

# PETROLOGY OF THE HYLLINGEN GABBRO COMPLEX, SØR-TRØNDELAGE, NORWAY\*

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The Hyllingen gabbro complex is a layered intrusive sheet lying in the eastern central Trondheim region. It is the southern part of the greater Fongen massif and is composed of a variety of rocks, ranging from ultrabasic to alcalic and acidic differentiates. The petrography and mineralogy of the various rock types are dealt with. The structure of the complex and its layered nature is described. Ten chemical and modal analyses of the rocks are presented from a traverse across the gabbro. The differentiation products show a combined 'normal' layered and a calc-alkaline trend caused by an initial high  $p_{H_2O}$  in the original magma and/or a high  $TiO_2$  content.

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The Hyllingen gabbro complex lies in the Haltdalen district in Sør-Trøndelag, Norway, and forms the southern part of a greater intrusive complex, the Fongen gabbro massif, in the eastern part of the Trondheim region. This complex stretches northwards from Haltdalen to the Meråker district – a distance of about 40 km – and has a width of 5–10 km (Fig. 1). The Fongen gabbro massif is the largest basic intrusive complex within an intrusion zone extending from the Tynset area through the Røros district and Haltdalen to Meråker. The intrusion zone comprises a variety of gabbroic rock types – from larger bodies of relatively unaltered gabbros and norites (the Trongabbro, the Øyungen-gabbro, the Eidet-gabbro and the gabbros of Fongen) to smaller bodies of meta-gabbro which occur frequently in the Røros district.

The earliest account of the Fongen massif was given by Hørbye (1861) and the first petrographical description of the Hyllingen gabbro was given by Möhl (1877). The layered nature of the complex was pointed out by Homan (1890) from the Tydal area. Later descriptions of the Fongen massif were given by Törnebohm (1896), C. W. Carstens (1920) and Vogt (1947). A more detailed petrographical study was given by Kisch (1962) from the Tydal region.

The Hyllingen gabbro complex is named after the mountain Hyllingen between Tydal and Haltdalen. The complex intrudes a series of Palaeozoic metasediments and metavolcanics which were folded and metamorphosed during the Caledonian orogeny. The general geology of the supracrustals was

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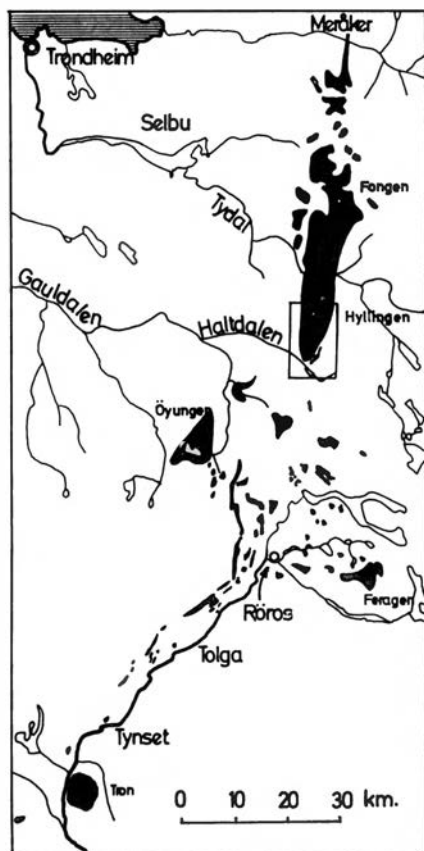


Fig. 1. Key map showing the distribution of gabbros (in black) in the eastern Trondheim region and the Hyllingen area (inset frame).

given by Nilsen (1971). They suffered thermal metamorphism when the complex was intruded (Birkeland & Nilsen 1971).

The present paper deals with the structure and petrology of the Hyllingen gabbro complex. An account of its geochemistry and differentiation trend will also be given. Ten chemical and modal analyses are presented of different rock types from the complex. Si, Ti, Al, Fe, Mn, Mg, Ca, K, P and Cr were analysed by X-ray fluorescence (Siemens) and Na by flame photometer (Beckman).

Transitions between the different rock units of the complex exist, and in the field a distinction between the different varieties has been difficult to establish. The map of the Hyllingen complex presented in Fig. 2 is based on field mapping combined with powder and thin section studies of about 75 specimens from various parts of the complex.

## Petrography of the complex

### *General outline*

The Hyllingen gabbro complex is a heterogeneous intrusive complex com-

posed of a variety of rock types, varying in composition from ultrabasic to acid and alcalic types. The following principal rock types are distinguished:

Ultrabasics (olivine-serpentine-tremolite rocks), peridotite, olivine gabbro and norite, gabbro, diorite, and monzonite.

The greater part of the complex is made up of olivine gabbros and norites. Transitions between these two types exist – depending on the relative amount of clinopyroxene and orthopyroxene in them.

The ultrabasic differentiates of the Hyllingen complex are of two kinds with respect to their mineralogy and their mode of occurrence. They are olivine-serpentine-tremolite rocks and magnetite-ilmenite peridotites. The former will be referred to in the following as ultrabasics – the latter as peridotite. The ultrabasics occur in minor amounts close to the western border of the complex as thick lens-shaped bodies. To the east, towards Skjelåfjell a layered sequence of peridotite and olivine gabbro occurs (Fig. 4). Primary banding from a few cm to several metres is an outstanding feature of this zone. The sequence grades into more massive, homogeneous olivine gabbros, and the eastern part of the complex is mainly composed of leuco-gabbros and diorites which on Jensfjellet grade into monzonitic varieties.

Swarms of quartz-monzonite occur within the mica-schists immediately to the east of the main complex and are thought to be the final differentiation products of the complex.

Generally, the complex has a layered structure. Its basic and ultrabasic differentiates occupy the lower and western parts, grading upwards and eastwards into the more acid and alcalic units. A schematic W-E section through the Hyllingen complex is shown in Fig. 3.

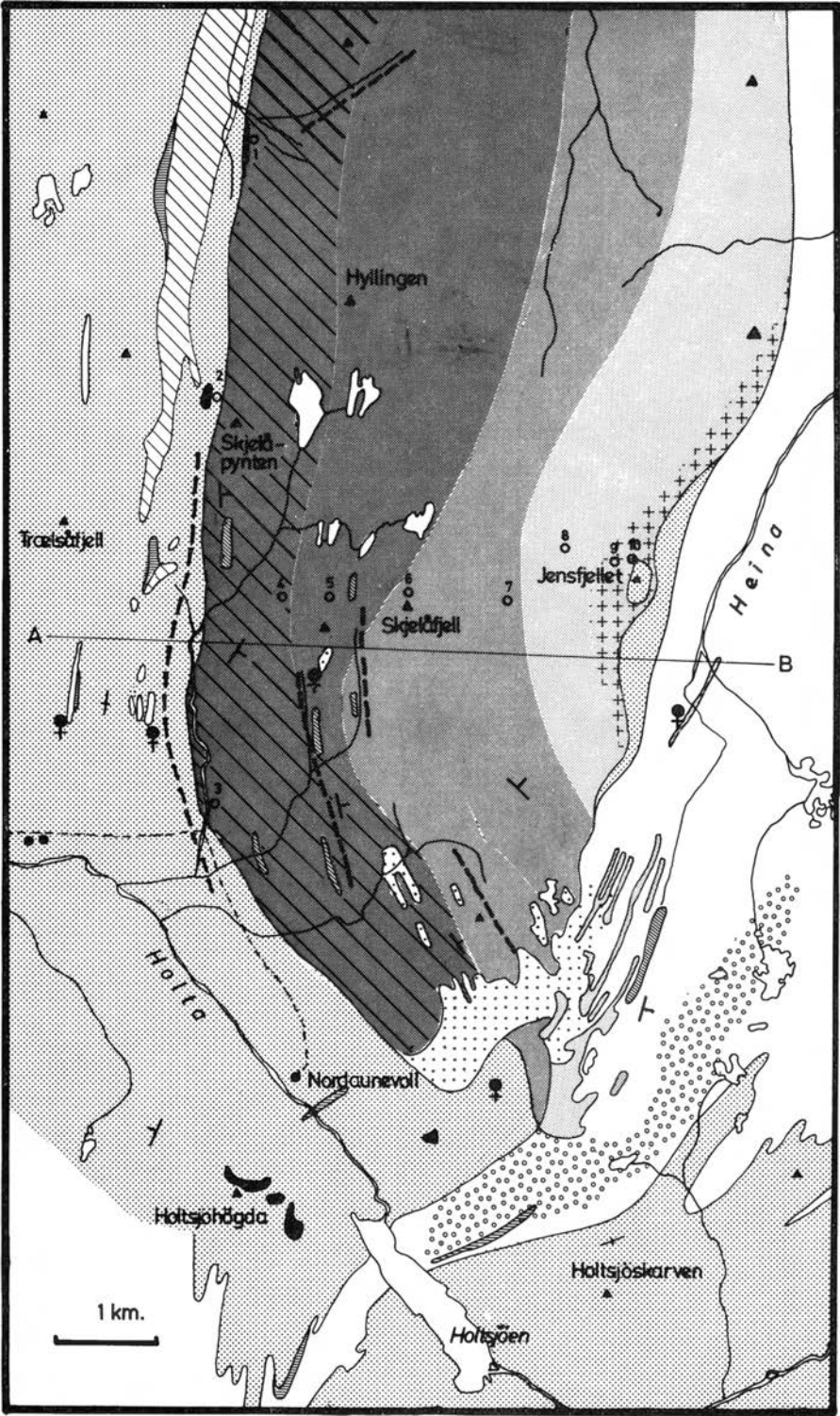
Flaser-gabbro and cummingtonite-bearing gabbros occur in narrow, N-S-running zones adjacent to minor, flat-lying faults within the complex. The complex is further encompassed and intersected by numerous dikes and small bodies of fine-grained porphyritic amphibolites (porphyrites). Only the greater swarms and bodies of this rock are shown on the map (Fig. 2).

#### *Ultrabasics (olivine-serpentine-tremolite rocks)*

Ultrabasics are exposed west of Skjelåpynten and at Holtsjøgda and occur as small knolls adjacent to the main gabbro massif. The ultrabasics at Skjelåpynten can be classified as pyroxenites and olivine-bearing serpentinites. The pyroxenites are mainly composed of diopside with minor amounts of tremolite, serpentine, talc, green spinel and oxide ore. They grade marginally into olivine-bearing tremolite rocks which constitute the major part of the ultrabasics here.

The ultrabasics north of Skjelåpynten and at Holtsjøgda are completely altered into dense tremolite-chlorite serpentinites. The rocks are medium-grained, massive and are dark green in colour.

The olivine of the ultrabasics is usually poikilitic, being replaced by colourless amphibole and serpentine (antigorite). It has a composition of Fo<sub>84-86</sub>. The opaque accessory constituents are magnetite, ilmenite, chromite and



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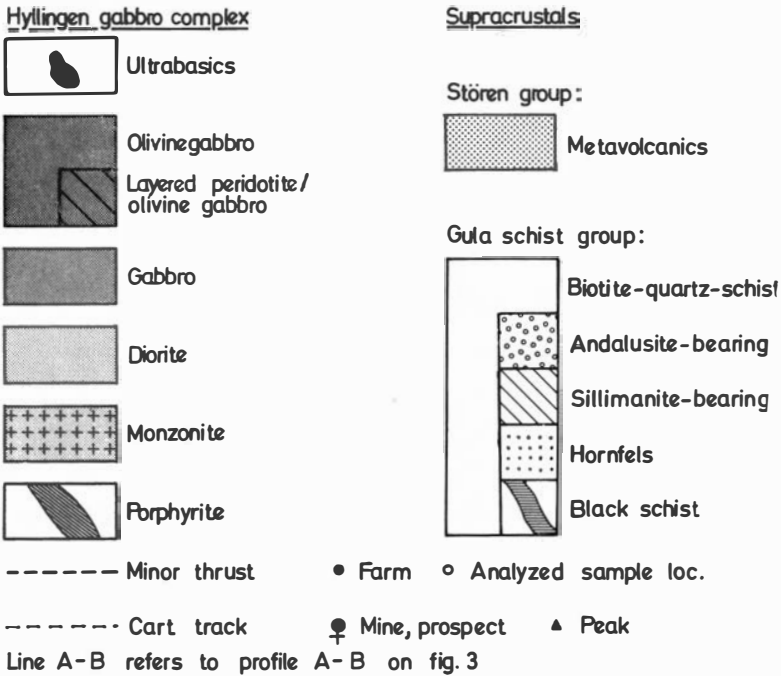


Fig. 2. Geological map of the Hyllingen gabbro complex.

pyrrhotite. The latter often displays small flames of pentlandite. Magnetite occurs either as exsolved myrmekitic intergrowths with olivine or as single grains – often as a mantle around some chromite individuals.

Analyses of two ultrabasics from Skjelåpynten area are presented in Table 1.

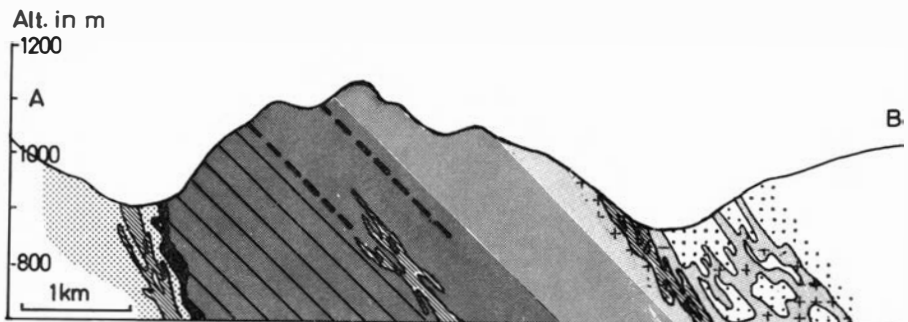


Fig. 3. Section through the Hyllingen gabbro complex (schematic) from Skjelåpynten to Jensfjellet. The section is indicated on the map (Fig. 2).

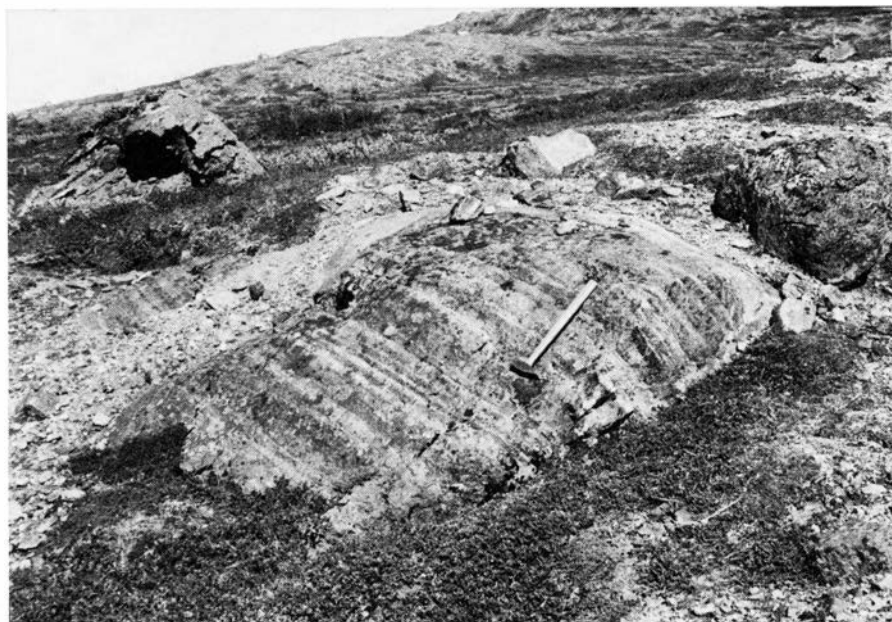


Fig. 4. Banded series of peridotite (dark) and olivine gabbro, N. Skjelåpynten.

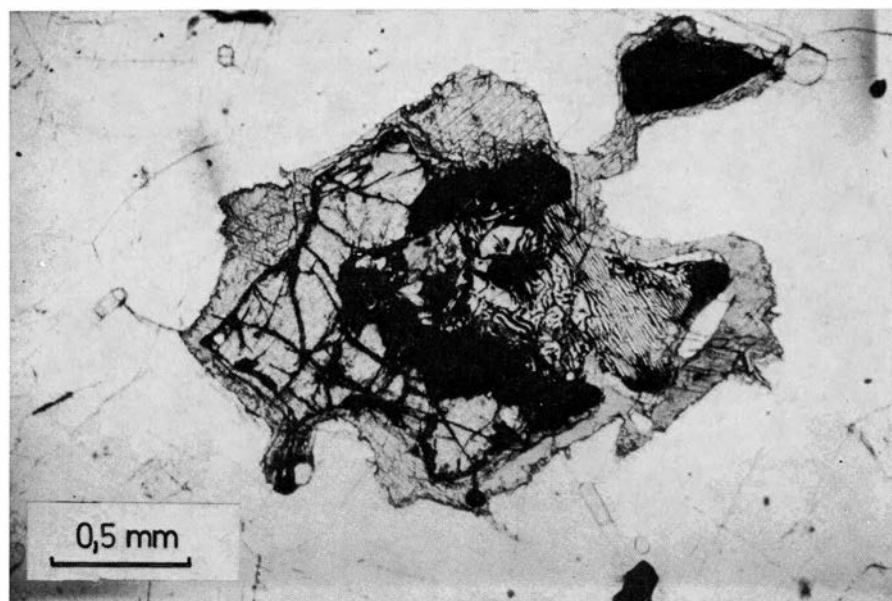


Fig. 5. Magnetite-hypersthene symplectite formed at the expense of olivine (left part of the grain). The grain has a rim of brown hornblende. From olivine gabbro, Skjelåfjell. Plane light.

Table 1: Chemical and modal analyses (wt.% resp. vol.%) of rocks from the Hyllingen gabbro complex. The column numbers refer to sample numbers indicated on the map (Fig. 2). 1: Tremolite-chlorite rock, N. Skjelåpynten. 2: Olivine-tremolite-chlorite rock, Skjelåpynten. 3: Olivine gabbro, Skjelåen. 4: Magnetite-ilmenite peridotite, Skjelåfjell. 5: Olivine gabbro, Skjelåfjell. 6: Norite, Skjelåfjell. 7: Hornblende norite, Skjelåfjell. 8: Cumingtonite-hornblende gabbro, Jensfjellet. 9: Monzonite, Jensfjellet. 10: Monzonite, Jensfjellet. x – accessory constituents in amounts below 1 vol.%.

	1	2	3	4	5	6	7	8	9	10
SiO <sub>2</sub>	45.32	43.65	45.45	35.81	47.31	48.19	52.99	48.45	61.44	62.61
TiO <sub>2</sub>	0.70	0.25	1.25	4.96	2.10	4.09	2.33	2.29	0.45	0.34
Al <sub>2</sub> O <sub>3</sub>	13.29	11.58	14.52	6.79	16.67	14.85	16.99	19.45	17.01	17.12
Fe <sub>2</sub> O <sub>3</sub>	1.81	1.82	4.08	5.34	3.48	2.94	2.18	2.79	1.75	1.45
FeO	12.27	7.33	19.86	25.44	14.08	9.50	11.75	11.02	5.06	3.63
MnO	0.14	0.16	0.82	0.73	0.42	0.20	0.41	0.22	0.17	0.13
MgO	14.83	22.20	1.74	8.82	2.55	7.33	3.14	2.07	0.18	0.08
CaO	9.43	8.26	6.31	8.98	8.78	9.83	7.93	7.15	2.82	1.58
Na <sub>2</sub> O	1.37	0.74	3.67	1.30	3.71	2.50	3.37	4.06	5.12	5.23
K <sub>2</sub> O	0.22	0.21	0.35	0.13	0.25	0.16	0.57	0.58	4.68	7.22
P <sub>2</sub> O <sub>5</sub>	0.08	0.05	0.45	1.74	0.69	0.05	1.04	0.99	0.05	tr.
CO <sub>2</sub>	–	tr.	–	–	–	–	–	–	–	–
Cr <sub>2</sub> O <sub>3</sub>	0.28	0.45	–	–	–	–	–	–	–	–
H <sub>2</sub> O <sup>+</sup>	3.18	3.66	0.47	0.40	0.28	0.45	0.41	1.22	0.34	0.52
H <sub>2</sub> O <sup>–</sup>	0.12	0.14	0.13	0.15	0.10	0.18	0.13	0.12	0.12	0.15
Total	102.92	100.36	98.97	100.44	100.32	100.09	103.11	100.29	99.07	99.91
q	3.10	3.04	3.14	3.54	3.02	3.06	2.99	2.93	2.72	2.66
Plagioclase	–	–	58.4	18.8	64.7	56.8	64.9	63.1	47.7	44.0
Microcline	–	–	–	–	–	–	–	–	32.3	40.0
Quartz	–	–	–	–	–	–	–	–	4.2	3.0
Hornblende	–	–	10.4	5.8	2.6	2.7	9.7	21.8	9.4	3.1
Tremolite	81.5	75.7	–	–	–	–	–	–	–	–
Cumm.	–	–	–	–	–	–	–	5.1	–	–
Clino-px.	–	–	x	25.0	6.9	–	–	–	2.9	2.5
Ortho-px.	–	–	5.2	x	x	33.7	18.4	–	–	–
Olivine	–	8.0	19.8	34.1	20.3	–	–	–	–	–
Biotite	–	–	x	–	–	–	2.2	4.0	2.8	5.6
Chlorite	18.4	12.2	–	x	–	–	–	–	–	–
Apatite	x	–	x	2.7	x	–	1.6	1.2	–	x
Spinel	–	3.0	x	x	–	–	–	–	–	–
Allanite	–	–	–	–	–	–	–	–	x	1.5
Rutile	–	–	–	–	–	–	–	–	x	x
Magnetite	–	x	2.3	4.8	1.9	1.5	–	1.4	–	–
Ilmenite	x	–	2.4	7.4	2.6	5.0	3.0	3.3	x	x
Pyrrhotite	–	x	x	x	x	x	–	–	–	–
Pyrite	x	–	–	–	–	x	–	–	–	–
Chromite	x	x	–	–	–	–	–	–	–	–
Pentlandite	–	x	–	–	–	–	–	–	–	–

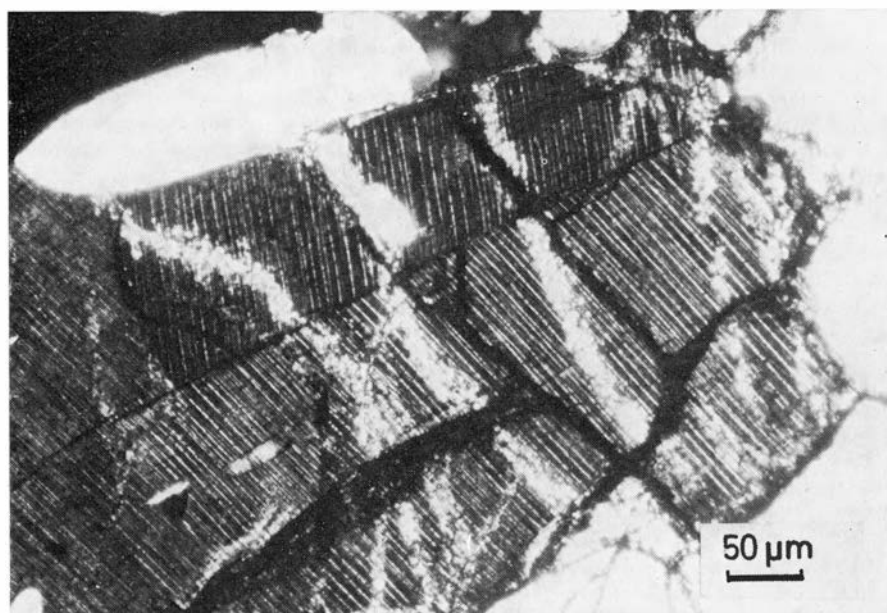


Fig. 6. 'Herringbone-pattern' in augite from olivine gabbro, Skjelåfjell. Crossed nicols.

### *Peridotite*

The western part of the main gabbro massif is composed mainly of dark peridotite layers alternating with more feldspathic olivine gabbros and norites. The layered structure is well exposed on the western slope of Skjelåfjell (Fig. 4). The peridotite layers have sharp borders against the olivine gabbro and are between 1 cm and several metres thick. The distance between the peridotite layers varies – in the western parts they are closely spaced, but to the east the layers may be hundreds of metres apart.

Usually the peridotite is a black, medium-grained and heavy rock with a grain size of 1–3 mm. It is chiefly composed of olivine, oxide ore, augite and hypersthene. Plagioclase and hornblende occur in minor amounts and apatite, biotite, chlorite, green spinel and sulphides are accessory constituents.

Olivine constitutes 30–45 vol.% of the rock and unaltered individuals generally show a high, but variable, iron content. However, in many cases the olivine is altered into a magnetite-hypersthene symplectite as shown in Fig. 5. In the symplectite, magnetite occurs as worm-like spindles, usually oriented more or less parallel the c-axis of the pyroxene. The formation of magnetite-hypersthene symplectite at the expense of olivine is described from various Norwegian gabbros by H. Carstens (1957) and is considered to be a common alteration phenomenon of olivine, formed in a late magmatic stage (Vaasjoki 1955).

Augite is the predominant pyroxene in the peridotites and occurs in varying amounts (10–25 vol.%). It is brownish grey in colour and often shows (001)/(100) parting (diallage). A characteristic 'herring-bone texture' is often



displayed due to numerous thin ( $\pm 2 \mu\text{m}$ ) pyroxene lamellae exsolved parallel to (001), combined with (100) twinning (Fig. 6). An optical identification of the lamellae is difficult due to the extremely fine grain. The orientation parallel (001) suggests an original pigeonite (Poldervaart & Hess 1951). Similar exsolution phenomena in augite is described from the Skaergaard intrusion by Brown (1957) and the (001) lamellae were identified as un-inverted pigeonite (Bown & Gay 1960).

Hypersthene occurs as an accessory constituent of the peridotite, often enveloping the augite or olivine. Brown hornblende usually occurs as homo-axial intergrowths with augite, enclosing olivine and ore.

Oxide ore occurs in relatively great amounts (12–25 vol.%) and comprises magnetite and ilmenite. Magnetite occurs either as graphic intergrowths with hypersthene or as single, anhedral grains – often together with ilmenite.

Plagioclase ( $\text{An}_{60-65}$ ) occurs interstitially as an accessory constituent.

Table 1, column 3 gives chemical and modal analyses of a peridotite from Skjelåfjell.

### *Olivine gabbro*

The peridotites grade into normal olivine gabbros by an increase of the plagioclase content of the rock. In the banded sequence the transition peridotite-olivine gabbro is abrupt, resulting in the conspicuous banding of the western part of the complex.



Fig. 7. Igneous lamination in olivine gabbro, Skjelåfjell.

The olivine gabbros of the banded series and of the more homogeneous parts are yellowish grey to brownish grey in weathering colour, and weather often into dark coloured masses of gravel and sand. No apparent petrographical differences exist between the gabbros in the banded series and in the more homogeneous olivine gabbros. Their mineral components are usually the same as for the peridotites, but the plagioclase content is 55 to 70 vol.%. The mineral occurs as hypidiomorphic laths – commonly with their (010) faces subparallel orientated, thus producing an igneous lamination in varying degree of perfection (Fig. 7). The An-content varies between An<sub>40</sub> to An<sub>60</sub>. The more sodic varieties are usually found in the eastern areas. The individuals are clear and unaltered and show albite, pericline, and carlsbad twinning.

Olivine occurs as small, well rounded and corroded individuals in lesser amounts (15–20 vol.%). The Fa-content is high and the crystals are partly transformed into magnetite-hypersthene symplectite.

The hypersthene/augite content ratio varies throughout the olivine-gabbro complex to a large degree, but generally hypersthene is the predominant pyroxene in the western areas. Thus in the banded series sequence the rock can be classified as olivine-norite whereas in the eastern areas olivine gabbros *sensu stricto* predominate.

Hypersthene mantles usually the corroded olivine crystals or occurs as single, hypidiomorphic grains showing a distinct pleochroism: *x* – pinkish brown, *y* – light yellow, *z* – pale greyish green. Thin lamellae of clinopyroxene are often exsolved parallel (100) to the host hypersthene (the ‘Bushveld-type’ of Hess (1960)). Augite usually envelops the hypersthene.

The ore content is fairly high, particularly in the western parts (3–6 vol.%) and comprises magnetite and ilmenite in roughly equal amounts. The presence of pyrrhotite (in amounts less than 1 vol.%) counts for the limonitic staining of the plagioclase laths along their crystal faces.

Brown hornblende is developed at the expense of pyroxene and may constitute up to 10 vol.% of the rock. A colourless amphibole often fringes radially olivine and hypersthene and may in certain areas replace the minerals totally. This light-coloured amphibole in these varieties is identified as cummingtonite and will be treated in the following section.

Table 1, columns 3 and 5 show the chemical and modal analyses of two olivine gabbros.

### *Gabbro and norite*

The olivine gabbro grades eastwards into olivine-free pyroxene gabbros by a gradual increase of the hypersthene content at the expense of olivine. The transition is smooth, and all transitions between olivine-free and olivine-rich gabbros exist.

The textural relationship is the same for these gabbros – thin-banded and laminated sequences of the olivine-free gabbros can be found (e.g. SE Skjellåfjell) due to regular, rapid variations in the salic/femic constituent ratio.

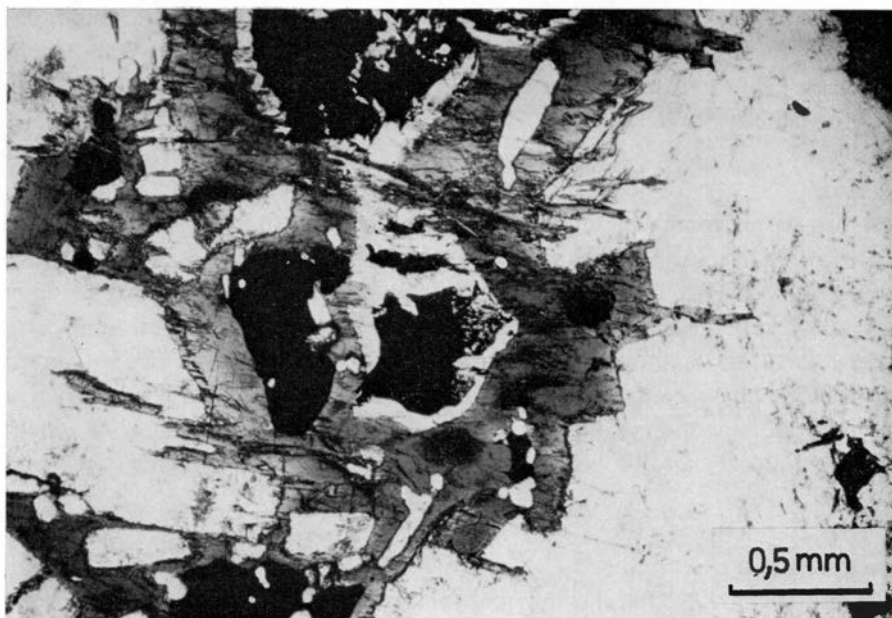


Fig. 8. Magnetite-cummingtonite symplectite (centre) as a relict core within an aggregate of bluish-green hornblende (grey). From cummingtonite-hornblende gabbro, Jensfjellet. Plane light.

The plagioclase content varies between 55–65 vol.% and the An-content is  $An_{35-47}$ . Clouding of the plagioclase is more common in the amphibole-rich varieties.

Hypersthene is the chief femic constituent of the rocks (20–35 vol.%), while augite occurs subordinate. However, amphibolitization is a common phenomenon, and in many places the original hypersthene is completely altered into a felted mass of amphiboles. The alteration of the pyroxene gabbro gives rise to gabbroic varieties which can be classified as uralite norites and cummingtonite-hornblende gabbros.

The cummingtonite-hornblende gabbros are found throughout the complex and are always associated with the NNW-SSE-running shear-zones. In the uralite norites remnants of hypersthene can be found, but in the cummingtonite-hornblende gabbros the pyroxenes (and olivines) are completely altered into zoned amphibole aggregates. An incipient amphibolitization with the formation of cummingtonite can be seen in most of the olivine gabbros.

In the amphibole aggregates cummingtonite forms an inner fibrous core, often containing the magnetite worms from the pre-existing magnetite-hypersthene symplectite (Fig. 8). The cummingtonite shows a high birefringence ( $\Delta = 0.022-0.028$ ) and displays the distinguishing polysynthetic lamellar (100) twinning. A coarser grained, bluish-green hornblende with lower birefringence forms a broad outer rim of the aggregate. Transitions into olive-green and olive-brown varieties exist. Optical data of the different amphiboles can be found in Kisch (1962).

Amphibole-aggregates may constitute up to 30 vol.% of the cummingtonite-hornblende gabbros. Analyses of olivine-free pyroxene gabbros are given in Table 1, columns 6 and 7 and an analysis of a cummingtonite-hornblende gabbro is given in Table 1, column 8.

### *Diorite*

By decreasing amounts of pyroxene and amphibole the gabbros grade into light coloured hornblende diorites to the east. Plagioclase ( $An_{20-35}$ ) constitutes about 70 vol.% of the rocks and bluish-green to olive-brown hornblende is the only femic constituent together with accessory biotite, zircon and oxide ore. Microcline as an accessory constituent has been found in some samples. No analysis has been made of a proper diorite due to a (mis)sampling of a light coloured cummingtonite-hornblende gabbro (Table 1 column 8) which, in the field, generally bears strong resemblance the cummingtonite-free diorites.

### *Monzonite*

Further to the east the diorites grade into monzonitic rocks, which can be studied at Jensfjellet at the slope down to the Heina river. The alcaic rock varieties are medium to coarse grained, massive rocks, light grey to pinkish-white in colour.

Microcline and plagioclase are the major constituents, bluish-green hornblende, clinopyroxene, biotite and allanite occur in minor amounts. Zircon, apatite, leucoxene, magnetite, quartz and sericite are accessory minerals.

The plagioclase laths show faint clouding and have an  $An$ -content of  $An_{04-10}$  (albite). Microcline occurs in nearly equal amounts and has a pink colour in hand specimen in the most eastern parts.

The femic minerals constitute less than 15 vol.% of the rocks and comprise a light greenish-grey clinopyroxene (Na-augite) and strongly pleochroitic blue-green hornblende (ferrohastingsite), usually as a mantle around the pyroxene. Biotite (stilpnomelane) occurs in small clusters.

The nearly equal proportions between microcline and albite, together with accessory amounts of quartz, point to a monzonitic composition in the igneous classification scheme of Streckeisen (1967). Though the classical Monzoni-rock was characterized by a calcic plagioclase together with sodic orthoclase (Brøgger 1895), most of the normal monzonites according to Johannsen (1937) contain sodic plagioclase together with microcline.

Chemical and modal analyses of two monzonites are presented in Table 1, columns 9 and 10.

Swarms of medium to fine-grained leucocratic rocks encompass the eastern border of the Hyllingen complex, intersecting the hornfelses and the schists as sills, 0.5–2 m in thickness. Their occurrence adjacent to the main complex and their special composition points to a close relationship with the gabbro complex and should be regarded as belonging to the rock suite of the complex. Here too microcline and albite/oligoclase occur in roughly equal

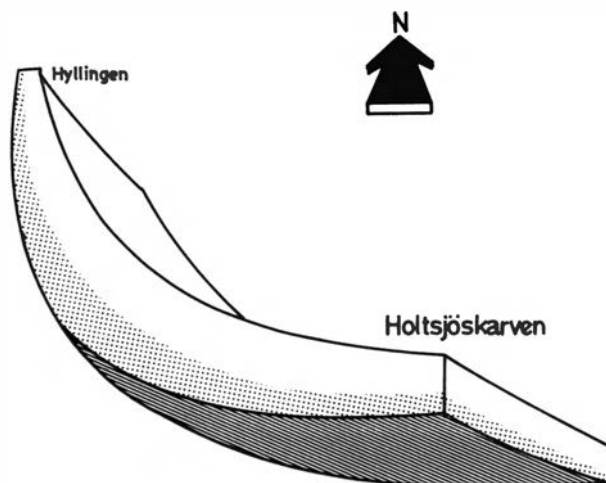


Fig. 9. Schematic outline of the flexed sheet structure of the Hyllingen complex.

amounts, but the quartz content varies between 15 and 20 vol.%. Biotite is the only femic constituent together with accessory garnet and the rocks may be classified as quartz-monzonites or adamellites.

### Structural considerations

The foliated nature of the complex was early recognized by Hørbye (1861). The foliation appears as a sheet-like fracture system (Fig. 7) which is specially prominent among the olivine gabbros and the peridotites. The sheets are from a few cm to several metres in thickness. Transitions into massive rocks without any planar structures are common and in the eastern part of the complex the rocks are usually unfoliated.

Foliation in igneous rocks is common among layered plutons and is commonly referred to as *igneous lamination* – a term first used by Wager & Deer (1939). It is defined as ‘... (a) degree of fissility due to an arrangement of the platy minerals parallel to the plane of layering’. (Wager & Brown 1968, p. 23). The parallel alignment of the plagioclase laths in the laminated gabbros indicates that crystal accumulation took place in a flowing magma (Grout 1918) and alternations with the more massive rock types may reflect variations in the velocity of the original magma currents. This fracture pattern is thus clearly related to the flow pattern of the complex.

In the northern parts the foliation planes point in a NNE–SSW strike direction, turning into a more NW–SE direction to the south. The dip is 30°–40° to the east.

The flat-lying shear zones indicated on the map (Fig. 2) run parallel to the foliation planes and can be recognized as narrow layers of flaser gabbro. Various pegmatites occur adjacent to the shear zones (hornblende pegmatite, plagioclase-biotite pegmatite and quartz pegmatite). One must assume that strain movement has acted parallel to foliation planes in the complex, thus

producing the flaser gabbro. Pegmatite formation may have taken place before the fracturing of the solid rock – in favourable joint zones in the cooling crystal mush (Walker 1953).

In addition to the prominent igneous lamination the complex displays a jointing normal to the foliation planes and parallel to their strike direction (i.e. longitudinal joints in the sense of Balk (1937)). The complex attains a cuesta-like morphology with steep western slopes and gentle eastern slopes.

From the structural observations the complex seems to have a structure of a flexed sheet, lying conformable with the enclosing schistose supracrustals. A thickness of about 3 km is estimated but a thinning of the sheet to the south is recognizable and a concave-convex form is suggested (Fig. 9).

### The layering of the complex

The petrological and structural data reveal that the Hyllingen gabbro complex is layered in nature. A zonal, asymmetrical distribution of the various differentiation products is present (Fig. 3). As can be seen, the mafic and the ultramafic rocks form the western 'bottom' of the complex, while the leucocratic rocks predominate the 'roof' of the sheet. The density of the various rock types is presented in Table 1, and a *gravity stratification* of the complex in the sense of Buddington (1936) seems evident. The effect of gravity stratification can be observed on a smaller scale in the various peridotite bands of the western banded sequence. The bands display a distinct density zoning – the base enriched in oxide ore, followed upwards by olivine and pyroxene, while hornblende and minor plagioclase predominate the upper part of the single layer (Fig. 10). Gravity stratification of this kind is known from the norite bands within the Stillwater pluton (Peoples 1936).

Two principal kinds of layering, viz. *cryptic layering* and *rhythmic layering* are present (Wager & Deer 1939, Wager & Brown 1968, Poldervaart & Taubeneck 1960).

*Cryptic layering* implies a progressive change in the mineral composition of the minerals forming solid solutions. This can be seen in the decreasing An-content in plagioclase throughout the complex – from the peridotites (An<sub>60-65</sub>) through olivine gabbros (An<sub>60-40</sub>), pyroxene gabbros (An<sub>45-35</sub>), diorite (An<sub>35-20</sub>) to monzonites (An<sub>10-05</sub>). No regular variation can be established on the composition of the olivines and the pyroxenes throughout the complex. The optical data from the southern Hyllingen complex combined with data from Kisch (1962) indicate, however, a slight iron enrichment of the orthopyroxenes from the olivine gabbros through the pyroxene gabbros. The orthoferrosilite component is fairly constant throughout the olivine gabbro series (Fs<sub>25-35</sub>) but Fs<sub>65-70</sub> has been measured in certain layers.

A sudden appearance or increase or disappearance of the main mineral constituents is referred to as *abrupt cryptic layering* (Poldervaart & Taubeneck 1960) and is revealed in the peridotite/olivine gabbro sequence by the sudden increase of femic constituents in the peridotite layers already

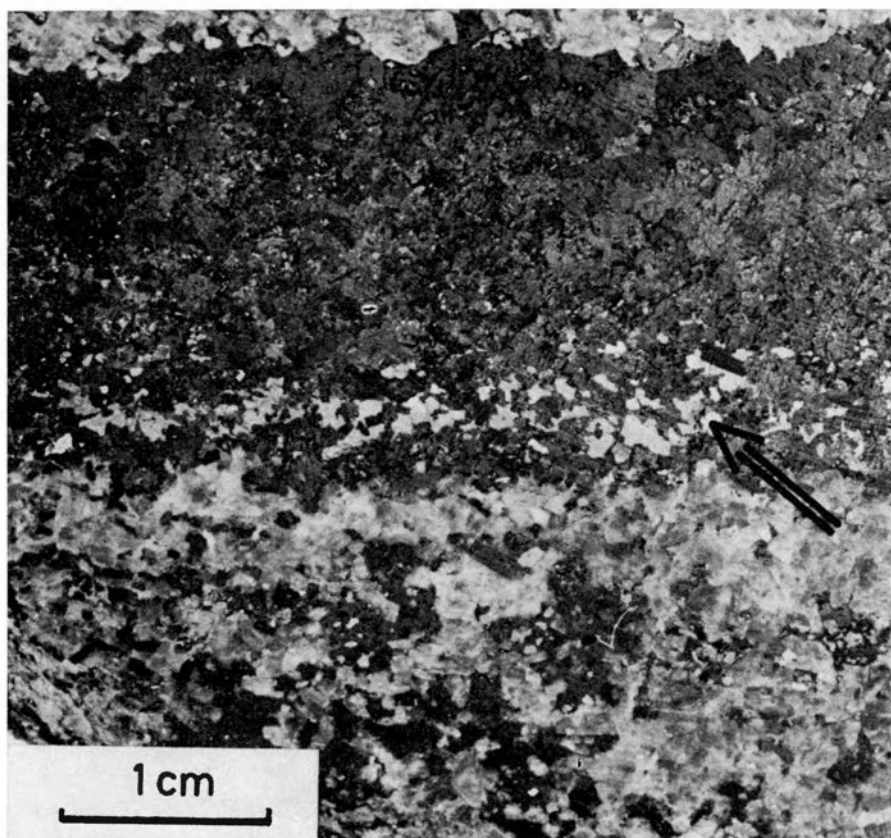


Fig. 10. Gravity stratification within a single peridotite layer, Skjelåpynten. Note the accumulation of magnetite (light grey (arrow)) at the bottom of the layer. Polished slab.

mentioned. The *rhythmic layering* produced by the succession of the peridotite layers within the olivine gabbros is a common feature in many layered intrusions. The phenomenon has been explained as a result of crystal settling, combined with convection currents in the magma (Wager & Deer 1939) set forth by temperature differences in the magma chamber, stoping of country rocks or slumping of the crystal mush. However, rhythmic layering may be produced by a rhythmic differential settling within a non-current magma as described by Coats (1936). However, the igneous lamination present in the sequence points to strong convective movements in the crystal settling during the first and intermediate stages of the differentiation of the magma.

### Differentiation trends

Compared with the well-known layered plutons in the world, e.g. the Bushveld, Stillwater, and Skaergaard plutons, the Hyllingen complex has a somewhat different differentiation-pattern. The ten chemical analyses of the various rock types, combined with the petrographical data should give a

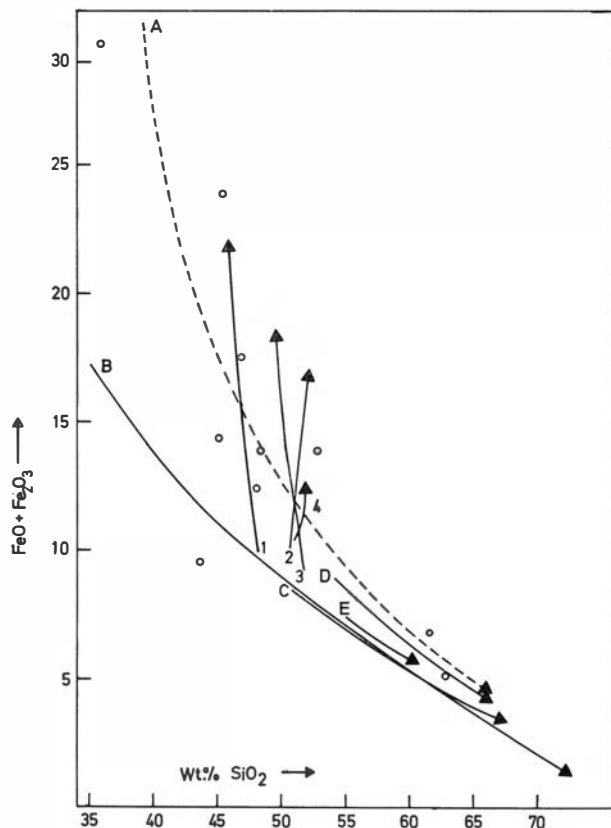


Fig. 11. Curves for magma series.

'Normal' layered intrusion series:

1: The Skaergaard liquids

2: Stillwater

3: Bushveld

4: Palisade diabase

Calc-alkaline series:

A: Estimated trend for the Hyllingen complex

B: Garabal Hill-Glen Fyne complex

C: Cascades series

D: Nockolds, averages

E: Paricutin lavas

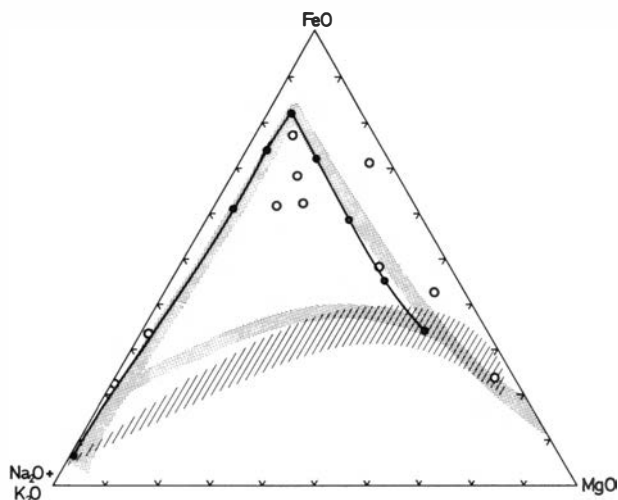
The curves 1-4, C, D and E are from Osborn (1962). Curve B is derived from the analyses of Nockolds (1941). Small circles represent the Hyllingen samples.

brief outline of the differentiation pattern of the complex.

The first differentiates of the complex are Mg-rich ultrabasics which are quantitatively less important. The relatively great concentrations of oxide ore in the peridotites and the olivine gabbros count for the high iron content of these rocks. The iron content decreases while the silica percentage increases going through the gabbros and diorites, and reaches a minimum in the monzonites. An inverse trend can be recognized in the Skaergaard pluton. Here the iron-enrichment during its differentiation gives rise to ferrogabbros with appreciable concentrations of oxide iron-ore as late differentiation products. Osborn (1959) has shown that the two principal different differentiation trends with respect to the iron oxides are due to different oxygen pressures during the crystallization. By a constant or an increasing  $p_{O_2}$  by fractional crystallization of a basaltic magma, magnetite will be an early precipitate. Thus, the rest-melt will be enriched with respect to silica and alkalis. Such a differentiation pattern is described from the Guadalupe complex in California by Best (1963). On the contrary, by low or decreasing oxygen pressures the iron will mainly remain in the ferrous state, fixed in the femic silicate constituents. By differentiation an enrichment of  $Fe^{++}$  in the rest-melt will produce the ferro-gabbros of the Skaergaard type.



Fig. 12. FeO-MgO-(Na<sub>2</sub>O+K<sub>2</sub>O) diagram of magma series from Poldervaart (1949). Grey – the Bushveld series, closely ruled – the Garabal Hill-Glen Fyne Complex, solid line – the Skaergaard series. Small circles – the Hyllingen samples.



The two different reaction series were presented in a later paper (Osborn 1962) with examples from known rock-series. In Fig. 11 the iron content is plotted against the percentage of silica in the two rock series designated by Osborn (op. cit.) as the 'normal' layered intrusion type and the calc-alkaline series. Plots of the ten Hyllingen analyses reveal a trend quite similar to the calc-alkaline series. However, the great scattering may indicate different paths of differentiation during the middle stages of crystallization of the magma. Evidence of different  $p_{O_2}$ -conditions according to Osborn's model during the differentiation of a layered gabbro was shown for the Pleasant Bay gabbro by Bickford (1963).

The Hyllingen samples clearly show a trend comparable with the Skaergaard and the Bushveld trends when plotted on an AFM diagram (Fig. 12). Thus it must be concluded that an interplay between the two differentiation trends may have acted during the crystallization of the Hyllingen complex. The  $p_{O_2}$  was sufficiently high to produce iron-rich early cumulates, but not so high as to oxidize all the ferrous components of the iron-rich magma. A 'normal' Skaergaard trend may have acted during the middle stages of solidification as shown on Fig. 12, but the depletion of most of the iron from the magma at an early stage can explain the quartz-bearing monzonitic late differentiates of the Hyllingen complex.

In addition to a high oxygen pressure the high TiO<sub>2</sub>-content may have been responsible for the early iron enrichment. As stated by Cornwall (1951), a high TiO<sub>2</sub>-content takes FeO from the magma to form ilmenite rather than having the FeO combine with SiO<sub>2</sub> to form pyroxene.

In orogens an intruding basaltic magma will assimilate water which is responsible for a constant oxygen pressure by the dissociation  $2H_2O \rightarrow 2H_2 + O_2$  which will increase by increasing temperature and pressure (Osborn 1959). At least at the early stages a high  $p_{O_2}$  caused by the dissociation of water may have acted upon the original Hyllingen magma, giving rise to the iron-rich

peridotites and olivine gabbros. It is thus doubtful whether the Fongen gabbro can be characterized as a solidified 'dry' magma (Vogt 1947).

By late magmatic processes the water may be responsible for the amphibolitization of olivine and pyroxene and the clouding of plagioclase. The shear zones may have acted as channels for the water vapour, thereby altering the adjacent olivine and pyroxene gabbros into cummingtonite-hornblende gabbros. Amphibolitization of the gabbros and peridotites is most prominent along the eastern margin, altering the rocks into coarse-grained, dark cortlandtites and hornblende pegmatites.

It is doubtful whether the ultrabasic bodies in the west represent primary differentiates of the Hyllingen magma. They may have been transformed into the apparent chlorite or tremolite varieties either by the same late magmatic process or by the post intrusive regional metamorphism which has acted upon the country rocks (Birkeland & Nilsen 1971). According to Kushiro & Yoder (1964), at 8 kb and 1000 °C the mineral association anorthite/forsterite will react according to the scheme:

Anorthite + Forsterite  $\rightarrow$  Enstatite<sub>(ss)</sub> + Diopside<sub>(ss)</sub> + Spinel

By  $p_{H_2O} = 10$  kb the association produces the assemblage diopside<sub>(ss)</sub> + amphibole + spinel (Yoder & Chinner 1960). Thus, high pressure conditions during the intrusion may have been responsible for the olivine-tremolite spinel associations of the ultrabasics and the high-grade metamorphism of the enclosing rocks (Nilsen 1971).

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