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PRECAMBRIAN ULTRAMAFIC ROCKS SOUTH OF SERMILIK, FREDERIKSHÅB DISTRICT, SOUTH-WEST GREENLAND

BY

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WITH 36 FIGURES, 4 TABLES AND 2 PLATES

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Abstract

The petrography and both whole rock and trace element chemistry of ultramafic bodies is described. The ultramafic bodies occur in large numbers in the Precambrian south of Sermilik and are associated with amphibolites. Their shapes are secondary, but in many cases the arrangement of both small lenses and major bodies suggests that they had a primary sheet-like form. The original contacts of the ultramafic rocks with the country rocks have not been preserved because they developed reaction zones with their host rocks during metamorphism under amphibolite facies conditions.

The ultramafics have been divided into three main groups. The first group consists of primary serpentinized peridotites and serpentinites, which escaped amphibolization and form the cores of the bodies. The second group includes amphibolized primary ultramafics such as foliated tremolite/actinolite-bearing rocks, which formed at the outer part of the ultramafic bodies as internal reaction zones. The third group comprises biotite hornblende rocks which form the outer reaction zones of the ultramafic lenses and arose from amphibolites or hornblende gneisses and not from the primary ultramafics.

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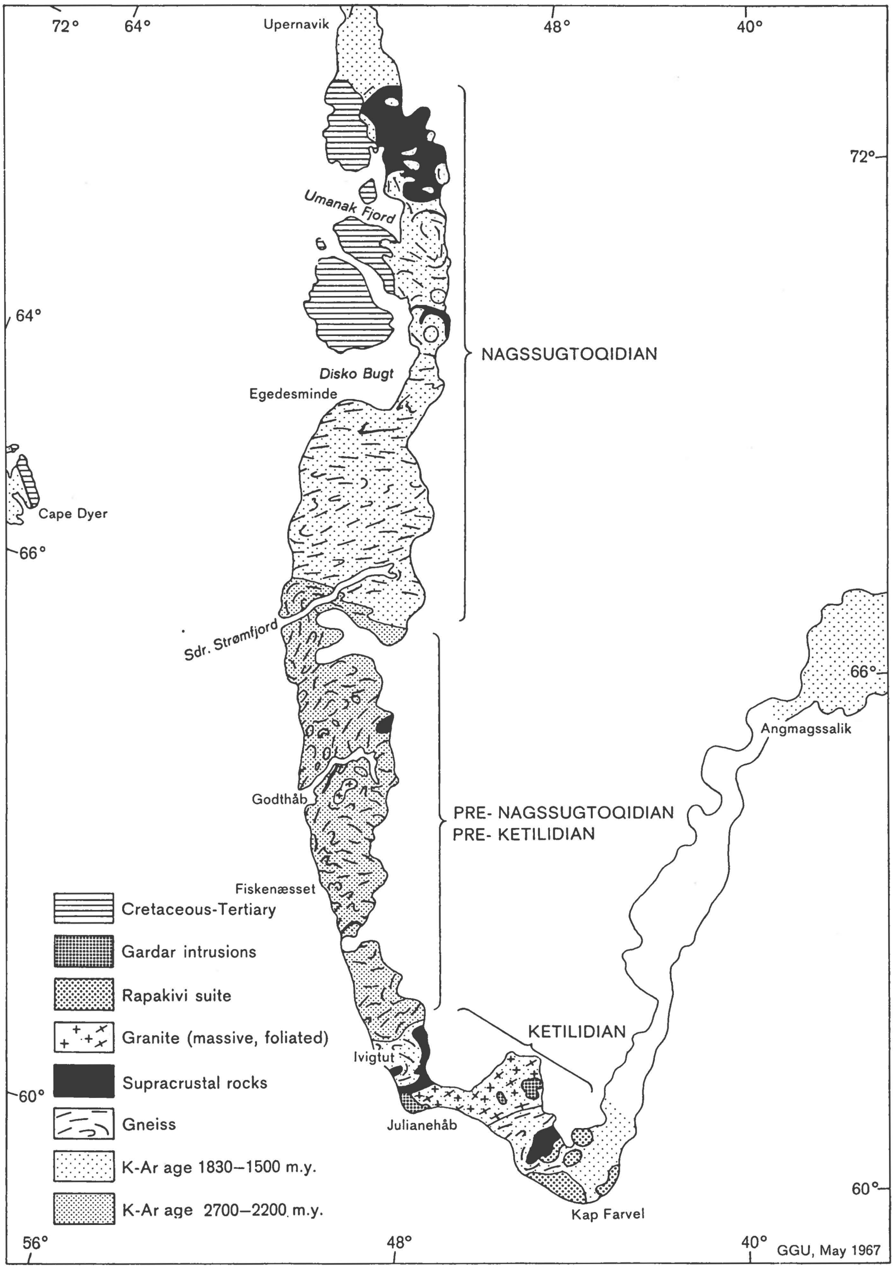

Fig. 1. Simplified geological map of West Greenland (after Pulvertaft, 1968).

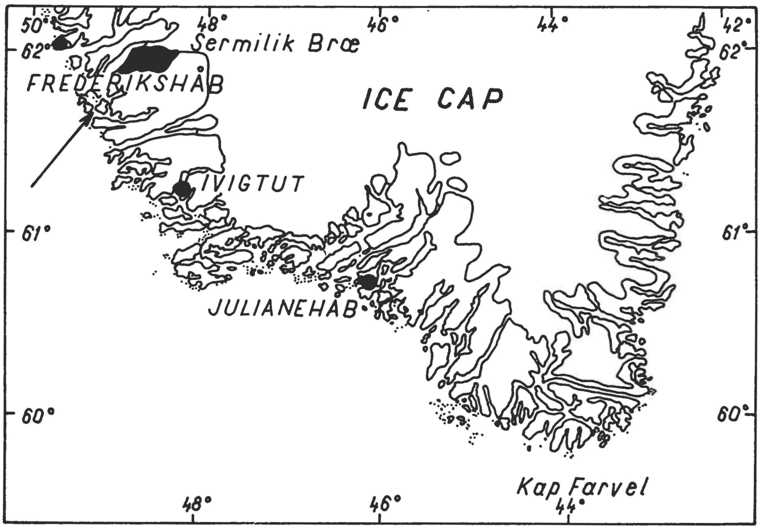

Fig. 2. Map of South-West Greenland with the area described shown in black.

INTRODUCTION

Ultramafic and ultrabasic rocks occur both in metamorphosed and unmetamorphosed portions of the Earth's crust. Their regional geological setting and origin, especially in relation to the upper mantle has been generally discussed and the origin of ultramafics is thought to be in the upper mantle but opinions differ on the depth at which ultramafics and basalts originate (Green, 1969; Kushiro, 1969).

Ultramafic rocks are here defined as rocks containing less than 30 per cent of light minerals and ultrabasic rocks less than 45 per cent of silica.

Ultrabasic rocks occur in both orogenic and cratonic areas but are most abundant in the former. The current division of ultrabasic rocks into Alpine and stratiform types does not seem to be sufficiently accurate. A more modern classification of ultramafic and ultrabasic rocks, in terms of their field associations and tectonic environment, operates with eleven distinct associations (Wyllie, 1969). Ultrabasic and ultramafic rocks providing primary thermal contacts present the only direct evidence of the character and activity of the ultrabasic mass in the Earth's crust. Unfortunately, contacts of ultrabasic rocks are more often of secondary character due to later tectonic movements, or remobilization (reintrusion) of ultramafic bodies, or due to metamorphic processes.

The ultramafic bodies described here were found by the author during geological mapping for the Geological Survey of Greenland (GGU) in the summers 1965 and 1966. The area, which was mapped at a scale of 1:20.000 is approximately 350 km^2 and is excellently exposed. This makes it possible to carry out detailed studies on the geological setting of the ultramafic bodies, their internal structure and especially their border relations.

Rock samples labelled with GGU numbers were studied petrologically and geochemically at the Department of Geology, Charles University, in the years 1967–1970.

Geography of the area

The area investigated is situated about 45 km south-east of Frederikshåb (62° N, 48° W). Its boundaries are formed by marked morphological features. To the west and north the boundary is the fjord Sermilik which has a glacial tongue at its eastern end. The eastern boundary at an altitude of 500 m is formed by a large lake which drains both to an ice-dammed lake at Sermilik Bræ to the north and to the fjord Tasiussaq to the south. The southern boundary is formed by a marked east-west valley from Sermilik to the area north of the head of the fjord Tasiussaq (fig. 2).

The rough land between the ice cap and the coast is dissected by several deep fjords. The height of the fjord walls reaches up to 500 metres. The highest part of the region (1200 metres) has an Alpine high-mountain character.

The landscape modelled by ice is morphologically complex. A prominent erosion level between 500 and 600 metres is the most important feature in the morphology of the area (Mísař, 1969), as it is in southern Greenland in general (Oen Ing Soen, 1965). Above this level, several morphological land types and erosion levels can be observed.

Regional geology

The most recent regional geological division of western Greenland, resulting from the GGU's activity, has been given by Pulvertaft (1968). Western Greenland is built up of three main structural units, younger mobile belts having developed on either side of an older block (fig. 1). The old block (pre-Nagssugtoqidian, pre-Ketilidian) consists mainly of granulite and amphibolite facies gneisses more than 2500 m.y. old. To the north of the old block, the younger Nagssugtoqidian mobile belt gives K-Ar ages from between 1790 and 1650 m.y. The greater part of the belt is formed by gneisses which are regarded as a reworked pre-Nagssugtoqidian basement. The metamorphic rocks of the Ketilidian mobile belts in the south have an age of *c.* 1800 m.y.

Accepting the idea of the existence of an old block culminating in the area of Fiskenæsset and Godthåb, the Sermilik area discussed here belongs to the southern part of this pre-Ketilidian block (fig. 1). The area is not far north of the Ketilidian mobile belt where the pre-Ketilidian basement must have been influenced by the Ketilidian orogeny. Retrograde metamorphism, Ketilidian structures superimposed on the basement gneisses, and the discrepancy in the age of the pre-Ketilidian gneisses characterize the basement near the Ketilidian mobile belt (PULVERTAFT, 1968, p. 102).

Present investigation in the Frederikshåb area

A resume of the results of systematic mapping in the Frederikshåb area carried out by different geologists has been given by JENSEN (1966,

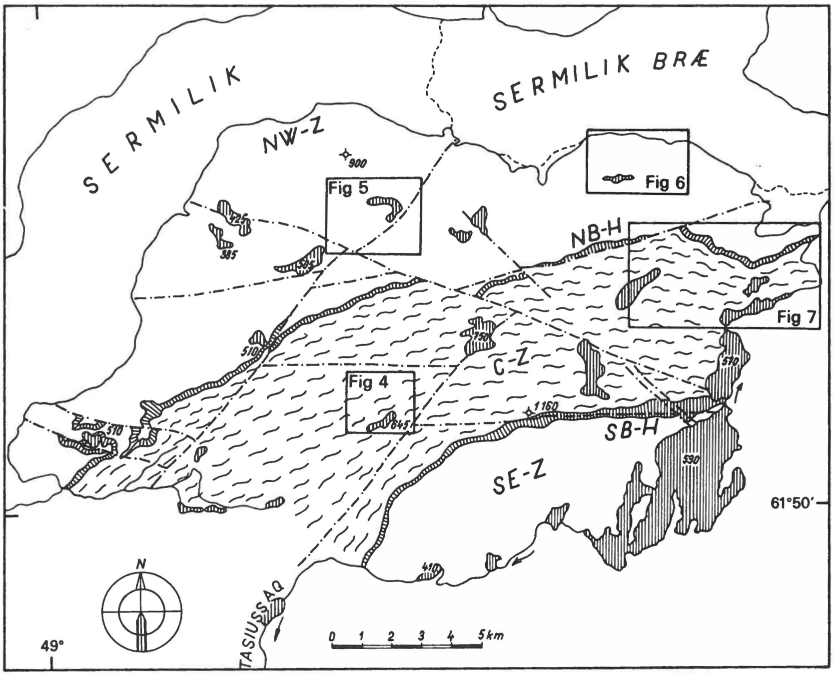

Fig. 3. Simplified geological map of the area south of Sermilik. *NW-Z* north-west zone of biotite gneisses, *NB-H* northern boundary amphibolite horizon, *SB-H* southern boundary amphibolite horizon, *SE-Z* south-eastern zone of biotite gneisses, *C-Z* central zone of hornblende gneisses. The vertical lines indicate amphibolite. The areas of figs 4–7 are indicated.

1968, 1969). Pre-Ketilidian gneisses of widespread occurrence are mainly biotite and hornblende gneisses with amphibolite bands and ultrabasics.

The main geological units in the area around Sermilik, described in several internal GGU field reports (i.e. of Friderichsen, Andrews, Ryan, Masson, Mísař, Thamdrup, Preston, Kalsbeek) may be correlated on a broad scale. The preliminary broad stratigraphy of the region may be defined in the Isorssua area (Masson, 1967). Masson distinguished the following units (from the bottom upwards):

1. lower biotite gneisses
2. brown schists
3. amphibolites
4. upper biotite gneisses passing gradually into 5
5. biotite gneisses with concordant layers of amphibolites
6. hornblende gneisses

The horizons 1 to 4 may belong to an older group, horizons 5 to 6 to a younger one. The author's idea of a large scale synformal structure with hornblende gneiss core was confirmed by the existence of a synformal closure in the Isorssua area. The hornblende gneiss core continues further to the south-west. Biotite gneisses can be followed on both sides of Sermilik.

In the Nigerdlikasik area north of Sermilik Andrews (1968, p. 48) was able to establish a structural chronology. His five folding phases can be correlated with folding phases observed on a mesoscopic scale in the area described here.

GEOLOGY OF THE BASEMENT

On the simplified geological map (fig. 3) only the main geological units and horizons are shown. In succeeding text figures detailed geological maps are presented of selected areas showing the important structures and ultramafics.

Local stratigraphy

The division of the area into three geological zones directly reflects the lithological sequence. The following are the zones from Sermilik to Tasiussaq:

1. north-western zone of biotite gneisses with abundant amphibolite bands and with ultramafics.
2. central zone of hornblende and biotite–hornblende gneisses containing also amphibolites and ultramafics.

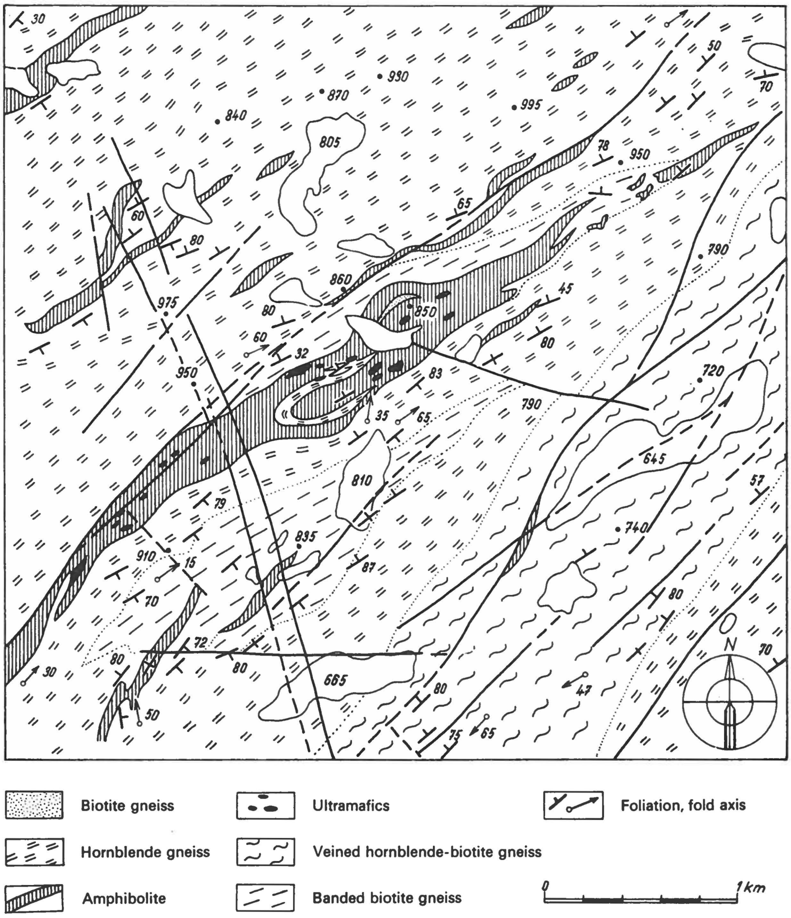

Fig. 4. Geological map of a portion of the central zone of hornblende gneisses. See index map, fig. 3.

3. south-eastern zone of biotite gneisses with less frequent amphibolites and rare ultramafics.

The central zone of hornblende gneisses is bordered by a marked amphibolite horizon, which is called the boundary amphibolite horizon. In the zones of biotite gneisses only few and small layers of hornblende and biotite-hornblende gneisses are encountered. The boundary amphibolite horizon clearly limits the central zone of hornblende gneisses and represents a distinct boundary in the lithological sequence. From a lithological point of view the biotite gneisses are a rather monotonous sequence in contrast to the central zone of hornblende gneisses which is a varied lithological unit (fig. 4).

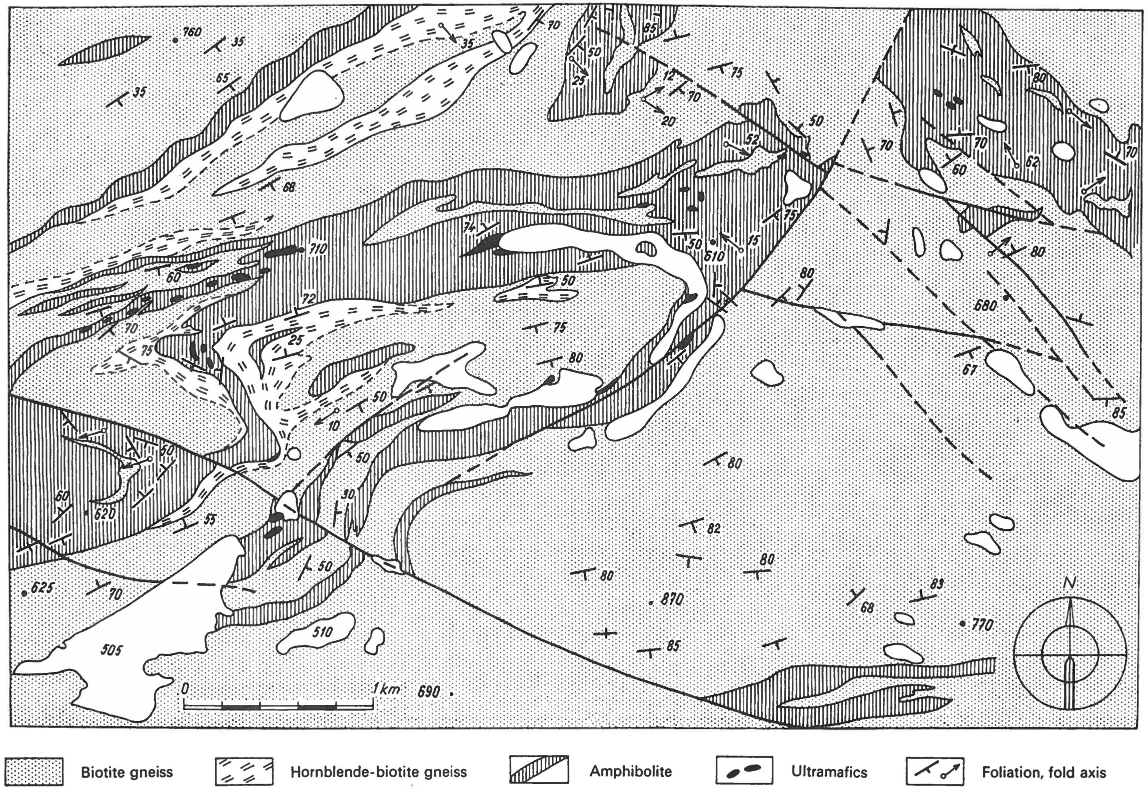

Fig. 5. Geological map of a portion of the north-western zone. See index map, fig. 3.

Several periods of dyking occur in the area. The main object of the paper being the ultramafics, the succession and setting of basic dykes in the basement are not discussed here.

Structures

The main structure of the area is controlled by an impressive, large-scale synform with hornblende gneisses in the core corresponding to ANDREWS' (1968) folding phase F_3. The axis of the synform trending south-westerly in the western part of the area has an E–W trend in the central part and further to the east the axis trends more northerly. But the basement underwent several folding phases. As the greatest part of the area is dominated by the synform it is difficult to establish a complete chronology of folding phases. Deformations older than the large F_3 synform are seen within it, e.g. the gneiss foliation, which seems to be parallel to a primary stratification, follow concordantly round the closure of the large synform as well as some medium-scale synforms and antiforms. Fold structure relics with steeply plunging axes can also be observed in the basement. Isoclinal fold structures may be correlated with the early folding phases of ANDREWS (F_1 and F_2).

After the large-scale synform had been formed a younger folding phase (ANDREWS', 1968, folding phase F_4) with fold axes trending generally north-westerly was superimposed on the older structures. There is very probably a younger folding phase (F_5) in the central part of the synform, producing small-scale open folds with nearly horizontal fold axes trending north-easterly.

The area was also affected by intensive faulting. Different fault systems dissected the area into many separate blocks bounded by fault planes of NW–SE, NNE–SSW, and E–W trend.

Geological setting and forms of the ultramafic bodies

Ultramafic rocks form lenses, deformed sheets or irregular bodies always controlled by structural phenomena of the country rocks in the three geological zones of the area. In general, the ultramafic bodies are conformable, but locally small transgressive bodies can be observed. The present forms and shapes of the ultramafic bodies must be considered as secondary resulting from primary sheet forms. This may be due to different competency of the ultramafics and the country rocks and to mineral assemblages, as mentioned by MÍSAŘ, ŠOLC & RŮŽIČKA (1971).

The ultramafic bodies are of variable thickness from several decimetres up to 100 metres. Large lenses and bodies show rather good foliations while small bodies and lenses are mostly massive (fig. 5).

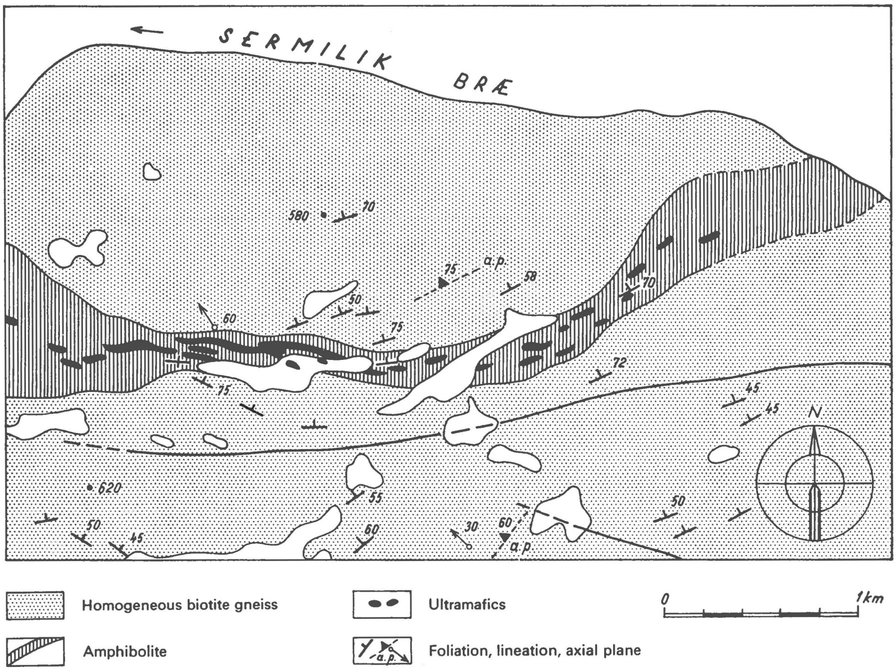

Fig. 6. Geological map of the north-eastern portion of the area. See index map, fig. 3.

The setting and distribution of ultramafic rocks in the area give evidence for their close relationship with amphibolites. More than 98 per cent of the ultramafics are found in amphibolites, very few ultramafics occurring in hornblende and biotite gneisses (figs 5, 6, 7).

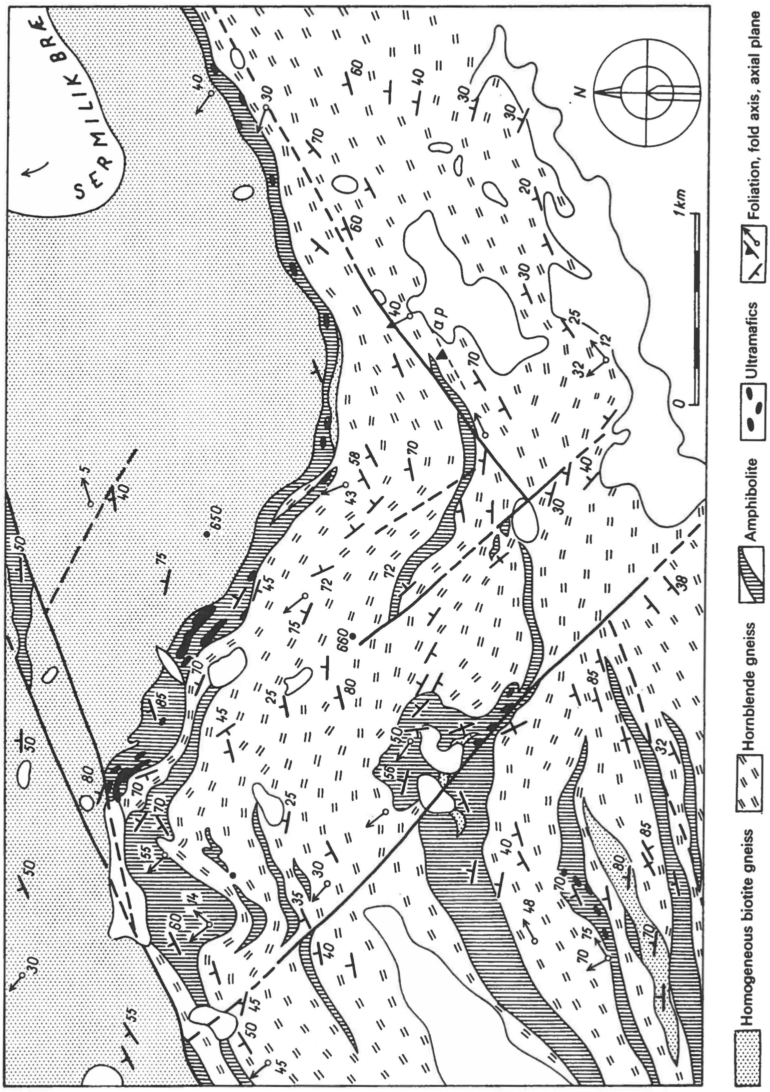

Fig. 7. Geological map showing the northern boundary amphibolite horizon between the north-western zone and the central zone. See index map, fig. 3.

LITHOLOGY AND PETROLOGY

Lithologically it is easy to define the main geological units, e.g. the zones of biotite gneisses, the central zone of hornblende gneisses and the boundary amphibolite horizon. Some difficulties arise in the more detailed lithology and petrological nomenclature, especially for the hornblende gneisses and ultramafic rocks.

Country rocks

The biotite gneisses are predominantly homogeneous, little laminated or banded when pegmatitic material is not considered. Occasionally, the gneisses have the appearance of normal granodiorites or granites. This may be due to local static metamorphic conditions or to a process of intensive homogenization.

Banded gneisses are composed of continuous alternating bands rich in biotite or in quartz-feldspar. The leucocratic bands contain quartz and plagioclase, a small amount of microcline and accessory biotite. The mafic bands are richer in biotite (up to 30 per cent) and occasionally contain a small amount of hornblende.

There are small differences between the biotite gneisses of the north-western and those of the south-eastern zone. In the latter zone, the gneisses are more homogeneous, nearly unfoliated, and hornblende is almost absent in them while the content of plagioclase and especially microcline continues to increase to the south-east.

Biotite gneisses are rather rare in the central zone where hornblende gneisses and biotite-hornblende gneisses predominate. Banded, veined, streaky and agmatitic gneiss types can be distinguished. Their main rock-forming minerals are oligoclase, hornblende, quartz, biotite, with accessory garnet, apatite, rutile, magnetite and diopside. Chlorite, sericite, saussurite and albite are secondary minerals.

The hornblende content varies from accessory to major amounts in the rocks. The foliation is often associated with several stages of both parallel and transgressive pegmatite veins (fig. 8).

The amphibolite horizons and lenses are usually well foliated and banded, but veined and agmatitic types are also found. The average

Fig. 8. Primary banded hornblende gneiss with streaks and lenses of ultramafic metamorphites (hornblendite), and parallel and transgressive pegmatitic veins. From the central zone of hornblende gneisses.

grain size of about 1 to 3 millimetres does not vary much between samples of different amphibolite bands. A characteristic feature of the amphibolites is the saussuritic patterns and streaks in the plagioclases, and the irregular patterns and veinlets of epidote minerals in the rocks.

Quartz has been found in almost all amphibolites forming 1–15 $^0/_0$ of the mineral composition. A special but rare amphibolite type has glomeroblasts of plagioclase up to 1 centimetre.

Small streaks and lenses of peculiar rocks are found in the central zone i.e. garnet-biotite gneiss, biotite-garnet schists rich in tourmaline, quartz-biotite hornfels, and in the same zone a few kilometres south-west of the area described here a cordierite-anthophyllite rock is present (FRIDERICHSEN, personal communication).

In the boundary amphibolite horizon small bands of muscovite-bearing rocks, garnet amphibolites and garnet gneisses and leucocratic fine-grained gneisses are found at some places.

Ultramafic rocks

The terms ultramafic and ultrabasic refer to a mineralogical and chemical classification, respectively. In the paper the term ultramafic used in a descriptive sense is preferred to the term ultrabasic.

Subdivision of the ultramafic rocks

The ultramafic rocks of the area differ in their geological setting, petrography, chemical composition and origin. Three types are distinguished:

1. primary ultramafic rocks
2. amphibolized, primary ultramafic rocks
3. ultramafic rocks formed by metamorphism (ultramafic metamorphites).

Primary ultramafic rocks are found in the form of armoured relics of different size in the country rocks. They are little affected by amphibolization, but there are gradual transitions from them to the surrounding amphibolitized ultramafic zones.

Amphibolized primary ultramafic rocks recrystallized after the necessary element exchange from primary ultrabasic rocks. They usually form small separate lenses or border zones. Larger transformed and well-foliated ultramafic bodies are of greater geological significance.

Ultramafic metamorphites originated by metamorphic differentiation and recrystallization accompanied by local migration and concentration of mafic constituents. The parent rocks may be metamorphosed basic rocks, e.g. hornblende gneisses and amphibolites, more rarely normal gneisses. Ultramafic metamorphites are found as smaller bodies, lenses, irregular patterns and border zones to other ultramafic bodies.

Primary ultramafics

The term primary ultramafic rocks is applied to all ultramafic rocks which were already in existence before the process of amphibolization. The growth of amphibole in the reaction zones and in larger primary ultramafic bodies connected with the formation of distinct foliation planes is a metamorphic process.

Non-transformed ultramafic rocks are quite rare in the area (fig. 9). All ultramafic rocks with less than 10 per cent of amphibole have been assigned to the primary ultramafic rocks. Practically, all primary ultramafic rocks are serpentinized to some extent and the attribute "serpentinized" can be added to nearly all the names. Many of these rocks approach normal serpentinites.

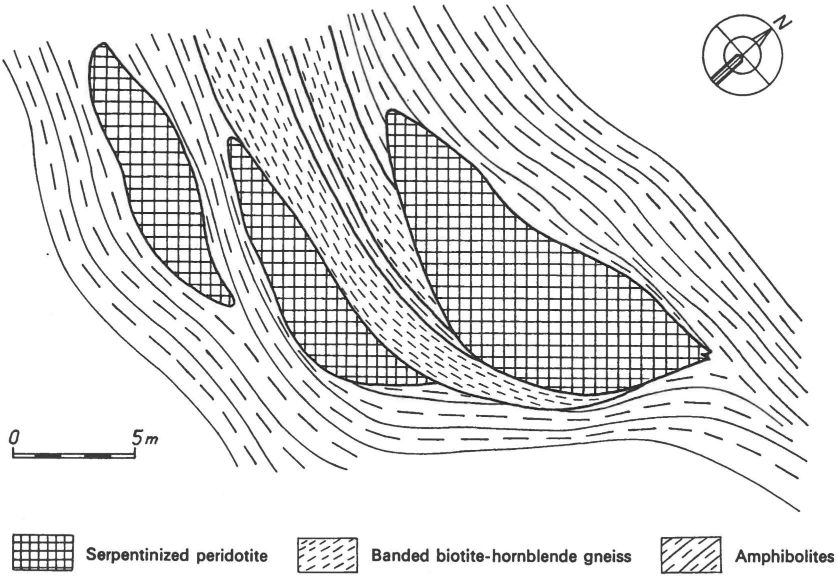

Fig. 9. Isolated lenses of primary ultramafic rocks in gneiss.

Primary ultramafics in the area are in general peridotites with harzburgites predominating over lherzolite, and less frequently dunites. Ultramafics containing plagioclase have never been found in the area.

The dunites are never monomineralic, but always contain some accessory minerals, such as hornblende (GGU No. 72642/2), which define an irregular banding of light green and dark green bands, several centimetres thick (fig. 10). When observed under the microscope, the light green band is made up of a network of polygonal, equigranular olivines with a small amount of hornblende (fig. 11). The olivines (Fo 90 $^0/_0$) are unusually fresh being converted into serpentine minerals only along cracks and fractures or along grain surfaces. The hornblende found between olivine grains is almost colourless, faintly pleochroic, and is little altered. The dark green bands consist of serpentine minerals and magnetite. Their dark green to black colour is due to the large amount of magnetite which forms a nearly continuous central zone within the serpentine band.

Other primary ultramafic rocks are serpentinized dunites. Fresh remnants of olivine survive although they are surrounded by a serpentine matrix extremely rich in magnetite. The fine "loop" structure of serpentinites was transformed locally into a planar, banded and laminated structure.

Serpentinites were collected from a few localities. The serpentinite (GGU No. 72850) contains serpentine minerals, phlogopite and magnetite

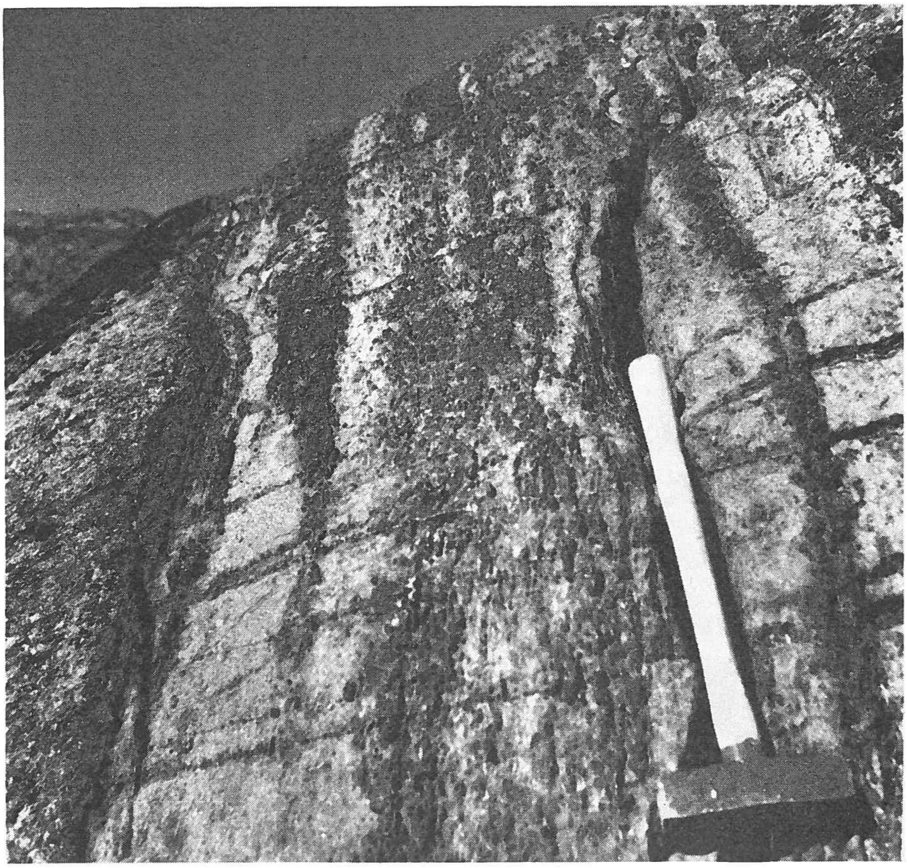

Fig. 10. Planar structures of an ultramafic body of the northern boundary horizon. Peridotites of varying grade of amphibolization alternate. Tremolite crystals in the coarse-grained portion of the body are 3 centimetres or greater in length.

(fig. 12). Phlogopite serpentinite is grass-green in colour, massive and brittle. Under the microscope large phlogopite flakes (up to 1.5 centimetres) or phlogopite aggregates disturb the fine flaky mass of serpentine minerals. Phlogopites are of approximately the same size, rarely rectangular, often with irregular "growing borders". They are fairly pleochroic, colourless to light brown, and almost uniaxial.

The serpentinized harzburgite (GGU No. 72857) is a coarse-grained black ultramafic rock built up of large altered orthopyroxenes surrounded by a serpentine matrix. The uralitic pseudomorphs after pyroxenes still show prismatic shapes and distinct cleavage. The orthopyroxene of a similar yet less altered peridotite-harzburgite (GGU No. 72848) was determined by X-ray diffraction methods as enstatite. In the same rock

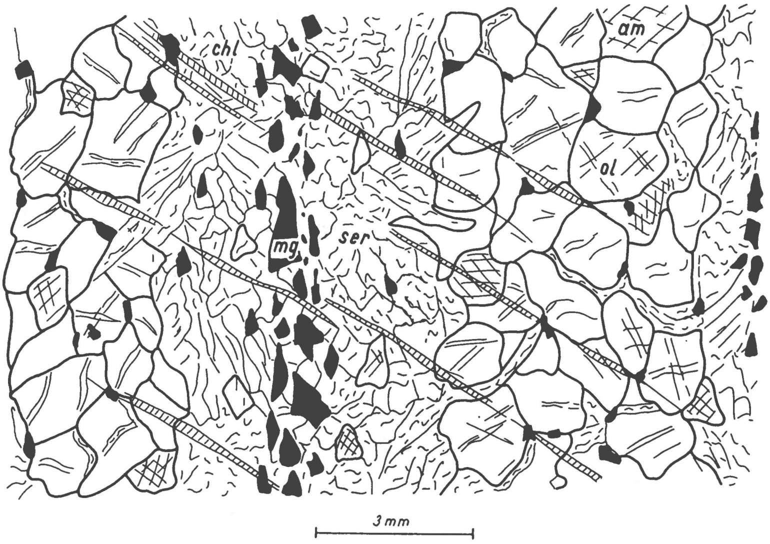

Fig. 11. Texture of banded ultramafic rocks with thin bands of olivine and serpentine. *mg* magnetite, *ol* olivine, *ser* serpentine minerals, *chl* chlorite, *am* hornblende. Ultramafic body in hornblende gneisses of the central zone.

sample antigorite predominates over chrysotile and lizardite as established by the same method.

Optical data of several olivine crystals from primary ultramafic rocks were obtained using the universal stage (table 1).

The 2 V measurements were only made when the angle between both optical axes could be measured directly. The interpretation of the Fo content is according to the diagrams of POLDERVAART (1950).

Table 1. *Optical data of olivine from primary ultramafic rocks*

Sample No.	2 V	Measurements		Average	Fo %
72634	+ 85.5	+ 86	+ 87.5	+ 86.5	93.5
72859		+ 87		+ 87	93
72700	+ 88	+ 89.5	+ 89	+ 89	88
72642	+ 88	+ 88		+ 88	90
72851	+ 87	+ 88	+ 88.5	+ 88	90
72686	+ 85	+ 86	+ 87	+ 86	94

Fig. 12. Surface of a phlogopite-bearing serpentinite with irregular net of asbestos veinlets. A small ultramafic body within biotite gneisses of the north-western zone.

Amphibolized primary ultramafics

Amphibolized ultramafic rocks occur either around cores of primary ultramafics as internal reaction zones, or as irregular patches in the primary ultramafics, as well as small lenses without a primary ultramafic core. The characteristic rock types contain tremolite, actinolite and anthophyllite. In the internal reaction zones these rocks pass gradually into primary ultramafic cores demonstrating that the amphibolized primary ultramafics are transformed primary ultramafic rocks. Frequently actinolite-tremolite rocks alternate with tremolite-actinolite serpentinites or peridotites in the larger banded ultramafic bodies.

Fig. 13 shows a small ultramafic body in hornblende gneisses near the contact with the northern boundary horizon. The relic core of serpentinized dunite is enveloped by zones of different petrographical

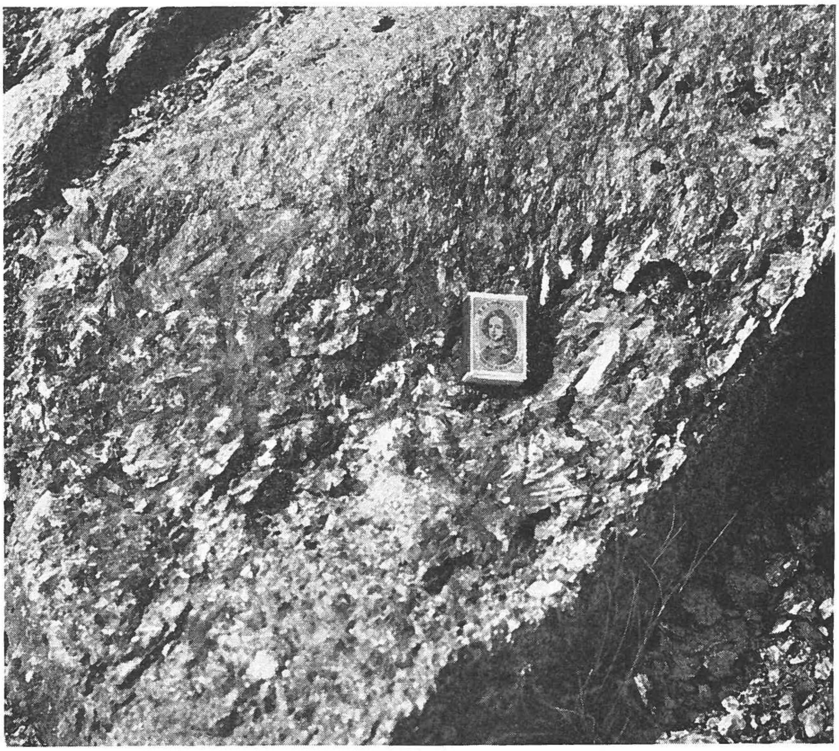

Fig. 13. A coarse-grained anthophyllite rock from the internal reaction zone at the contact of serpentinized dunite with amphibolite. From a small body in the northern boundary amphibolite horizon.

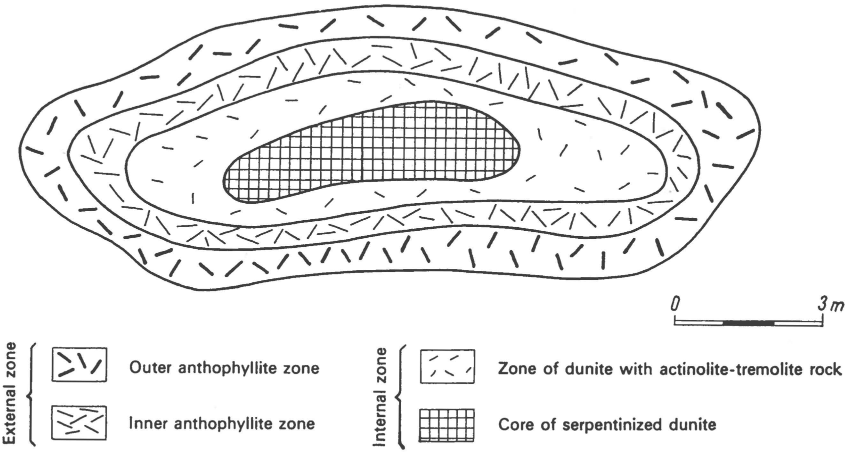

Fig. 14. Scheme of reaction zones between primary ultramafic rock and amphibolite. The coarse-grained anthophyllite zone abuts directly onto the biotite zone. Small ultramafic body in amphibolite of the central zone.

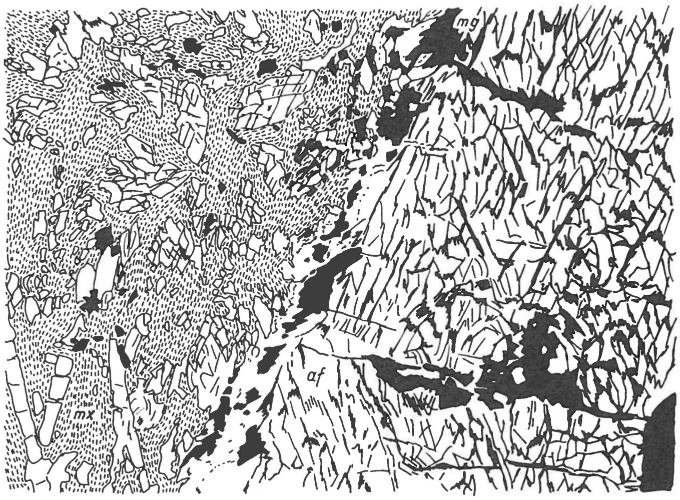

Fig. 15. Texture of coarse-grained anthophyllite rock (drawn from a microphotograph). On the left hand side of the figure minor columns of anthophyllite are surrounded by a fine-grained felty matrix (*mx*). On the right hand side a large crystal of anthophyllite (*af*) contains many crystals of magnetite (*mg*). GGU sample No. 72692/1 from the central zone of hornblende gneisses.

composition: tremolite serpentinite, medium-grained anthophyllite rock and coarse-grained anthophyllite rock (fig. 14).

Large anthophyllite crystals form the outer reaction zone. In the field, coarse-grained anthophyllite rock is very distinct by its gravel formation and grey-green colour. Single prismatic crystals attain the length of 3–5 centimetres (fig. 13). Under the microscope, the idiomorphic,

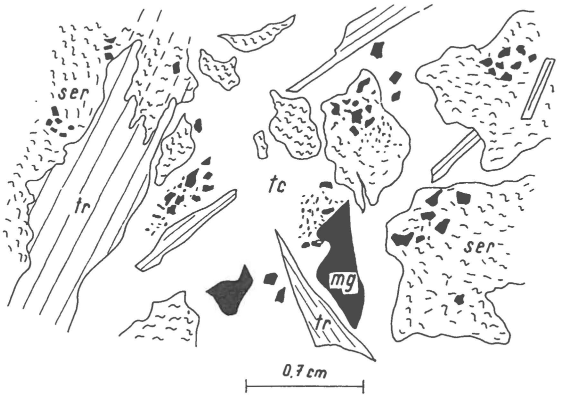

Fig. 16. Texture of serpentinized dunite with tremolite crystals. Tremolite-serpentine minerals and talc are roughly in the same proportion. *mg* magnetite, *ser* serpentine minerals, *tc* talc, *tr* tremolite. GGU sample No. 72692/3 from the central zone of hornblende gneisses.

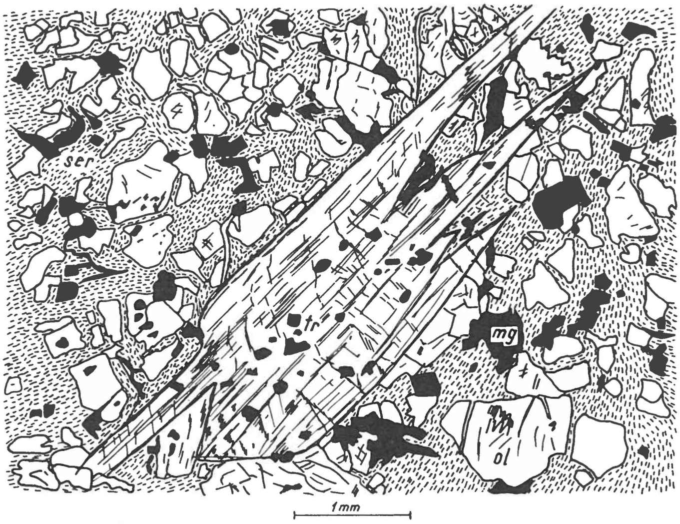

Fig. 17. Serpentinized dunite with accessory tremolite. In the serpentine mass (*ser*) with abundant magnetite (*mg*) numerous relics of olivine (*ol*) are preserved. Tremolite (*tr*) is seen as long needle-like porphyroblasts. GGU sample No. 72692/4 from the central zone of hornblende gneisses.

porphyroblastic shapes of anthophyllite, the aggregates of anthophyllite and fibrous matrix are distinctive of this rock. The fibrous and fine-grained matrix between anthophyllite crystals is difficult to study; however, minerals such as flaky talc, needles of amphibole, magnetite grains, chlorite, serpentine minerals and rare relics of olivine have been found (fig. 15). Optical determinations of several (single) crystals of orthorhombic amphibole have revealed the presence of anthophyllite ($2\ V_\alpha = 84.5°$ in very large crystals, and $2\ V_\alpha = 83°$ in smaller crystals).

The medium-grained anthophyllite rock of the second (inner) zone differs in the grain size and mineral proportions from the rocks of the outer zone. The size of anthophyllite crystals ranges from 0.5 to 1 centimetre. The inner zone is very inhomogeneous and is composed of anthophyllite and talc in varying proportions. Anthophyllites from the inner zone do not differ in optical properties from those of the outer zone ($2\ V_\alpha = 83.5°$, $\gamma = 1.633$, $\beta = 1.615$, Mg component = 88 $^0/_0$).

The rock of the third zone is a tremolitic serpentinized dunite with talc (fig. 16). It passes gradually into the serpentinized dunite containing tremolite, serpentine and talc in approximately equal proportions. The olivines are present as relics. Towards the centre of the body the amount of the serpentine minerals increases and the quantity of talc and tremolite decreases (fig. 17). The olivine contains 95 per cent of Fo ($2\ V_\alpha = +\ 86°$). Optically, amphiboles belong to tremolite with Mg component of 95 $^0/_0$ ($2\ V_\alpha = 87°$, $\gamma: z = 17°$, $O_1: z = 29.5°$).

The central part of the body is rather massive and no minerals can be distinguished with the naked eye. According to the relics of olivine (about 95 per cent of Fo) the rock may be simply called serpentinite or serpentinized dunite.

The mineral proportions in the amphibolized primary ultramafic rock vary irregularly. The amphibole minerals seem to grow at the expense of the serpentine minerals, olivine and pyroxene (plate 1a & 1b). Thus, a continuous series from the primary ultramafic rock to completely transformed (amphibolized) rocks can be seen.

Amphibolized ultramafics also occur as small lenses in amphibolites and hornblende gneisses and as bands, streaks and zones in large bodies of serpentinites or serpentinized peridotites. In these cases, actinolite, tremolite and hornblende predominate over anthophyllite. Megascopically tremolite and actinolite cannot be distinguished from each other, and so the rock is referred to as a tremolite/actinolite rock.

The optical character of some of these amphiboles has been studied with the use of a universal stage and the diagrams of Fediuk (1965).

Tremolite from a banded tremolite serpentinite (GGU No. 58902) represents a variety of nearly 100 per cent of tremolite component ($2\,V_\alpha = 85°$, $\gamma : z = 18°$, $O_1 : z = 28°$).

Actinolite from another banded ultramafic rock (GGU No. 72828) occurs as large distinctly zoned crystals ($2\,V_\alpha = 81°$, $O_1 : z = 31.5°$, Mg component about 75 per cent for the centre; $0_1 : z = 34.5°$ and Mg component about 50 per cent for the thin border zone of the same crystal).

Hornblende from the peridotite (GGU No. 72605) is very rich in Mg and is also zoned ($2\,V_\gamma = 89°$, $O_1 : z = 28°$, Mg component 75 per cent for the centre; $O_1 : z = 24°$ and Mg component 92 per cent for the border zone of the crystal).

Ultramafic metamorphites

These rocks occur as small bands, streaks, lenses, balls and irregular patches of coarse-grained black rocks in hornblende gneisses and amphibolites. The rocks consist of hornblende and biotite with accessory

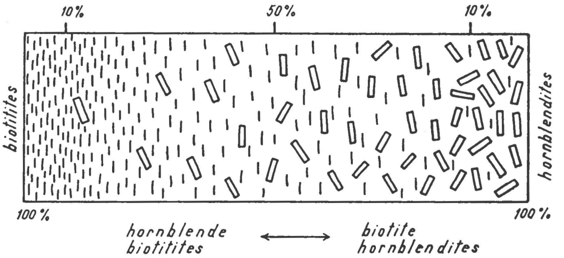

Fig. 18. Scheme of the nomenclature of ultramafic metamorphites. The end members are hornblendite and biotitite, the transitional members are biotite-hornblendites and hornblende-biotitites.

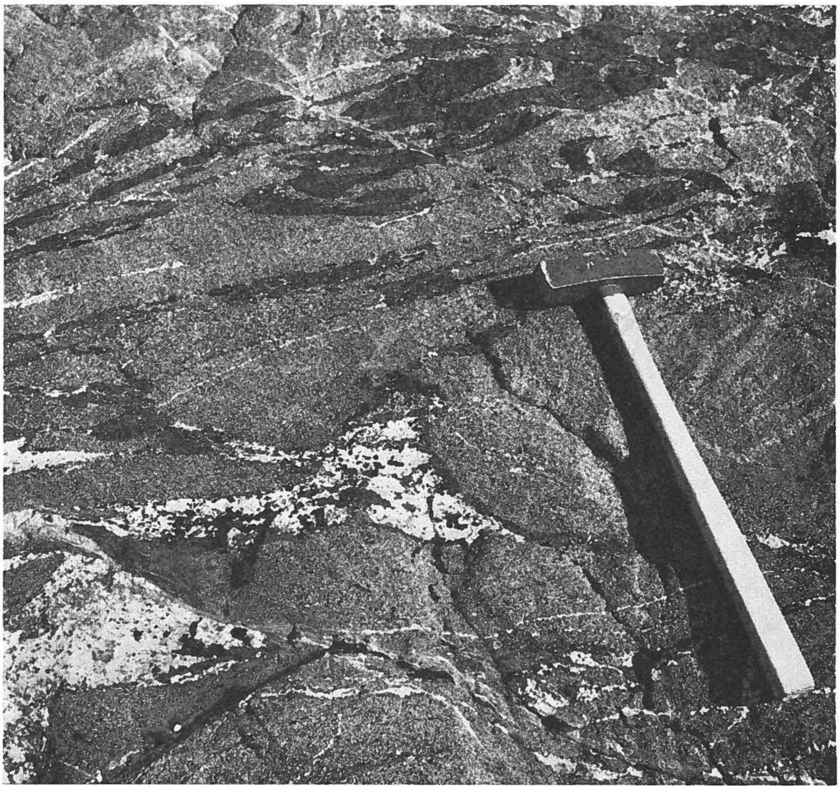

Fig. 19. Example of hornblendite of ptygmatic character in amphibolite. Pegmatitic veins are also present (in the foreground) containing large crystals of hornblende.

magnetite, rutile, zircon and plagioclase. An ultramafic metamorphite containing less than 10 per cent of biotite and more than 90 per cent of hornblende is called hornblendite. Similarly, with the reverse proportions the rock is called biotitite (plate 2a). Transitional members are represented by biotite-hornblendite rocks and hornblende-biotitite rocks (plate 2b and fig. 18).

Rarely, rocks composed of more than 70 per cent hornblende and 30 per cent or less of plagioclase occur as pegmatitic veins of metamorphic origin (fig. 20).

The hornblendites are coarse-grained with hornblende crystals up to 2–3 centimetres long. Although it is enclosed by rocks of a marked planar fabric, the hornblendites are massive or only slightly foliated. Its chaotic orientation of hornblende and mica flakes may indicate mineral growth in local stress shadows in the crest of folds and in corners of brecciated magmatitic structures.

Several types of ultramafic metamorphites were found in the area. One type of hornblendite resembles the altered small primary ultrabasic

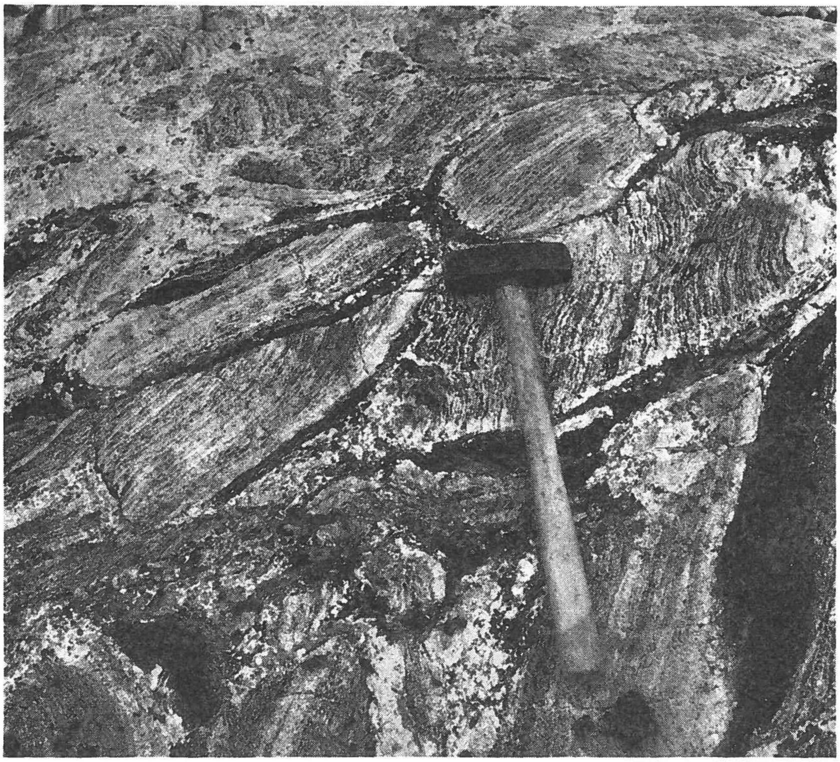

Fig. 20. Hornblendite and hornblende pegmatites cementing larger blocks of hornblende gneisses. The central zone.

bodies, but the massive character of the rocks, the presence of hornblende and biotite, and absence of olivine or pyroxene relics suggest a metamorphic origin.

Another type of hornblendite occurs as "ptygmatic" veins, several centimetres thick; the hornblende is black in sharp contrast to that in the amphibolite host rocks which are green (fig. 19). The occurrence of these hornblendites corresponds genetically with venites in the sense of HOLMQVIST (1916), being "sweat-outs" from the country-rock amphibolites.

Hornblendite occurs in brecciated hornblende gneisses, as "cement" between large fragments of gneiss (fig. 20). The hornblende rocks behave here like metamorphic pegmatites.

Hornblendites and biotitites also occur in zones between basic and acid rocks and such features have been previously described as ultramafic reaction and basic fronts. A classical example is shown in fig. 21 where a thin zone of hornblendite, biotitite and hornblende-biotite rock has

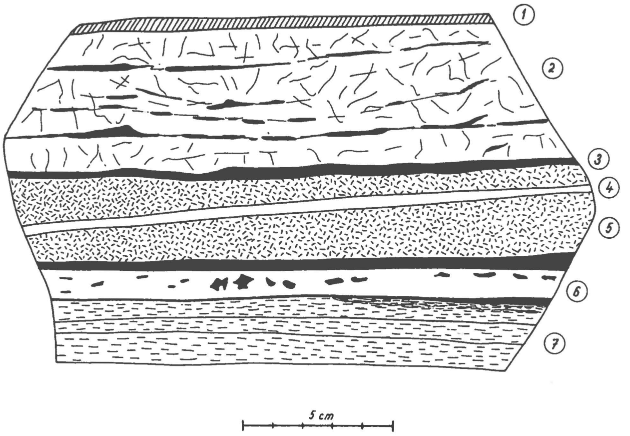

Fig. 21. Complex structure of hornblende gneisses with banding and later pegmatitic veins. *1* coarse-grained, biotite-hornblende rock, *2* pegmatitic vein with streaks of hornblende, *3* "basic front" with hornblendite, *4* discordant pegmatite veinlet, *5* homogeneous hornblende gneiss, *6* pegmatitic vein with hornblende, *7* laminated portion of hornblende gneisses. Field sketch. The central zone of hornblende gneisses.

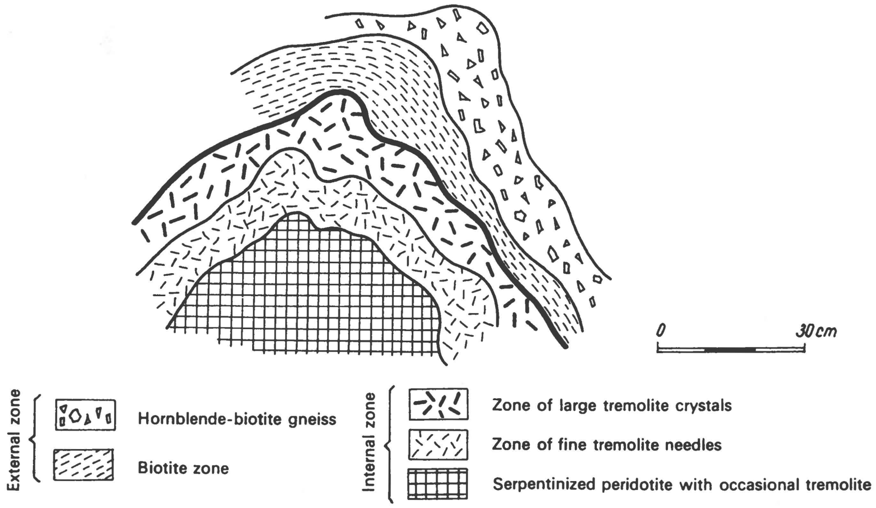

Fig. 22. Simple contact of ultramafic body with hornblende-biotite gneisses (Nos 58901, 58902).

developed where pegmatitic material is in contact with hornblende-bearing bands.

Ultramafic metamorphites are seen around primary ultramafics and amphibolized primary ultramafics as external reaction zones (fig. 22). They are formed from the more acid country rocks and not from the primary ultramafics. The external zones consist of hornblendite, and biotitite and attain a width of between several decimetres and a metre.

The character and optical properties of the hornblendes and biotites in the biotitites and hornblendites do not vary essentially. The hornblende from a coarse-grained hornblendite (No. 72602) was studied on the universal stage. The hornblende displays α almost colourless, β bluish and γ blue-green. According to the optical data $2V_\alpha = 86°$, $O_1 : z = 26.5°$ it might contain 89 per cent of Mg component, (according to FEDIUK'S (1965) diagram constructed from values given by DEER, HOWIE & ZUSSMAN, 1963, p. 296 & 274–281). Refractive indices of the same hornblende crystals are $\alpha = 1.639$ and $\gamma = 1.662$ which indicates an Mg component of 73 per cent. The Fe_2O_3 determined by X-ray spectrographic method is 12.8 per cent and is in good accord with the result of chemical analyses. The Fe_2O_3 of hornblende when related to 100 Mg: $(Mg + Fe^{2+} + Fe^{3+} + Mn)$ documents the content of *c.* 70 per cent of the Mg component in the hornblende. The hornblende of the biotite-hornblende rock (GGU No. 72603) and of serpentinized dunite shows similar chemical and optical properties. The hornblende of the banded gneisses (GGU No. 72801) contains approximately 35 per cent of the Mg component and is probably a sodic amphibole.

The mica of hornblende-biotite rock and biotitite (GGU No. 72604) was determined by X-ray spectrographic method and by refractive indices $\beta = \gamma = 1.604$ as phlogopite with *c.* 15 weight per cent of $FeO + 2\ (Fe_2O_3 + TiO_2)$.

Discussion on the lithology

The unit of biotite gneisses and the unit of hornblende gneisses are separated by the amphibolite boundary horizon. Amphibolite bands with ultramafic rocks occur both in the biotite and hornblende gneisses. The hornblende gneisses, structurally the upper unit in the large scale synformal fold, contain amphibolite horizons and lenses. The amphibolites are thought to be transformed effusive and intrusive basic rocks. The whole unit is interpreted as a mixed sedimentary–volcanic series of a geosynclinal character. This idea (MÍSAŘ, field reports 1965, 1966) agrees with the working hypothesis of KALSBEEK (1970), whose predictions were tested and considered to be correct by KALSBEEK & LEAKE (1970).

In contrast to the mixed character of the hornblende gneisses, the biotite gneisses forming the structurally lower unit have a less varied composition and are thought to be derived from geosynclinal sediments, e.g. greywackes, arkoses and sandy shales although remnants of unambiguous metasediments have not been encountered in these gneisses. The amphibolites here are also interpreted as intrusive and effusive rocks.

The boundary amphibolite horizon may represent a volcanic–sedimentary series of flysch character rich in basic rocks. The thickness of alternating compositional layers varies from several centimetres to several metres. In the case of amphibolite bands the boundary is rather sharp. However, a good transition exists between amphibolites and gneisses differing only in the amount of hornblende.

Ultramafic rocks occur in all these geological units, most frequently in amphibolite horizons. The primary ultramafics are of the greatest importance because they are thought to have been part of a sedimentary–volcanic group before the metamorphic processes and before the amphibolization occurred. Because they have been strongly deformed, no evidence can now be seen to show whether these ultrabasics were emplaced extrusively or intrusively into geosynclinal sediments, or tectonically emplaced as solid lenses. The fine interbanding of ultramafics with basic effusive and intrusive rocks and with mixed volcanic–sedimentary geosynclinal rocks suggests that the ultramafics originated as members of an ophiolitic suite. The problems of the occurrence of series in orogenic belts of different age and in both metamorphic and non-metamorphic states have been extensively discussed, e.g. AUBOUIN (1965), MÍSAŘ (1967), THAYER (1967, 1969), E. DEN TEX (1969), CHALLIS (1969), MAXWELL (1969) and ZOUBEK (1968). Ultramafic bodies can be autochthonous in the sense of AUBOUIN (1965) or allochthonous when uplifted in the form of a rigid ultramafic column by the mechanism of SIMKIN (1967), or tectonically emplaced.

TYPES OF BORDER REACTION ZONING

Following the classical papers of **Read** (1934), **Du Rietz** (1935) and **Phillips** & **Hess** (1936), many geologists have discussed the metamorphic zonation of ultramafic rocks in more detail e.g. **Sørensen** (1952; 1954), **Jahns** (1967), **Mísař** (1969), **Curtis** & **Brown** (1969). They do not discuss primary contacts and associated contact metamorphism as described recently by **Challis** & **Lauder** (1966), **Green** (1967), **Karamata** (1968) etc. but contacts of a secondary nature.

Regional metamorphism was responsible for the transformation of the contact rocks between ultramafic and host rocks. Both the mineral assemblage of the internal reaction zones formed from the primary ultramafic rocks and of the external zones formed from the country rocks reflects the chemical character of the source rocks, the ability and rate of element migration, and the conditions of metamorphic facies.

Border zoning of the ultramafics in the area

No primary contact relations for the ultramafics in the author's area were found. Several mineral assemblages in the border zones show that they have all been recrystallized under amphibolite facies metamorphism.

A summary of these types of metamorphic reaction zones is given in fig. 23. The ultramafic metamorphites forming the external zones, biotitite, biotite-hornblende rock and hornblendite, do not have an ultramafic origin but were formed through the migration of elements during metamorphism. The parent rocks most probably were gneisses and amphibolites which were desilicified during metamorphism.

The amphibolized ultramafics of the internal zones originated from the primary ultramafic rocks, the grade of amphibolization and the kind and size of amphibole varying from place to place.

The boundary between the external and internal zones is knife-sharp and indicates the border of the primary ultramafic body and the country rocks. The boundaries of the external and internal subzones, however, are irregular and transitional. In greater detail, the zones and subzones possess their characteristic structures, e.g. spotted structure in an

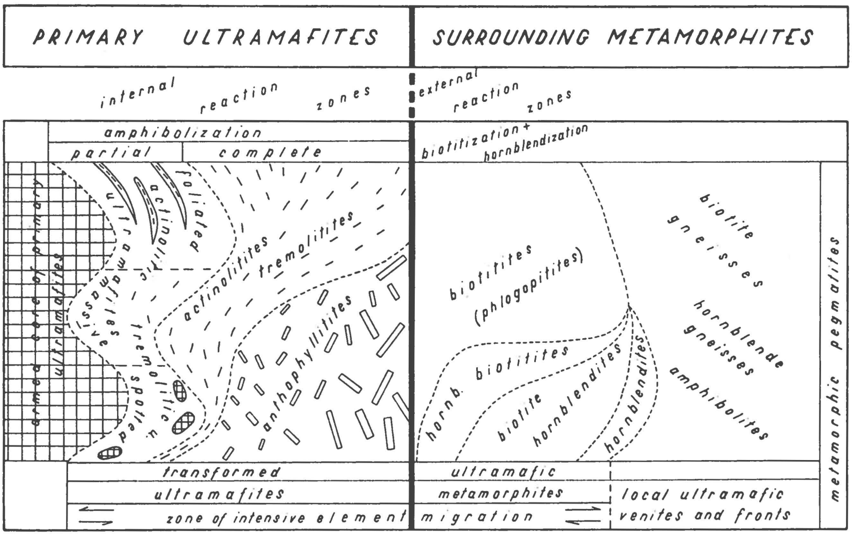

Fig. 23. A scheme of the relationship and distribution of ultramafic rock types in the basement of the area south of Sermilik.

amphibolized primary ultramafic in which small oval islands of the primary ultramafic rocks are surrounded by a matrix of actinolite-tremolite rock (fig. 24).

The sequence of ultramafic metamorphites in the external zones appears to be regular. A biotite zone forms the contact around all the

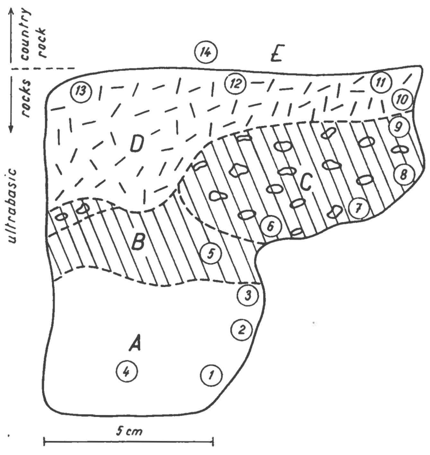

Fig. 24. Internal reaction zones and their inhomogeneity in a hand specimen (No. 72684). *A* dark green serpentinite, *B* fine-grained homogeneous tremolite-actinolite rock, *C* heterogeneous portion of the same zone in which the islands of serpentinite are surrounded by actinolite-tremolite matrix, *D* zone of coarse-grained anthophyllite rock, *E* hornblende gneiss. Numbers 1–14 in circles represent places geochemically analyzed (see also fig. 36).

ultramafic rocks and is well developed where primary ultramafics are in contact with biotite gneisses. Where the country rocks are hornblende gneisses or amphibolites an outer hornblende zone occurs between the country rocks and the biotite zone.

In the internal zones actinolite, tremolite and anthophyllite have crystallized during a strong migration of elements. Anthophyllite only occurs in the first internal subzone at the contact with the external biotite subzone, and it always occurs in a CaO-poor environment. Tremolite/actinolite are more common in the ultramafic bodies, and occur closer to the centre of the ultramafic bodies, and in banded and foliated ultramafics.

Three types of zoning have been distinguished in the metamorphosed ultramafic rocks including the transformed primary ultramafics and ultramafic metamorphites:

1. Zoning with tremolite/actinolite + biotite zones developed when primary ultramafic rocks are in contact with either biotite gneisses or hornblende-biotite gneisses (fig. 23). The external biotite zone is thin. In the thicker internal tremolite-actinolite zone the coarseness and quantity of tremolite/actinolite crystals decrease towards the centre of the ultramafic body. The thickness of the internal zone varies from body to body and the size of the youngest amphiboles also varies within one body. Long thin needles of tremolite (up to 5 centimetres in length) can often be seen at a distance of 10 metres or more from the contact. Tremolite/actinolite also forms bands and streaks in well-foliated and transformed peridotites.

2. Zoning with actinolite/tremolite + biotite + hornblende zones is rather common at the contact between primary ultramafic rocks and hornblende gneisses and amphibolites (fig. 25).
   Usually, the internal reaction zones are monomineralic and consist of actinolite/tremolite crystals, while the external zones are ultramafic metamorphites rich in biotite and hornblende.

3. Zoning with actinolite/tremolite + anthophyllite + biotite + hornblende zones is also restricted to the contacts of primary ultramafics with hornblende gneisses or amphibolites. Typical examples of zoning with anthophyllite rock was mentioned above (fig. 14). The amphibolized primary ultramafics in the internal zones are almost entirely actinolite and anthophyllite; the rocks representing the external zones are biotitite, biotite hornblende rocks, and hornblendite.

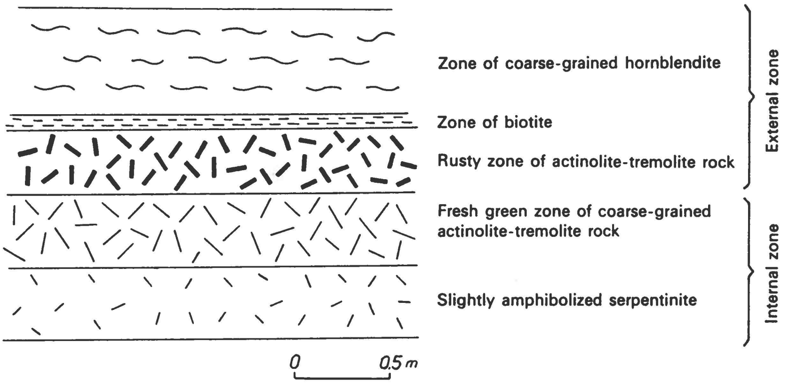

Fig. 25. Contact between primary ultramafics and amphibolites. From the northern boundary horizon.

Minerals such as actinolite, tremolite, anthophyllite in ultramafic border reaction zones have been mentioned by several geologists working in Greenland. Sørensen (1952) reported that anthophyllite commonly occurs where an ultrabasic rock is in contact with pegmatitic material: anthophyllite grew at the expense of hornblende (p. 239). Bondesen (1964) has described ultrabasic xenoliths in a volcanic breccia from Sermersût in which the xenoliths have a distinct zoning with actinolite crystals at the border and a mixture of actinolite + talc + magnetite + magnesite in the centre. Bridgwater & Gormsen (1968) found small ultrabasic bodies in gneisses in East Greenland. The altered centre of the bodies is enveloped by zones of talc + chlorite and tremolite/actinolite.

GEOCHEMISTRY OF THE ULTRAMAFICS

True ultrabasic rocks contain less than 45 per cent of SiO_2, and therefore only some of the ultramafic rocks of this area are ultrabasic. Generally the primary ultramafics have a SiO_2 content of about 45 per cent, the amphibolized ultramafics have a higher percentage of SiO_2 and the ultramafic metamorphites also contain about 45 per cent of SiO_2.

Representative rock samples of the three ultramafic groups have been chemically analysed and the results are shown in tables 2 to 4. Various chemical parameters (C.I.P.W. norms, Zavaritsky values, Köhler–Raaz indices, Niggli numbers) presented in the tables and in diagrams were advantageous in obtaining an instructive picture of the chemical relationships of the ultramafic rocks and of the migration of elements in the boundary reaction zones.

Geochemistry of primary ultramafics

Serpentinites and serpentinized dunites contain roughly 40 per cent SiO_2, 35 per cent MgO and total iron as FeO of 9 per cent (*c.* 43 % SiO_2, 40 % MgO and 10 % FeO (= total iron recalculated water-free)). The lowest SiO_2 content was found in serpentinized dunite of the sample No. 72692/3 34.97 % (40.47 % water-free).

The content of Al_2O_3 is relatively low, 1.6 % on average. The rocks have also low Na_2O and K_2O contents throughout, below 1 %. In some of the analyzed serpentinites the Na_2O and K_2O content is in the order of 10^{-2}.

The TiO_2 content may be of considerable significance for the genetic interpretation of primary ultramafics. In the serpentinites and serpentinized dunites the content of Ti_2O has a range within 0.07–0.43 %. The lowest TiO_2 content was found in the serpentinites with phlogopite. The substantially higher fluorine content (2.62 %) in the sample No. 72850 fully agrees with the phlogopite proportion in the rock.

The content of Cr_2O_3 ranges within 0.10–0.84 %, that of NiO within 0.16–0.60 % and that of CoO does not exceed 0.1 %. Copper occurs as a trace element in the rocks.

The chemical composition of the peridotites varies from one sample to another. The untransformed peridotite rich in olivine (No. 72851) contains a very high amount of MgO (45.95 $^0/_0$, or 46.91 $^0/_0$ water-free) and distinctly small amounts of SiO_2 (39.60 $^0/_0$, 40.42 $^0/_0$ water-free). This representative peridotite has only trace amount of Ti, Na, K and very low contents of Al_2O_3 and CaO while the contents of Cr_2O_3, NiO and CoO remain constant.

Geochemistry of amphibolized primary ultramafics

Slightly transformed serpentinites and serpentinized dunites cannot be easily separated from normal serpentinites and serpentinized dunites in their contents of SiO_2, MgO and even of K_2O and Na_2O. Some differences arise when CaO and Al_2O_3 are calculated. Both oxides are of increasing trend in transformed serpentinites and sepentinized dunites. A very high content of CaO in the sample No. 72639 is in good agreement with the presence of hornblende in the rock. From the chemical point of view (higher content of SiO_2 and lower of MgO) the serpentinites with phlogopite (sample No. 72647) follow rather the trend of transformed ultramafics.

In amphibolized peridotites the content of SiO_2 exceeds 45 per cent (when recalculated water-free), the MgO content is generally lower than that in normal peridotites, serpentinites and serpentinized dunites.

Due to higher CaO content in amphibolized peridotites, on average about 3.5 per cent, actinolite-tremolite $Ca_2 (Mg, Fe^{+2})_5 [Si_4O_{11}]_2 [OH]_2$ is more abundant than anthophyllite $(Mg\ Fe^{2+})_7 [Si_4O_{11}]_2 [OH]_2$.

Strongly amphibolized peridotite with actinolite/tremolite (No. 72849) shows 8.05 per cent of CaO while in nearly monomineralic anthophyllite rock (No. 72692/1) the CaO content is in the order of 0.01 $^0/_0$.

Variations in the FeO/Fe_2O_3 ratio reflect the process of amphibolization. In primary ultramafics proper, Fe_2O_3 exceeds FeO, while in amphibolized ultramafics the ratio is just reverse.

No conspicuous changes can be observed in the proportions of Na_2O, K_2O, TiO_2, Cr_2O_3, NiO and CaO.

The ultramafics of the internal reaction zones (actinolite, tremolite, anthopyllite rocks), represent the product of the most advanced amphibolization. They obey the above-mentioned principles concerning higher content of SiO_2 and Al_2O_3, lower MgO content and, if actinolite/tremolite is present in the rock, higher CaO content.

Geochemistry of ultramafic metamorphites

Because of their content of hornblende and biotite, the ultramafic metamorphites contain high amounts of Al_2O_3. The normal hornblendites contain about 10 % of Al_2O_3, the biotite-hornblende rocks approximately 14 % and the biotitites about 16 % of Al_2O_3. All these rocks have a substantially low content of MgO (15.66–19.33 %) and of the iron oxides, FeO prevails over Fe_2O_3. In the hornblendites the CaO content is uniform at 10 %, in the biotitites the same oxide is of negligible amount. The enhanced Na_2O content in hornblendite and an abrupt rise of up to 8 % K_2O in biotitite fully agree with the chemical formulas of biotite and hornblende. The TiO_2 content of the ultramafic metamorphites is substantially higher than that of the primary and amphibolized ultramafites, and it can even be used as a criterion to separate them.

Chromium, nickel, cobalt and copper occur as trace elements in the ultramafic metamorphites.

Ultramafics related to chemical classifications and systems

The chemical analyses of ultramafics of the area were calculated for different classifications and systems (Niggli, Köhler–Raaz, Zavaritsky and C.I.P.W.). The relationship of the three main rock groups could thus be studied and interpreted in a much easier way. The parameters of the systems used are given in tables 2 to 4 and are plotted in figures 26 to 31.

In the Köhler–Raaz diagram (fig. 26) the primary ultramafics, the transformed primary ultramafics and ultramafic metamorphites occupy distinctly limited fields. The values of $-qz = 30$ and the very high $-(F-fm)$ control the position of the primary ultramafics in the diagram. The plot of $-qz$ for the transformed ultramafics shows the trend of increasing amount of SiO_2 in the rocks, while lower indices $-(F-fm)$ of ultramafic metamorphites reflect the smaller MgO content.

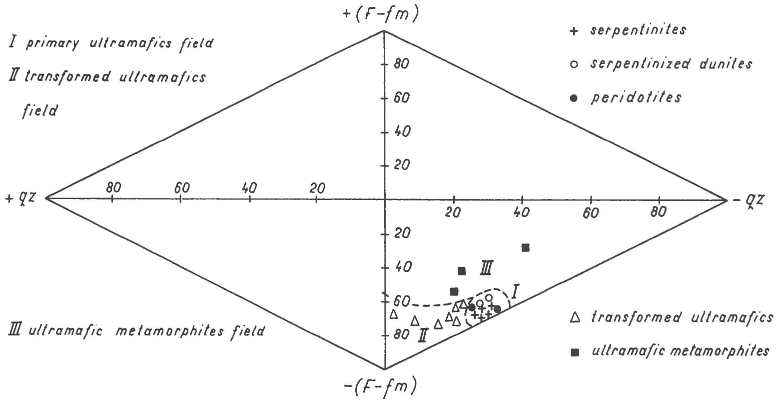

Fig. 26. Plot of Köhler–Raaz indices qz and $(F\text{-}fm)$ in the diagram after Köhler–Raaz.

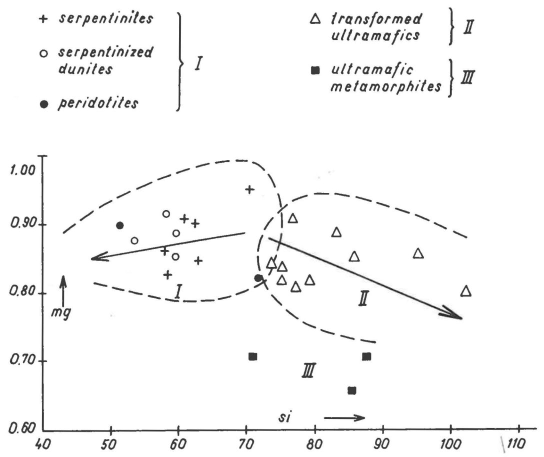

Fig. 27. Plot of Niggli *si* against *mg* of analyzed primary ultramafics, transformed ultramafics and ultramafic metamorphites. *I*, *II* & *III* as in fig. 26.

Clearly separate fields of the primary ultramafics and the transformed ultramafics are shown by a plot of the Niggli values *si* and *mg* (fig. 27). The field of biotitite and hornblende-biotite rock does not overlap the fields of primary and transformed ultramafics. The fields of primary and transformed ultramafics are less well-defined on a plot with Zavaritsky parameters (fig. 28).

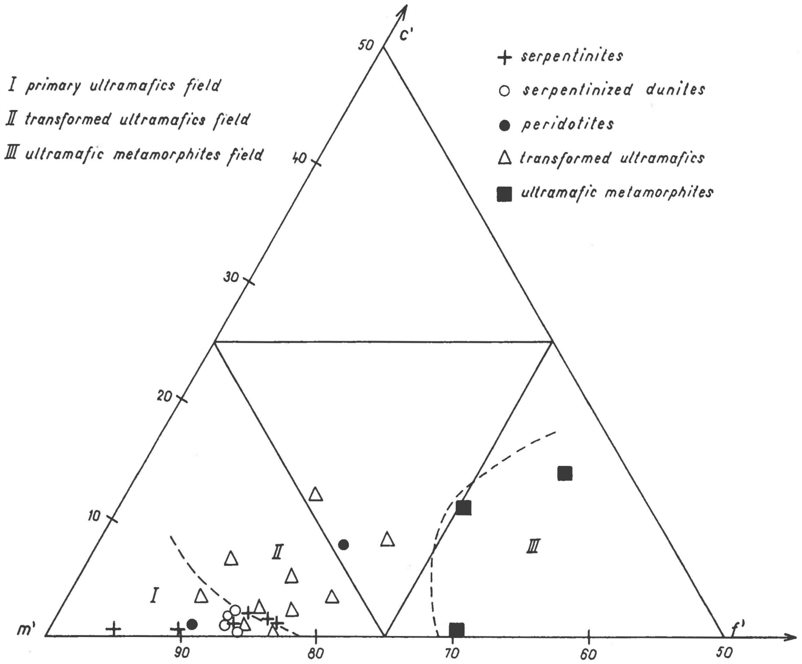

Fig. 28. Plot of Zavaritsky $m' + c' + f' = 100$ of analyzed primary ultramafics, transformed ultramafics and ultramafic metamorphites.

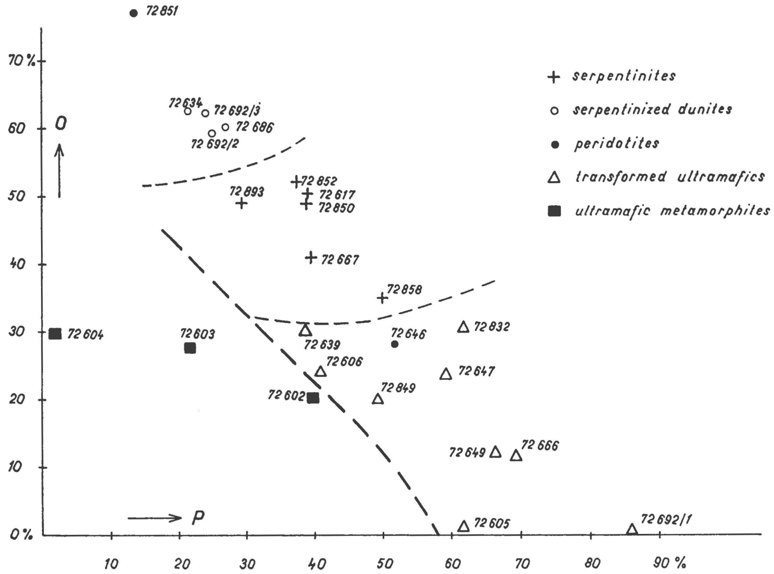

Fig. 29. Plot of C.I.P.W. norms *P* against *O*. The fields of ultramafic metamorphites, serpentinites, serpentinized dunites, and transformed and untransformed peridotites can be clearly delimited.

C.I.P.W. ratios *P* and *O* also indicate the reality of three chemically separable ultramafic rock groups (fig. 29), and divide the primary ultramafics into serpentinized dunites and serpentinites, separating them from the transformed peridotites. An exceptional position occupied by the peridotites rich in olivine (No. 72851) corresponds to the high value of *O* (76.03 $^0/_0$).

The character of the primary ultramafic rocks can be presumed by their *M*/*F* ratio calculated from the formula:

$$\frac{\mathrm{MgO}}{\mathrm{FeO} + 2\,\mathrm{Fe_2O_3} + \mathrm{MnO} + \mathrm{NiO}}$$

The calculation is based on the molecular values (weight per cent divided by molecular weight) of these oxides.

Hess (1938) demonstrated on the ratio Mg/Fe the possibility of distinguishing the serpentinites related to a peridotite magma, from the ultrabasic rocks differentiated from a basaltic magma. In the first case, the ratio exceeds 6, in the second, it ranges between 3.5 and 7.5.

In recent years the classification of ultrabasic rocks by Sobolev (1959) has become established, distinguishing three types as follows:

1. Hypermagbasites with *M*/*F* ratio = 8–12. These rocks are associated with fundamental structural lines and fault zones in the

Earth's crust; they can be attributed directly to the upper mantle.

2. Ultraferrbasites with M/F ratio ranging between 4 and 7. The rocks, being regarded as differentiates of gabbro magma, are nearer to the Earth's crust.
3. Ultrabasites of zoned central intrusions occupy a special position due to higher alkali contents and indistinct petrological relations.

The above-mentioned trend of the ratio M/F leads to the conclusion that the rocks which are assumed to have originated at considerable depths, contain more MgO in relation to the iron content.

The M/F ratio of serpentinized dunites is rather constant ranging from 6.11 to 7.19 (table 3b). Among the serpentinites some samples are characterized by very high M/F values (8.87 to 15.8) while other samples only have values of about 5.5. The serpentinite (No. 72850) with the highest M/F ratio contains large flakes of phlogopite and geologically it forms an isolated body surrounded by homogeneous gneisses. Similarly, the serpentinite with an M/F ratio of 9.48 occurs in biotite-hornblende gneisses. These facts may be of genetical significance.

The M/F ratio of peridotites and transformed ultramafics in general is lower, between 3.91 and 6.0, with the exception of the strongly transformed and altered peridotite (No. 72832, $M/F = 11.7$) which contains abundant talc and chlorite, and primary orthorhombic pyroxenes (table 4b). When the magnesium:iron ratio of the monomineralic transformed ultrabasics, anthophyllite and actinolite-tremolite rocks are considered, the anthophyllite rocks have an M/F ratio of 6.02 but actinolite-tremolite rocks only 3.91.

With the use of the M/F ratio the ultramafic metamorphites are separated very clearly from other ultramafic types (table 4b). The ratio is very low for biotitite ($M/F = 2.79$) and for hornblendite and biotite-hornblende rocks ($M/F = 2.08$ to 2.59).

Using the classification of Sobolev (1959), some of the serpentinites can be assigned as hypermagbasites, other serpentinites and serpentinized dunites and all transformed peridotites as ultraferrbasites. The low M/F ratio of the ultramafic metamorphites suggests that they have a crustal origin.

The ratio SiO_2: $Na_2O + K_2O$ was used by Yoder (1967) as a criterion for distinguishing tholeiitic and olivine basaltic magmas. In fig. 30 primary ultramafics and transformed ultramafics are interpreted as belonging prevailingly to the tholeiite field or approach the limit between the two groups. Simultaneously, the sharp boundary between primary and transformed ultramafics and between them and ultramafic metamorphites can be observed.

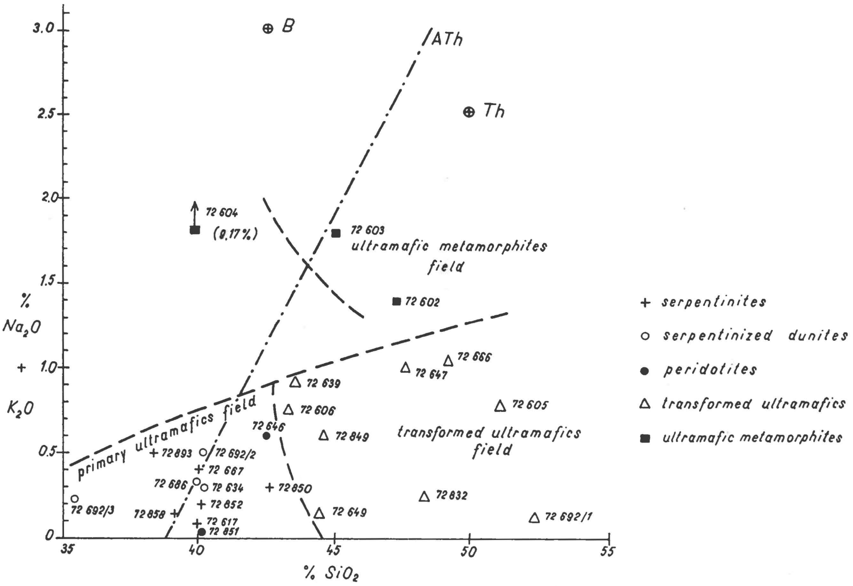

Fig. 30. Plot of $Na_2O + K_2O$ weight per cent against SiO_2 weight per cent of analyzed primary ultramafics, transformed ultramafics and ultramafic metamorphites. The boundary *ATh* between tholeiites and alkali basalts is according to Yoder (1967). Plot of basanitoide (*B*) and tholeiite (*Th*) as interpreted by Tilley, Yoder & Schairer, (1965, p. 70–71).

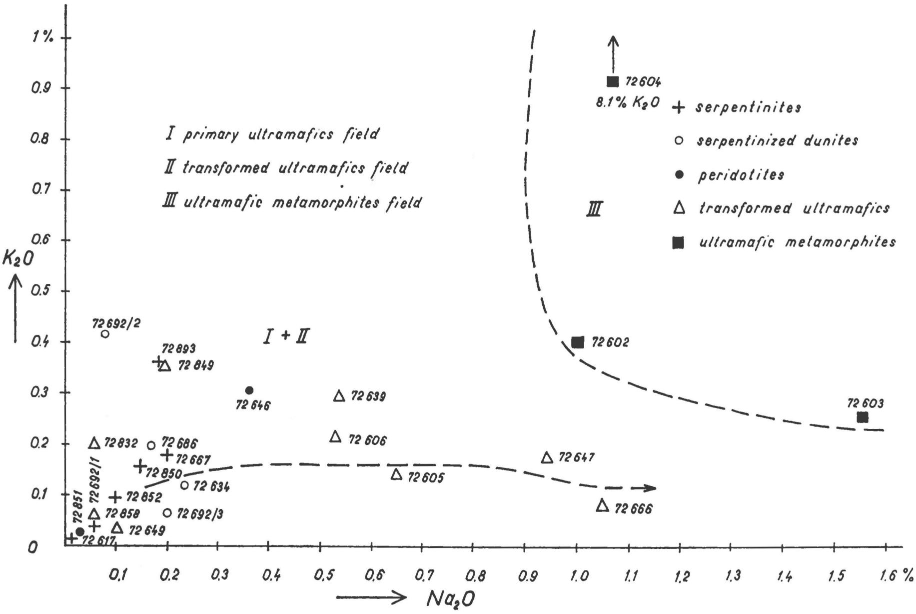

Fig. 31. Plot of Na_2O weight per cent against K_2O weight per cent of analyzed primary ultramafics, transformed ultramafics and ultramafic metamorphites.

In a plot of Na_2O against K_2O (fig. 31) the field of ultramafic metamorphites is distinct, but the limits of the field of primary and transformed ultramafics are rather vague. However, the transformed ultramafics have a much more valuable Na_2O content than the primary ultramafics.

Ultrabasics derived from peridotite magma are characterised by a very low content of TiO_2, never exceeding 0.2 weight per cent (Pinus, 1957; Marmo, 1958), while ultrabasics formed by differentiation of a gabbroic magma contain higher amounts of TiO_2 (Eliseev *et al.*, 1961). Few serpentinites and serpentinized dunites of this area possess more than 0.2 weight per cent of TiO_2 and in some primary ultrabasics TiO_2 is present in only trace amounts.

Geochemical aspects of border reaction zones

The transformed ultramafics of the internal and external reaction zones differ markedly from each other. In order to study the variations of the chemical composition and the possible trend of element migration in reaction zones, the rocks were subjected to complete chemical analyses and semiquantitative spectral analyses. Representative rock samples from reaction zones in isolated profiles were also analyzed.

An idealized geochemical profile can be constructed from the representative ultramafic rocks (fig. 32). The section starts with primary ultramafites and goes through transformed ultramafics and ultramafic

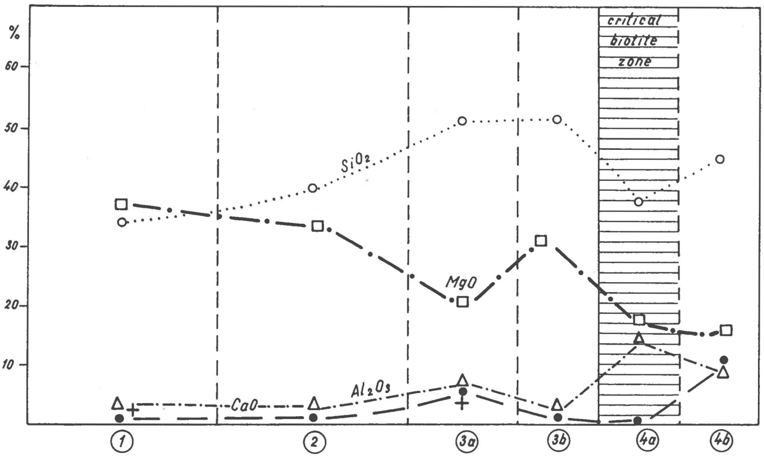

Fig. 32. Idealized geochemical section through primary ultramafic rocks containing country hornblende gneisses or amphibolites. *1* serpentinized dunite (72692/3), *2* serpentinized dunite with tremolite (72686), *3a* serpentinized peridotite with tremolite (72666), *3b* anthophyllite rock (72692/1), *4a* biotitite (72604), *4b* hornblende and biotitite hornblendite (average of 72602 + 72603).

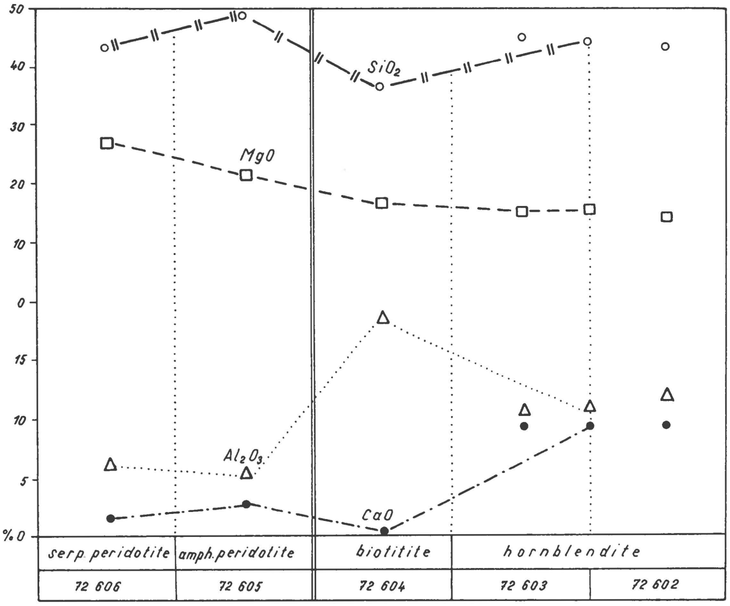

Fig. 33. Diagram representing trends of four major oxides in rocks at the contact between serpentinized peridotite and amphibolite.

metamorphites and terminates in the country-rock hornblende gneisses. The SiO_2 content increases through the tremolite-actinolite zone and the anthophyllite zone when compared with the content in primary ultramafics. Simultaneously, the MgO contents are clearly reduced in the zones of transformed ultramafics and the contents of Al_2O_3 and CaO show an increasing trend in the actinolite-tremolite rocks.

The same aspects of the relative geochemical trend were studied on a continuous geological section (figs 33 & 34). It begins with an amphibolized peridotite, goes through the internal zone of tremolite-actinolite to the external zones of biotitite and biotite-hornblende rock. Of the main oxides (fig. 33) MgO declines towards the country rocks, SiO_2 and CaO form conspicuous depressions and Al_2O_3 an increase in the biotite zone. The K_2O has a maximum in the biotite zone (fig. 34). The Na_2O content increases continuously from the amphibolized peridotites towards the country rocks reaching a peak in the zone of biotite-hornblende rocks and not in the biotite zone.

Chromium and nickel show a distinct drop in concentration from the primary ultramafic rocks to the hornblendites. Their radius of migration seems to be short. The TiO_2 maximum is pronounced in the biotite zone. The relative migration of TiO_2 into the biotite zone from country hornblende gneisses and amphibolites should be taken into consideration.

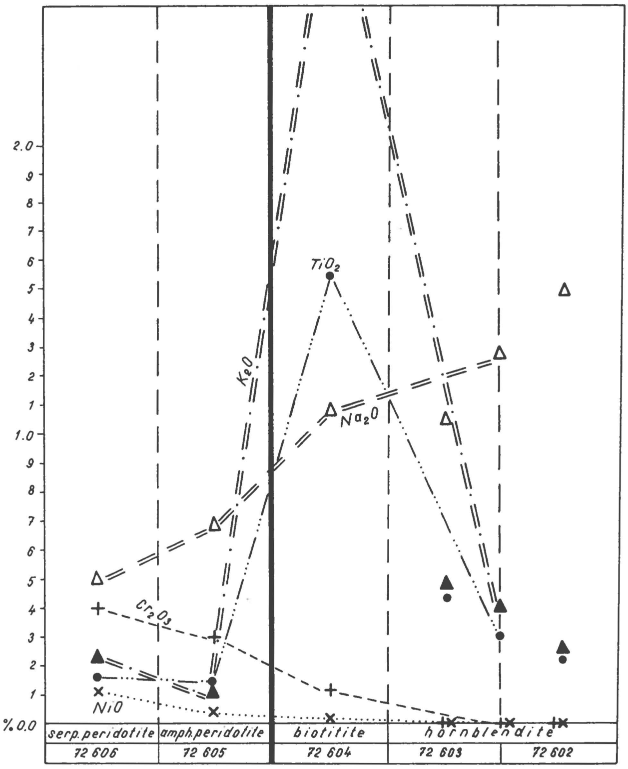

Fig. 34. Diagram with the trend of five oxides in the section as in fig. 33.

One piece of an ultramafic rock with conspicuous internal reaction zones was subjected to a detailed geochemical study. The structural character of the individual zones has been shown in fig. 24. The semi-quantitative spectral analysis of parts of the individual zones show some interesting results (fig. 35). Boron, generally occurring in serpentinized ultrabasic rocks (Thompson & Melson, 1970) has been identified in zone A (dark green serpentinite) but not in zones of transformed ultramafites.

Other features of the serpentinite zone that are noteworthy, are a higher percentage of nickel, a lower percentage of calcium and an indefinable amount of sodium. However, beginning with zones B and C (in fig. 35) containing tremolite, the calcium and sodium proportions substantially increase and a rapid change in the quantity of nickel and zinc appears. The distinctly highest concentration of cobalt in the C zone is interesting. Most of the samples with tremolite possess traces of tin, a fact which makes these samples distinct from the greater part of the rock samples.

samples	Al	B	Ba	Ca	Co	Cr	Cu	Ga	Fe	Mg	Mn	Na	Ni	Sn	Si	Ti	V	Zn	
1	•	•		•	•	•	○	•	+	+	⊘		⊘		+			⊘	A
2	•	•		•	•	•	•	•	+	+	⊘		⊘		+			○	
3	•	•		•	•	○	○	•	+	+	⊘		⊘		+			○	
4	○			•	•	○	○	•	+	+	⊘	•	⊘	•	+			○	
5	○			⊘	•	○	○	•	+	+	⊘	⊘	⊘	•	+			○	B
6	•			⊘	○	○	○	•	+	+	⊘	⊘	○	•	+			•	C
7	•			⊘	○	•	○	•	+	+	⊘	⊘	○	•	+			•	
8	○			⊘	○	○	⊘	•	+	+	⊘	⊘	○		+			•	
9	○			⊘	○	○	⊘	•	+	+	⊘	⊘	○		+			•	
10	○			⊘	•	○	⊘	•	+	+	⊘	⊘	○		+		•	•	D
11	○			⊘	•	•	⊘	•	+	+	⊘	⊘	○		+		•	•	
12	○			⊘	•	•	⊘	•	+	+	⊘	⊘	○		+		•	○	
13	⊘			⊘	•	○	⊘	•	+	+	⊘	⊘	○	•	+		•	○	
14	+		•	⊘	•	•	•		+	+	⊘	⊘	•		+	○	⊘	•	E

N_0 72 684

+ : >1% ⊘ : 1.0-0.1% ○ : 0.1-0.01 % • : 0.01-0.001

Fig. 35. Spectral analyses of samples taken from the individual portions of the internal reaction zones. Numbers of samples and nomenclature of the zones are the same as those in fig. 24.

The zone D with anthophyllite displays some geochemical peculiarities. Higher percentages of copper and sodium continuing from the preceding zone, lower contents of nickel, cobalt and probably also chromium, as well as the characteristic presence of vanadium document the zone of anthophyllite. Geochemically separated is the biotite zone (E). The biotite zone does not contain even traces of gallium which otherwise is ubiquitous in primary and transformed ultramafites; the contents of nickel and copper are lower by one grade of the order of magnitude and, as an entirely characteristic element, titanium is present in a substantial amount. Barium is of unique occurrence in the biotite zone.

Discussion on the geochemistry of ultramafics

The geochemical data on the primary ultramafics, transformed ultramafics and ultramafic metamorphites show that each group is geochemically distinct. All these types can be correlated with ultramafic rocks known from different orogens of varied development and age. The data also provide evidence of element migration in the transformed primary ultramafics and especially in reaction border zones.

In the area of Sermilik, the dunite-harzburgite rock association predominates over serpentinites when the clan of primary ultramafics is considered.

A quite similar dunite-harzburgite rock association has been studied recently in detail in the drill-hole at Mayagüez in Puerto Rico (BURK, 1964). The layers of dunites and harzburgites alternate many times in the drill-hole about 300 metres deep (MATTSON, 1964) and both rock types are chemically distinguishable (HESS & OTALORA, 1964). In the area studied some bodies are also formed from serpentinized dunites and peridotites and the rocks geochemically approach the average chemical composition of dunites and harzburgites as calculated by HESS & OTALORA (1964, p. 58).

HESS (1964, p. 141) compared the chemical composition of the dunites from the Mayagüez bore-hole with those of rocks regarded as upper mantle material (the ultrabasic rocks from Tinaquilo, Venezuela; dunites of St. Paulo; olivine nodules in basalts). Comparable are also serpentinites collected from the oceanic bottom. In HESS's conception dunites and peridotites are thought to be upper mantle material which after developing layering were intruded enmasse into the crust (LAPHAM, 1964, p. 143). The components Na_2O, K_2O, TiO_2, CaO and Al_2O_3 of the serpentinized dunites and serpentinites in the author's area agree geochemically with ultramafics from the oceanic bottom (compare HESS, 1964, p. 170) and the serpentinites with phlogopite reveal a close relation to those ultramafics occurring as xenoliths in kimberlite breccias. Recently, phlogopite has been regarded as possible mantle material (FLOWER, 1969). However, the phlogopites in the serpentinites described here seem to be of metamorphic origin.

The geochemical data of the transformed ultramafics show that a migration of certain elements must have taken place. Generally, the MgO contents are lower and the contents of SiO_2, Al_2O_3 and CaO are higher in the transformed ultramafics when compared with primary ultramafics.

The migration of elements by diffusion in the internal reaction zones is usually thought to be restricted to a shorter distance (see e.g. THAYER, 1966, p. 685). This may not be true when an ultrabasic body underwent intensive metamorphic processes (see e.g. the anthophyllite asbestos ball in the Paakkila quarry, Finland; HALONEN & PALOMÄKI, 1969). The origin of the foliated, laminated and banded ultramafics with actinolite-tremolite or anthophyllite in the area of Sermilik can be explained by accepting the possibility of long distance migration of Si, Ca, K, Na in tectonic zones and along foliation planes.

The primary ultramafics proper, in the transformed ultramafic rocks, may be a source of high contents of critical elements, but only to a limited extent. The source rocks of SiO_2 must be the country rocks. Large balls of anthophyllite asbestos in the Karelian metamorphites (HALONEN & PALOMÄKI, 1969) and the rocks rich in anthophyllite from the Rio Grande do Sul area (GOÑI, 1962) or the anthophyllite rocks in the ultrabasic rocks of Železné hory Mts (MÍSAŘ, 1969) are all completely surrounded by acid and mostly granitic rock types. In the area of Sermilik, under the same metamorphic conditions, the tremolite-actinolite ultramafics predominate over anthophyllite rocks, probably due to more basic country rocks (hornblende gneisses and amphibolites). A limited migration radius can be observed for Cr, Ni, Co and Ga.

The most exact picture of migration of elements can be obtained from the chemistry of the rocks forming the internal and external reaction zones. The relative rate of migration seems to have been controlled by the chemical properties of the elements themselves, by the chemical discordance between ultramafic and surrounding acid rocks and by the metamorphic facies conditions.

When comparing the type of reaction contact of the ultramafics in this area with the types described by PHILLIPS & HESS (1936), all the contacts described belong to the higher temperature type reflecting the metamorphic conditions of amphibolite facies. According to PHILLIPS & HESS the higher temperature type of contact displays a pronounced outer biotite zone and a well-developed actinolite zone. Hornblendites are often associated with the biotite zone.

Conditions of metamorphism at greater depths were studied by SØRENSEN (1954). The olivine-bronzite-phlogopite gneiss series (p. 10) is thought to be the result of a reaction between dunite and gneiss under granulite facies conditions. The reaction zones between granulite and ultramafics followed by ROST (1966) show a distinct concentration of TiO_2 in the phlogopite zone and a lowering trend of Cr_2O_3, NiO and MnO towards the country rocks. The MnO contents in the anthophyllite zone are somewhat higher as compared with the MnO amount in a normal ultrabasic rock.

READ (1934) found a SiO_2 culmination within serpentinite bodies where serpentine minerals were replaced by talc; the culmination of CaO occurs in the zone with actinolite. The external zones, the biotite and chlorite zones, show culminations of Al, K, Na and H_2O and a depression of SiO_2. The same principles have been pointed out by PHILLIPS & HESS (1936), especially in the case of a lower temperature type of contact.

SØRENSEN (1954, p. 40) summarized the results of his study of migration of elements at the contact of ultrabasic bodies with country rocks under the conditions of granulite facies, writing: "Thus there is an internal front of Si in all facies, but while Ca is found inside Al, K and H_2O in the lower facies, the opposite may be true for the granulite facies". In other words, there is a concentration of Ca, Na and Al in the zone rich in plagioclase outside the phlogopite.

REYNOLDS' (1947) general principle of a culmination of Si in the internal zone (in the zone of actinolite) and of a depression of the same element in the first external zone (that of biotite) is fully confirmed by the author's study. Where an ultramafic body is in contact with basic

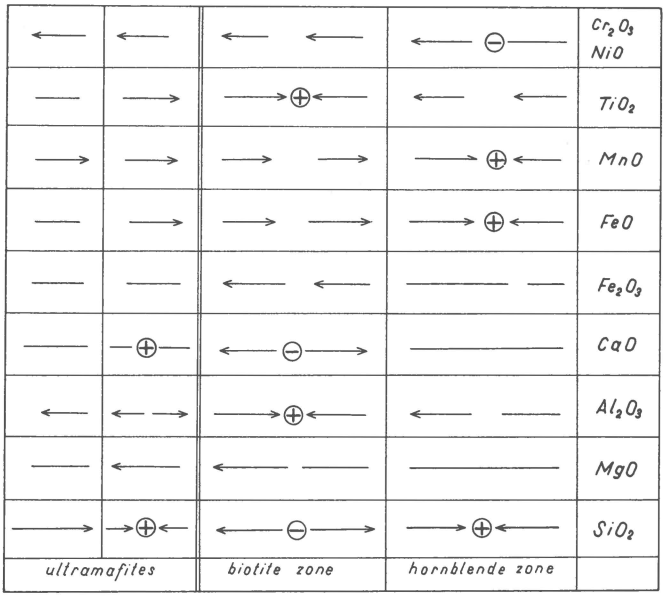

Fig. 36. Scheme showing author's opinion of the relative migration of the elements in the reaction zones.

rocks—with amphibolites or hornblende gneisses—a second partial SiO_2 maximum may arise in the hornblende zone.

The scheme shown in fig. 36 expresses the author's views of the migration of the main elements in the reaction zones. The biotite zone is marked by a geochemical depression of SiO_2 and CaO, and with a pronounced increase of Al_2O_3, K_2O and TiO_2.

At contacts where only a simple biotite-phlogopite zone is developed between ultramafics and gneisses, this zone becomes the main site for concentration of FeO, Fe_2O_3 and MnO. However, at contacts between ultrabasic and basic rocks, this concentration of elements has shifted into the hornblende zone (fig. 36). The MgO contents show a distinct rising trend towards the cores of ultrabasic bodies.

The relative distribution between Al_2O_3 and CaO appears to show an inverse proportionality. Aluminium is concentrated in the biotite zone at the expense of the neighbouring more acid rocks and partially of the transformed ultramafics. The absolute CaO depression in the biotite zone is bordered by a partial elevation in the internal zone and in plagioclase-bearing rocks, of the external zone.

The biotite zone is extremely rich in potassium. The origin of potassium may be attributed to a dealkalization process in an ultramafic body only to an insignificant extent, but more probably the main source of potassium is in the country rocks. The active radius of migration of potassium is assumed to be generally high.

SUMMARY AND CONCLUSIONS

1. The ultramafic rocks in the crystalline complexes of the area south of the fjord Sermilik, south-east of Frederikshåb, occur in several zones. Their country rocks are mostly amphibolites or hornblende gneisses. The amphibolites with ultramafics form part of the north-west zone of biotite gneisses, the central zone of hornblende gneisses and the amphibolite boundary horizon.
2. The main structure in the area is a synform which can be traced for many kilometres with hornblende gneisses in the centre and structurally lower biotite gneisses forming the flanks of the synform. The boundary amphibolite forms a marked horizon between these two units and contains many bodies of ultramafics.
3. The central zone of hornblende gneisses is considered to have been derived from a sedimentary–volcanic succession in which sedimentary rocks alternated with volcanic rocks (basic lavas and tuffs). The lithologically more monotonous series of biotite gneisses may have originated as a sequence of greywackes.
4. The primary and transformed ultramafic bodies occur as lenses in the up to 100 metres thick amphibolites. The arrangement of the lenses in a particular horizon suggests that they originated by boudinage from primary concordant competent layers. The ultramafic metamorphites occur as bodies of substantially smaller size, as small lenses and nodules. Ultramafic metamorphites also occur as "cement" between isolated blocks of amphibolites and hornblende gneisses and as small "ptygmatically folded" veinlets in the amphibolites.
5. The ultramafics can be divided into three groups:

   a. primary ultramafics, *b.* transformed (amphibolized) primary ultramafics and *c.* ultramafic metamorphites. Primary ultramafics are dunites, serpentinized dunites, peridotites, serpentinized peridotites and serpentinites. The second group is made up of transformed ultramafics, such as dunites, peridotites or serpentinites with tremolite-actinolite and/or anthophyllite and tremolite, actinolite and anthophyllite rocks. The last three rock types are almost monomineralic and have originated by an intensive amphibolization process. The ultramafics of the third group are composed of biotite and hornblende; these rocks form a continuous series between two end members, biotitite and hornblendite.

6. The ultramafics of the second and third groups chiefly occur as the inner and outer reaction zones of ultramafic bodies surrounding the core of primary ultramafics. Amphibolized primary ultramafics also appear within major bodies of primary ultramafics, where they possess planar structures conformable with the foliation of the country rocks. Therefore it is clear that both metamorphic and deformational processes must have played a role during their formation.

7. The contact of the primary ultramafic rocks with the surrounding amphibolites and gneisses is secondary, developed as reaction zones formed under amphibolite facies conditions.

8. The primary ultramafics, amphibolized ultramafics and ultramafic metamorphites also form distinct geochemical groups. The character of the individual groups is determined especially by SiO_2, Al_2O_3, MgO, CaO and to a considerable extent also Na_2O and K_2O as well as chromium, nickel and titanium. In the primary ultramafics, dunites, serpentinized dunites and peridotites are to some extent distinguished from each other. The serpentinites and serpentinites with phlogopite can be more clearly separated geochemically from the dunite-peridotite family.

   The amphibolized primary ultramafics show a lower MgO content and a higher content of Al_2O_3 and SiO_2 than the primary ultramafics. When tremolite-actinolite is present in the transformed ultramafics the CaO content is distinctly higher.

   The ultramafic metamorphites are geochemically distinct. They generally contain 45 $^0/_0$ SiO_2. Biotitites contain an enormous amount of K_2O, a higher percentage of Al_2O_3, and a higher proportion of TiO_2 than the primary and transformed ultramafics. The higher TiO_2 content and the distribution of some trace elements in the ultramafic metamorphites help to separate them from the other ultramafics.

9. The geochemical study of the outer and inner reaction zones has confirmed some already known principles and has also brought some more accurate data on the migration of elements. In the biotite zone a marked maximum for Al_2O_3 and TiO_2 arises together with a distinct SiO_2 and CaO minimum. Both the latter oxides display their

maxima on both sides of the biotite zone. The content of Cr_2O_3, NiO and CaO drops to the minimum in the biotitite and biotite-hornblende rocks.

10. The close association of the primary ultramafics with amphibolites is thought to represent a primary volcanic association as part of the ophiolite series. The mode of emplacement of the ultramafics cannot be determined. They could have originated as either ultramafic differentiates of basic effusives (basic lava flows) differentiated *in situ*, or ultramafics intruded or extruded as a crystal "mush" in platy, relatively cool bodies.

    The serpentinites with phlogopite occupy a peculiar position because of their chemical composition and setting in biotite gneisses. They display the highest M/F values and are very poor in alkalis and TiO_2. Structurally, they form separate lenses with no direct relation to amphibolites. Regardless of the origin of phlogopite, they could represent material of upper mantle restites or slices of a serpentinite layer of oceanic type transported upwards by tectonic processes into a geosyncline.

11. The whole rock association with ultramafic, basic and sedimentary geosynclinal sediments underwent several phases of folding and metamorphism.

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Table 2a. *Analyses of peridotites*

GGU No.	72606	72666	72849	72649	72646	72832	72851
Mode (vol. %)							
olivine	12	4	5	–	1	8	76
pyroxene	20	18	25	3	31	28	13
serpentine	5	48	7	26	50	5	8
uralite	20	15	8	7	–	2	<1
amphiboles	35	7	49	27	6	8	<1
magnetite, ilmenite	5	1	5	6	8	1	3
phlogopite	1	<1	–	4	–	1	–
chlorite, talc, etc.	2	7	1	27	4	47	<1
Chemical analyses (wt. %)							
SiO_2	43.49	48.60	44.55	44.15	42.06	48.78	39.60
TiO_2	0.17	0.39	0.80	0.38	0.37	0.07	0.07
Al_2O_3	6.93	1.30	6.62	2.27	2.26	0.70	0.51
Fe_2O_3	5.04	4.29	4.46	5.80	6.99	2.22	5.59
FeO	5.46	5.53	5.52	5.95	6.22	3.68	5.60
MnO	0.16	0.10	0.21	0.16	0.19	0.11	0.16
MgO	27.02	30.46	24.50	29.15	27.41	37.70	45.95
CaO	3.72	0.99	7.64	1.97	4.94	1.91	0.33
Na_2O	0.53	1.06	0.19	0.10	0.35	0.06	0.01
K_2O	0.22	0.09	0.36	0.04	0.30	0.20	0.01
P_2O_5	0.02	–	–	–	0.10	–	0.01
CO_2	0.11	–	–	–	–	–	0.06
H_2O^+	5.88	5.73	4.51	6.78	6.83	3.86	1.87
H_2O^-	0.19	0.23	0.22	–	–	0.18	0.07
Cr_2O_3	0.41	0.38	–	0.10	0.10	–	0.12
NiO	0.11	0.20	–	0.70	0.40	–	0.31
CuO	–	0.01	–	0.10	–	–	–
CoO	0.01	0.01	–	–	0.10	–	0.01
S	0.17	0.72	–	–	–	–	0.63
Total	99.64	100.09	99.58	97.65	98.62	99.47	99.91

72606: Amphibolized peridotite. The central zone.
Analyst: Chemical laboratory, UVR, Prague

72666: Amphibolized serpentine peridotite. The north-western zone.
Analyst: J. Adam, ÚGV, Prague

72849: Strongly amphibolized peridotite. The north-western zone.
Analyst: J. Adam, ÚGV, Prague

72649: Amphibolized peridotite. The boundary amphibolite horizon.
Analyst: Ib Sørensen, GGU, Copenhagen

72646: Serpentinized peridotite. The boundary amphibolite horizon.
Analyst: Ib Sørensen, GGU, Copenhagen

72832: Transformed peridotite with abundant talc. The boundary amphibolite horizon.
Analyst: J. Adam, ÚGV, Prague

72851: Slightly serpentinized peridotite rich in olivine. The north-western zone.
Analyst: Chemical laboratory, UVR, Prague

Table 2b. *Parameters of peridotites*

GGU No.	72606	72666	72849	72649	72646	72832	72851
Niggli numbers							
si	75.39	86.45	77.93	78.15	71.74	76.61	51.09
al	7.36	1.62	6.83	2.37	2.47	0.65	0.45
fm	84.53	94.56	78.13	93.67	87.79	95.84	99.03
c	6.97	1.89	14.32	3.74	9.03	3.21	0.46
alk	1.14	1.93	0.73	0.22	0.91	0.29	0.06
k	0.21	0.05	0.55	0.20	0.36	0.68	0.38
mg	0.83	0.85	0.82	0.82	0.79	0.92	0.89
ti	0.22	0.52	1.05	0.51	0.47	0.08	0.07
p	0.03	0.01	0.00	0.00	0.07	0.00	0.01
Köhler–Raaz indices							
qz	−23.2	−14.7	−21.5	−19.1	−24.5	−19.8	−32.3
F	6.7	4.2	6.2	2.1	2.4	0.8	0.3
fm	70.0	81.1	72.3	78.8	73.1	79.4	67.4
−(*F*–*fm*)	63.3	76.9	62.1	76.7	70.7	78.6	67.1
M/*F*	4.1	5.8	4.9	4.38	4.89	11.7	8.02
C.I.P.W. norms							
F	23.14	7.09	20.95	7.44	9.25	2.86	1.58
P	41.01	70.36	48.73	66.42	51.30	61.01	12.68
O	25.95	12.98	21.88	15.46	27.30	32.60	76.03
H	0.65	0.60	0.00	0.00	0.00	0.00	0.18
T	0.35	0.79	1.60	0.80	0.77	0.14	0.32
M	0.99	1.38	1.60	0.80	0.77	0.14	0.14
A	1.04	2.89	1.01	0.01	0.26	0.01	2.59
di	1.46	4.02	17.99	3.59	17.33	6.88	0.00
hy	39.64	63.71	30.74	62.84	33.97	54.13	12.68
ol	25.94	12.98	21.88	15.96	27.30	32.60	76.03
Sal	23.14	7.09	20.95	7.45	9.25	2.87	1.60
Fem	69.05	87.61	72.23	83.20	79.63	93.76	91.61
Sal: Fem	0.34	0.08	0.29	0.09	0.12	0.03	0.02
$\frac{K_2O + Na_2O}{CaO}$	0.16	1.02	0.05	0.06	0.10	0.09	0.14
$K_2O : Na_2O$	0.27	0.06	1.25	0.26	0.56	2.19	0.66
Zavaritsky values							
a	1.3	1.5	0.8	0.2	1.1	0.3	0.1
c	3.5	0.6	3.5	1.2	0.8	0.2	0.2
b	50.5	51.2	49.9	54.0	55.9	56.0	65.8
s	44.7	46.7	45.7	44.6	42.3	43.5	33.9
a	–	–	–	–	–	–	–
f	17.2	13.3	16.5	17.6	19.0	7.7	10.8
m	81.6	84.7	74.0	80.7	73.0	89.4	89.1
c	1.1	2.0	9.5	1.7	8.0	2.9	0.1
n	78.5	92.4	44.5	79.2	63.9	31.3	60.3
t	0.3	0.6	1.3	0.6	0.7	0.1	0.1
q	−16.9	−10.1	−13.3	−12.6	−18.4	−13.9	−32.5

Table 3a. *Analyses of serpentinites and serpentinized dunites*

GGU No.	72617	72647	72893	72686	72634	72852	72667	72858	72850	72639
Mode (*vol.* $^0/_0$)										
olivine	1	< 1	–	52	55	–	6	–	–	–
pyroxene	–	–	–	–	–	–	1	–	–	–
serpentine	86	72	87	40	29	94	75	84	96	43
amphiboles	3	–	2	3	10	< 1	7	6	–	47
magnetite, ilmenite	8	12	6	3	4	5	7	9	< 1	4
phlogopite	2	6	3	1	1	< 1	3	1	4	5
chlorite, talc, etc.	< 1	10	2	1	1	1	1	< 1	< 1	1
Chemical analyses (*wt.* $^0/_0$)										
SiO_2	39.51	47.61	37.78	39.59	39.45	40.21	39.30	38.00	43.71	43.28
TiO_2	0.08	0.17	0.40	0.15	0.14	–	0.43	trace	0.07	0.38
Al_2O_3	1.52	1.92	1.53	2.31	2.05	0.76	1.30	1.64	1.77	6.06
Fe_2O_3	5.12	2.66	8.93	4.36	4.32	6.30	8.03	9.36	2.09	5.00
FeO	2.04	5.02	3.28	4.72	5.77	1.61	4.42	2.08	2.06	5.53
MnO	0.08	0.18	0.21	0.10	0.10	0.35	0.80	0.10	0.08	0.10
MgO	37.94	30.03	35.38	37.13	37.33	37.92	35.53	35.98	37.16	26.41
CaO	0.47	3.31	1.12	1.75	2.05	0.92	1.27	1.68	0.69	6.12
Na_2O	trace	0.94	0.19	0.17	0.23	0.10	0.20	0.10	0.15	0.53
K_2O	0.06	0.18	0.36	0.20	0.12	0.10	0.20	0.06	0.18	0.30
P_2O_5	0.04	–	–	0.08	0.09	–	–	–	–	–
H_2O+	11.19	5.19	10.54	8.75	6.33	10.96	9.31	11.95	8.48	6.80
H_2O^-	0.15	0.15	0.27	–	–	0.15	–	0.11	0.24	–
Cr_2O_3	0.42	0.84	–	0.10	0.25	–	0.10	–	0.31	0.10
NiO	0.39	0.22	–	0.60	0.60	–	0.60	–	0.16	0.30
CuO	0.01	–	–	–	–	–	–	–	–	–
CoO	0.01	0.01	–	0.10	0.10	–	0.10	–	0.01	0.01
S	–	0.40	–	–	–	–	–	–	0.02	0.19
F	–	–	–	–	–	–	–	–	2.62	–
Total	99.03	99.55	99.99	100.11	98.93	99.38	100.87	100.06	99.80	100.11

72617: Serpentinite. The central zone.
Analyst: J. Adam, ÚGV, Prague

72647: Transformed serpentinite with phlogopite. The boundary amphibolite horizon.
Analyst: J. Adam, ÚGV, Prague

72893: Serpentinite. The boundary amphibolite horizon.
Analyst: Chemical laboratory UVR, Prague

72686: Serpentinized dunite. The boundary horizon.
Analyst: Ib Sørensen, GGU, Copenhagen

72634: Serpentinized dunite. The boundary horizon.
Analyst: Ib Sørensen, GGU, Copenhagen

72852: Serpentinite. The north-western zone.
Analyst: J. Adam, ÚGV, Prague

72667: Serpentinite. The north-western zone.
Analyst: Ib Sørensen, GGU, Copenhagen

72858: Serpentinite. The north-western zone.
Analyst: J. Adam, ÚGV, Prague

72850: Serpentinite with phlogopite. The north-western zone.
Analyst: J. Adam, ÚGV, Prague

72639: Hornblende serpentinite. The boundary amphibolite horizon.
Analyst: Ib Sørensen, GGU, Copenhagen.

Table 3b. *Parameters of serpentinites and serpentinized dunites*

GGU No.	72617	72647	72893	72686	72634	72852	72667	72858	72850	72639
Niggli numbers										
si	61.95	83.31	58.22	59.82	58.44	62.35	63.19	58.68	71.76	73.68
al	1.67	2.56	1.39	2.06	1.79	0.70	.123	0.58	1.91	6.08
fm	97.48	89.43	96.12	96.66	94.51	97.52	96.06	96.42	96.44	81.50
c	0.79	6.21	1.85	2.83	3.25	1.53	2.19	2.78	1.21	11.16
alk	0.06	1.80	0.64	0.44	0.45	0.25	0.52	0.21	0.43	1.26
k	0.93	0.11	0.55	0.43	0.25	0.39	0.39	0.28	0.44	0.30
mg	0.91	0.88	0.85	0.88	0.87	0.90	0.84	0.86	0.94	0.82
ti	0.09	0.22	0.46	0.17	0.16	0.00	0.52	0.00	0.09	0.49
P	0.03	0.00	0.00	0.05	0.06	0.00	0.00	0.00	00.0	0.00
Köhler–Raaz indices										
qz	−27.4	−18.2	−31.0	−29.9	−30.5	−28.0	−28.3	−29.7	−23.1	−25.0
F	0.3	3.1	1.4	1.8	1.6	0.7	1.3	0.6	1.6	5.8
fm	72.3	78.7	67.6	68.3	67.9	71.4	70.4	69.7	75.3	69.3
−(*F*–*fm*)	72.0	75.6	66.2	66.5	66.3	70.7	69.1	69.1	73.7	63.5
M/F	9.48	6.91	5.60	7.15	7.19	8.87	5.20	6.11	15.8	4.68
C.I.P.W. norms										
F	2.78	10.15	6.71	8.35	7.47	3.12	5.55	2.63	6.47	20.96
P	38.73	59.29	28.74	24.67	22.02	38.36	41.26	35.15	47.93	38.56
O	48.71	22.99	50.15	59.46	63.13	49.12	39.12	49.15	41.31	31.96
H	1.87	1.32	2.21	1.00	0.00	2.20	6.00	5.29	0.52	0.00
T	0.17	0.35	0.85	0.31	0.29	0.00	0.92	0.00	0.15	0.77
M	2.04	1.67	3.07	0.32	0.29	2.20	0.92	5.30	0.67	0.77
A	0.11	0.77	0.01	0.21	0.23	0.01	0.01	0.01	0.09	0.01
di	0.00	14.32	2.85	2.77	4.59	2.82	3.69	6.35	0.00	14.40
hy	38.73	45.98	25.89	21.91	17.43	35.54	37.57	28.79	47.93	24.16
ol	48.71	22.99	50.15	59.46	63.13	49.14	39.12	49.15	41.31	31.96
Sal	3.58	10.16	6.71	8.35	7.48	3.13	5.55	2.63	6.57	20.96
Fem	89.60	85.72	81.97	84.67	85.68	89.71	81.32	89.60	90.00	71.30
Sal: Fem	0.04	0.12	0.08	0.10	0.09	0.03	0.07	0.03	0.07	0.29
$\frac{K_2O + Na_2O}{CaO}$	0.08	0.29	0.34	0.10	0.14	0.16	0.24	0.08	0.35	0.11
$K_2O : Na_2O$	39.48	0.13	1.25	0.77	0.34	0.66	0.66	0.39	0.79	0.43
Zavaritsky values										
a	0.1	2.0	0.8	0.6	0.6	0.3	0.6	0.3	0.5	1.5
c	0.5	0.1	0.5	1.0	0.9	0.3	0.4	0.2	0.7	2.8
b	61.0	52.2	61.6	60.5	61.3	60.9	59.8	62.4	56.6	51.9
s	38.4	45.7	37.2	37.9	37.3	38.5	39.1	37.1	42.1	43.8
a	1.1	–	–	–	–	–	–	–	0.1	–
f	8.9	11.6	15.3	11.5	12.6	10.0	16.1	13.8	5.7	16.5
m	89.9	82.0	83.6	87.2	85.5	86.9	82.4	83.8	94.1	76.3
c	–	6.3	1.1	1.3	2.0	1.1	1.5	2.4	–	3.2
n	2.5	88.8	44.5	56.4	74.4	60.3	60.3	71.7	55.9	69.7
t	0.9	0.3	0.8	0.3	0.3	–	0.8	–	0.1	0.7
q	−23.8	−12.6	−27.8	−26.4	−27.5	−23.9	−23.5	−26.6	−17.4	−18.2

Table 4a. *Analyses of ultramafics of the reaction zones*

GGU No.	72602	72603	72604	72605	72606	72692/1	72692/2	72692/3
Mode (vol. %)								
phlogopite	2	9	98	1	< 1	< 1	1	3
hornblende	96	88	1	–	–	–	–	–
amphiboles	–	–	–	92	55	65	7	1
olivine	–	–	–	< 1	12	< 1	2	13
talc, chlorite	–	–	–	5	2	25	12	< 1
magnetite, ilmenite	2	3	1	2	4	10	8	10
pyroxene	–	–	–	–	2	–	–	–
serpentine	–	–	–	< 1	5	< 1	70	73
Chemical analyses (wt. %)								
SiO_2	46.28	45.33	38.14	51.06	43.49	52.63	40.14	34.97
TiO_2	0.42	0.24	1.54	0.14	0.17	0.11	0.03	0.03
Al_2O_3	10.24	13.84	15.98	5.11	6.93	1.65	1.52	1.01
Fe_2O_3	3.99	2.12	3.97	5.41	5.04	1.75	5.57	8.64
FeO	9.06	7.94	8.24	4.49	5.46	7.41	5.18	3.06
MnO	2.00	0.17	0.39	0.23	0.16	0.22	0.14	0.12
MgO	16.10	15.20	18.47	21.08	27.02	30.65	39.26	37.84
CaO	10.04	10.03	0.27	5.65	3.72	0.03	0.27	0.27
Na_2O	0.98	1.57	1.07	0.65	0.53	0.07	0.07	0.06
K_2O	0.41	0.27	8.10	0.14	0.22	0.08	0.42	0.20
P_2O_5	trace	0.03	–	0.02	0.20	–	trace	–
CO_2	–	0.07	–	0.09	0.11	–	–	–
H_2O+	0.69	2.73	1.70	2.57	5.88	2.30	7.05	13.15
H_2O^-	0.07	0.08	1.11	0.02	0.19	0.07	0.56	0.67
Cr_2O_3	–	–	0.14	0.31	0.41	0.33	0.01	0.08
NiO	0.01	0.04	0.01	0.06	0.11	0.05	0.05	0.05
CuO	–	–	0.01	–	–	0.09	–	0.01
CoO	–	0.01	0.01	0.01	0.01	0.01	0.01	0.01
S	0.03	0.02	–	0.77	0.17	1.14	–	–
F	–	–	0.19	–	–	–	–	–
Li	–	–	–	–	–	–	–	0.08
Total	100.32	99.79	99.34	99.81	99.59	99.39	100.28	100.25

72602: Coarse-grained hornblende rock. The central zone.
Analyst: J. ADAM, ÚGV, Prague

72603: Biotite-hornblende rock. The central zone.
Analyst: Chemical laboratory, UVR, Prague

72604: Biotite rock. The central zone.
Analyst: J. ADAM, ÚGV, Prague

72605: Actinolite-tremolite rock. The central zone.
Analyst: Chemical laboratory, ÚVR, Prague

72606: Amphibolized peridotite. The central zone.
Analyst: Chemical laboratory, ÚVR, Prague

72692/1: Coarse-grained anthophyllite rock. The boundary horizon.
Analyst: J. ADAM, ÚGV, Prague

72692/2: Slightly amphibolized serpentine dunite. The boundary horizon.
Analyst: J. ADAM, ÚGV, Prague

72692/3: Serpentinized dunite. The boundary horizon.
Analyst: J. ADAM, ÚGV, Prague

Table 4b. *Parameters of ultramafics of the reaction zones*

GGU No.	72602	72603	72604	72605	72606	72692/1	72692/2	72692/3
Niggli numbers								
si	85.27	87.79	71.02	103.47	75.43	96.33	58.44	52.46
al	11.12	15.80	17.64	6.35	7.37	2.02	1.31	0.94
fm	66.82	60.10	70.26	79.92	84.58	97.70	97.78	98.34
c	19.82	20.81	0.54	12.27	6.91	0.06	0.42	0.43
alk	2.24	3.29	11.56	1.46	1.14	0.22	0.49	0.28
k	0.22	0.10	0.83	0.12	0.21	0.42	0.79	0.68
mg	0.66	0.73	0.73	0.80	0.83	0.86	0.87	0.86
ti	0.58	0.35	2.16	0.21	0.22	0.15	0.03	0.03
P	0.00	0.02	0.00	0.02	0.01	0.00	0.00	0.00
Köhler–Raaz indices								
qz	−20.8	−22.5	−41.2	−8.0	−23.2	0.5	−30.2	−32.7
F	11.5	16.8	11.2	7.3	6.7	−0.5	0.8	0.6
fm	67.6	60.6	47.6	84.7	70.0	90.2	69.0	66.7
−(*F*–*fm*)	56.1	43.8	36.4	77.4	63.3	81.7	68.2	66.1
M/F	2.08	2.59	2.79	3.91	4.1	6.82	6.92	6.13
C.I.P.W. norms								
Q	0.00	0.00	0.00	7.36	0.00	2.92	0.00	0.00
F	33.16	46.24	0.00	17.44	23.15	1.21	4.71	3.46
P	39.44	22.57	0.00	61.06	41.01	86.64	26.12	19.77
H	0.00	0.00	0.15	5.57	0.65	0.50	0.02	2.13
T	0.80	0.47	2.19	0.17	0.35	0.22	0.06	0.07
M	0.80	0.47	2.34	5.75	0.99	0.72	0.08	2.19
A	0.12	0.31	0.28	8.39	1.00	4.42	0.01	0.01
di	22.18	15.88	0.00	13.01	1.46	0.00	0.00	0.00
hy	17.25	6.68	0.00	48.05	39.64	86.64	26.12	19.77
ol = *O*	20.66	27.23	29.78	0.00	25.94	0.00	59.84	62.67
Sal	33.17	46.25	63.30	24.81	23.15	5.59	5.23	3.71
Fem	61.02	50.58	32.40	75.19	69.03	91.78	86.05	84.65
Sal: Fem	0.54	0.91	1.95	0.33	0.34	0.06	0.06	0.04
$\frac{K_2O + Na_2O}{CaO}$	0.11	0.16	21.45	0.12	0.16	3.70	1.16	0.64
$K_2O : Na_2O$	0.28	0.11	4.98	0.14	0.27	0.75	3.95	2.19
Zavaritsky values								
a	2.5	3.7	13.0	1.5	1.3	0.2	0.6	0.4
c	5.0	7.1	0.3	2.3	3.5	–	0.3	0.3
b	43.9	36.9	45.6	44.0	50.5	50.9	62.2	64.9
s	48.5	50.2	41.1	52.2	44.7	48.8	36.9	34.5
a	–	–	13.4	–	–	3.0	0.8	0.4
f	29.1	23.7	23.4	18.6	17.2	14.0	12.8	13.9
m	56.9	64.1	63.2	72.7	81.6	83.0	86.4	85.7
c	14.1	12.1	–	8.7	1.1	–	–	–
n	78.4	89.8	16.7	87.6	78.5	57.1	20.2	31.3
t	0.7	0.4	2.9	0.2	0.3	0.2	0.1	0.1
q	−13.0	−14.2	−44.0	−1.0	−16.9	−2.9	−27.7	−32.0

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PLATES

Plate 1

a. Needles of tremolite in slightly amphibolized serpentinized dunite. Tremolite has grown as porphyroblasts in an olivine-pyroxene-serpentine-magnetite-talc-matrix. GGU sample No. 72692/3. Crossed nicols, magnification × 32.

b. Serpentinized dunite. Irregular patches of tremolite, talc and chlorite occur in a matrix of olivine and serpentine minerals. GGU sample No. 72832. Crossed nicols, magnification × 25.

Plate 1 a.

Plate 1 b.

Plate 2

a. Biotitite – a monomineralic rock consisting of large flakes of mica with accessory magnetite and apatite. GGU sample No. 72685. Crossed nicols, magnification × 14.

b. Coarse-grained biotite hornblendite with hornblende, biotite and magnetite. GGU sample No. 72670. Crossed nicols, magnification × 14.

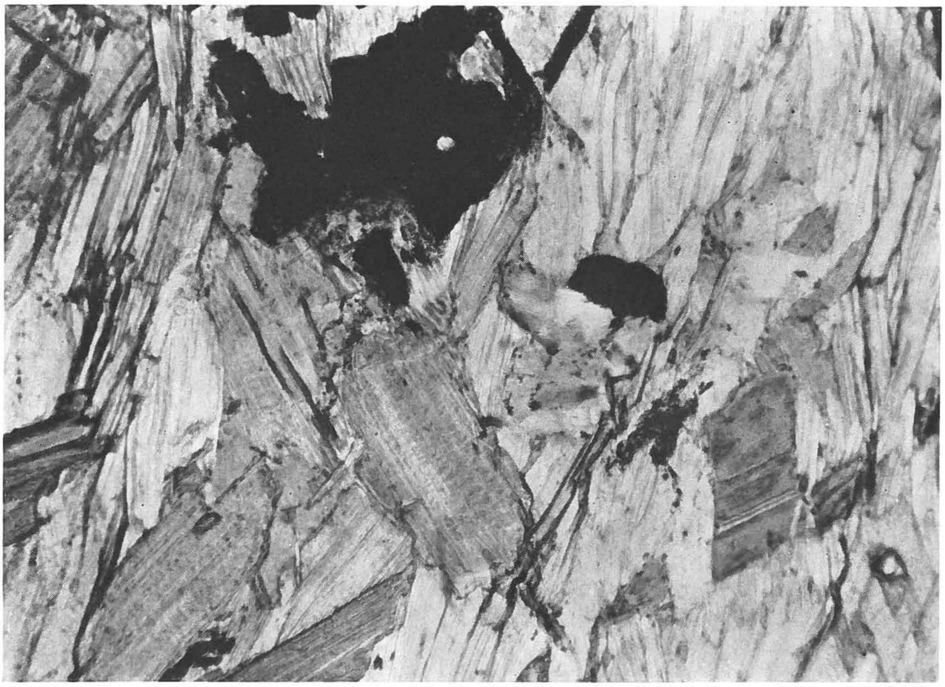

Plate 2 a.

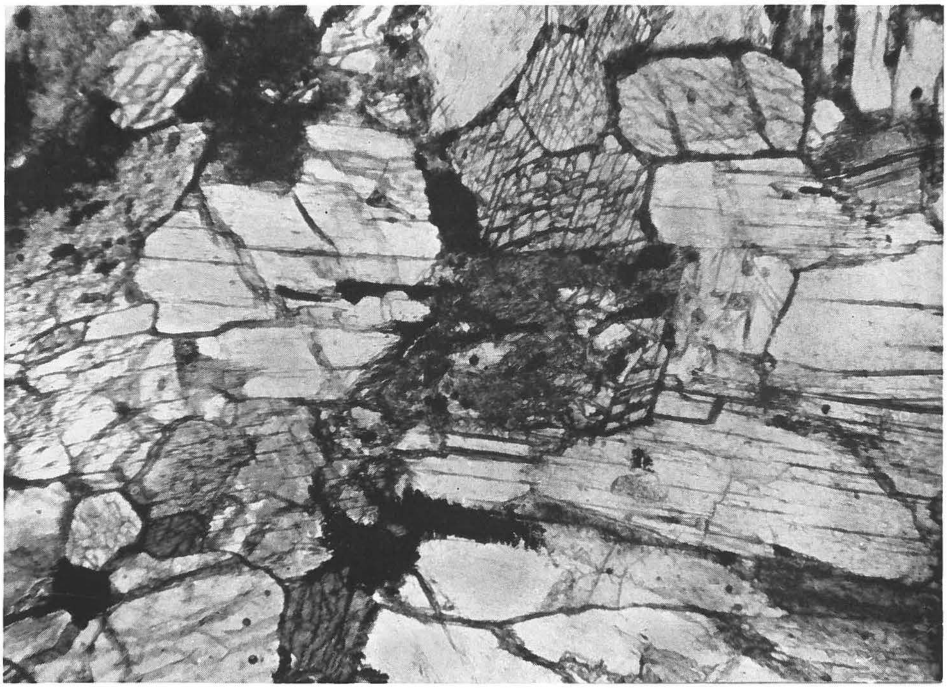

Plate 2 b.