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INFLUENCE OF MINERAL COMPOSITION AND MICROSTRUCTURES ON THE MECHANICAL PROPERTIES OF HOST ROCKS OF THE KEMI (ELIJÄRVI) CHROMITE DEPOSIT, FINLAND

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The study deals with the feasibility of using as rock aggregate the host rocks (metaperidotites, metapyroxenites, serpentinites, dolerites, granite gneisses and albitite) mined from the Kemi open pit in association with ore extraction. The strength properties of the rocks were investigated with 60 polished thin sections and three thin sections. Mineral compositions were determined on the thin sections by point counter analysis (1000 points per section). Strength properties were established with Los Angeles, improved Swedish impact value and abradability tests. So far 14 strength tests have been made on drill core samples and four on lumpy samples. The test data were correlated with the mineral composition and microstructures of the samples.

The metaperidotites studied were divided on the basis of their mineral composition and microstructure into cumulate, serpentine, chlorite, pyroxene and amphibole peridotites; the metapyroxenes were likewise classified as websterites, amphibole pyroxenites and talc pyroxenites. The serpentine and chlorite peridotites belong to strength class A (classification: A, I, II III, where A is the highest and III the lowest class) and the more altered of the cumulate peridotites tested to strength class I; the cumulate peridotite with well preserved microstructures belongs to class III. The pyroxene peridotites fluctuate between strength classes I and II. The amphibole pyroxenite belongs to strength class II, but the talc pyroxenite is classless. Serpentinite derived from peridotites other than dunite is in strength class I, that formed from dunite is classless. Dolerites and albitites come in strength class A. According to strength tests conducted earlier, the granite gneisses are in the two highest classes A and I.

The strength of the metaperidotites is increased by small grain size, intense alteration and a moderate abundance of amphibole and serpentine. Alteration reduces the grain size of the rock. The strength of the rock is low if its cumulus structure has been preserved and if the pseudomorphs after olivine still exhibit distinct borders. The metaperidotites containing these pseudomorphs and the serpentinites derived from dunites are medium-grained rocks. The serpentinites that lost their primary structure in serpentinization are stronger than those which have retained it. The metapyroxenites are medium-grained rocks. The strength of the amphibole pyroxenites is enhanced by their texture of interlocked acicular amphibole crystals. The abundance of talc weakens the abradability value of the talc pyroxenites.

Being aphanitic, the albitites are wear-resistant rocks. Dolerites are also wear-resistant due to their small grain size and subophitic and ophitic texture. The strength of the granite gneisses can partly be attributed to the fine-grained quartz that joins the plagioclase grains to one another.

Key words (GeoRef Thesaurus, AGI): rock mechanics, aggregate, chromite ores, host rocks, metaperidotite, metapyroxenite, serpentinite, granite gneiss, mineral composition, ultrastructure, mechanical properties, strenght, classification, Elijärvi, Keminmaa, Finland

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INTRODUCTION

The study is part of a project on the exploitation of host rocks in mines and quarries undertaken by the Rock Aggregate Research Unit of the Geological Survey of Finland (GSF) in 1991-93. The objective of the project, which was financed by Outokumpu Chrome Oy, the Ministry of the Environment and the GSF, was to find country and host rocks in mines and quarries that could be used for civil engineering purposes. The investigation started with a study of the strength properties of the host rocks in the Elijärvi open pit of the Kemi mine, with special reference to the microstructures of the metaperidotites, metapyroxenites and serpentinites. The test data on the rocks were correlated with those on mineral composition and texture. The albitites, dolerites and granite gneisses in the Elijärvi open pit were also studied.

METHODS FOR STUDYING THE STRENGTH OF ROCK AGGREGATE, AND STRENGTH SPECIFICATIONS

Laboratory studies of the strength of rock aggregate are conducted using methods that simulate the wear to which aggregate is submitted at the site of application. The methods used in Finland in 1991 to determine the strength and durability of rock aggregate were: the Los Angeles test, the improved Swedish impact value test, the abradability test, the point-load test and the ball-mill test. These methods are described in papers by Collis and Fox (1985), Grönholm (1993) and Heikkilä (1991). The mineral composition, microstructure, alterations, grain size and microfissuring of the samples tested for strength were also studied under the microscope in transmitted light.

Strength specifications

Rock aggregate is submitted to various types of wear, depending on the application. The specifications the aggregate has to meet thus vary from one application site to the next. However, some general constraints can be set for all types of aggregate and the rocks from which they derive.

The raw material of any aggregate type should not be weathered. Nor should it contain clay, silt, peat, mull, roots, wood fragments, snow, ice or other impurities in harmful amounts. However, there is still no standard weathering test indicating the maximum permitted abundances of minerals that weather easily (sulphides and micas) (Jokinen 1991). As a rule, the maximum abundance of micas has been 10% and that of sulphides 5%. No pyrrhotite is permitted in the rock aggregate used for road surfacing. Other harmful minerals are graphite, clay minerals and asbestos.

Strength specifications for surfacing aggregate

Table 1 lists the aggregate strength classes and class boundary values applied by the Finnish National Road Administration in 1991, (Tielaitos 1991). Table 2 gives the corresponding classification for 1993.

Strength specifications for concrete aggregate

Concrete is an artificial rock composed of aggregate and a binding cement paste. The cement paste is made mainly of water and cement. The aggregate is usually either gravel or crushed rock. Fly ash, blast furnace slag and expanded clay can also be used.

Table 1. Classification scheme and class boundary values for crushed-rock aggregate (Finnish National Road Authority, 1991).

Strenght Class	Is(50) Point-load Index*	TIE 237 Abradability Value*	TIE 232 Improved Swedish Impact Test Value**	TIE 231 Los Angeles Test Value**
A	≥13	≤1.8	≤18	≤20
I	≥11	≤2.3	≤22	≤25
II	≥9	≤2.8	≤26	≤30
III	≥7	≤3.3	≤30	≤35

* Rock aggregate used in road surficing

** Aggregate for unbound road base and surficing if the poin-load index has not been determined.

Table 2. Classification scheme and class-boundary values for mechanical properties of crushed-rock aggregate (Finnish National Road Authority, 1993).

Strength Class	Los Angeles Test Value TIE 231	Is(50) Point-load Index (MPa) TIE 241	Ball-mill Value (weight-%) TIE 242	Abradability Value (cm^3) TIE 237*
I	≤ 20	≥ 13	≤ 7	≤ 1.5
II	≤ 25	≥ 10	≤ 11	≤ 2.1
III	≤ 30	≥ 8	≤ 14	≤ 2.6
IV	≤ 35	≥ 6	≤ 17	≤ 3.1

* = Replaces the ball-mill value during the transition period.

Rock aggregate accounts for 70-80% of the volume of the concrete and for over 90% of that of asphalt.

According to Juvas (1990), the most important properties of rock aggregate for high-quality concrete are

- grain-size distribution and grain shape
- strength
- physical durability (wear, frost attack)
- chemical durability
- colour
- homogeneity

The concrete specifications (Betoninormit 1990) state that rocks used as concrete aggregate should not be weathered or have properties that would impair the properties of fresh or cured concrete. The chloride concentration in the aggregate should not exceed 0.02 wt% calculated to water-soluble chloride. Nor should the concrete contain humus. In general, then, the rocks of Finland are strong enough for concrete.

Rock aggregate should not be brittle or porous. Micas are common minerals that markedly impair the strength of concrete. Owing to their large specific surface area, they also increase the need for water in concrete.

The strength of rock aggregate is crucial for high-strength concretes. The durability of rock aggregate is assessed with the Los Angeles test and improved Swedish impact test. When host rocks from mines are used as aggregate the effect of the ore on the properties of the concrete should be established beforehand (Juvas 1990).

Coarse, usually crushed, rock aggregate is the dominant feature on the surface of concrete, where its colour is accentuated by the concrete itself. If the grain-size distribution is uniform, though, the colour of fine aggregate dominates. For white concrete it is imperative to ensure that the aggregate does not contain rusting minerals. Limestone and white quartz are appropriate for this type of concrete.

Strength specifications for railway ballast

Railway ballast is used in the supporting layer under rails. It can be made of crushed rock, boulders or stones with diameter of at least 150 mm. The quality of the raw material is dictated by the improved Swedish impact test value and the abradability value (Table 3, Harjula 1990).

Table 3. Specifications for aggregate suitable as railway ballast (Harjula 1990)

	Impact test value	Abradability value
Ballast for standard track	≤22	≤2.7
Ballast for points and switches	≤18	≤2.2

The strength requirements for the railway ballast used at switches are stricter than for that used elsewhere on railway lines owing to the higher lateral stress to which ballast is submitted at switches.

The following gives examples of the relationship between improved Swedish impact test values and the ability of the material in the supporting layer to remain in good condition in some test track sections (Harjula 1990):

	Improved Swedish impact values
Section with wooden sleepers where condition is well maintained	21
Section with wooden sleepers where condition is poorly maintained	28
Sleeper material transitional area	24
Section with concrete sleepers where condition is well maintained	30
Section with concrete sleepers where condition is poorly maintained	28

Railway ballast should not be susceptible to weathering, contain sulphides or be electrically conductive (Harjula 1990).

Strength specifications for airport surfacing aggregate

Maximum strength is not required for the rock aggregate used in airport surfacing; strength class II is sufficient. The following international strength specifications have been set: the improved Swedish impact value < 25, and the Los Angeles test value < 30. Further, the aggregate should not be readily weatherable (Tasanen 1992). The stress on runways increases with the increase in the maximum weights of aeroplanes, thus raising the quality requirements for materials in all runway structures.

OBJECTIVE AND METHODS

The gangue extracted from the Kemi mine in association with the mining of ore was studied with a view to its applicability as rock aggregate.

Most of the samples taken for the study were gangue from the Elijärvi open pit but some were from Nuottijärvi, an open pit to be opened in the near future. The samples were collected from the part of cross-section A-A' (Fig. 3, p. 10 and 4, p. 11) that is composed of basement gneiss and ore and which is about 350 m long and 1200 m wide.

The study was based on 34 drill cores, for 26 of which partial logs were made. In addition, lumpy samples were taken from the Elijärvi and Länsi-Viia pits.

Most of the host rocks of the orebodies are talc-carbonate rocks, which account for about 80% of the gangue in the open pit. Being soft, however, talc-carbonate rocks are not suitable for aggregate and so were not included. The study then concentrated on the metaperidotite variants, which account for 10%, or 20 million tonnes of gangue. The strength properties of metapyroxenites, various serpentinites, and dolerite and albitite dykes were also investigated.

The strength properties of the granite gneiss that occurs south of the formation are briefly treated on the basis of previous strength tests.

The relationship between strength properties and the alteration, mineralogical composition, microstructures, fissuring and orientation of the host rocks was studied on 60 polished thin sections. Forty-two of them were metaperidotites, 11 metapyroxenites, two serpentinites, three granite gneisses, one albite dolerite and one dolerite.

Three serpentinite thin sections were studied. The mineral compositions were determined with point-counter analysis (1000 points per section). Microanalyser (14) and X-ray diffraction determinations (2) were made to identify very fine-grained minerals.

The polished thin sections were prepared and the mineral identifications were made at the GSF in Espoo. The strength properties of the rocks were established from 14 technical strength determinations on drill cores made at the laboratory of the Oulu Road and Waterway District. The tests were made on altered peridotites, metapyroxenites, albitite, dolerite and serpentinites. Four lumpy samples representing albitite, dolerite, serpentinite and cumulate peridotite were also tested. The results of point-load tests are not included because most of the tests were made in 1991, at a time when methods to determine the point-load index were still at the development stage.

KEMI CHROMITE DEPOSIT

Geological setting

The bedrock at Kemi area can be divided into three geological units: the Pudasjärvi Archaean granite gneiss complex in the southeast; supracrustal early Proterozoic Peräpohja schists; and Proterozoic plutonic rocks (Fig. 1).

The dominant rocks in the Pudasjärvi granite gneiss complex are the medium to coarse-grained plutonitic gneisses that form the depositional basement for the Peräpohja schists are. The bedrock in the schist area is composed of sedimentary rocks

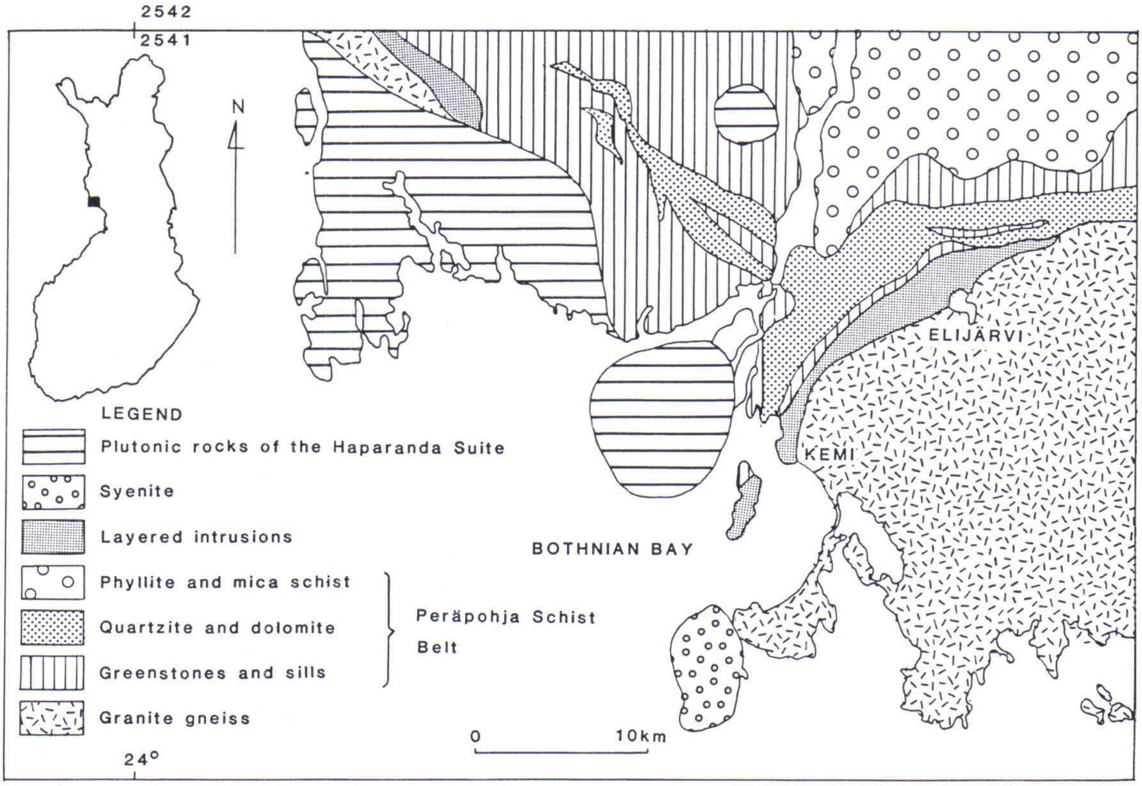

Fig. 1. Simplified geological map of the Kemi intrusion and its surroundings, after Perttunen (1991).

alternating with mafic volcanites and dyke rocks. Between the Peräpohja schists and the Pudasjärvi granite gneiss complex there is a chain of three early-Proterozoic layered intrusions (Tornio, Kemi and Penikat). The Proterozoic plutonic rocks of the Haparanda suite are calc-alkalic quartz monzonites, tonalites, quartz diorites and granodiorites in chemical composition. They are almost 1900 Ma old (Perttunen 1991).

The layered intrusions exhibit magmatic layering. The basal parts of the intrusions are composed of ultramafic and mafic rocks with olivine, chromite, bronzite, augite and plagioclase as cumulus minerals. Pyroxene and plagioclase are intercumulus minerals but in different layers. Other intercumulus minerals are alkali feldspar and quartz. Alterations are common: olivine has altered into serpentine, talc, magnesite and magnetite; pyroxenes have uralitized; plagioclase has saussuritized; and the rocks of the Pudasjärvi granite gneiss complex in the floor of the layered intrusions have altered into rocks rich in albite close to the intrusions.

Albitite and dolerite dykes cut across the rocks of the layered intrusions. Chromite, which occurs in all three intrusions, has the greatest commercial value (Perttunen 1991).

The Kemi chromite deposit formed when chromite concentrated on the floor of the magma chamber by crystal settling. The chromite layer reached its current exploitable proportions during early-stage deformations. Svecokarelidic metamorphism altered the mafic minerals in the lower and upper parts of the intrusion into chlorite, serpentine, talc, amphibole and carbonate; the middle part of the intrusion remained intact (Alapieti et al. 1989).

Elijärvi and Nuottijärvi chromite orebodies

The plutonic rock formation with chromite orebodies is at its thickest in the Nuottijärvi-Elijärvi area, where there are eight separate orebodies within a distance of about 4.5 km (Fig. 2).

The host rocks of the chromite orebodies and their mutual relations are shown in Fig. 3. p. 10 Figure 4 depicts the study area, and Fig. 5 p. 11 is a stratigraphic scheme of the Kemi intrusion and gives the variation in mineral composition in the different rock types.

Granitoids of the Pudasjärvi granite gneiss complex occur in the floor of the intrusion. In the contact of the intrusion with the granite gneiss there is a mylonitic

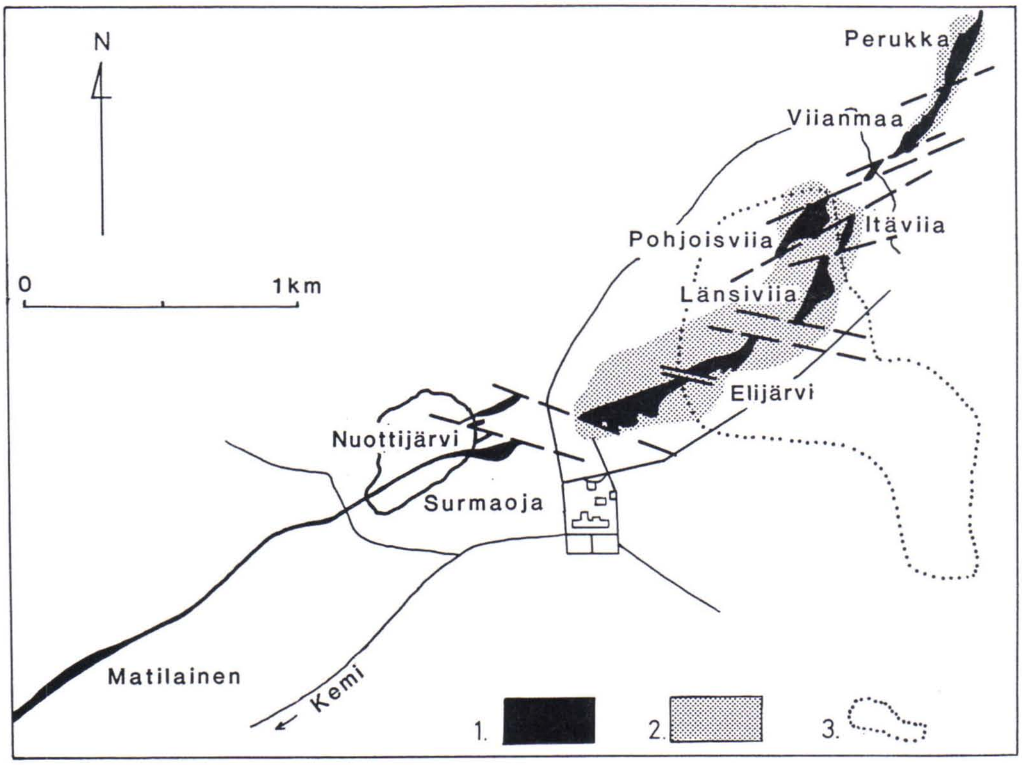

Fig. 2. Distribution of chromite orebodies in the Nuottijärvi-Elijärvi area, and the Kemi mining area, after Alapieti et al. (1989). 1. = ore; 2. = open pit; 3. previous lake.

talc-chlorite schist, 5-50 m thick. This is overlain by a heterogeneous ultramafite with alternating layers of peridotite, pyroxenite, dunite and chromite ore.

Along the margin of the chromite orebody the ultramafites are altered into serpentinites and talc-carbonate rocks. The layer rich in chromite is about 15 km long and from a few millimetres to about 90 m thick.

Above the chromite layer there are 550 m of metaperidotite with olivine, chromite and bronzite as cumulus minerals. The metaperidotite has about 15 chromite-rich layers from 5 cm to 2.5m thick; the uppermost is about 500 m above the chromite ore layer. The peridotites around the chromite orebody have altered into serpentinites and talc-carbonate rocks. In places there are pyroxenite layers, 5-10 m

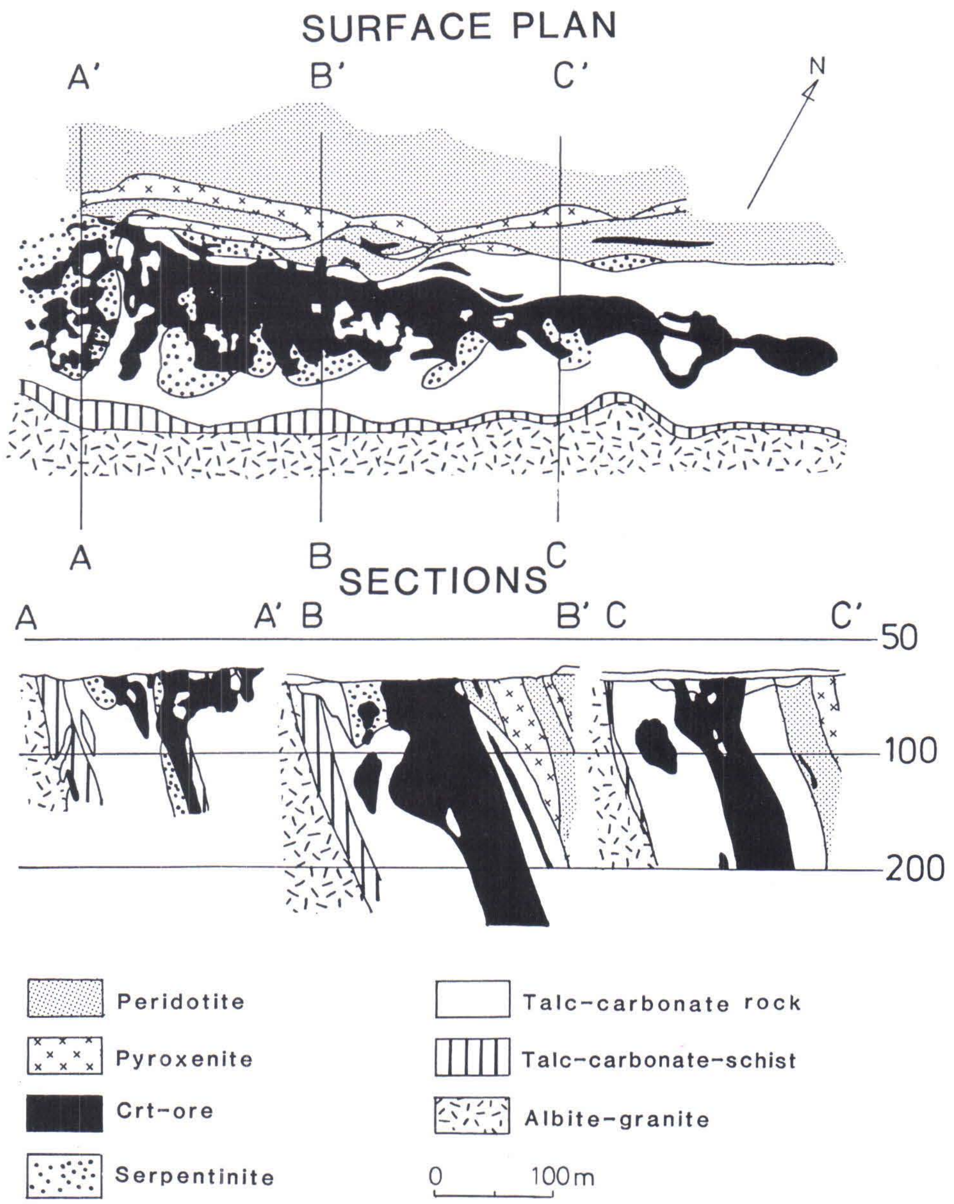

Fig. 3. Profiles across the Elijärvi orebody, after Alapieti et al. (1989).

thick, in peridotite. Abundant phlogopite, up to 10%, occurs in the upper part of the peridotite layer. On either side of the chromite ore layer there are sulphides in the peridotite as a weak dissemination. Chalcopyrite, pyrite, pyrrhotite and millerite are the dominant sulphides (cf. Fig. 5). The upper part of the formation is composed of amphibolitized pyroxene gabbros with anorthositic interlayers. Adjacent to the ultramafic portions of the formation the pyroxene gabbros are fresh and norites in composition. The gabbro stratum is about 1 km thick at its maximum.

The intrusion is cross-cut by albite dolerite dykes and coarse-grained albitite dykes. Other dyke rocks, although less common, are quartz keratophyre and quartz dykes, and carbonate-feldspar dykes with sulphides and gold.

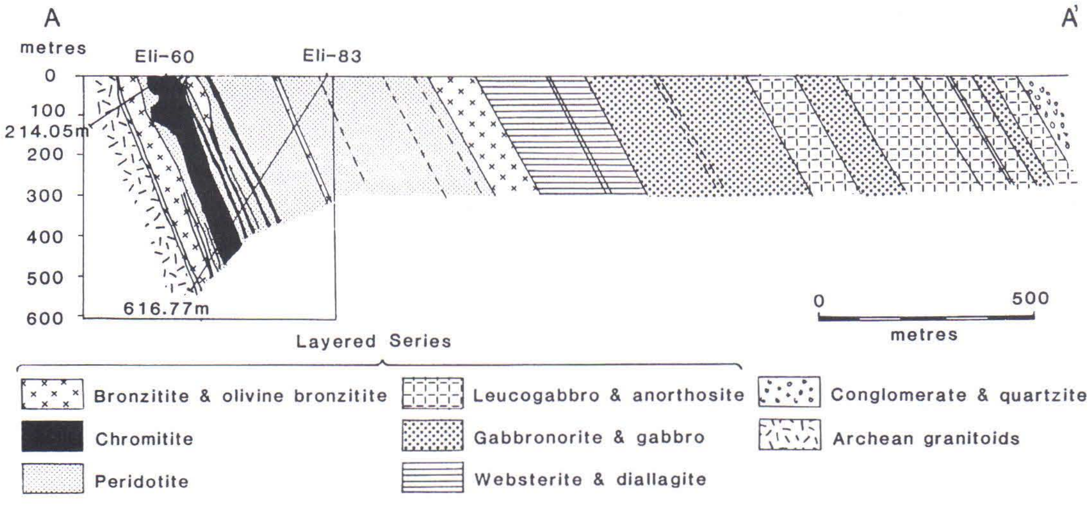

Fig. 4. Section along profile A-A', with the study area delineated on the left after Alapieti et al. (1989).

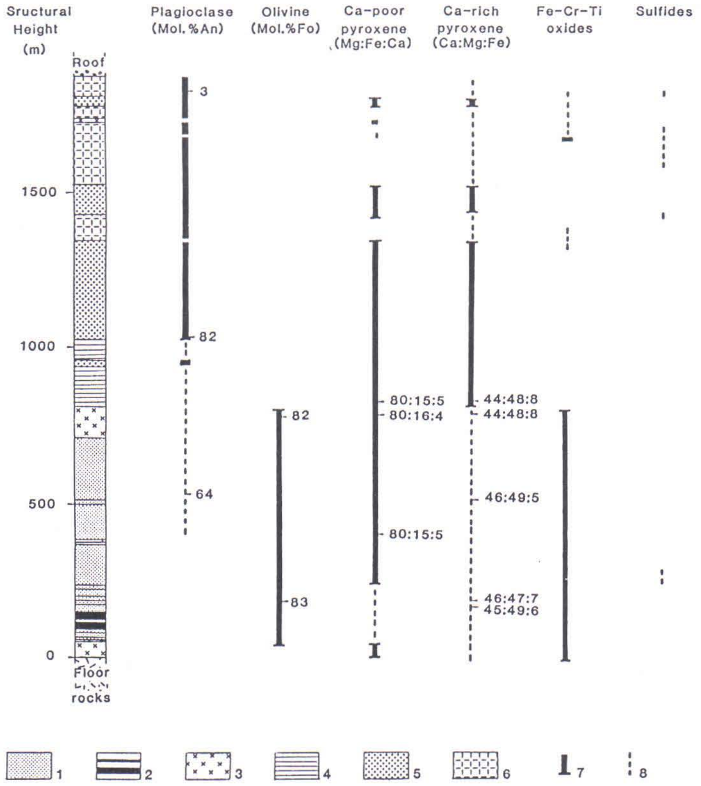

Fig. 5. Stratigraphic profile of the Kemi layered intrusion showing the variation in cumulus minerals in the rock types. 1. Peridotite. 2. Chromite. 3. Bronzite and olivine-bronzite. 4. Websterite and diallagite. 5. Gabbro-norite and gabbro. 6. Leucogabbro and anorthosite. 7. Cumulus minerals. 8. Intercumulus minerals (after Alapieti et al. 1989).

HOST ROCKS OF THE CHROMITE OREBODIES

Classification of the study material on the basis of mineral composition

Metaperidotites

Samples with over 40% olivine and its alteration products were considered metaperidotites.

On the basis of the original mineral composition, 42 study samples were classified as metaperidotites. However, owing to alteration, none of the samples represented fresh peridotites. The least altered metaperidotite was called cumulate peridotite.

The Kemi metaperidotites were thus divided into the following types on the basis of their mineral composition:

Cumulate peridotites
Serpentine peridotites
Chlorite peridotites
Amphibole peridotites
Pyroxene peridotites

Cumulate peridotite

Metaperidotites still clearly exhibiting the original orthocumulus structure under the microscope were classified as cumulate peridotites. The cumulus structures of mafic and ultramafic rocks are shown in Fig. 6 (Bard 1986). In the orthocumulus structure of the Kemi cumulate peridotites, the euhedral olivine crystals are enveloped by intercumulus xenomorphic orthopyroxenes or clinopyroxenes (cf. Fig. 7, p. 14). Only one of the samples contained abundant orthopyroxenes and clinopyroxenes (ELI-67-9.30-9.40). Olivine, with an average abundance of 10%, has largely altered into serpentine and magnetite.

The classification used in this work was based on the microstructure that clearly differed from that of the other metaperidotites rather than on mineral composition. The cumulate peridotite samples contain distinctly more olivine than do the rocks of the other

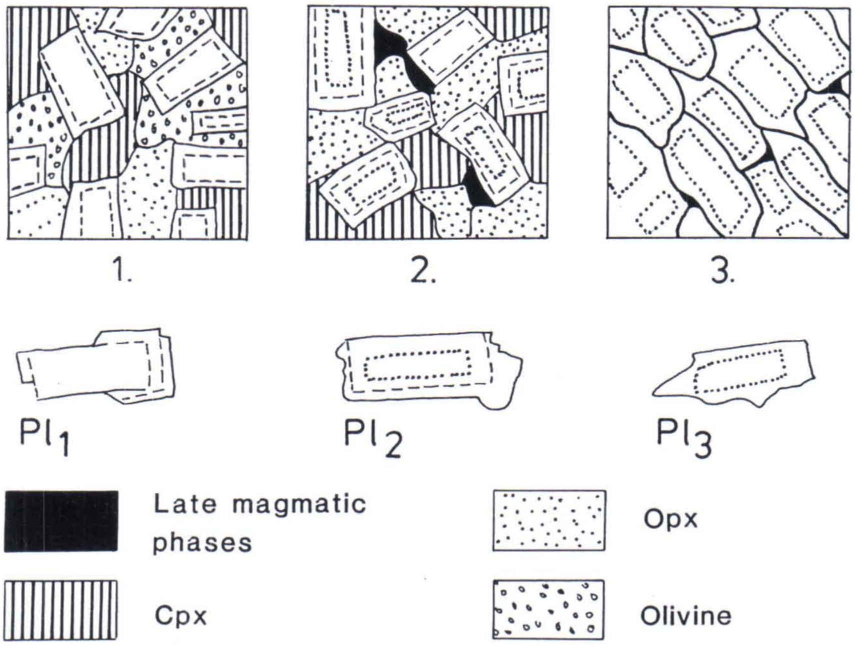

Fig. 6. Cumulus structures in mafic and ultramafic rocks (after Bard 1986, Fig. 4.7 A). 1. orthocumulus structure, 2. mesocumulus structure and 3. adcumulus structure. Pl_1 = cumulus plagioclase with overgrowth structures on its outer zone. Pl_2 = mesocumulus plagioclase (dotted line: original crystal, dashed line: overgrowth structure). Pl_3 = cumulus plagioclase with postcumulus overgrowth structure (adcumulus structure).

Table 4. Modal composition of cumulus peridotites. Alteration products (Px) are listed in order of decreasing abundance.

Mineral/Minerals	1	2	3	4	5
Olivine	9.9	10.8	9.9	10.3	12.3
Clinopyroxene	2.0	23.1	26.8	0.8	10.7
Ortopyroxene	-	20.8	-	-	-
Amphibole	17.2	5.5	5.2	6.8	17.4
Chlorite	17.2	8.5	11.5	23.2	15.5
Serpentine	12.3	20.4	30.9	42.7	24.4
Phlogopite	0.2	0.3	-	-	3.3
Talc	-	-	-	-	2.1
Magnetite	18.0	5.3	6.6	14.4	13.1
Chromite	1.0	1.3	0.4	1.8	1.2
Alteration products (Px)	22.2	4.0	8.7	-	-
Pyrite	< 0.1	-	-	-	-

1 = Sample Eli-674-6.30, Tr, Srp
2 = Sample ELI-67-9.30-9.40, Srp, Tlc, Crb, Phl
3 = Sample ELI-83-47,70, Srp, Tr
4 = Sample ELI - 4
5 = Sample ELI-47-30-49

groups. With an increase in the abundance of secondary amphibole, the strength properties of the rock also improve (sample ELI-674-6.30). However, the formation of abundant chlorite and serpentine without obliterating the microstructure significantly weakens the abradability value of the rock (sample ELI-83-47.70; Table 14, p. 30).

In drill core samples, cumulate peridotites can readily be distinguished from the other metaperidotite types with the unaided eye. They are brownish green in colour, olivine shows up clearly as brown spots on the weathered surface, and pyroxene and chlorite are green. Owing to magnetite, some pyroxene grains are lustrous or brownish. The most altered sample of the group (ELI-674-6.30) still shows the same microstructure although the rock is markedly paler.

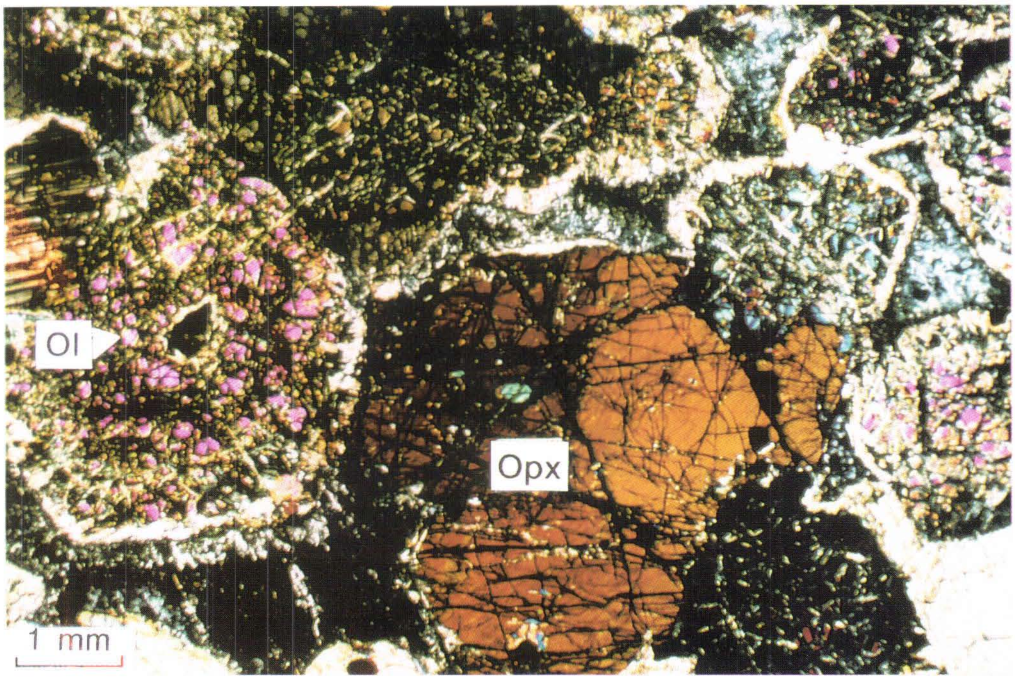

Fig. 7. Microstructure of a cumulate peridotite. Sample ELI-83-47.7 showing olivine (Ol) and bronzite orthopyroxene (Opx) (see Appendix 1). Photo Sari Grönholm.

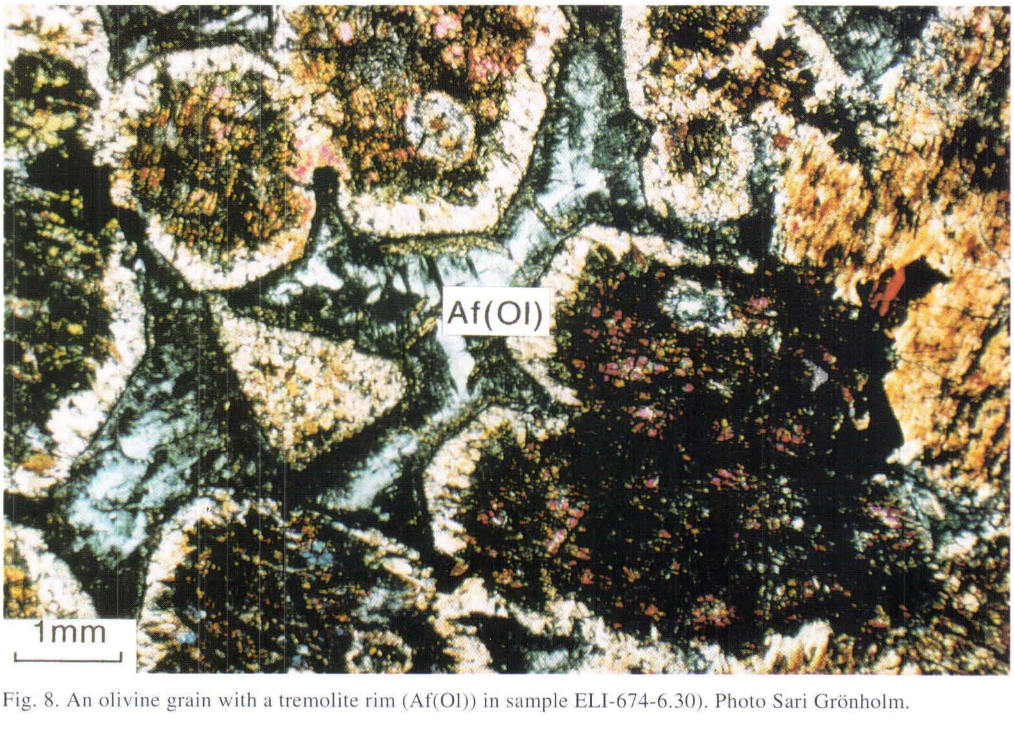

Fig. 8. An olivine grain with a tremolite rim (Af(Ol)) in sample ELI-674-6.30). Photo Sari Grönholm.

The microstructure of the cumulate peridotites differs from that of the other peridotites in that the pseudomorphs after olivine exhibit clear boundaries and the true grain size of the rock is close to the grain size of the pseudomorphs (Fig. 7.).

The pseudomorphs after olivine average 3-5 mm and the pyroxene grains 1 cm in size. Olivine occurs as small grains in the middle of the pseudomorphs. The margins of the pseudomorphs are often rimmed with amphibole (Fig. 8).

Alteration products of olivine include serpentine (frequently yellowish in plane-polarized light), colourless amphibole and magnetite. In samples ELI-67-9.30-9.40 and ELI-83-47.70 the pyroxene grains are only slightly altered. In other samples the pseudomorphs after olivine are enveloped by fine-grained chlorite, which shows blue interference colours and is the alteration product of pyroxene. The pyroxene grains are partly altered into tremolite, chlorite, serpentine, magnetite and talc (Table 4, p. 13).

Chlorite peridotite

The chlorite peridotites contain over 14.9% chlorite (Table 5), with a maximum abundance of 22.6%. The content is higher in some cumulate peridotites, but they have a different structure. Here, chloritization means chloritization of the intercumulus pyroxene, accompanied by partial replacement of olivine by amphibole. In association with chlorite the intercumulus phase often contains abundant carbonate as do the carbonatized pyroxene peridotites. The serpentine in sample R25-65.75 was found to be antigorite in structure (I.R) (Fig. 10.). Pyrite occurs in every sample but in none does its abundance exceed 5%.

The chlorite peridotites are fine-grained, green rocks. On the weathered surface·altered pyroxene can be distinguished from dark-green chlorite as grains with a lighter green hue. The magnetite in some pyroxene grains makes them lustrous on the weathered surface. Veins, 1-3 mm wide and filled with carbonate, are common. As shown by scratch tests on the drill cores the chlorite peridotites are somewhat softer than the serpentine peridotites.

In most of the chlorite peridotites, olivine has altered totally into fine-grained serpentine, magnetite and amphibole. The alteration products of pyroxene include serpentine, magnetite, tremolite, phlogopite and carbonate. The pseudomorphs after olivine measure 1-5 mm, and the pyroxene grains are slightly larger than 1 cm at their maximum. In places the pyroxene is fairly well preserved. Between the pseudomorphs after olivine and the intercumulus minerals there is often acicular amphibole as an alteration product of olivine, blurring the grain boundary between the pseudomorphs and chlorite.

Chlorite, too, occasionally contains acicular amphibole. The amphibole is fine-grained with an average grain size of 0.5 mm. Since the grain size of the alteration products of pyroxene and olivine is very small the rock can be considered fine-grained, even though it was primarily medium-grained. Microstructures of the chlorite peridotites are shown in Figs 9 and 10.

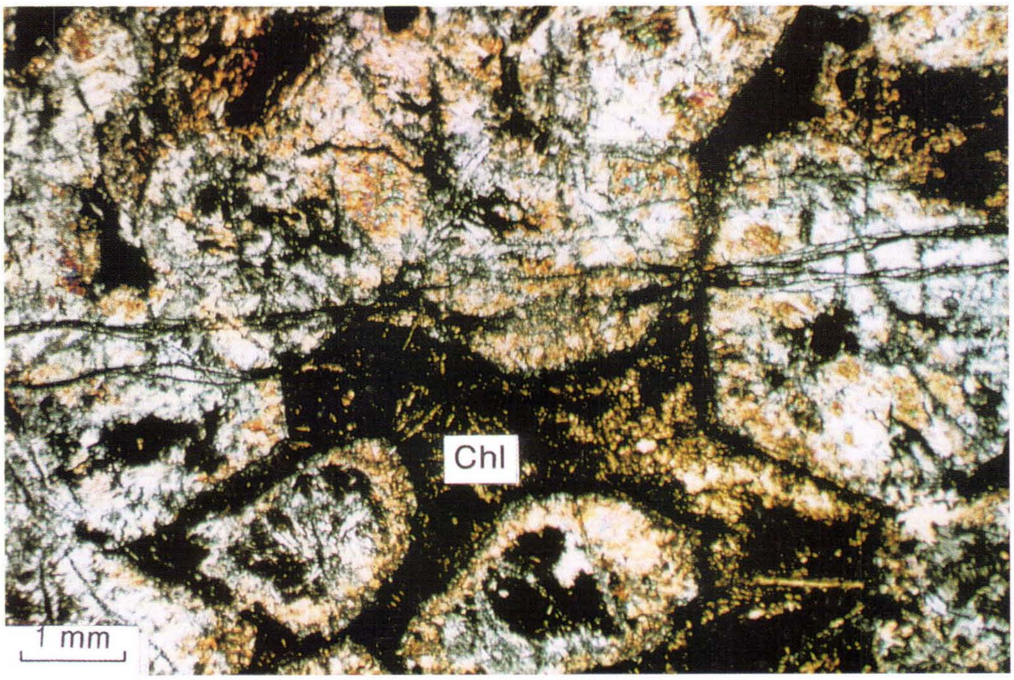

Fig. 9. Microstructure of chlorite peridotite tested (sample R25-1-15.00). Chl = chlorite. Photo Sari Grönholm.

Table 5. Modal composition of chlorite peridotite. Alteration products of pyroksene (Px) are listed in order of decreasing abundance.

Mineral/Minerals	1	2	3	4	5	6	7	8
Olivine	-	-	-	-	3.5	-	6.4	4.3
Pyroxene	-	0.5	-	2.6	10.5	6.6	0.5	0.7
Serpentine	52.9	41.8	51.5	53.2	41.3	43.9	57.3	42.9
Chlorite	14.9	18.6	20.2	20.3	17.1	17.7	16.6	22.6
Amphibole	2.5	11.6	7.6	9.5	8.1	-	-	15.1
Phlogopite	-	-	-	0.1	0.3	0.1	0.3	2.1
Carbonate	7.9	9.4	11.1	4.3	-	-	0.3	-
Alteration products (Px)	14.3	10.7	5.6	2.0	-	18.5	-	7.5
Magnetite	7.5	5.7	0.8	6.5	18.5	11.4	9.9	3.6
Chromite	-	1.7	3.2	1.5	0.7	1.8	8.7	1.2
Pyrite	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Pyrrhotite	-	-	< 0.1	-	-	-	-	< 0.1
Chalcopyrite	-	-	< 0.1	-	-	-	-	-

1. Sample R25-65.75, Tr, Mag, Srp, Crb
2. Sample ELI-675-15.00, Srp, Tr, Mag
3. Sample ELI-674-26.25, Tr, Srp, Mag, Crb
4. Sample ELI-671-13.5, Tr, Srp, Mag
5. Sample R25-15
6. Sample ELI-674-15.75, Tr, Srp
7. Sample R25-23.50
8. Sample ELI-673-8.50, Tr, Srp, Mag

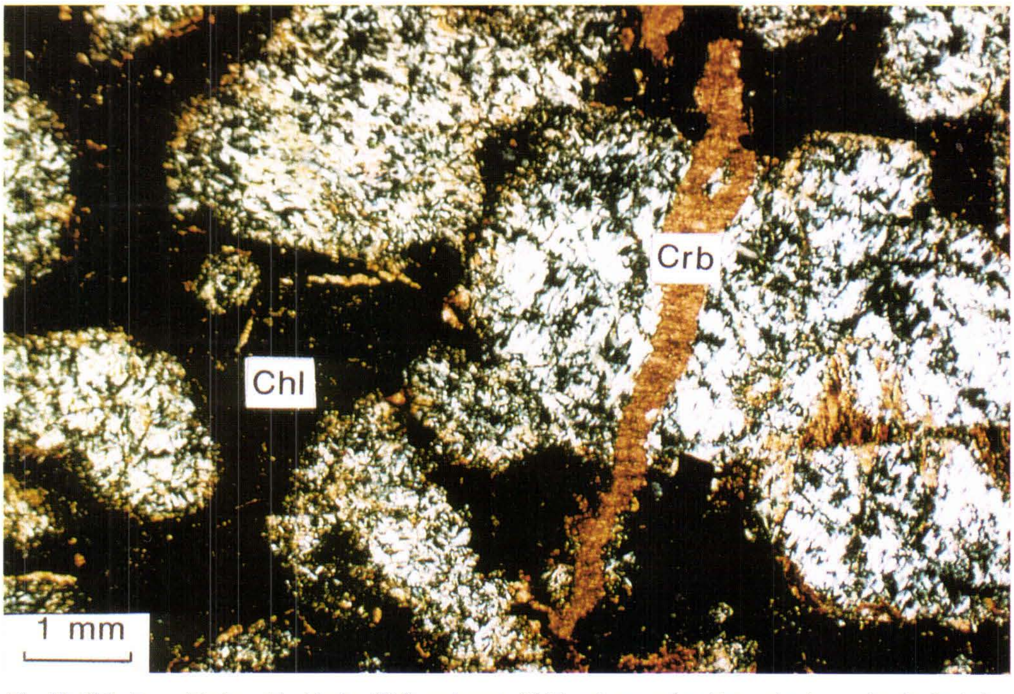

Fig. 10. Chlorite peridotite with chlorite (Chl), carbonate (Crb) and serpentine (determined as antigorite by infrared method) (sample R25-65.75).

Serpentine peridotite

The serpentine peridotites are the most thoroughly altered peridotites. They contain 56-68% serpentine and 5-17% chlorite (Table 6). The serpentine is an alteration product of olivine and pyroxene. The pyroxene grains, either partly or totally altered, usually measure less than 1 cm, and the pseudomorphs

Table 6. Modal composition of serpentine peridotites. Alteration products of pyroxene (Px) are listed in order of decreasing abundance.

Mineral/Minerals	1	2	3	4	5
Olivine	-	-	0.1	-	-
Pyroxene	-	-	3.7	4.6	-
Serpentine	56.7	68.4	68.0	64.0	60.8
Chlorite	13.7	11.0	4.7	8.1	6.6
Amphibole	3.5	0.1	-	0.4	9.4
Phlogopite	-	-	4.8	2.3	-
Carbonate	8.4	9.5	-	3.0	7.7
Alteration products (Px)	14.5	8.5	0.6	-	-
Magnetite	2.5	-	17.2	16.3	-
Chromite	0.7	2.5	0.9	1.3	15.5
Pyrite	< 0.1	-	< 0.1	< 0.1	< 0.1
Pyrrhotite	-	-	-	-	-

1 = Sample ELI-670-6,00, Tr, Tlc, Mag, Srp, Crb
2 = Sample ELI-211-142,15, Tr, Srp, Mag, Crb
3 = Sample R22-72
4 = Sample ELI-671-8
5 = Sample ELI-674-36,30

Table 6 cont.

Mineral/Minerals	6	7	8	9	10
Olivine	-	-	-	4.5	-
Pyroxene	-	0.2	-	9.1	1.7
Serpentine	61.2	59.7	56.2	58.3	60.4
Chlorite	14.2	11.1	10.9	9.0	17.3
Amphibole	9.9	2.8	1.4	0.8	9.2
Phlogopite	-	1.1	0.1	4.7	0.9
Carbonate	8.4	3.4	11.2	-	0.6
Alteration products (Px)	-	19.0	18.5	-	-
Magnetite	4.3	1.3	0.4	13.5	9.9
Chromite	2.0	1.4	1.3	0.1	-
Pyrite	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Pyrrhotite	< 0.1	-	-	-	-

6 = Sample ELI-675-4,75
7 = Sample ELI-670-15,50, Mag, Tr, Srp, Crb, Tlc
8 = Sample ELI-675-27.50, Tr, Tlc, Srp, Mag
9 = Sample ELI-672-16,90
10 = Sample ELI-195-33,10

after olivine 3 mm. The serpentine is very fine-grained (0.15-0.3 mm) and aphanitic. The alteration of pyroxene is characterized by tremolitization, seen as a weakly pleochroic brown pigment in pyroxene grains when examined in plane-polarized light (Fig. 11). Talc is another common alteration product.

The abundance of chlorite is usually lower and that of serpentine higher than in the chlorite peridotites. Associated with the serpentinization there are narrow fissure veins with opaque minerals. Many samples contain abundant carbonate.

The serpentine peridotites are homogeneous, aphanitic rocks, with pyroxene grains visible only as hazy specks on the weathered surface. The serpentine peridotites, too, often have veins, a few millimetres wide, filled with carbonate. When tapped with a

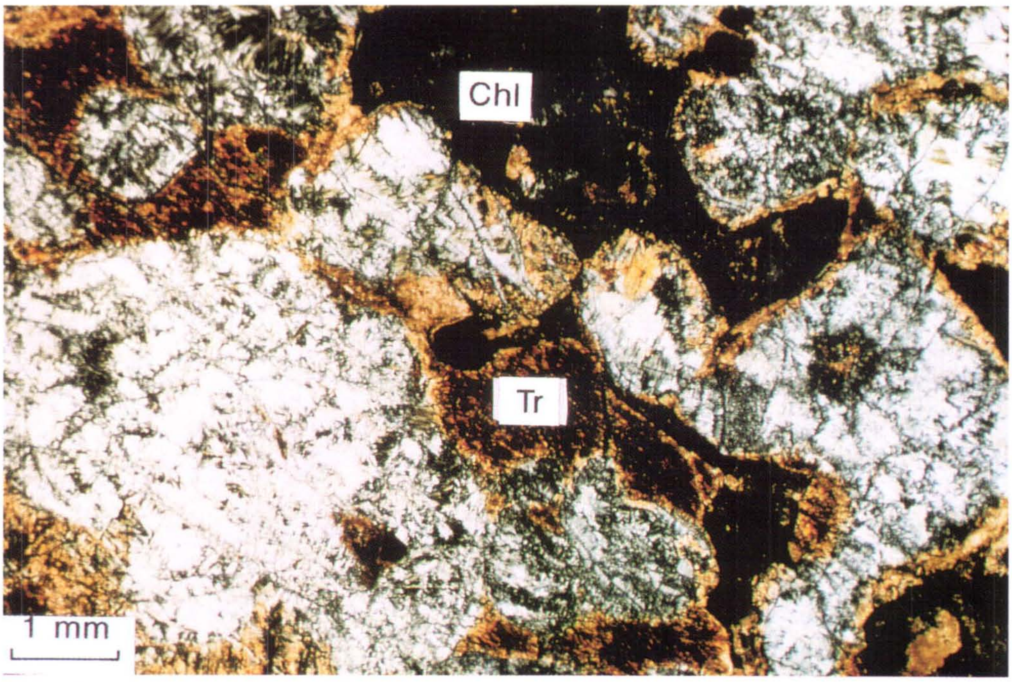

Fig. 11. In serpentine peridotite, pyroxene is often altered into tremolite (Tr) and chlorite (Chl). Sample ELI-670-6.00. Photo Sari Grönholm.

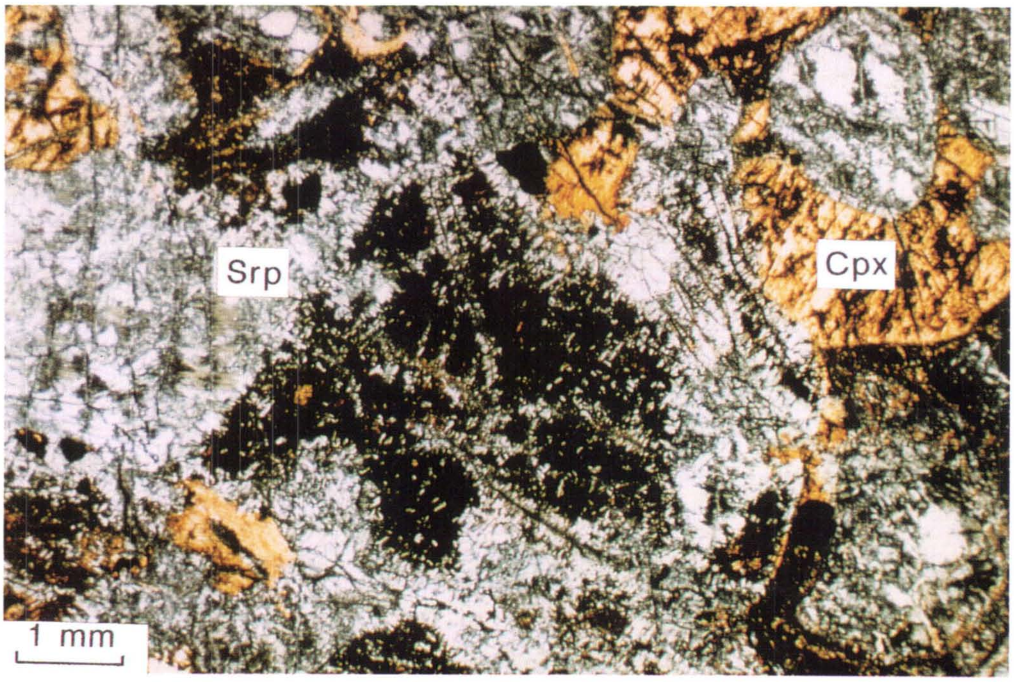

Fig. 12. Typical microstructure of serpentine peridotite, with serpentine (Srp) and relict clinopyroxene (Cpx). Sample ELI-671-8.00. Photo Sari Grönholm.

hammer, a sample of serpentine peridotite makes a ringing sound slightly higher in pitch than that made by chlorite peridotite.

Figure 12 illustrates a typical microstructure of the serpentine peridotite. Tiny grains of olivine, and also of pyroxene, are preserved in places. The grain boundaries are indistinct. Serpentinization of pyroxene did not proceed along the cleavages but was restricted to the opaque-bearing fissure veins.

Amphibole peridotite

The amphibole in the amphibole peridotites is tremolite in composition. It is an alteration product of pyroxene and occurs as reaction rims on the margins of olivine grains. The amphibole peridotites contain 14.8-28.40 % amphibole (Table 7). Four of the samples studied were amphibole peridotites.

The amphibole peridotites resemble chlorite

Table 7. Modal composition of amphibole peridotites. Alteration products of pyroxene (Px) are listed in order of decreasing abundance.

Mineral/Minerals	1	2	3	4
Pyroxene	-	0.2	-	-
Serpentine	41.8	36.5	49.0	46.0
Chlorite	18.8	25.8	16.9	6.4
Amphibole	20.3	22.5	14.8	28.4
Phlogopite	0.1	0.1	0.9	-
Carbonate	3.5	0.6	1.5	2.0
Alteration products (Px)	13.3	13.4	14.6	-
Magnetite	-	-	-	0.4
Chromite	2.2	0.9	2.3	16.8
Pyrite	< 0.1	< 0.1	< 0.1	-

1 = Sample ELI-675-21,00, Tr, Chl, Mag
2 = Sample ELI-672-24,50, Mag, Srp, Tr, Chl
3 = Sample ELI-673-71,4, Tr, Mag, Srp, Crb
4 = Sample ELI-672-28,80

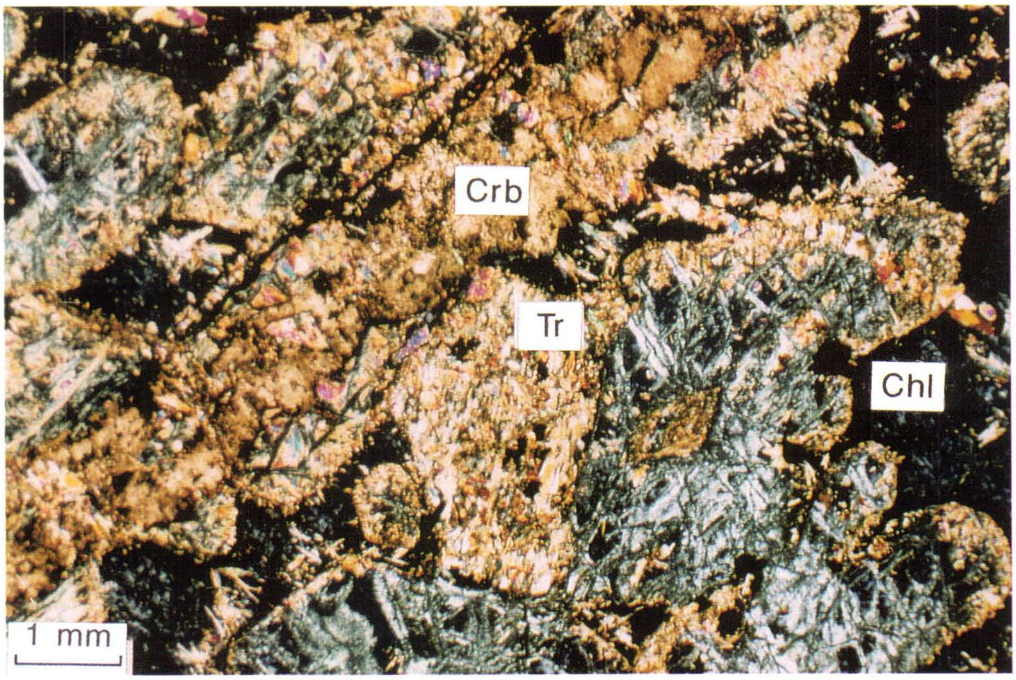

Fig. 13. Microstructure of amphibole peridotites with carbonate (Crb), tremolite (Tr) and chlorite (Chl). Sample ELI-675-21.00. Photo Sari Grönholm.

peridotite macroscopically. On the weathered surface of some samples amphibole is discernible as a pale, somewhat fibrous mineral. However, the greatest difference between these peridotite types lies in the microstructure (Fig. 13).

A characteristic feature of the amphibole peridotites is alteration of pyroxene into acicular tremolite (Fig. 13). Olivine grains are rimmed with amphibole, and pyroxene grains have altered into amphibole along the margins and in the core. The central parts of the olivine grains have altered into serpentine. Amphibole occurs in association with the chlorite between pseudomorphs. The pseudomorphs after olivine are 2-5 mm in size and the pyroxene relicts less than 4 mm. In places there are talc-bearing fissure veins.

Pyroxene peridotite

The pyroxene peridotite group contains the peridotites in which the abundance of alteration products of olivine exceeds 40% and the abundance of pyroxene and its alteration products varies in a range of 18-45% (Table 8, p. 22). On the basis of the pyroxene alteration, the samples of the group might be subdivided into peridotites that have undergone carbonate, serpentine, magnetite or talc alterations. However, since not all the alteration types could be tested here, the group was named on the basis of the original pyroxene abundance. The grain size of the alteration products of pyroxene was so small that these products were not identified for all the samples in the calculations of mineral composition.

The pyroxene peridotites are macroscopically pale green, almost non-oriented rocks with altered pyroxene grains that show up on the weathered surface as subhedral crystals paler in colour than chlorite. They are coarser than the chlorite peridotites and serpentine peridotites and, as shown by scratch tests, also softer.

Sample ELI-47-20.57 resembles the cumulate peridotites but is much paler. On the basis of microstructure and mineral composition, the sample was classified as pyroxene peridotite. It is dense and unfractured, and has abundant large poikilitic pyroxene grains that are clearly visible with the unaided eye. The grains are brownish, measuring 4 x 1.5 cm on average. The pyroxene has largely altered into chlorite, magnetite, phlogopite and serpentine, and to a minor extent into carbonate, too.

The pyroxenes altered into magnetite show up as lustrous grains on drill core samples. The pyroxene relicts are about 1 mm in size. Phlogopite is covered with dusty magnetite and, with the exception of a few single scales, the grains are similar to those of pyroxene in shape (Fig. 14). The cumulate peridotite in the lower part of the same drill hole resembles this type in structure, but its minerals are better preserved and the pyroxene grains are dark brown. In places, microfissures at intervals of 1cm on average occur in swarms about 1 m wide.

The olivine in the pyroxene peridotites has altered totally into serpentine, amphibole and magnetite in all samples but one. The pseudomorphs after olivine are usually 2-3 mm in size. Serpentine, amphibole,

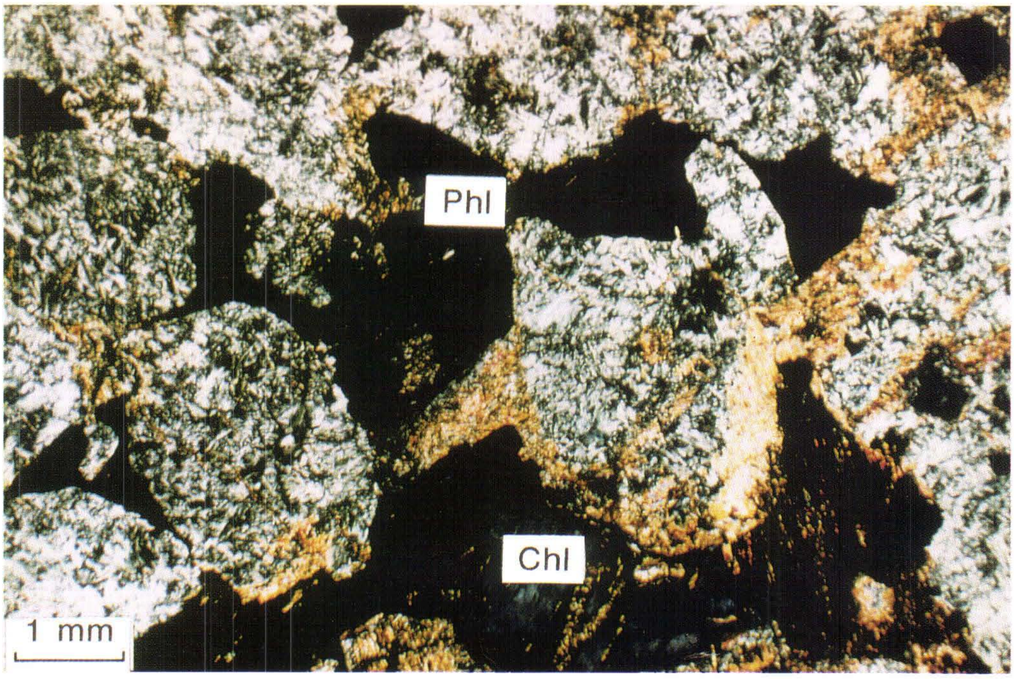

Fig.14. Poikilitic pyroxene grains in pyroxene peridotite with chlorite (Chl) and phlogopite (Phl). Sample ELI-47-20.57. Photo Sari Grönholm.

talc, magnetite, carbonate and phlogopite (Table 8) are alteration products of pyroxene. Pyroxene grains measure 4 mm on average, and in some samples pyroxene has altered almost completely into magnetite. Alteration has been so intense that the true grain size of some samples is that of the alteration products, i.e. less than 1 mm. Chlorite often occurs in the interstices between the pseudomorphs. The scattered phlogopite scales encountered here and there are usually 1 mm in size. Carbonate is a common alteration product of pyroxene, and often occurs together with chlorite between the pseudomorphs. Microstructures of the pyroxene peridotites are shown in Figs 14 and 15.

Pyroxenites

The pyroxenites in the study material were divided into three main types on the basis of their alteration products: fresh pyroxenite (websterite), amphibole pyroxenite and talc pyroxenite. The mineral compositions of the pyroxenites are given in Tables 9, p. 23, 10, p. 24 and 11, p.25. The altered pyroxenites in the study material were originally bronzites. Sample ELI-670-74.50 m (Fig. 18, p. 25) has pseudomorphs after olivine, suggesting that the rock was originally olivine bronzite.

Fresh pyroxenite

According to Alapieti et al. 1989, the pyroxenites of the Elijärvi orebody at Kemi are bronzites, olivine bronzites, websterites and diallagites. The pyroxenite studied here was the websterite that occurs in the Kemi intrusion 800 - 1000 m above the contact of the intrusion with granite gneiss (Fig. 5, p. 12).

The websterites are mainly composed of augite and bronzite, with intercumulus plagioclase (An 64) in places. The composition of calcium-poor orthopyroxene is almost constant, with a 100xMg/(Mg+Fe+Mn) ratio of about 83. The Cr_2O_3 concentration is fairly high, 0.41 - 0.60%, as is the chromium concentration in augite, 0.83% (Alapieti et al. 1989).

Fresh pyroxenite is an almost non-oriented, medium-grained rock pale green in colour. Single pyroxene grains are clearly discernible on the weathered surface.

Under the microscope, the pyroxene grains appear virtually unaltered (Fig. 16, p. 23). Slight alteration has proceeded along the cleavages in pyroxene, producing very fine-grained amphibole, magnetite and chlorite. The pyroxene grains are subhedral, measuring 5 mm on average. In some places the boundaries between grains are bay-like but usually they are straight. The interstices between the pyroxene grains contain subhedral lamellar plagioclase that has undergone slight serisitization and saussuritization. Table 9 shows the mineral composition of sample ELI-2-150.45-150.55.

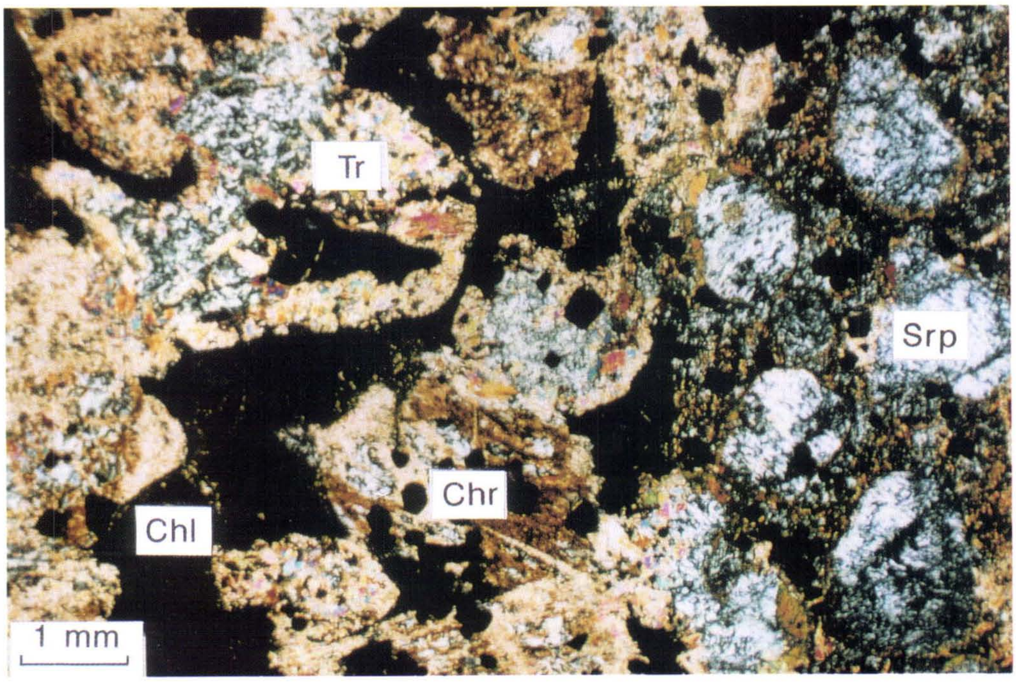

Fig. 15. Microstructure of pyroxene peridotite tested with chlorite (Chl), chromite (Chr), serpentine (Srp) and tremolite (Tr). Sample ELI-674-77.40. Photo Sari Grönholm.

Table 8. Modal composition of pyroxene peridotites. Alteration products of pyroxene (Px) are listed in order of decreasing abundance.

Mineral/ Minerals	1	2	3	4	5	6	7	8
Olivine	-	-	-	-	-	1.9	-	-
Pyroxene	9.1	-	-	-	2.0	6.2	2.4	-
Serpentine	55.1	58.1	43.1	44.9	37.7	32.0	53.1	51.7
Chlorite	8.3	0.7	14.6	5.9	4.5	8.6	14.5	12.3
Phlogopite	8.8	1.0	0.1	0.6	0.6	0.5	-	0.3
Carbonate	3.1	0.4	-	2.2	1.4	0.1	0.1	4.9
Amphibole	6.9	-	4.4	2.5	3.6	5.9	0.1	11.7
Alteration products (Px)	-	32.8	35.5	42.7	45.0	41.3	0.3	18.2
Magnetite	5.7	2.5	-	-	-	2.2	26.6	0.8
Chromite	3.0	4.5	2.3	1.2	5.2	1.3	2.9	0.1
Pyrite	-	< 0.1	-	-	-	< 0.1	< 0.1	< 0.1

1 = Sample ELI-47-20.57
2 = Sample R22-47,0, Tr, Crb, Tlc, Chl, Srp, Mag
3 = Sample ELI-675-54.1, Tlc, Tr, Srp, Chl
4 = Sample R22-109, Tr, Crb, Mag, Srp
5 = Sample R22-98, Mag, Tr, Srp, Chl
6 = Sample ELI-672-5,7, Mag, Tr, Srp, Chl
7 = Sample R22-87, Mag
8 = Sample ELI-671-25.7, Tr, Chl, Srp, Crb, Mag

Table 8, cont.

Mineral/ Minerals	9	10	11	12	13	14	15
Pyroxene	-	-	-	-	-	0.5	0.2
Serpentine	51.1	56.9	51.8	38.8	41.1	31.1	46.4
Chlorite	11.0	7.6	15.2	8.2	17.0	16.2	12.2
Amphibole	5.2	1.9	1.1	7.0	9.6	36.7	15.5
Phlogopite	0.2	3.2	-	-	-	-	-
Carbonate	6.4	0.6	7.4	7.9	0.4	4.1	11.40
Talc	-	-	-	-	-	-	3.90
Alteration products (Px)	19.5	28.2	20.7	30.0	31.2	-	-
Chromite	6.0	1.3	3.8	8.1	-	10.7	10.4
Magnetite	0.6	0.3	-	-	0.7	0.7	< 0.1
Pyrrhotite	< 0.1	-	-	-	-	-	< 0.1
Pyrite	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

9 = Sample ELI-670-23, Tlc, Srp, Tr, Crb, Mag
10 = Sample ELI-675-63, Tr, Mag, Crb, Tlc, Srp, Chl
11 = Sample R22-119,50, Crb, Tr, Tlc, Srp, Chl, Mag
12 = Sample ELI-673-20,10, Chl, Srp, Crb, Tr, Mag
13 = Sample ELI-673-61,00, Tr, Tlc, Srp, Chl
14 = Sample ELI-674-77,40
15 = Sample ELI-670-43,50

Table 9. Modal mineral composition of websterite.

Pyroxene	90.30
Ampfibole	1.70
Chlorite	0.10
Plagioclase	5.10
Sausserite	2.60
Chromite	0.20

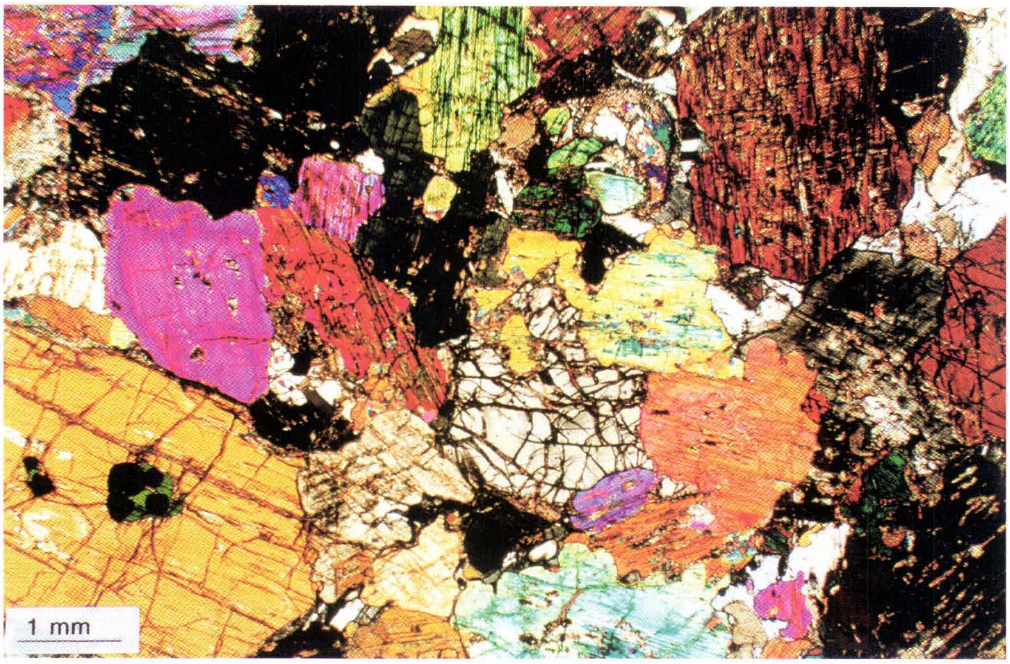

Fig. 16. Microstructure of websterite in sample ELI-2-150.45-150.55 m. Photo Sari Grönholm.

Amphibole pyroxenite

Seven samples, from drill holes ELI-670, ELI-672, ELI-674 and R-22, were amphibole pyroxenites. The mineral compositions of these rocks are given in Table 10.

The weathered surface of amphibole pyroxenite is a slightly darker green than that of fresh pyroxenite owing to the fine-grained chlorite between the altered pyroxenite grains. On the fresh surface, the pyroxene grains that have altered into amphibole show up as nematoblastic grains, 5 mm in size on average, still with the shape of pyroxene crystals.

The amphibole pyroxenites typically have a nematoblastic texture. Amphibole grains have frequently grown across the former pyroxene grains, binding the minerals tightly together. Pyroxene occurs as tiny grains in the middle of the alteration products. As well as amphibole, the alteration products are talc, phlogopite, chlorite and serpentine. Very fine-grained chlorite occurs between the altered pyroxene grains. The pseudomorphs after pyroxene measure 3-5 mm on average. The amphibole grains are usually less than 1.5 mm long.

The largest amphibole grains occur in rounded pseudomorphs, probably those after olivine (Fig. 17).

The amphibole pyroxenites contain small amounts of pyrite or pyrrhotite (less than 5%). Magnetite is also present in low abundances (maximum encountered, 5.5%, in sample ELI-674-65.70).

Table 10. Modal mineral compositions of Elijärvi amphibole pyroxenites. Alteration products of pyroxene (Px) are listed in order of decreasing abundance.

Mineral/Minerals	1	2	3	4	5	6	7
Pyroxene	30.4	-	42.6	57.4	7.4	14.7	-
Amphibole	29.4	70.5	30.6	28.7	60.7	44.8	76.6
Chlorite	24.0	27.5	21.1	12.4	16.5	32.6	11.5
Serpentine	3.1	1.2	-	-	-	0.1	3.6
Phlogopite	0.1	-	-	0.1	-	-	-
Talc	4.9	-	3.7	1.2	15.4	6.9	-
Alteration products (Px)	7.9	-	-	-	-	-	-
Carbonate	0.1	-	-	-	-	-	2.8
Magnetite	0.1	0.8	2.0	0.2	-	0.9	5.5
Chromite	< 0.1	< 0.1	-	-	-	< 0.1	< 0.1
Pyrrhotite	-	-	-	-	< 0.1	-	< 0.1
Pyrite	-	< 0.1	< 0.1	-	-	< 0.1	< 0.1

1 = Sample ELI-670-52.50 Fine - grained material after pyroxene
2 = Sample R22-56.00
3 = Sample ELI-674-73.00
4 = Sample ELI-672-45.60
5 = Sample ELI-672-34.00
6 = Sample ELI-672-30.80
7 = Sample ELI-674-65.70

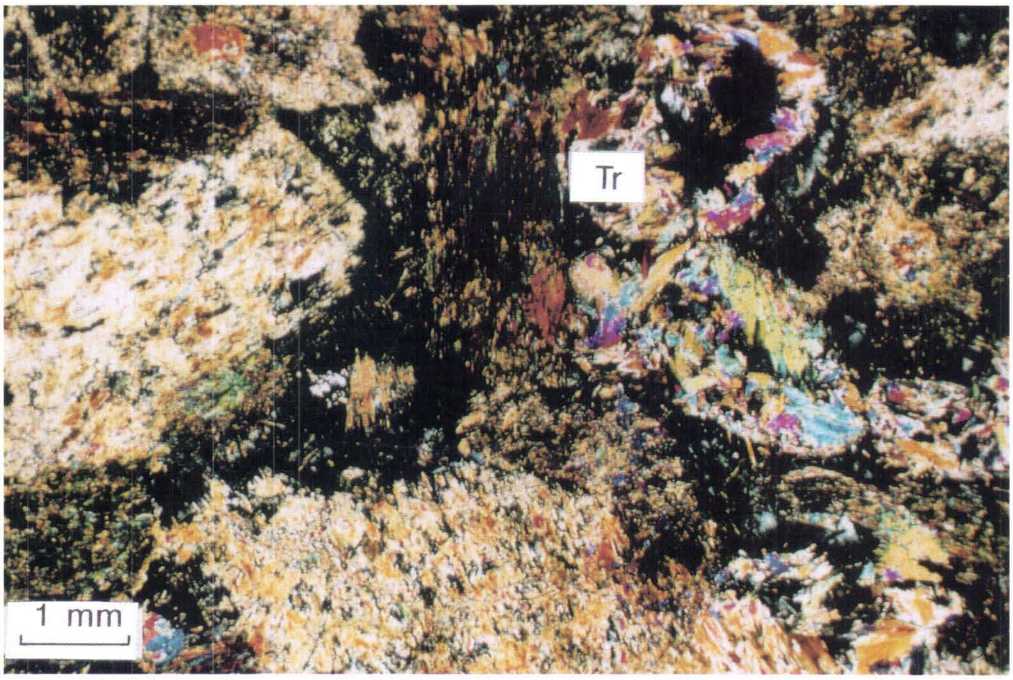

Fig. 17. Tremolitic amphibole pyroxenite. Sample ELI-674-73.00. Photo Sari Grönholm.

Talc pyroxenite

Talc pyroxenites, too, were primarily bronzites and olivine bronzites. The talc pyroxenite tested (ELI-670-74.50) was originally olivine bronzite because it exhibits indisputable pseudomorphs after olivine and has a fairly high serpentine abundance. However, unlike pyroxene, olivine has not altered into talc. The sample material contained three talc pyroxenites. Their mineral compositions are shown in Table 11.

The composition of talc was analysed on samples ELI-670-74.50 and R-25-57 and that of chlorite on sample R-25-57 (Appendix 1).

The talc pyroxenites are a slightly paler green than the amphibole pyroxenites. On weathered surfaces

Table 11. Modal composition of talc pyroxenites. Sammple numbers and alteration products of pyroxene (Px) are listed in order of decreasing abundance.

Mineral/Minerals	1	2	3
Pyroxene	-	1.5	1.5
Amphibole	5.3	27.4	15.8
Chlorite	13.3	35.4	18.0
Talc	-	33.2	50.0
Serpentine	22.5	0.6	1.4
Phlogopite	0.2	0.3	1.2
Plagioclase	-	-	-
Alteration products (Px)	57.7	-	9.7
Magnetite	1.0	1.6	2.4
Chromite	< 0.1	< 0.1	-
Pyrite	< 0.1	< 0.1	< 0.1

1 = Sample ELI-670-74.50, Tlc, Tr
2 = Sample R25-57.00
3 = Sample R25-27.00, Srp, Tr

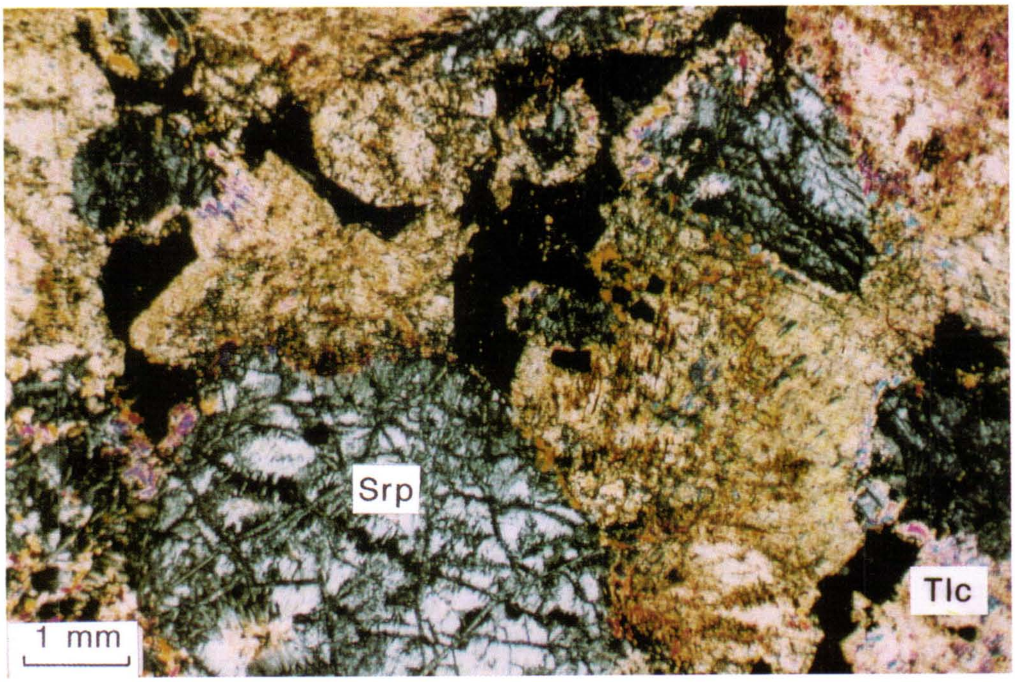

Fig. 18. Microstructure of talc pyroxenite with serpentine (Srp) and talc (Tlc). Sample ELI 670-74.50 m. Photo Sari Grönholm.

talc can be recognized as a soft pale mineral.

Talc, which is an alteration product of pyroxene, occurs as very fine-grained dissemination in pseudomorphs after pyroxene together with fine-grained amphibole and chlorite (Fig. 18). The pseudomorphs measure 3-4 mm and the amphibole grains are less than 1 mm long. Amphibole is colourless under the microscope in plane-polarized light or weakly pleochroic (brownish-colourless). The talc pyroxenites contain small amounts of pyrite, chromite and magnetite.

Serpentinites

Rocks with a serpentine abundance exceeding 70% are called serpentinites here. There are two types of serpentine: those deriving from peridotites and those from dunites. The serpentinites formed from peridotites are typical of the Elijärvi and Nuottijärvi orebodies. Dunites and the serpentinites derived from them occur mainly in the Nuottijärvi area. The mineral compositions of serpentinites are given in Table 12.

Table 12. Modal composition of serpentinites.

Mineral/ Minerals	1	2	3	4	5
Serpentine	90.2	75.7	71.3	78.6	81.8
Chlorite	-	-	9.7	-	0.1
Carbonate	1.2	10.1	-	-	3.4
Talc	-	2.1	-	-	8.9
Magnetite	8.6	10.0	16.9	18.9	-
Chromite	-	2.1	2.1	2.5	5.8

1 = Sample ELI-550-38.55
2 = Sample ELI-512-34.80
3 = Sample ELI-51-140.39
4 = Sample ELI-731-147.45
5 = Sample ELI-SP-2

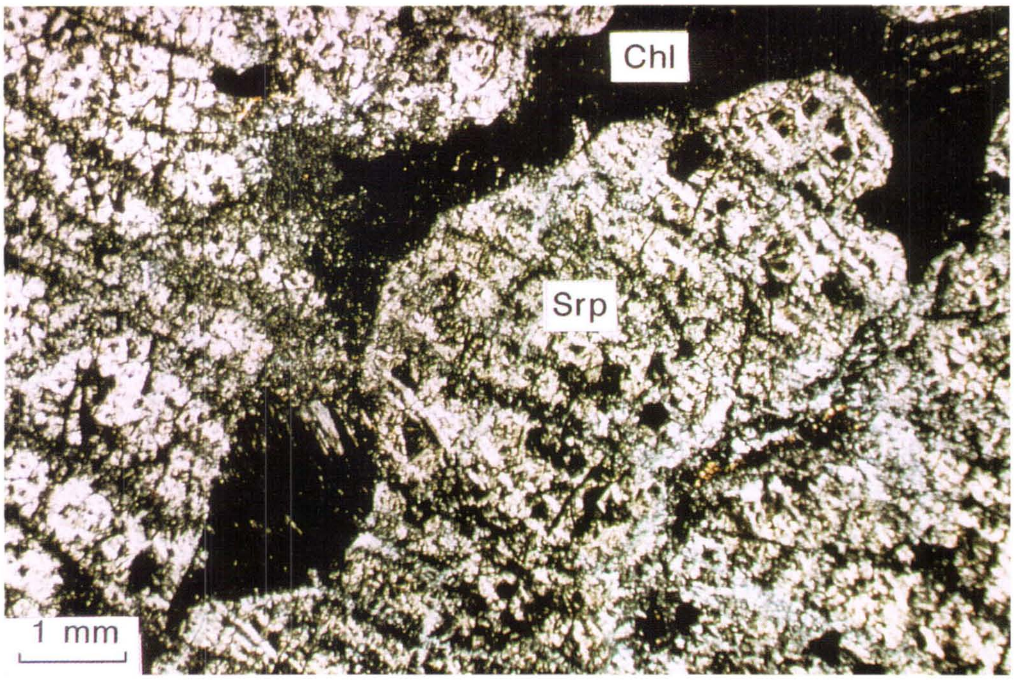

Fig. 19. Microstructure of serpentinite derived from peridotite, with serpentine (Srp) and dark-green chlorite (Chl), pseudomorph after pyroxene. Sample ELI-51-140.39-140.49. Photo Sari Grönholm.

Microstructure of serpentinite derived from peridotite

The serpentinites that derive from peridotites other than dunite are very fine-grained homogeneous rocks. They are dark greenish grey in colour. Serpentinite is composed almost exclusively of fine-grained antigorite flakes that are colourless in plane-polarized light (Fig. 19). The primary orthocumulate structure of the rock is vaguely discernible on weathered surfaces; in places it has been totally obliterated.

Under the microscope the primary structure of the rock is revealed by the pseudomorphs after olivine and pyroxene, which show up in the groundmass owing to the magnetite dust formed in alteration. The serpentine of the pseudomorphs after olivine is slightly coarser than elsewhere in the rock. The rock also contains fine-grained massive carbonate and euhedral chromite crystals here and there. Talc, too, is encountered occasionally. The average grain size of the rock is about 0.15 mm and the largest chromite grains measure 1 mm.

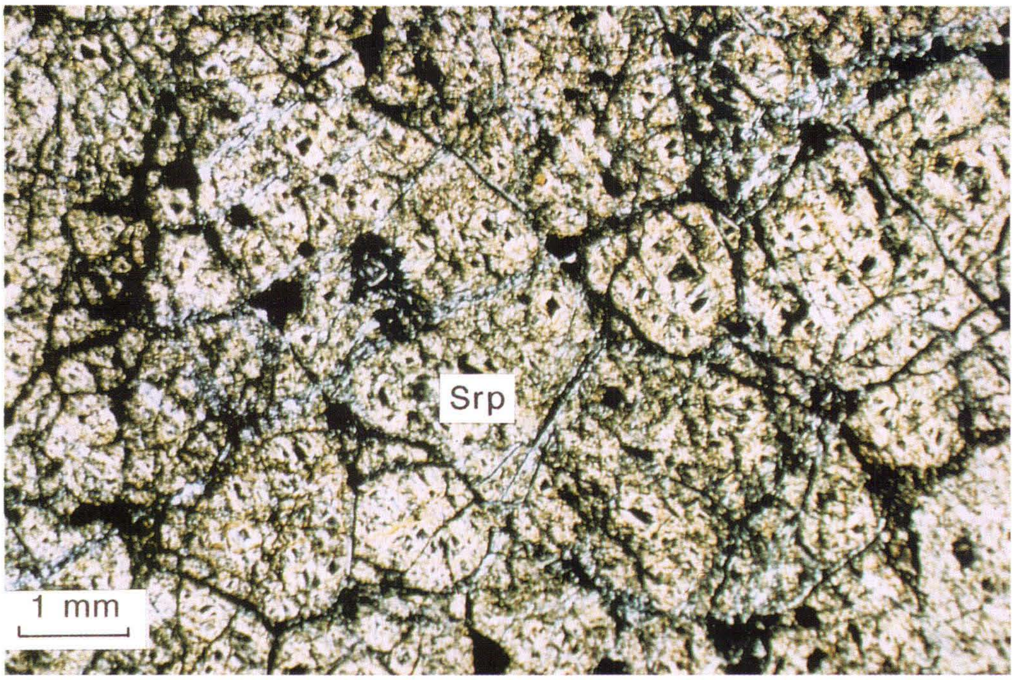

Fig. 20. Microstructure of serpentinite derived from a dunite protolith, with original outlines of former olivine grains still discernible. Sample 731-147.45-147.50 m. Photo Sari Grönholm.

Table 13. Modal composition of granitic gneiss (1), albitite dyke (2) and metadolerite (3).

Mineral/Minerals	1	2	3
Albite	56.4	66.5	-
Chlorite	1.0	-	1.6
Carbonate	0.9	-	-
Tremolite	-	16.6	0.2
Quarts	10.8	16.8	1.2
Hornblende	-	-	56.8
Saussurite	12.1	-	33.8
Sericite	18.2	-	-
Apatite	-	-	0.1
Titanite	-	0.1	2.5
Plagioclase	-	-	3.8
Muscovite	0.6	-	-

The serpentinites were assigned to strength class I on the basis of a strength test on a lumpy sample.

Microstructure of serpentinite derived from dunite

The serpentinite derived from dunite is composed almost exclusively of serpentine and magnetite. It has an adcumulate structure and thus lacks intercumulus material. Fine-grained magnetite outlines the pseudomorphs after olivine (Fig. 20), which measure 2 mm on average. As shown by the test data (Table 14, p. 30 sample ELI-731-147.45), the serpentinite formed from dunite is classless in strength properties. The microstructure of the serpentinites derived from dunites is clearly different from that of the serpentinites formed from the other peridotites.

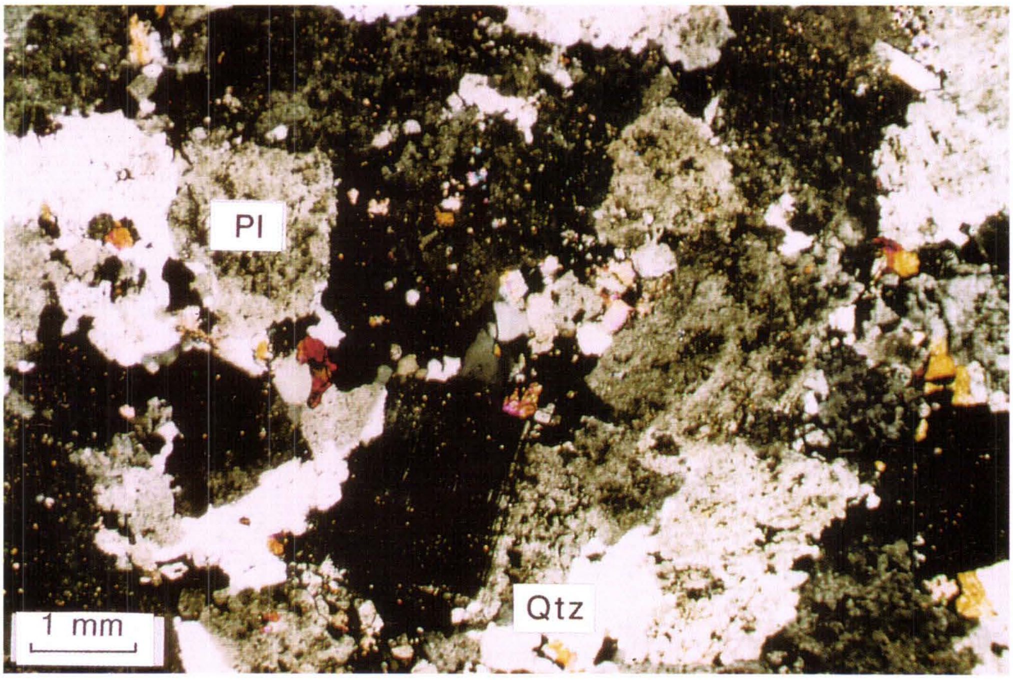

Fig. 21. Microstructure of granite gneiss with quartz (Qtz) and plagioclase (Pl). Sample ELI-1. Photo Sari Grönholm.

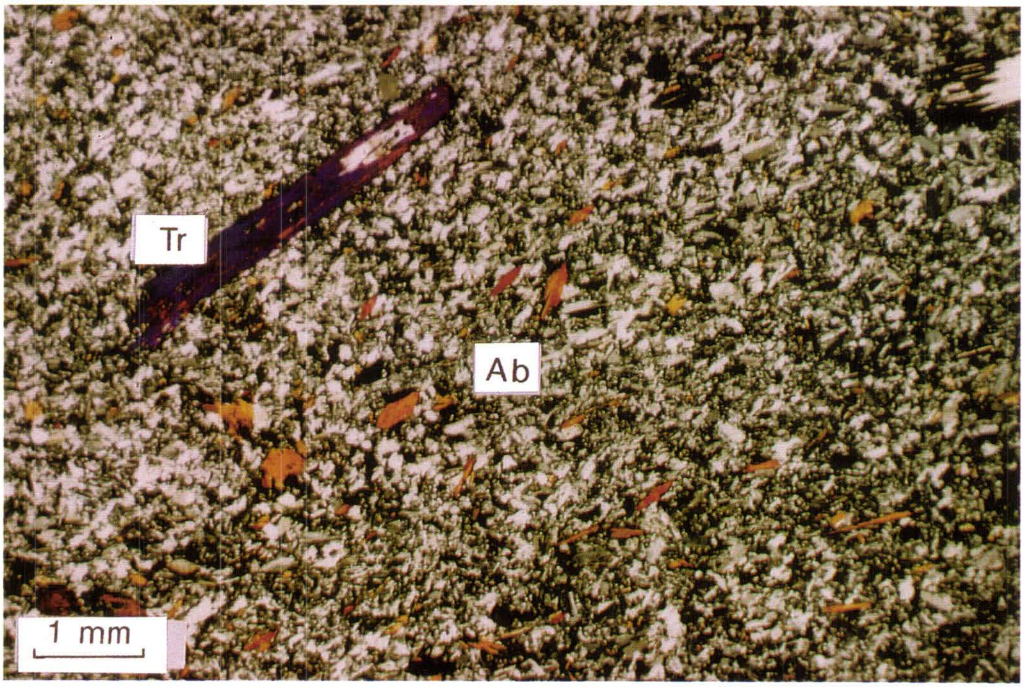

Fig. 22. Microstructure of an albitite dyke with albite (Ab) and tremolite (Tr). Sample ELI-2. Photo Sari Grönholm.

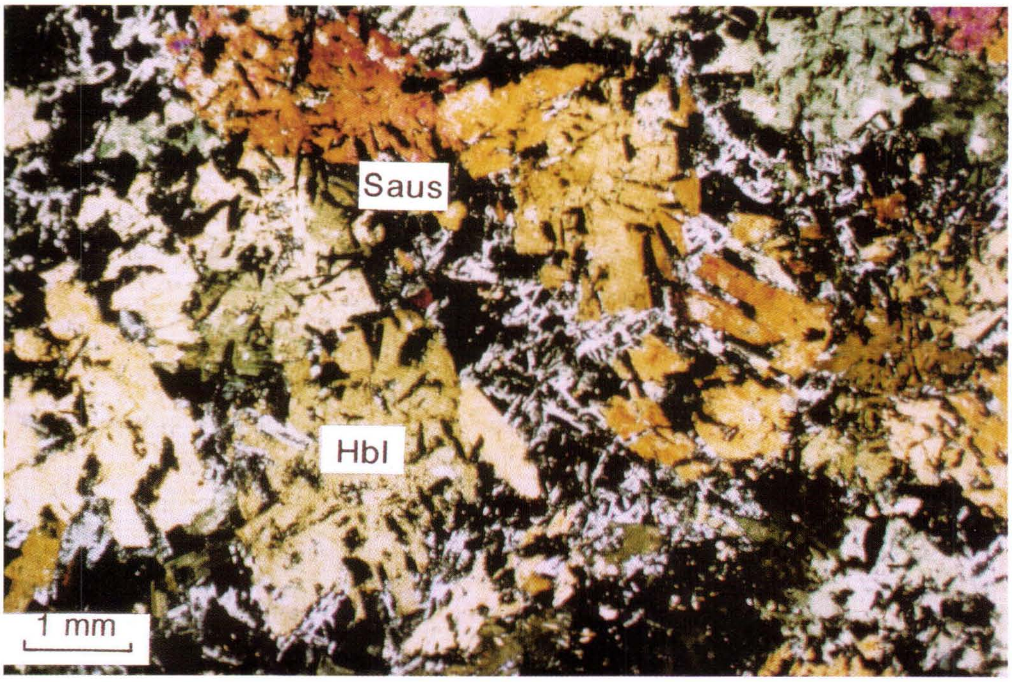

Fig. 23. Microstructure of metadolerite with saussurite (Saus) and hornblende (Hbl). Sample ELI-3. Photo Sari Grönholm.

Other host rocks

Lumpy samples were taken from granite gneiss, dolerite and an albitite dyke. The mineral compositions of the samples are given in Table 13, 27. The strength classes of the dolerites and albitites are listed in Table 14.

Granite gneiss

The lumpy sample studied represents the granite gneisses located in the floor of the Kemi ultramafic intrusion (Fig. 1, p. 8). The sample is pinkish green and slightly oriented. The greenish hue is due to intense sericitization and saussuritization of plagioclase (albite). Plagioclase has also altered into carbonate.

The borders of the plagioclase grains are bay-like and serrate, although with quartz grains there are also straight borders. The plagioclase grains have rounded edges and are platy but not lath-shaped (Fig. 21).

Some of the plagioclase crystals are twinned. The grains have a maximum length of 4.5 mm and an average length of 3 mm. The plagioclase grains are rimmed with fine-grained quartz with an average grain size of less than 0.5 mm. Saussurite is clinozoisite and its grain size, too, is less than 0.5 mm.

The granite gneisses were assigned to classes A and I on the basis of previous tests. The granite gneiss studied here was not submitted to strength tests.

Albitite dykes

The Kemi ultramafic intrusion is cross-cut in places by almost non-oriented, fine-grained albitite dykes that are greenish grey in colour.

The rock is mainly composed of albite, tremolite and quartz (Table 13, p. 27). Plagioclase occurs as lath-shaped dactylitic grains (Fig. 22.) bound together by very fine-grained quartz. Some quartz crystals exhibit serrate edges. Amphibole is slightly greenish or colourless. Some of the grains show lamellar twinning, and at least a few of the amphibole (tremolite) grains are asbestos (length at least 5 µm, width no more than 3 µm, and length to diameter ratio at least 3:1).

Dolerite dykes

The sample investigated was taken from the Länsi-Viia open pit (Fig. 2, p 9.). The dolerite is dark green and almost non-oriented in structure. It is composed mainly of green hornblende and very intensely saussuritized plagioclase (Table 13, p. 27).

The hornblende is platy and anhedral in shape. Saussuritized plagioclase laths, which are partly inside hornblende grains, form an ophitic and subophitic structure (Fig. 23.). The saussuritized grains are often rimmed with quartz. The hornblende grains have an average length of 2 mm or slightly less, and the plagioclase grains are about 0.7 mm long. Hornblende shows very little alteration into biotite and chlorite. In addition, it contains a few acicular tremolite grains (colourless). Titanite occurs as fairly large (0.7 mm) grains.

STRENGTH PROPERTIES OF HOST ROCKS OF THE CHROMITE OREBODIES

Test results and rock classification

Twelve drill core samples were tested, of which nine were peridotites, two pyroxenites and one serpentinite. Four lumpy samples of albitite, dolerite, serpentinite and cumulate peridotite were also tested. The strength tests were made on drill core samples 8.50-10.50 m long. The results are given in Table 14.

According to the test results and with reference to the strength specifications of the Finnish National

Table 14. Strenght-test results for some rock types from the Kemi chromite deposit. Lumpy samples marked with (*). n.d. = not determined.

Sample	ImV	LosA	ABR	D	SC
1	11.90	9.10	1.72	2.84	A
2	11.20	8.20	1.60	2.78	A
3	12.00	7.60	1.68	2.79	A
4	11.50	8.10	1.81	2.85	I
5	14.10	10.00	1.84	2.86	I
6	10.80	9.40	2.10	2.88	I
7	13.60	10.10	2.58	2.84	II
8	11.30	8.60	2.06	2.93	I
9	9.90	8.50	2.59	2.91	II
10	11.90	11.10	3.35	2.89	>III
11	14.40	n.d.	2.93	2.89	III
12	18.10	n.d.	5.70	2.68	>III
13*	14.50	11.80	1.17	2.67	A
14*	10.40	9.04	1.18	3.07	A
15*	13.70	11.70	3.47	2.86	>III
16*	13.90	12.80	2.03	2.73	I

1 = R25-15, Chlorite peridotite
2 = Eli-670-6.00, Serpentine peridotite
3 = Eli-671-8.00, Serpentine peridotite
4 = Eli-672-16.90,Serpentine peridotite
5 = Eli-670-43.50, Pyroxene peridotite
6 = Eli-674-6.30, Cumulus peridotite
7 = R22-47.00, Pyroxene peridotite
8 = Eli-674-77.40, Pyroxene peridotite
9 = Eli-674-65.70, Amfibole pyroxenite
10 = Eli-670-74.50, Talc pyroxenite
11 = Eli-83-47.70, Cumulus peridotite
12 = Eli-731-147,45, Serpentinite
13* = Elijärvi, Albitite
14* = Länsiviia, Dolerite
15* = Elijärvi-4 ,Cumulusperidotite
16* = Eli-Sp-2, Serpentinite
ImV = Improved Swedish Impact Test Value
LosA = Los Angeles Test Value
ABR = Abradability Value
D = Density
SC = Strenght Class (Finnish National Road Authority, 1991)
>III = Classless

Road Administration (1991, p. 6), the chlorite peridotites, serpentine peridotites, albitite dykes and dolerites belong to class A. The amphibolitized cumulate peridotite is in strength class I, and the intensely chloritized cumulate peridotite with well preserved primary structures class III. The pyroxene peridotites fluctuate between classes I and II. The amphibole pyroxenite is in class II, whilst the talc pyroxenite is classless. The serpentinite derived from peridotite is in class I and the serpentinite formed from dunite is classless.

The strength class of a rock is defined by the test that gives the lowest strength. For metaperidotites, metapyroxenites and serpentinites the decisive test was the abradability value test; had the strength of these rocks been tested with the Los Angeles tests and improved Swedish impact test alone, all the rocks would have been assigned to class A. The values of the Los Angeles and improved Swedish impact tests usually correlate well with one another (Alkio & Vuorinen 1990), i.e. they measure more or less the same properties. Note, however, that the point-load index was not determined for these rocks. In the future it will replace both the Los Angeles and the improved Swedish impact tests (Heikkilä 1991).

FACTORS AFFECTING THE STRENGTH PROPERTIES OF ROCKS

Microstructures

The components of microstructure, or texture, that contribute to the strength of a rock are grain size, mineral shapes and mineral intergrowths.

Grain size

In engineering geology rocks are classified as fine-grained (less than 1 mm), medium-grained (1-5 mm), coarse-grained (5-50 mm) and very coarse-grained (over 50 mm) rocks. Grain size affects abradability, fine-grained rocks being more durable than coarse-grained ones (Kauranne et al. 1979).

The range of grain size distribution is narrow for the main minerals in even-grained rocks but wide in rocks with phenocrysts. It is assumed that the wider the distribution the weaker is the rock. However, the effect of grain size distribution as a factor weakening a rock depends on the amount of phenocrysts and their orientation. Sparsely distributed phenocrysts separated from each other do not weaken a rock, whereas abundant phenocrysts in parallel orientation do (Vähäsarja 1976).

All the above rock types assigned to class A are fine-grained (grain size 1 mm). The size of the pseudomorphs after olivine and pyroxene in some samples of chlorite and serpentine peridotites is 3-4 mm. The grain boundary between the pseudomorphs and the enveloping fine-grained serpentine or chlorite mass is so irregular, though, that the true grain size of the rock is usually the same as that of the alteration products, i.e. less than 1 mm, and often even less than 0.5 mm. In some cases the grain boundaries are better preserved, but then the pseudomorphs behave like sparse separate phenocrysts and do not significantly weaken the rock.

The cumulate metaperidotite, which was assigned to class I, is in places medium-grained in its true grain size, because the cumulus structure is fairly well preserved (cf. Fig. 8, p. 14). Nevertheless, the test results indicate a strong rock, because the pseudomorphs after olivine have altered along their margins into amphibole, thus making the rock less brittle. According to the test results, the less altered cumulate peridotites are class III or classless (cf. Table 14, samples ELI-83-47.70 and Elijärvi 4 and Fig. 7, p. 14).

The talc pyroxenite is classless in technical properties. As suggested by the pseudomorphs after olivine, the rock was originally olivine bronzite. The pseudomorphs after olivine composed of serpentine occur as islets in a fine-grained mass of talc and amphibolite. The talc pyroxenites belong to the group of classless rocks because of their high abundance of soft talc.

Grain shape

Grain shapes can be defined on the basis of general structural terms as, for instance, in Fig. 24 (Papunen 1984).

A mineral can be euhedral, subhedral or anhedral depending on its shape. The borders of the euhedral grains are crystal faces and hence often straight, whereas the shape of anhedral grains is determined by the surrounding minerals. The euhedral crystals in igneous rocks such as olivine and pyroxene are the first minerals to crystalize from magma.

Many unaltered or only slightly altered igneous rocks and some metamorphic rocks contain abundant euhedral minerals. When submitted to metamorphism, minerals become less euhedral and are often bound closely together. The Los Angeles and improved Swedish impact tests have demonstrated that granites composed of subhedral minerals are weaker than gneisses with a similar mineral composition. The cataclastic structure typical of some gneisses (Fig. 24) is a strong structure, as shown by the tests.

The crystal boundaries between anhedral minerals tend to be irregular (Fig. 25).

The above holds for the rock types tested here, too: as the abundance of euhedral minerals increases (olivine and pyroxene) the abradability of the rock decreases distinctly. The strength properties of a rock improve with the obliteration of the cumulus structure.

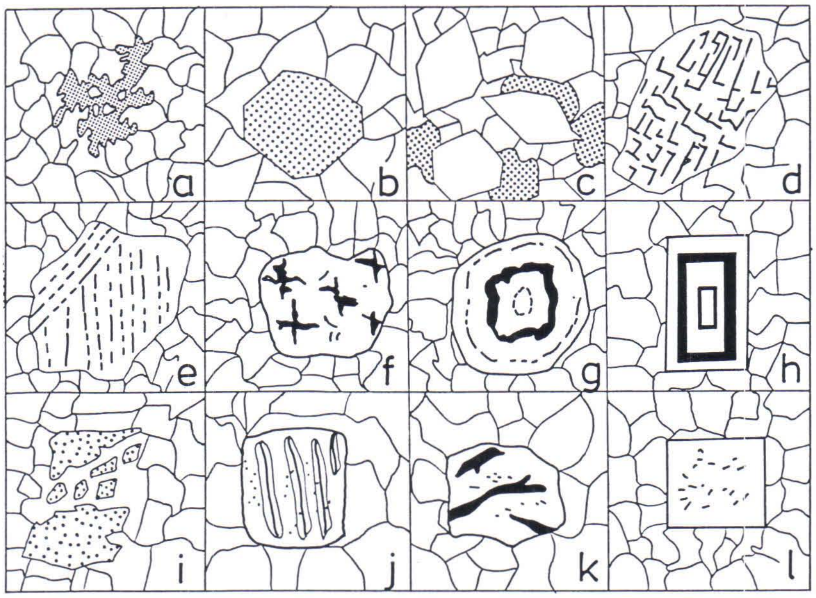

Fig. 24. Grain shapes. a = poikilitic, b = euhedral, c = anhedral, d = graphic intergrowths, e = inclusion trains, f = exsolution structures, g = zoned inclusions, h = compositional zoning, i = cataclastic, j = alteration or zoning, k = fracture filling, l = porphyroblast (after Papunen 1984).

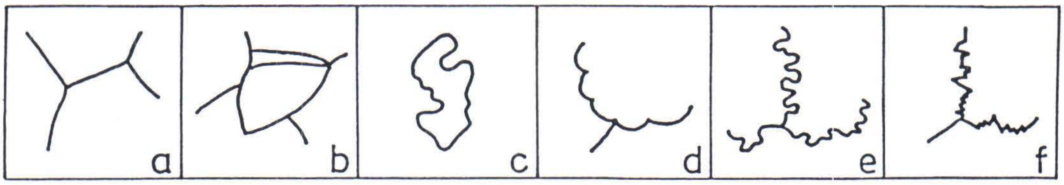

Fig. 25. Shapes of grain boundaries between mineral crystals (after Spry 1974). a = straight, b = curved, c = embayed, d = conchoidal, e = lobated and f = serrated.

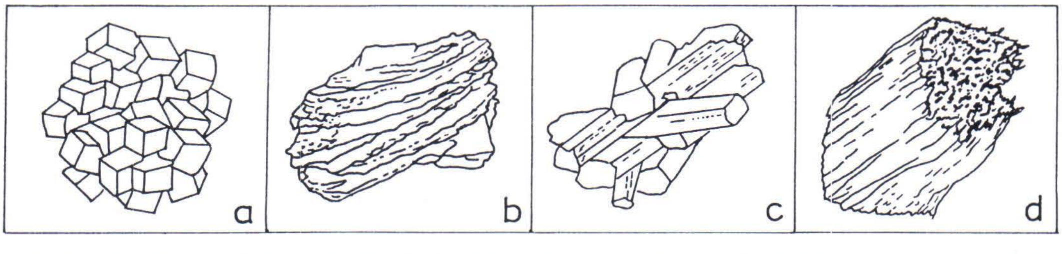

Fig. 26. Different kinds of mineral habit and morphology: a) granular, b) flaky or lepidoblastic, c) nematoblastic and d) fibrous (after Korhonen et al. 1974).

Mineral intergrowths

Minerals can be granular, flaky, nematoblastic or fibrous in habit (Fig. 26, Korhonen et al. 1974).

The bond between two different minerals may be almost as strong as the cohesive force that holds the crystal structure of the mineral together. However, if the minerals are incompatible in their crystal structure, adhesion is much smaller than cohesion, and the boundary surfaces are shear planes.

Grain boundaries are zones of low ordering composed of impurities, vacancies and pores. The grains may be enveloped by a fluid film mainly composed of water and dissolved salts. The film is assumed to be 1-10 nm thick and to grade into the grain proper through a transitional zone (Fig. 27).

The strength of a rock depends on the cohesion and adhesion of the mineral grains. Cohesion is reduced by cleavages. Adhesion depends on the properties of the contact surface. If it is even, adhesion is low but, if serrate, adhesion is stronger. Alien materials on the contact surface, such as alteration products, fluid, gas or voids, are of special importance.

Lath-shaped fibrous or irregular mineral grains make a rock structure stronger than do those with straight, smooth or rounded surfaces (Maijala et al. 1976, Vähäsarja 1976). The structure of the Kemi metaperidotites is strengthened by the nematoblastic amphibole that typically rims olivine. As a result of serpentinization, the grain size of the rock has been greatly reduced and the euhedral olivine crystals, several millimetres in size have altered into very fine-grained, flaky serpentine. Pyroxene grains have also often altered into amphibole and serpentine.

As for the orientation of the minerals, the strongest rocks with the highest durability are those which are non-oriented and homogeneous. In the ophitic structure typical of gabbros and dolerite, subhedral or euhedral plagioclase crystals are intermixed with pyroxene and amphibole minerals (Fig. 28).

The strength of a rock in a certain direction usually decreases with the increase in the degree of orientation, as cohesion and adhesion act in different directions. The strength properties of a rock perpendicular to the orientation are different from those parallel to the orientation. For instance, the compressive strength is higher in the plane perpendicular to schistosity than parallel or oblique to it. This is a property typical of mica schists. Mylonites are examples of highly oriented rocks, yet, due to the recrystallization of their minerals, their cataclastic structure and their fine grain size they are strong rocks.

The metaperidotites and metapyroxenites of the Kemi deposit are almost non-oriented. None of the other rock types studied show marked orientation either.

The strength of dolerites is attributed to their ophitic structure. The ductility of the amphibole peridotites and pyroxene peridotites here is partly due to the nematoblastic structure of the amphiboles, which binds the grains together (cf. Fig. 26 c).

Mineral composition

The strength and abrasion resistance of a rock depend on the hardness, cleavage and weatherability of its minerals. These can be classified as soft, hard, ductile or brittle. On the basis of the properties of their major minerals, rocks can thus be classified as soft and ductile, and brittle and hard. Rocks are soft if the total abundance of soft minerals - micas, talc, chlorite and carbonate - exceeds 40%; brittle if they contain over 40% feldspars and less than 25% amphiboles and pyroxenes; ductile if they have at least 25% amphiboles and pyroxenes; and hard if the abundance of quartz exceeds 40%. The strength of

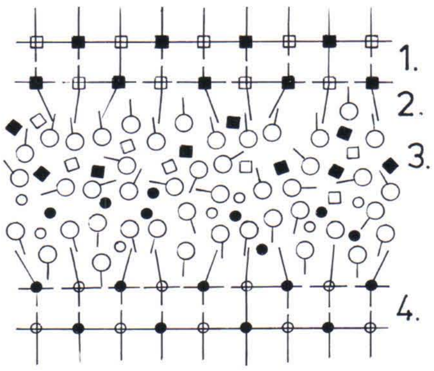

Fig. 27. Scheme of a fluid film on a grain boundary (after Bard 1986). 1 = grain A, 2 = adsorption layer, 3 = fluid film, 4 = grain B.

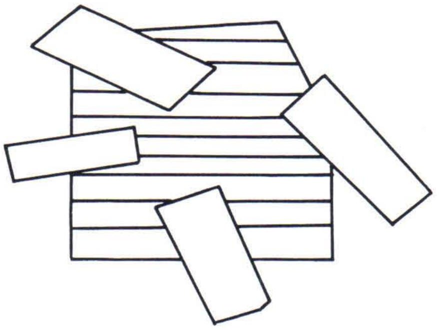

Fig. 28. Typical idealized example of ophitic structure (after Bard 1986).

the intermineral bonds is not taken into account in the above classification (Korhonen et al. 1974).

The hardness of rocks and minerals is generally given as scratch hardness. Hardness, like cleavage, is a property typical of every mineral and depends on the type of internal bond of the mineral, the size and coordination of the atoms and ions, the amount of "alien" replacing atoms in the lattice (diadochy), the charge and valence of the cations, and the crystal lattice. The hardness of anisotropic minerals depends on the crystal direction. For instance, on Mohs' scale the hardness of muscovite and biotite is 2 1/2 parallel to the basal plane or cleavage but 4 perpendicular to it; that of serpentine and chlorite is 2-3; that of pyroxenes and amphiboles 5-6; that of olivine 7; and that of talc 1 (Best 1982).

However, scratch hardness on Mohs' scale is only relative. Another unit for measuring hardness is Vickers hardness. Vickers hardness is the ratio of the mass (g/kg) loading the diamond tip to the surface area (square micrometre or millimetre) of the indentation. The diamond tip used in the tests is a pyramid with a square base and an apex angle of 136°. The perfect indentation is a square with two diagonals of equal length.

$$\mathrm{VHN} = \frac{2 * \sin 68^\circ * L}{d^2}$$

where L = weight and d = the length of the diagonal

The Vickers hardness test mainly measures plastic and elastic properties; it does not fully describe the properties of brittle substances (Young & Millman 1964).

Mineral hardness can also be studied with a simple impact test in which hard-metal tips provided with variable weights are dropped onto the mineral surface (Vilen 1991). The depth and surface area of the indentation caused by the impact are then measured. Impact tests show that diopside and hornblende are almost equally durable; potassium feldspar and plagioclase are clearly more brittle than either of them; and muscovite has the lowest resistance against impact. According to Vilen (1991), the best road-surfacing aggregate is composed of quartz and feldspar (50%) and amphiboles and/or pyroxenes (50%). Mica is one of the minerals that improve impact resistance.

When submitted to load, minerals usually break according to their crystal structure and parallel to the crystal faces but sometimes quite irrespective of the internal structure. Cleavage occurs in the plane with the weakest bonds. Micas break most readily parallel to the plane of the scales. Some minerals may lack a cleavage plane altogether. For instance, quartz and garnet break along irregular surfaces.

Mineral cleavage affects the strength of rocks, those composed of minerals that split readily being weaker than those composed of minerals without distinct cleavage. The weakening caused by cleavage increases relative to the size, abundance and preferred orientation of the mineral grains with distinct cleavage (Maijala et al. 1976).

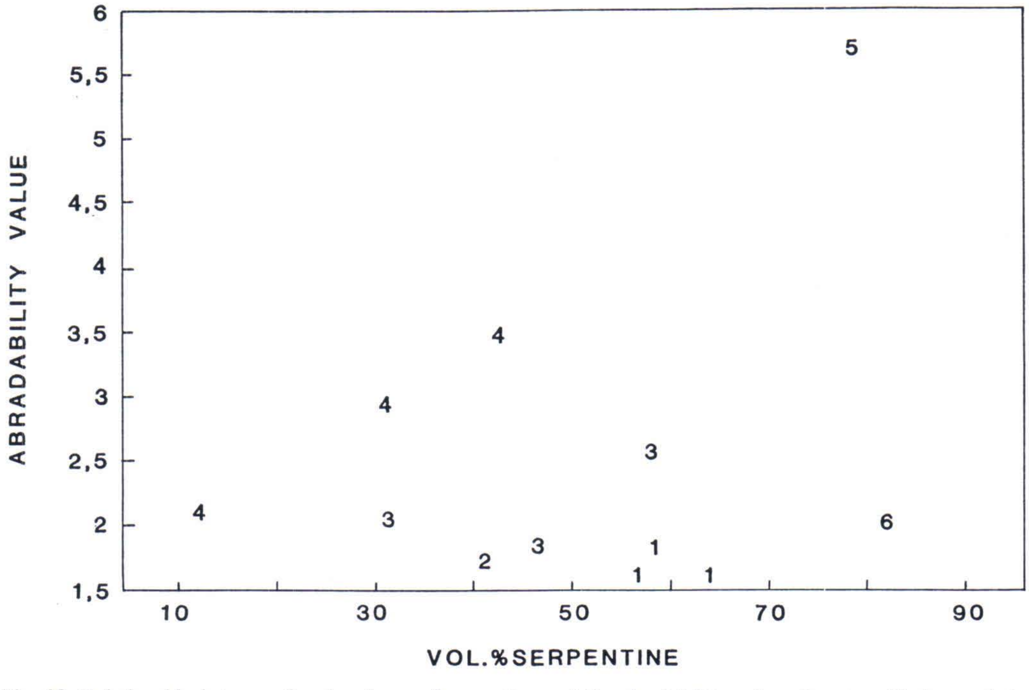

Fig. 29. Relationship between the abundance of serpentine and the abradability value of metaperidotites and the serpentinite derived from dunite. 1 = serpentine peridotite, 2 = chlorite peridotite, 3 = pyroxene peridotite, 4 = cumulate peridotite, 5 = serpentinite derived from dunite and 6 = serpentinite derived from peridotite.

When rocks composed of hard minerals are loaded they usually break along the boundary surfaces of the minerals, whereas rocks with ductile minerals break along the cleavage planes of the minerals.

As a rule, the strength properties of a rock type depend on the hardness of its major minerals. However, the hardness of a rock type should not be deduced directly from the results of scratch tests or the Vickers hardness test, because the microstructure also contributes markedly to the strength of the rock. The strength of a rock type depends on the combined influence of the hardness of the major minerals and the microstructure of the rock, i.e. on its ductility. Good examples of this are the serpentine and chlorite peridotites in the Elijärvi open pit at Kemi, which are largely composed of serpentine and chlorite, but which, owing to their strong structure and small grain size, are ductile rocks. The abundance of serpentine does not seem to weaken the abradability value of the metaperidotites (Fig. 29). The abradability value of serpentinite derived from peridotite is low even though the abundance of serpentine exceeds 80%; the high abradability value of serpentinite derived from dunite is due to its microstructure.

SUMMARY

The metaperidotites studied were divided into serpentine, chlorite, pyroxene, amphibole and cumulate peridotites on the basis of their microstructure and mineral composition. The strength properties of the metaperidotites mainly depend on their grain size, degree of serpentinization, microstructure and mineral composition. In general, serpentinization of the groundmass in the rocks of the Elijärvi open pit, Kemi, increases the strength of the rock, its grain size being reduced from medium to fine or even to very fine and the original cumulate structure of the rock being obliterated. The serpentinites derived from peridotites other than dunites belong to strength class I (classification: A, I, II, III, where A is the highest and III the lowest class). Those formed from dunites still exhibit the primary cumulate structure, and so are classless in terms of strength properties. The cumulate peridotites that have preserved their primary structures are also weak.

The presence of pyroxene impairs the strength of the metaperidotites, as does in practice the high abundance of chlorite, even though the chlorite peridotites are assigned to class A by the tests. The moderate abundance of nematoblastic amphibole increases the strength of the chlorite peridotites. The occurrence of amphibole also increases the strength of the metapyroxenites, of which, however, only amphibole pyroxenite (class II) and talc pyroxenite (classless) have been tested so far. Amphibole grains tie the former pyroxene grains tightly together and the grain size of the rock decreases. The abundance of soft talc in the rock weakens the abradability value.

The albitites and dolerites studied are fine-grained rocks with a strong microstructure. According to the tests, these rocks belong to strength class A. As shown by tests conducted previously, the strength of Kemi granite gneiss varies between classes A and I. The sample studied here was not tested for strength. The high test values obtained earlier can partly be attributed to the microstructure of the granite gneiss in which fine-grained quartz binds plagioclase grains together. Intense saussuritization may also contribute to the strength of the rock.

For the final classification of the metaperidotites, metapyroxenites and serpentinites the 18 strength tests conducted are not sufficient. The samples should also be submitted to point-load and ball-mill tests.

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Appendix 1. Phlogopite, serpentine, chlorite, diopside, talc, tremolite, bronzite and augite compositions from the Elijärvi-deposit. Alteration products = fine-grained material after pyroxene. ELI-672-16.90 = serpentine peridotite, ELI-672-24.50 = amphibole peridotite, ELI-670-74.50 = talc pyroxenite, R-25-57 = talc pyroxenite, ELI-672-28.80 = ampfibole pyroxenite, ELI-83-47.7 = cumulus peridotite.

Sample/Mineral	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	BaO	Cr_2O_3	SUM
ELI-672-16.90											
Phlogopite	36.270	4.081	12.689	6.968	22.680	0.031	0.001	8.619	0.489	1.337	93.163
Serpentine	44.895	0.013	1.380	7.238	37.096	0.013	0.007	0.007	0.004	0.034	90.685
Diopside	51.671	0.203	2.705	4.165	16.296	22.839	0.048	0.026	0.007	1.104	99.061
ELI-672-24.50											
Serpentine	43.165	0.020	2.687	9.266	34.683	0.004	0.005	0.016	0.005	0.002	89.852
Serpentine	43.047	0.012	2.520	9.229	35.470	0.010	0.002	0.012	0.000	0.000	90.302
Chlorite	33.196	0.014	15.252	7.235	31.471	0.007	0.017	0.008	0.000	0.000	87.202
Chlorite	34.721	0.041	12.641	7.782	32.141	0.025	0.003	0.052	0.023	0.000	87.402

Appendix 1. cont.

Sample/Mineral	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	NiO	SUM
ELI-670-74.50											
Talc	59.395	0	1.061	4.081	0.025	28.599	0.033	0.127	0.393	0.043	93.757
Talc	57.672	0	1.684	4.91	0.05	28.304	0.001	0.184	0.554	0.165	93.524
Talc	58.746	0	1.56	4.808	0.023	29.435	0.029	0.13	0.446	0.166	95.343
R-25-57											
Chlorite	33.578	0	12.254	8.913	0.068	29.968	0.004	0	0.075	0.066	84.926
Chlorite	33.381	0.006	12.233	9.256	0.041	29.552	0.025	0.028	0.017	0.023	84.562
Chlorite	34.352	0	12.192	9.653	0.069	30.921	0.057	0.001	0.053	0.04	87.338
Chlorite	34.178	0	11.831	8.646	0.079	30.311	0	0.01	0.06	0	85.115
Chlorite	33.825	0	12.782	9.407	0	31.2	0.022	0	0.062	0.066	87.364
Talc	57.779	0.007	1.898	4.976	0.031	30.071	0.026	0.138	0.005	0.078	95.009
ELI-672-28.80											
Tremolite	55.312	0.022	1.104	3.346	0.122	21.602	12.706	0.461	1.053	0.068	95.794
ELI-83-47.7											
Bronzite	55.108	0.092	1.701	9.641	0.232	29.755	1.626	0.041	0.553	0.010	98.757
Augite	52.241	0.318	2.736	6.141	0.163	19.201	16.767	0.368	0.947	0.047	98.928
Alteration-product	30.670	0.012	14.873	10.822	0.750	25.191	0.602	0.048	0.004	0.025	82.997

Appendix 1. cont.

Sample/Mineral	MgO	CaO	MnO	ZnO	FeO	SUM
ELI-672-24.50						
Calcite	0.728	56.344	0.286	0.031	0.280	57.668

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