW Storelv
2. S 164 Peridotite 3 km SW Storelv
3. S 58 Metagabbro Steinvann, Storelv
4. S 75 Metagabbro ½ km W of Steinvann, Storelv
5. S 91 Metagabbro Steinvann, Storelv
6. S 118 Metagabbro Storelvdalen, Storelv
7. S 865 Feldspathized metagabbro Storelv
8. S 61 "Quartz-Monzonite" Steinvann, Storelv
9. S 9015 "Quartz-Monzonite" Storelvdalen, Storelv

from Gammelgaard on the western side of Donnesfjord. This eastern extremity of the gabbro on Dønnesfjord Øen is enriched in sphene, probably as a consequence of extensive metasomatic and hydrothermal alteration (E. C. Appleyard, personal communication). The Breivikbotn gabbro shows relative enrichment in CaO (Tabs. 1 and 3). It has been demonstrated from their field relationships that the two gabbros are broadly coeval and that they have been intruded and crystallized at similar crustal levels. The authors consider the slight compositional differences to be a consequence of differences in the crystallization histories of the two gabbros and in the degree and type of contamination of the respective local magmas by country rock materials.

Table 2: *Analyses of gabbroic rocks from Breivikbotn*

	1 SD5	2 SB41	3 SB157	4 SB203	5 SB225	6 SB278
SiO_2	42.80	44.50	48.90	46.40	43.80	43.20
Al_2O_3	15.40	10.20	13.00	19.40	16.80	10.00
Fe_2O_3	3.61	3.08	5.34	2.95	5.15	3.13
FeO	9.95	7.78	5.87	5.69	7.06	9.96
MgO	6.96	12.32	8.58	7.61	7.31	19.73
CaO	11.00	15.79	12.31	11.70	14.39	11.21
Na_2O	3.77	1.95	2.06	4.33	2.83	1.56
K_2O	1.06	0.44	0.43	0.90	0.87	0.20
TiO_2	2.68	2.02	2.05	0.95	1.76	1.37
MnO	0.19	0.16	0.16	0.11	0.03	0.16
P_2O_5	0.10	0.10	0.13	0.08	0.09	0.05
H_2O^+	0.80	0.48	0.36	0.28	0.32	0.64
H_2O^-	0.09	0.05	0.05	0.09	0.03	0.08
CO_2	0.01	0.34	0.01	0.01	0.37	0.01
Total	98.42	99.21	99.25	100.50	100.81	101.20
Normative Minerals						
Qz	–	–	1.14	–	–	–
Or	6.67	2.22	2.22	5.56	5.56	1.11
Ab	7.34	3.67	17.29	12.58	8.91	1.57
An	21.96	18.07	25.02	31.40	30.58	19.74
Ne	13.06	6.82	–	12.78	7.95	6.05
Cc	0.20	0.70	0.20	0.20	0.70	0.02
Di	25.56	46.21	27.85	21.10	29.90	28.05
Hyp	–	–	11.68	–	–	–
Ol	11.62	12.38	–	10.90	6.19	35.54
Mt	5.34	4.41	7.66	4.41	7.66	4.41
Il	6.66	3.80	3.95	1.82	3.34	2.58
Ap	0.34	0.34	0.34	0.34	0.67	0.34

Analyst: R. Thomas, University College London (rapid methods)

1. SB 5 Metagabbro Gammelgaard, Dønnesfjord
2. SB 41 Metagabbro Flagenvann, near Breivikbotn
3. SB 157 Metagabbro (border facies) east of Haraldseng
4. SB 203 Metagabbro Flågenvann, near Breivikbotn
5. SB 225 Metagabbro Overflågenvann, near Breivikbotn
6. SB 278 Peridotite Hasfjordvann

2. *The Trace Elements.*

In the course of more detailed investigations now in progress, information on the trace element content of a number of samples of these gabbros has been obtained, by X-ray fluorescence and optical spectrography.

Table 3: *C I P W NORMS, Storelv rocks.*

	1	2	3	4	5	6	7	8	9
	S2055	S164	S58	S75	S91	S118	S865	S61	S9015
Qz.	–		–	–	1.32	–	–	1.74	29.94
Or	2.78	3.89	4.45	7.78	2.78	3.34	10.01	17.79	31.69
Ab	10.48	14.67	8.62	24.10	24.10	22.01	28.30	53.45	27.77
An	15.85	16.40	25.02	25.84	21.13	28.91	26.41	6.12	5.66
Ne	–		1.14	–	–	–	3.12	–	–
Cor	–		–	–	–	–	–	–	0.82
Cc	0.30	0.20	–	–	–	–	–	–	–
Di	9.07	12.17	31.01	21.26	27.37	21.47	11.27	5.31	–
Hyp	2.10	–	–	–	8.01	1.83	–	9.44	6.15
Ol	50.49	41.04	8.74	8.23	–	7.84	8.45	–	–
Mt	3.71	5.80	6.73	5.80	5.57	6.73	2.32	3.94	0.84
Il	2.43	2.74	5.78	6.57	9.12	7.30	6.23	1.52	0.91
Ap	0.34	0.34	0.34	0.67	0.34	1.01	1.34	0.36	0.34

1.2: Peridotite
3.7: Metagabbro
5: Feldopathic Metagabbro
6: Metagabbro
7: Feldopathic Metagabbro
8.9: Quartz-Monzonite

For details of localities, refer to Table 1.

Even at this preliminary stage certain characteristic differences especially as regards Rb, Zr, Ba, Ni and Cu (Tables 6 and 7) can be observed. The response of the trace element paragenesis to metamorphism is considered below.

The values obtained for each element determined in the Sørøy rocks are compared in most cases with those obtained by Wager and Mitchell (1951) for Skaergaard, by Liebenberg (1960–61) for the Bushveld, by Nockolds and Mitchell (1948) for Scottish Caledonian igneous rocks, and with the average values adopted by Ahrens and Fleischer (1960) for W 1 and G 1. These four sources are not referred to again in the discussion to avoid repetition.

1) Strontium.

The Sr-values in both gabbros range from 400–1150 ppm. For comparison, it might be noted that the amount of Sr in the original Skaergaard magma was 350 ppm; the hypersthene-olivine gabbros of the layered

Table 4: *Analyses of Limestone Xenolith in Brevikbotn Gabbro Compared with Metamorphosed Limestone outside the Gabbro.*

	SB 407	BR 240	
SiO_2	49.40	4.58	*SB 407*
Al_2O_3	9.90	3.61	Forsterite-diopside-wollastonite
Fe_2O_3	1.87	0.16	skarn in gabbro. 2 km S.W. of
FeO	3.39	0.35	Breivikbotn.
MgO	11.58	tr.	Analyst: R. Thomas (rapid methods)
CaO	23.45	50.97	
K_2O	0.01	0.03	
Na_2O	0.67	0.57	
TiO_2	0.50	–	*BR 240*
MnO	0.15	–	Metamorphosed limestone
P_2O_5	0.05	0.01	(unaffected by contant
H_2O^+	0.27	0.30	metamorphism). 1 km E of
H_2O^-	0.07	0.02	Breivik.
CO_2	0.01	39.33	Analyst: J. Bartle
Total	101.46	100.20	
Ti	2,700	20	
V	n.d.	5	n.d. = not determined
Cr	85	15	x = below limits of detection,
Ni	50	x	with method used.
Cu	n.d.	10	
Zn	120	x	
Sr	440	2,300	
Zr	105	x	

series contained 600 ppm Sr; Liebenberg (1960) gives Sr-values ranging rom 130–195 ppm for Main Zone Gabbros from the Bushveld Igneous Complex. The value of 1000 ppm Sr for Caledonian basic plutonic rocks from Scotland is considered too high by Wager and Mitchell (1951). Sr in W1 is 175 resp. 220 ppm.

From data so far available the Sr content of the Sørøy gabbros appears to be comparatively high. Certain relations between the Sr-content of these rocks and the amount of plagioclase present, do, no doubt, exist. Butler and Skiba (1962) found that the Sr-content of feldspars from three basic intrusions in Somalia are similar for comparable anorthite contents. Information is not yet available, however, on the Sr-content of feldspars from the Sørøy gabbros.

Table 5: *Trace elements in Breivikbotn rocks.*

	16 SD5	17 SB 203	18 SB157	19 SB41	20 SB455	21 SB132	22 SB448	23 SB225	24 SB278	25 SB28
Ti	18,000	n.d.	12,300	12,120	5,800	37,200	20,160	10,500	5,300	10,500
Sr	440	820	600	350	400	720	590	800	290	165
Rb	25	–	–	–	–	–	13	–	10	–
Ba	–	200	350	150	–	280	600	–	–	370
Y	–	25	35	35	–	15	30	–	–	20
Zr	110	80	75	100	170	50	80	100	70	65
Mn	2,600	700	1,200	1,100	1,250	1,000	2,000	n.d.	1,000	1,860
Cr	200	180	180	500	660	105	80	90	1,250	650
Cu	50	80	150	200	50	215	30	110	110	75
Co	100	45	55	35	75	n.d.	n.d.	75	100	n.d.
Ni	110	120	150	300	225	100	30	160	550	660
V	360	200	120	250	120	480	280	360	180	225

n.d. = not determined
– = not detected (below sensitivity of method)

16 SD 5, Metagabbro, Gammelgaard, Dønnesfjord
17 SB 203, Metagabbro, Flågenvann, near Breivikbotn
18 SB 157, Metagabbro, (border facies) east of Haraldseng
19 SB 41, Metagabbro, North of Flågenvann, near Breivikbotn
20 SB 455, Pyroxene-Mica-Diorite, Flågenvann, near Breivikbotn
21 SB 132, Metagabbro, South of Flågenvann, near Breivikbotn
22 SB 448, Norite, Flågenvann, near Breivikbotn
23 SB 225, Metagabbro, Overflågenvann, near Breivikbotn
24 SB 278, Peridotite, Hasfjordvann
25 SB 28, Peridotite dyke in metasediments, Hvitness, near Barvik

2) Rubidium.

Samples of the Breivikbotn gabbro have Rb-values which are extremely low or not detectable with the methods used. Not even the accepted average for W1 (22 ppm) is reached (table 6). Wager and Mitchell found Rb-values in basic rocks from Skaergaard to be below sensitivity of the analytical method. On the other hand, Rb-values in the Storelv gabbro are higher, and vary between 20 and 155 ppm. No distinct relationships between the Rb and K contents was observed in the rocks analysed. This indicates that only part of the total Rb is accommodated in the feldspars. Heier (1960) ascribed the higher Rb content of certain amphibolite facies gneisses to their high biotite content. The higher Rb-values in the Storelv gabbro may perhaps be related to the greater abundance of biotite. Rb can, to a limited extent, take the place of K in biotites. The virtual absence of Rb in the Breivikbotn gabbro is comparable to the extremely

Table 6: *Trace elements in Storelv rocks.*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	S73	S75	S91	S58	S118	S113	S61	S865	S164	2055	R8	R34	R35	R51	R63
Ti	17,200	16,800	15,400	18,120	23,000	n.d.	5,160	19,400	n.d.	7,560	n.d.	n.d.	n.d.	n.d.	n.d.
Sr	570	500	450	820	1,150	430	590	770	430	160	630	630	240	450	610
Rb	20	20	15	–	80	90	120	35	–	15	120	50	155	110	60
Ba	–	–	–	200	200	1,000	600	1,230	200	240	2,180	570	2,945	690	720
Y	–	–	75	35	35	70	35	55	–	–	70	20	100	50	10
Zr	190	170	180	100	100	200	400	180	100	55	270	85	310	115	100
Mn	1,450	1,300	1,350	1,200	1,050	1,150	550	1,400	1,470	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cr	85	170	50	100	100	30	–	40	600	2,150	30	75	65	35	95
Cu	–	50	35	50	80	50	10	5	180	50	Tr.	35	25	Tr.	45
Co	–	50	75	45	45	25	10	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ni	550	60	45	40	40	40	40	10	640	980	25	65	60	20	100
V	–	360	300	350	350	125	80	300	200	180	85	360	85	345	220

n.d. = not determined

– = not detected (below sensitivity of method)

1. S 73, Metagabbro, 1 km E of Steinvann, Storelv
2. S 75, Metagabbro, ½ km W of Steinvann, Storelv
3. S 91, Metagabbro, Steinvann, Storelv
4. S 58, Metagabbro, Steinvann, Storelv
5. S 118, Metagabbro, Storelvdalen
6. S 113, Feldspathized metagabbro (much biotite) Storelvdalen, Storelv
7. S 61, "Quartz-Monzonite", Steinvann, Storelv
8. S 865, Feldspathized metagabbro, Storelv
9. S 2055, Peridotite, 3 km SW Storelv
10. S 164, Peridotite, 3 km SW Storelv
11. R 8, Hornblende-Biotite Schist with feldspar augen. Storelv Point, Storelv
12. R 34, Metagabbro (boudin in hornblende schist) ½ km W of Strømmen
13. R 35, Biotite Schist 400 m. W of Strømmen
14. R 51, Metagabbro 500 m. S of Storelv
15. R 63, Metagabbro 400 m. ENE of Mebotn

Table 7: *Trace Elements in the Storelv and Breivikbotn Gabbros compared with those in Basic Igneous Rocks from the Scottish Caledonides,*[1] *Skaergaard,*[2] *the Bushveld*[3] *and in W 4* [4].

Element	Storelv	Breivikbotn	Scottish Caledonian	Skaergaard	Bushveld	W. 1.
V	320	280	150	220	115	240
Cr	75	210	300	230	340	120
Ni	40	150	200	120	100	82
Co	55	55	70	48	35	38(51)
Cu	40	150	n.d.[5]	67	24	110
Zr	150	80	60	33	30	100
Mn	1,300	1,000	1,100	700	1,090	1,300
Sr	660	660	1,000	600	160	220(175)
Rb	43	–	n.d.	n.d.	3,5	22
Ba	600	245	150	18	95	225
Y	35	20	n.d.	n.d.	n.d.	35

[1] Nockolds and Mitchell, 1948 (Sr too high)
[2] Wager and Mitchell, 1951
[3] Liebenberg 1960 (Average of 9 main zone gabbros)
[4] Ahrens and Fleischer, 1960
[5] n.d. = not determined

low Rb-values (1–7 ppm) found in uncontaminated gabbros and norites from the Bushveld. The presence of substantial amounts of Rb (>30 ppm) in gabbroic rocks (by comparison with W1, Skaergaard etc.) would appear to indicate the effects of either contamination or metamorphism.

3) Zirconium.

In the Storelv gabbro Zr varies from 100 to 200 ppm, as seen in table 7. The Zr-content of the Breivikbotn gabbro is lower (50–100 ppm). Much of the Zr is located in zircon, forming well-developed crystals up to 70 microns in length. Liebenberg's (1960) analyses of uncontaminated gabbros and norites from the Bushveld show Zr-contents between 25 and 40 ppm. Only in norites from the border phase does Zr reach 100 ppm. The average Zr-content of hypersthene-olivine gabbros and ferrogabbros from Skaergaard is 33 ppm and 20 ppm, resp. It is interesting to note that especially high Zr-values occur in feldspathized gabbros from Storelv (Nos 6, 7 and 8, Table 7). The potential correlation of this observation to the granitization of the Storelv gabbro has to be considered.

4) Barium.

Considerable variations in Ba-content can be observed in both the Storelv (200–3000 ppm Ba) and the Breivikbotn gabbro (200–600 ppm Ba). Feldspathized gabbros (for instance, Nos S 113 and 865) show distinctly higher Ba-values than less altered ones. Wager and Mitchell give 18 ppm Ba for hypersthene-olivine gabbros and 60 ppm Ba for ferrogabbros from Skaergaard. Liebenberg (1960) quotes 70–146 ppm Ba for Bushveld gabbros. Caledonian basic plutonic rocks from Scotland contain on average 150 ppm Ba. The respective values for G1 are 1220 ppm Ba and for W1 225 ppm Ba. In a feldspathized gabbro from Storelv (S 865) a value of 1230 ppm. was obtained, similar to the accepted values for G1. The differences between Storelv (average 600 ppm Ba) and Breivikbotn (average 245 ppm Ba) are perhaps related to granitization which has been so intense in the Storelv area.

The geochemistry of Ba (ion radius 1,43 Å) in igneous rocks is characterized by its close relation to K (ion radius 1,33 Å). The K_2O/Ba ratios recorded from the Bushveld range from 10 to 30, in Sørøy from 12 to 39, without any noticeable difference between the Breivikbotn and Storelv gabbros. With the exception of SB 157 (border facies of Breivikbotn gabbro) the Sørøy results plotted on the K/Ba diagram of Heier (fig. 3) follow the same trend as the metamorphic and igneous rocks from Langøy.

5) Titanium.

Much of the titanium present in basic igneous rocks is concentrated in ilmenite, titano-magnetite and sphene. The close relations between ilmenite-content and Ti-values has already been noted. Generally the ilmenite-and sphene-rich Storelv gabbro is richer in Ti (15,000–23,000 ppm) as compared with the Breivikbotn gabbro. These figures are distinctly higher than those for hypersthene-olivine gabbros from Skaergaard (5,000 ppm Ti), for Bushveld gabbros (700–1300 ppm Ti), for Caledonian basic igneous rocks in Scotland (5,000 ppm Ti), and for W 1 (7,400 ppm Ti). However, ferrogabbros from Skaergaard and diorites from the Bushveld are more comparable with 15,000 ppm and more than 10,000 ppm Ti respectively. The analytical data available so far indicates that even in intensely feldspathized gabbro (S 865, for instance) the Ti-content does not differ noticeably from that of less altered samples.

The differences in the Ti-content of the two gabbros are reflected in

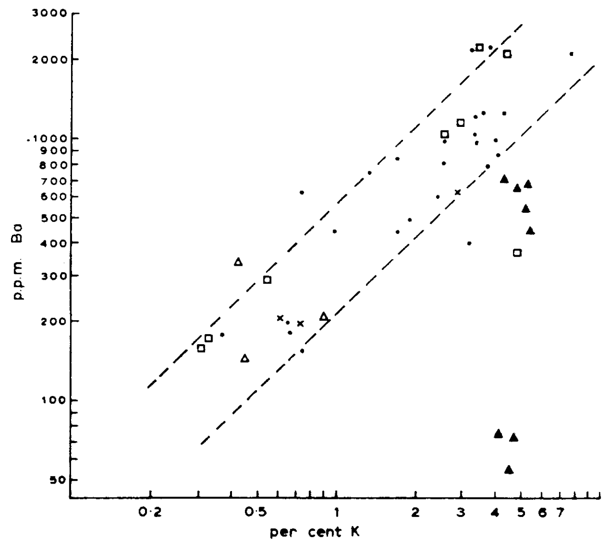

Fig. 3. Relationship between K and Ba in rocks from Langøy (Heier, 1960) and from Sørøy.

▲ = Young Red Granites, Langøy

□ = Eidet–Hovden intrusion, Langøy

● = Regional metamorphic rocks (Amphibolites, granulites, gneisses), Langøy

× = Storelv gabbro, Sørøy

△ = Brevikbotn gabbro, Sørøy

the ore mineral parageneses. Ilmenite is the dominating primary ore mineral in the Ti-rich Storelv gabbro and titano-magnetite dominates in the Breivikbotn gabbro. This suggests slight differences in the Ti-concentration of the respective local magmas.

6) Chromium.

Maximum Cr-contents were found in the peridotites (up to 1,250 ppm). The Breivikbotn gabbros have a tendency for higher Cr-values (80–600 ppm) than the Storelv gabbros (50–170 ppm). The comparative values for main zone gabbros from the Bushveld complex are 60–610 ppm, for hypersthene-olivine gabbro from Skaergaard 230 ppm and for Scottish Caledonian basic intrusives 300 ppm Heier (1960) gives analyses of three gabbros from the Eidet–Hovden intrusion, Langøy, in which the values for Cr are 46, 231 and 541 ppm, respectively.

7) Copper.

It is widely assumed that Cu, due to its volatile character, is easily mobilized during metamorphism. Thus, the behaviour of Cu in metamorphic rocks has become of interest not only for the pure geochemist but for the economic geologist also (see Cornwall and Rose, 1957, Heier, 1960; Vokes, 1957). Deposits of Cu-sulphide ores are widespread in many areas of low grade regional metamorphism, and the question, has to be considered whether they can be explained as metamorphosed sedimentary orebodies or if mobilization of Cu from basic igneous rocks may lead to economic concentrations of Cu-sulphides.

Vokes (1957) has discussed the application of the latter assumption to genetic problems of the Birtavarre copper deposits, Troms, Northern Norway: an area which has many general geological and geotectonic aspects in common with Sørøy. Views as to the actual location of Cu in the respective magmatic "source rocks" still show certain discrepancies, especially as some authors tend to emphasize the role played by the substitution of Mg^{2+} and Fe^{2+} by Cu^{2+} in the lattice of ferromagnesian minerals. Heier (1960) assumes that a higher proportion of Cu may be accommodated in the lattice of silicates of the more acid rocks than of the more basic rocks. Definite conclusions on the matter, can, however, only be reached if geochemical data are compared with the results of detailed ore-microscopic investigations of the rocks in question. Ramdohr (1940) and Newhouse (1936) have shown that most basic and many acid igneous rocks contain chalcopyrite. Unfortunately, much of the recent geochemical data as regards distribution of Cu are not correlated with ore-microscopic observations. The present authors suggest that chalcopyrite, even if present in minute grains only, is the main source for the Cu-content of the igneous rocks investigated. This does not exclude the possibility of small amounts of Cu being accommodated in the lattice of ferromagnesian silicates. No doubt the amount of S available in the magma largely determines the amounts of certain metallic elements that may become fixed in sulphides during the course of crystallization.

With few exceptions, all the Sørøy gabbros investigated contain chalcopyrite, higher amounts being present in the Breivikbotn gabbro. On comparing the analytical data for Cu from Storelv with those from Breivikbotn, it is seen that the Cu-values in the Breivikbotn gabbro are higher, ranging from 80–215 ppm. In Storelv, the corresponding values are 5–50 ppm Cu. (W1: 110 ppm, G1: 13 ppm Cu). Bushveld main zone gabbros contain 6–47 ppm and Eidet-Hovden gabbros (Langøy) 65 ppm Cu. In the Skaergaard intrusion, hypersthene-olivine gabbros show average Cu-values of 67 ppm, ferrogabbros, 400 ppm.

8) Nickel.

In the Breivikbotn gabbro, Ni-values range from 50 to 300 ppm and average about 150 ppm. Exceptions are represented by peridotites with considerably higher values (55, resp. 650 ppm), and a pyroxene-mica-diorite with only 27 ppm Ni. The above value of 150 ppm corresponds well with data for basic igneous rocks from Germany (Goldschmidt, 1958; 160 ppm Ni), U.S.A. (Sandell and Goldich, 1943: 160 ppm) and Greenland, (Skaergaard hypersthene-olivine gabbro, Wager and Mitchell, 1951: 120 ppm). Gabbros of the Main Zone of the Bushveld Igneous Complex contain 50–170 ppm Ni 82 ppm Ni are recommended for W1. In the Storelv gabbro (with the exception of peridotitic portions) the Ni-contents are considerably lower: they vary from 10 to 60 ppm and average about 40 ppm. Since there is good agreement between ore-microscopic evidence and geochemical data, it appears that as suggested above for Cu, much of the Ni is in a sulphide phase, which in this case is pentlandite. Data on the actual amount of Ni present in the ferromagnesian silicates of these rocks is not yet available.

Some of the traditionally accepted features as regards the origin of sulphides in basic igneous rocks will have to be reconsidered in the light of new evidence which Kullerud and co-workers have accumulated in recent years. This applies especially to minerals in the systems Fe-Ni-S and Cu-Ni-S (Kullerud, 1963; Moh and Kullerud, 1963; Kullerud and Yoder, 1963); it has been shown that a separation of sulphide and silicate melts before emplacement of the respective magma is improbable.

Furthermore, Kullerud's experiments indicate that metals, such as Fe, Ni, Co and Cu may originally be present in silicates. During late- or post-magmatic addition of S they can easily react with S to form sulphides. It has, for instance, been possible to produce pyrrhotite-pentlandite associations very similar to those observed in ores by heating fayalite containing a small amount of Ni with 33⅓ mole S at 800° C and 2000 bars. This, however, does, not exclude the possibility of disseminated iron-nickel sulphides crystallizing from a magma. The only exception is pentlandite, which formed through reaction in the solid state between primary sulphides. Kullerud (1963, p. 182, 187) found that the (Fe, $Ni)_{1-x}S$ (pyrrhotite) phase reacts with the high-temperature (Fe, $Ni)_{3=x}S^2$ phase at 610° C to form pentlandite. There exists, in addition a certain amount of pyrrhotite-pentlandite solid solution which, with further decrease in temperature, results in unmixing of pentlandite from pyrrhotite. The significance of this data for a better understanding of the much-debated question if certain metals are accommodated in silicates or in sulphides and of the genesis of pyrrhotite-pentlandite deposits, is obvious.

9) Mn, Co, V and Y.

In addition to the elements discussed above, Mn, Co, V and Y have been determined in most samples. Apparently, there are no significant differences between the Storelv and Breivikbotn gabbros as regards the distribution of these elements and they are, therefore, not discussed in detail.

The Mn-values in Storelv gabbros vary from 1050 to 1450 ppm, in Breivikbotn gabbro they are slightly lower (table 6). All these data are in the same range as those known from Caledonian basic igneous rocks (1100 ppm Mn) and from the Bushveld Main Zone gabbros contain 700 ppm Mn, ferrogabbros 3300 ppm Mn.

The average Co-content in Sørøy gabbros is 55 ppm: this is in the same range as the values of 70 ppm given for Caledonian basic igneous rocks and the figures suggested for W1 (38 resp. 51 ppm). Liebenberg gives 20–60 ppm Co for gabbros from the Main Zone of the Bushveld Igneous Complex.

The average V-contents of the Breivikbotn and Storelv gabbros are very similar: 280 resp. 320 ppm. Corresponding data from Bushveld gabbro are 70–186 ppm, from Skaergaard olivine-hypersthene gabbro 220 ppm. A value of 240 ppm V is recommended for W1. No relationship has so far been established between the magnetite content and the amounts of V present, in the rocks investigated. It is well known, however, that certain magnetites contain a few per cent of vanadium, and vanadium can also be accommodated in ilmenite. Vincent and Philips (1954) give analyses of ilmenites from the Skaergaard intrusion which contain 0.32 and 0.18 % V_2O_3 (corresponding to about 2000 resp. 1200 ppm V). Similar possibilities are anticipated for the Sørøy gabbros; analytical data on ilmenites will be available in due course.

21 ppm Y for G1 and 35 ppm Y for W1, are recommended as "a good magnitude". Considering this not very pronounced difference, it does not seem permissible to draw conclusions from the fact that the average Y content in Storelv gabbros is 35 ppm, in Breivikbotn gabbros 20 ppm. In the Skaergaard intrusion, Y values above the sensitivity of the method used (30 ppm) have been observed only in the fayalite ferrogabbro. Liebenberg (1960) does not give data on the distribution of Y in Bushveld rocks.

From the limited analytical evidence presented, the following tentative conclusions can be drawn: The differences in Ti-contents of the Storelv and Breivikbotn gabbros suggest slight differences in the composition of the original local magmas. No significant differences in the Sr, Mn, V and Co values of the two gabbros are to be observed. The values for Rb, Zr and Ba in the Storelv gabbro are distinctly higher than in the Breivikbotn gabbro. The assumption that these elements have, to a certain extent, been introduced during granitization is supported by the fact that the highest values are found in feldspathized portions of the gabbro. On the other hand, the amounts of Cr, Cu and Ni present in the Breivikbotn gabbro are higher than those from Storelv. As regards Cr and Ni, they correspond more closely to data available from similar rocks in the Bushveld, Skaergaard and Scottish Caledonian regions, whereas the Storelv rocks seem to show relative depletion in these elements.

The high Cu-content in the Breivikbotn gabbro is obviously a primary magmatic feature. The question as to the potential primary difference in the Cu-contents of the two gabbros can only be answered if analytical data from non-granitized portions of the Storelv gabbro become available. The suggestion is put forward, however, that the low Cu-values in Storelv may, at least partly, be due to mobilization and removal of Cu during metamorphism and granitization. The low Cr- and Ni-values in Storelv seem to be determined by similar factors. Summarizing these considerations, it can be stated that the geochemical differences between the Storelv and Breivikbotn gabbros can partly be explained by slight differences in the composition of the original magmas. Metamorphism and granitization seem, however, to have has a distinct influence on the Storelv gabbro and may be, at least partly, responsible for the introduction of Rb, Zr and Ba and for the mobilization of some of the original Cr, Cu and Ni.

The ore minerals.

I. *Breivikbotn gabbro.*

a) Ilmenite.

Ilmenite is the most widespread ore mineral in the rocks investigated. Two main types of occurrence can be distinguished:

1. Irregular grains of up to several mm. diameter. Ramdohr (1940) suggests that such grains crystallized as droplets of high surface tension in the intergranular spaces of already solidified silicates.
2. Lamellae orientated parallel to the cleavage of pyroxenes (resp. hornblende). Their diameter does not normally exceed a few microns, but they may be up to 50 microns long. (Fig. 4).

The lamellae have been altered to sphene to a much higher degree than the grains. In fact, only a few "fresh" ilmenite lamellae can be observed. This process is obviously related to the metamorphism responsible for the uralitization of the original pyroxenes. Thus, the original pyroxene cleavage directions, outlined by sphene lamellae, can be preserved in basal section of amphiboles (Fig. 5).

The independent ilmenite grains have been affected by alteration to a limited extent only. In some cases, however, thin "coronas" of sphene have developed around the ilmenite. Formation of rutile frequently seems to mark an initial stage of oxidation (Fig. 6). It is followed later by the growth of sphene, a process which requires a certain mobility of Ca and Si.

Oxidation of ilmenite usually follows the well know formulae,

$$2\,FeTiO_3 + O \rightarrow Fe_2O_3 + 2\,TiO_2 \quad \text{or}$$
$$3\,FeTiO_3 + O \rightarrow Fe_3O_4 + 3\,TiO_2$$

In the two Sørøy gabbros investigated, however, no Fe_2O_3 (hematite) could be detected. Furthermore, the rutile present does not exhibit any textures indicating former intergrowth with Fe_2O_3.

According to Ramdohr (1940), $Fe_2O_3 - TiO_2$ intergrowths are frequently produced by metamorphism. Examples for this reaction have been described from a Lewisian epidiorite from Loch Inver, Assynt (Stumpfl, 1961). The absence of Fe_2O_3 as a decomposition product of ilmenite in the Storelv and Breivikbotn gabbros suggests the local removal

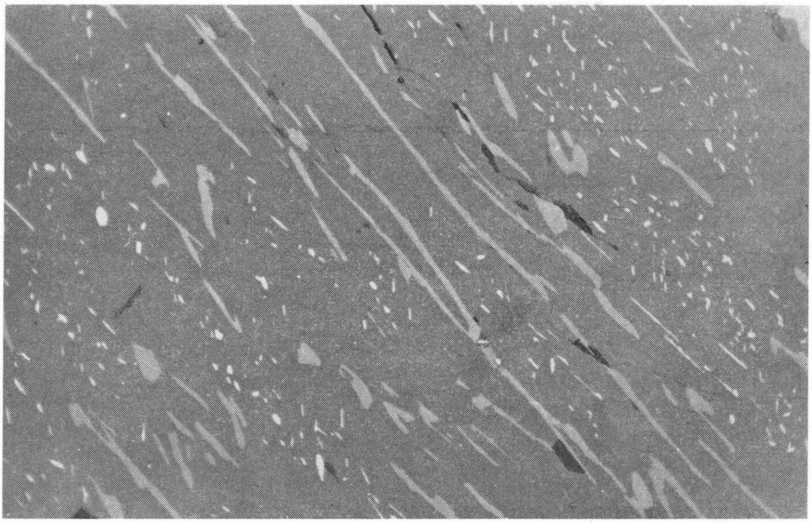

Fig. 4. Sphene lamellae (light grey) in pyroxene (medium grey). Small white lamellae are unaltered ilmenite. Breivikbotn. Magnif. 200 ×.

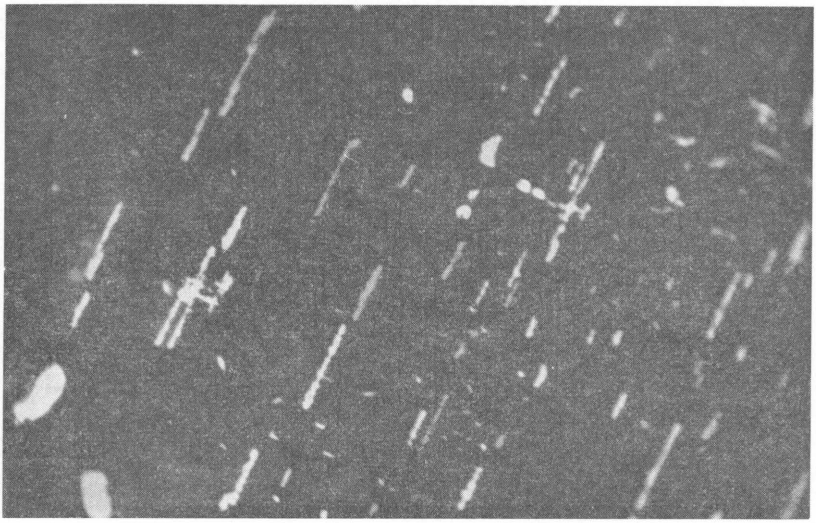

Fig. 5. Ilmenite lamellae (white), altered into sphene (light grey), follow basal cleavage directions of pyroxene. Breivikbotn. Magnif. 330 ×, oil immersion.

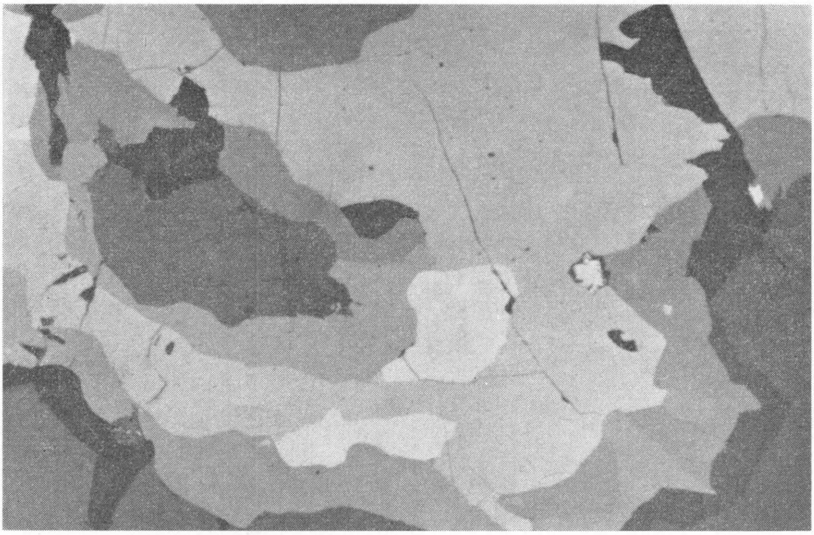

Fig. 6. Oxidation of ilmenite (medium grey) produces rutile (light grey, internal reflections) and sphene (reflection pleochroism). Dark grey is gangue. Breivikbotn. Magnif. 200 ×.

Fig. 7. Rutile (light grey) and sphene (dark grey rim) after ilmenite. Breivikbotn. Magnif. 330 ×. Oil immersion.

of Fe during metamorhism and, perhaps, recrystallization of rutile to form the large crystals now present (Fig. 7).

Ramdohr (1940) mentionst he possibility of "rutile only" occuring as decomposition product of ilmenite. The question of removal of Fe is not discussed.

Not a single grain of unmixed hematite-ilmenite, so widespread in many basic igneous rocks, has been detected in the Storelv and Breivikbotn gabbros.

For unmixing of hematite in ilmenite a minimum content of 6 % Fe_2O_3 in ilmenite is required (Edwards, 1954). Hematite with unmixing of ilmenite or rutile has not been found, either. Hematite with unmixing lamellae of rutile parallel to (2243) in six directions is concentrated in beach sands of the Baltic sea (Stumpfl 1958). It is a characteristic constituent of many Scandinavian polymetamorphic rocks.

b) Magnetite.

There are three main types of magnetite to be distinguished in the rocks investigated:

1) Independent grains, frequently with "exsolution" lamellae of ilmenite.
2) Coarse-grained magnetite-ilmenite aggregates, without any "exsolution" textures.
3) Myrmekitic magnetite-silicate (especially pyroxene) intergrowths.

Lamellae of ilmenite are arranged parallel to the (111)-directions of magnetite (Fig. 8). Usually, the total $FeTiO_3$-content of Fe_3O_4 is present in lamellae: Edwards (1954) found small ilmenite "bubbles" in Australian magnetites the bulk analyses of which showed only 0.01 % Ti. The results of Lindsley (1962) indicate that the well known magnetite-ilmenite intergrowths are not necessarily to be explained as products of exsolution: identical textures can result from oxidation of magnetite-ulvøspinel solid solutions. This hypothesis is supported by recent experimental data (Webster and Bright, 1961) showing that the stable solubility of ilmenite even at 1200–1300° C is much too small to account for the quantities of ilmenite present in natural intergrowths. Augusthitis (1964) found ilmenite "exsolution" lamellae in blastic magnetites in chlorite schists from S. Ethiopia which he assumes to have formed at temperatures of about 300° C.

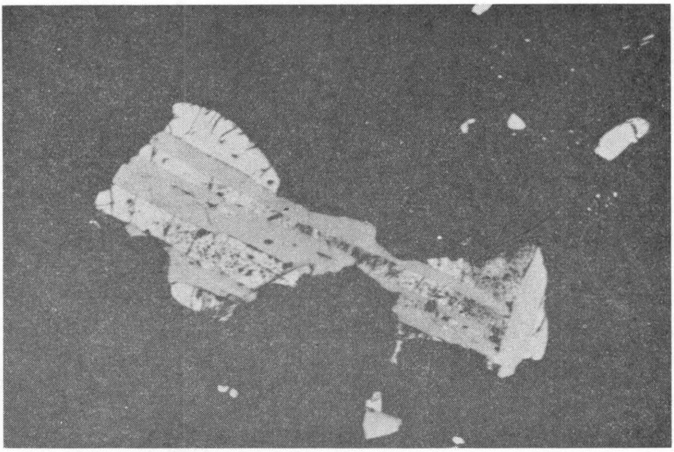

Fig. 8. Magnetite (light grey) with unmixing lamellae of ilmenite (medium grey). Breivikbotn. Magnif. 90 ×.

Unmixing of spinel (hercynite or pleonast) can be observed in many titanomagnetites from the Breivikbotn gabbro. Spinel occurs partly as minute lamellae in networks parallel to the (111) or (100) directions of the magnetites, and also as tiny round and oval grains along the rims of ilmenite lamellae. At × 1000 magnification fine exsolution patterns can be observed in some magnetites. These may be ulvøspinel (Fe_2TiO_4), but, due to the extremely fine nature of the intergrowth, the diagnosis is only tentative. The presence of ulvøspinel in differentiated basic igneous rocks indicates FeO-surplus. Ulvøspinel is, accordingly, not found in examples where ilmenite contains exsolution bodies of hematite. The fact that no hematite occurs in the Breivikbotn ilmenite tends to suggest that fine-grained intergrowths as ulvøspinel may be present.

Coarse intergrowths of magnetite and ilmenite grains are much rarer. The same applies to magnetite-silicate myrmekites: these are especially well developed in a banded metagabbro. According to Ramdohr (1948), these textures are partly reaction rims and partly due to unmixing (and sometimes, recrystallization).

High magnification reveals the presence in some magnetites of two phases, a light yellowish brown one and a slightly darker one, with a violet tinge. Preliminary investigation of similar magnetites from Sierra Leone with the X-ray microanalyser has indicated, that the above varia-

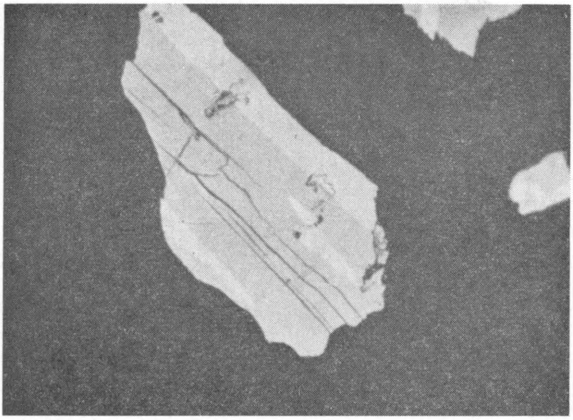

Fig. 9. Pyrrhotite (medium grey) with lamellae of pentlandite (white). Chalcopyrite (light grey), gangue (black). Breivikbotn. Magnif. 330 ×, Oil immersion.

tions in reflectivity are due to slight variations in the Mn-content of respective phases.

The magnetites in the Breivikbotn gabbro are remarkably fresh; no signs of martitization were found. Hydrothermal alteration, to which the rock was exposed in later stages of its history, affected the ore paragenesis only superficially: these features will be discussed later.

c) Sulphides.

Pyrrhotite, pentlandite, chalcopyrite and pyrite are the main sulphides in the Breivikbotn gabbro. Pyrrhotite and chalcopyrite can be considered as products of crystallization from the original magma. Pentlandite has formed by reaction in the solid state of pyrrhotite with $(Fe, Ni)_{3-x}S_2$ (Kullerud, 1963) and by unmixing from pyrrhotite. It occurs in typical flameshaped lamellae parallel to (0001) of FeS. FeS, (Fe, Ni)S and $CuFeS_2$ frequently are closely associated with each other (Fig. 9). The comparatively high Ni- and Cu- values in samples of Breivikbotn gabbro are no doubt due to the presence of the above sulphides.

Clusters of well-developed pyrite crystals can be seen in many polished sections. They are (with a few exceptions) products of post-magmatic hydrothermal alteration. Frequently, oxidation has altered these pyrites aggregates of a α and γ – FeOOH, which still maintain the cubic outlines (Fig. 10).

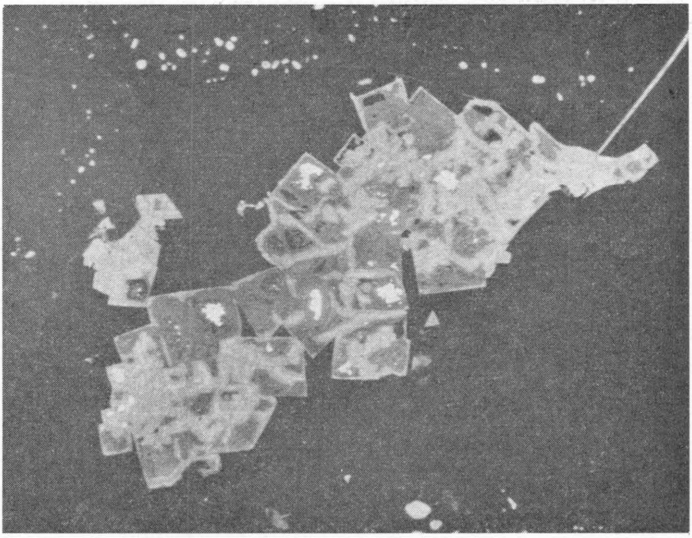

Fig. 10. Pyrite cubes (white), nearly completely altered into goethite (α-FeOOH; dark grey) and lepidocrocite (γ-FeOOH; light grey). Breivikbotn. Magnif. 230 ×, oil immersion.

II. *Storelv gabbro.*

a) Ilmenite.

Up to 90 % of the bulk ore content in the Storelv gabbro is made up by ilmenite which may form independent grains sometimes of considerable size (Fig. 14) and also thin lamellae parallel to the cleavage of pyroxenes and hornblendes. Tectonic deformation is responsible for twinning after (10$\bar{1}$1) which occurs in some ilmenites. Two directions of twinning lamellae are developed; due to the comparatively strong reflection pleochroism the characteristic pattern can be seen in plain polarized light. (Fig. 12). Ilmenite crystallized after solidification of the silicates. Thus, it sometimes outlined grain boundaries. Further growth of some silicates (especially plagioclases: zones of lower An-content) took place during metamorphism. In certain of these examples, the original grain boundaries, as indicated by ilmenite, have been preserved within the silicates (Fig. 13).

The most remarkable feature, however, is the intense alteration of ilmenite to sphene. No unaltered grains were found in the sections investigated. Typical sphene coronas are visible in thin section. Often only

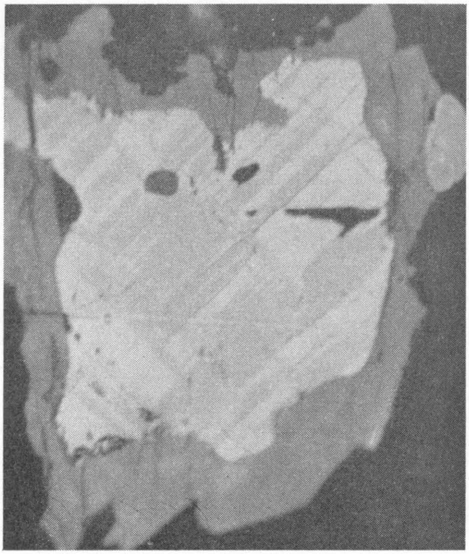

Fig. 12.

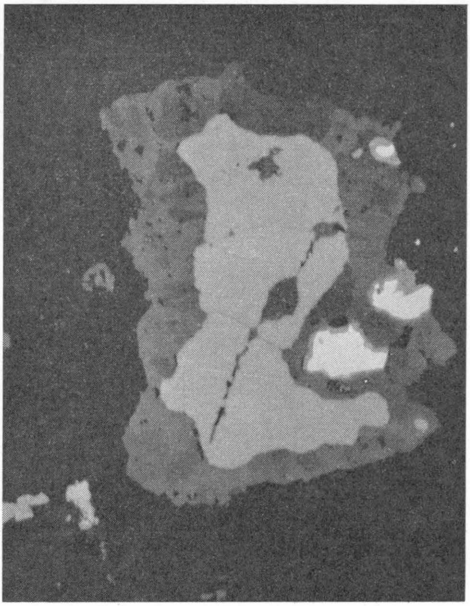

Fig. 14.

Fig. 11.

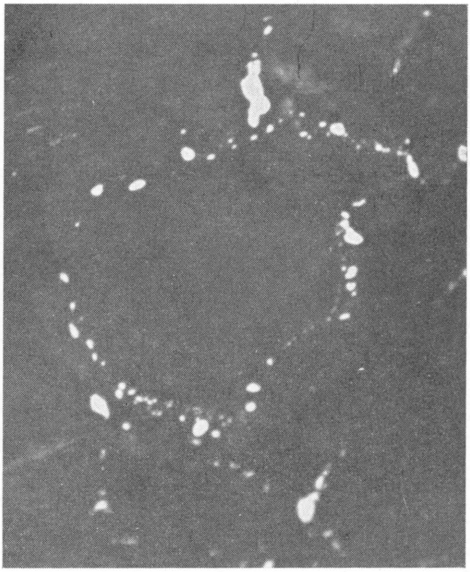

Fig. 13.

Fig. 11. Ilmenite with corona of sphene (reflection pleochroism). Storelv. Magnif. 90 ×.

Fig. 12. Ilmenite with twinning lamellae after (1071) and corona of sphene. Storelv. Magnif. 330 ×, oil immersion.

Fig. 13. Old grain boundaries (premetamorphic) in silicate (plagioclase) outlined by ilmenite. Storelv. Magnif. 330 ×, oil immersion.

Fig. 14. Ilmenite (light grey) with corona of sphene. White are grains of pyrite with limonite rim. Storelv. Magnif. 90 ×.

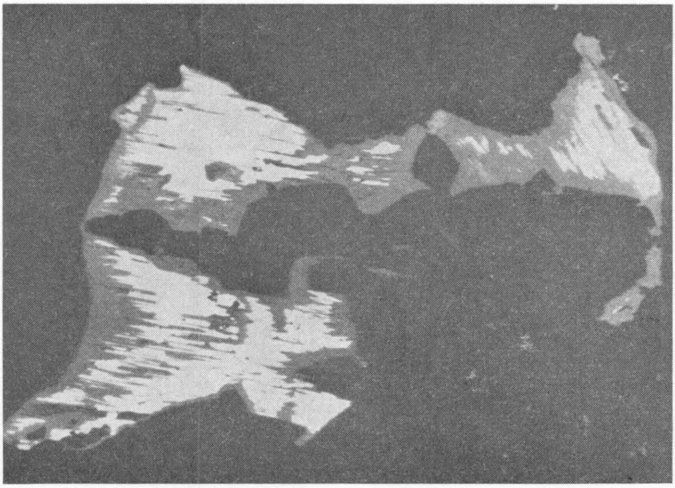

Fig. 15. Pyrrhotite (white) replaced by limonite following (0001)-directions. Gangue is black. Storelv. Metagabbro. Magnif. 250 ×, oil immersion.

small relics of the original ilmenite are present, embedded into extensive areas of sphene (Fig. 11).

In the few cases where primary magmatic pyrite was enclosed in ilmenite, alteration of pyrite to limonite proceeded contemporaneously with the formation of sphene from ilmenite (Fig. 14).

Ilmenite-hematite and hematite-ilmenite do not occur in the Storelv gabbro.

b) Magnetite

is present in subordinate amounts only. No intergrowths with ilmenite have been observed.

c) Sulphides

are less widespread than in the Breivikbotn gabbro. Pyrrhotite, pentlandite and chalcopyrite are lacking completely in many sections. Pyrrhotite has been affected intensively by oxidation, which follows the (0001)-directions. Frequently only small relics of pyrrhotite are preserved (Fig. 15). Decomposition of pyrrhotite first produces fine-grained aggregates the mineralogical composition of which cannot be determined microscopically. X-ray powder diagrams, however, show that marcasite and pyrite are the essential constituents (Ramdohr, 1960). These aggre-

Fig. 16. Limonite in botryoidal textures along fissure. Light grey grains are sphene. Storelv, Metagabbro. Magnif. 330 ×, oil immersion.

gates are altered into limonite (goethite, α-FeOOH, and lepidocrocite, γ-FeOOH). The basal directions of the original pyrrhotite can sometimes still be recognized in the limonite The "Zwischenprodukt" (intermediate product) which Frenzel (1955) describes as frequently forming before pyrite-marcasite aggregates develop from pyrrhotite, has not been found in the specimens investigated. Pentlandite, which occurs as small lamellae in pyrrhotite, has also been affected by these oxidation processes; and part of the gabbro's original Ni-content has been removed: This perhaps explains the low values for Ni (40–70 ppm) determined in samples of Storelv gabbro.

Pyrite can frequently be observed and with a few exceptions, is of secondary, hydrothermal origin. There are, however, a few fresh primary pyrite grains in the Storelv gabbro; though most of them have been altered into aggregates of α – and γ – FeOOH.

Transport of Fe in late stages of the rock's history is further illustrated by the widespread occurence of limonite in thin layers along cracks and fissures (Fig. 16). Limonite has frequently been deposited in botryoidal textures.

Summarizing the above data, it is obvious that the ore mineral paragenesis of the strongly sheared Storelv gabbro has been affected by post-magmatic alterations (i.e. during metamorphism) much more than the Breivikbotn gabbro. This resulted in

a) Formation of large amounts of sphene from ilmenite.
b) Large-scale decomposition of sulphides and removal of Cu, Ni and Cr.

The lack of magnetite in the Storelv gabbro, however, may be ascribed to primary differences in the ore mineralogy of both rock types. No supporting evidence (as relic textures) is available for the possibility that magnetite should have been destroyed by oxidation. This feature may perhaps reflect subtle differences in the composition of the original magmas.

Conclusions.

The study of the field relationships, petrology and geochemistry of the Breivikbotn and Storelv gabbros indicate the following sequence of events:

1) First phase of folding (F 1)
2) Emplacement of gabbros and associated ultrabasic rocks during the closing stages of the early movements.
3) Almandine amphibolite facies regional metamorphism with accompanying granitization.
4) Second phase of folding (F 2).

In spite of the fact that the Breivikbotn and Storelv intrusions are broadly coeval, they show certain compositional differences. This is probably due to slight differences in the composition of the respective local magmas and in their crystallization and contamination histories. Further effects are to be expected as a result of differences in the metomorphic modifications of the gabbros. The intensely sheared Storelv gabbro was affected by granitization which accompanied the almandine amphibolite facies metamorphism. This resulted in the partial destruction of the original sulphide paragenesis (pyrrhotite, pentlandite and chalcopyrite) which is well preserved in the Breivikbotn gabbro, not affected by granitization. Accordingly, these processes may be responsible for the lower Cu-, Ni- and Cr-values found in the Storelv gabbro. Ilmenite has largely been altered into sphene.

The granitization of the Storelv gabbro has been responsible for the increase in the amount of biotite, andesine and K-feldspar, and possibly explains the high values of Zr, Rb and Ba.

Acknowledgements.

We would like to thank Prof. S. E. Hollingworth, Prof. B. C. King and Dr. H. Bjørlykke for the constant interest they have taken in our work and for their help and advice. The trace element determinations have been carried out at the Mineralogisk-Geologisk Museum, Oslo (B. A. S.), at the Mineralogisches Institut, University of Münster/Westphalia (E. F. S.) and at the Geochemistry Department, Imperial College, London (A. Z. Smith and R. Berlin). We are indebted to Prof. T. F. W. Barth, Prof. H. Harder and Dr. J. R. Butler for kindly providing the respective facilities. Dr. D. M. Ramsay has discussed many of the problems with us in the field and has most generously allowed us to use some unpublished data. We would like to thank Miss Rose Thomas, University College London, for the chemical analyses. Drs. J. R. Butler, S. H. U. Bowie, R. W. R. Rutland and M. K. Wells kindly read the manuscript and made valuable suggestions. The investigation was made possible by grants from the Central Research Fund of the University of London.

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