

Chapter 2

THE KEMI INTRUSION AND ASSOCIATED CHROMITITE DEPOSIT

Tuomo T. Alapieti

Department of Geosciences, P.O. Box 3000, FIN-90014 University of Oulu, Finland

Timo A. Huhtelin

Outokumpu Chrome Oy Kemi Mine, P.O. Box 172, FIN-94101 Kemi, Finland

INTRODUCTION

The Kemi Layered Intrusion (Fig. 1) may be considered the most significant of the early Palaeoproterozoic (2.5-2.4 Ga) Fennoscandian layered intrusions, since the only functioning mine is located in its area, namely the Kemi chrome mine (Alapieti *et al.*, 1989a). The chromitite deposit is hosted by a layered intrusion extending some 15 km northeast of Kemi, a town on the coast of the Gulf of Bothnia. U-Pb zircon data yield an age of 2.44 Ga for the Kemi Intrusion (Patchett *et al.*, 1981), and Pb-Pb data for whole rocks define an age of 2.44 ± 0.16 Ga (Manhes *et al.*, 1980).

In essence the Kemi Intrusion was already known in the 1940s (Härme, 1949, Mikkola, 1949), but because of its poor outcropping, the chromite-bearing basal part, particularly the chromite deposit, remained hidden until the 1950s, when, owing to the relatively thin soil cover, a fresh-water channel was excavated through the solid rock. The first chromite-bearing blocks were discovered in this excavated channel in 1959 by Matti Matilainen, a local diver who was interested in ore prospecting, and he sent them to the Geo-

logical Survey of Finland for examination. Based on these blocks, the Geological Survey began the exploration which led to the discovery of a chromitite-bearing layer. From 1960 onwards the exploration was conducted by Outokumpu Oy under contract from the government of Finland.

The exploration carried out by Outokumpu Oy lasted until the late summer of 1964, and included geophysical, mainly gravimetric surveys, diamond drilling, concentration tests on the drill cores and on 10,000 metric tons of ore extracted for mining, and metallurgical tests. By the end of the exploration period, 30 million metric tons of chromite ore had been located, and in autumn 1964 Outokumpu Oy decided to begin mining the chrome ore. Construction of the mine began in spring 1965. In 1966 through 1968 the ore was extracted only in summer and was treated in a pilot concentration plant, but since then it has been mined throughout the year using open pit mining. The main open pit has now reached a depth of 180 meters and annual production during recent years has amounted

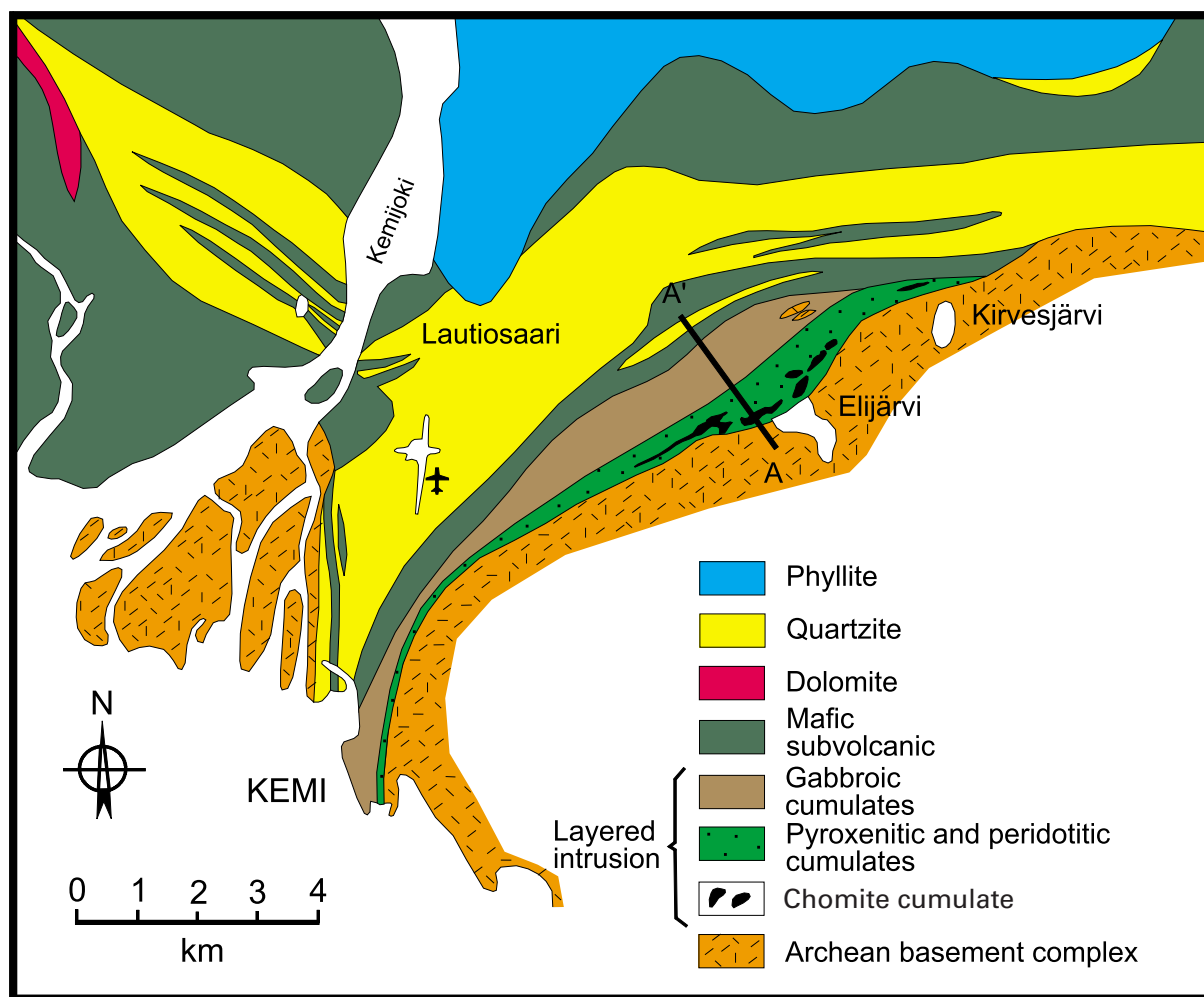


Fig. 1. Generalized geologic map of the Kemi Intrusion, showing the location of drilling profile A-A' (see Fig. 2), after Alapieti *et al.* 1989.

to around 1.2 million tons of ore and about 3.5 million tons of barren rock. Construction of the underground mine began in 1999. The opening ceremony of the underground mine was held in September 2003. Change-over to underground mining is taking place and open pit mining will be fully replaced by underground mining by 2006.

The associated industrial facilities, including the ferro-chrome plant and stainless steel works at Tornio, were completed in 1976. The ore was originally concentrated by wet grinding followed by drying and high intensity magnetic separation with a Salzgitter separator, but Jones heavy magnetic wet separators were added between the grinding and

dry magnetic separation stages in 1972 and the Salzgitter separators were replaced with Reichert cones in 1979. The heavy magnetic separators were removed in 1982, and since 1984 heavy media separation has been applied between crushing and grinding.

At present, the chrome ore feed is concentrated into upgraded lumpy ore and fine concentrate. In the first stage of the process, at the crushing plant, the ore is crushed and screened to a diameter of 12 - 100 millimeters. After crushing, ore lumps are processed by means of heavy media separation. In this process upgraded lumpy ore is separated from the ore. Further processing takes place in the concentrating plant where the ore is

first ground in the rod mill and in the ball mill. The fine concentrate is produced by gravity separation using spirals and Reichert

cone separators. In addition high gradient magnetic separation is used in the latter stage of the process.

SHAPE AND LAYERING OF THE INTRUSION

The present surface section of the Kemi Intrusion is lenticular in shape, being some 15 km long and 0.2 to 2 km wide (Fig. 1, 2 and 3). It represents a cross-section of an originally funnel-shaped intrusion which was tilted by tectonic movements during the Sve-cokarelidic orogeny to form a body dipping about 70° northwestward and, according to geophysical interpretations, extending down for at least 2 km. The geologic map also shows that the individual cumulate layers are thickest in the middle part of the intrusion and become thinner toward the ends. This feature is well established from the variation in thickness of the ultramafic cumulates (Fig. 1). Underground inclined tunneling has recently proved that the magmatic conduit which fed the magma chamber was located just below the thickening, as suggested earli-

er by Alapieti et al. (1989a). This feeder dike, which is also visible on the southeastern wall of the open pit (Fig. 4) is about 20 m thick. It is composed of a fine-grained, uralitized rock types close to the contacts which grade more coarse grained ones inward, and the middle part of the dyke is composed of a few meter thick, almost vertical chromitite. The foot-wall rock of the intrusion consists of late Ar-chean granitoids, and the hanging-wall rocks are either younger mafic volcanics or subvo-lcanic sills 2,150 Ma in age (Sakko, 1971), or a polymict conglomerate of unknown age but younger than the intrusion. This indicates that the present upper contact is erosional, implying that the original roof rocks and the uppermost cumulates of the layered series, together with the possible granophyre layer, may have been obliterated by erosion. The

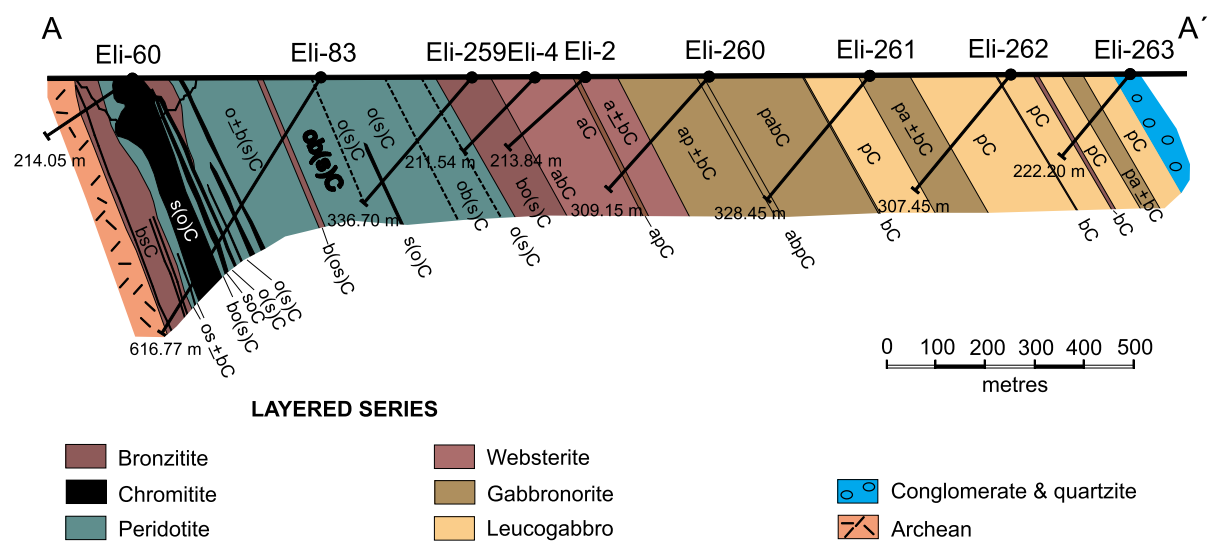


Fig. 2. Cross-section of the Kemi Intrusion based on drilling profile A-A', marked in Figure 1. For abbreviations, see Table 1.

feeder dikes of the subvolcanic sills, referred to as albite diabase, intersect the Kemi Intrusion.

The area of the Kemi Intrusion underwent lower amphibolite facies metamorphism during the Svecokarelidic orogeny. The original magmatic silicates have been completely altered to secondary minerals in the lower and upper parts of the intrusion, whereas those in the middle have been preserved and are fresh

in appearance. Many chromites have nevertheless preserved their original composition in their cores, even though the silicates of the same rock have been completely altered. The unaltered cores of the chromites are quite easy to find by careful examination under an electron or light microscope. The altered rocks have preserved their cumulate textures fairly well, however, and despite alteration, many of the primary minerals can still be

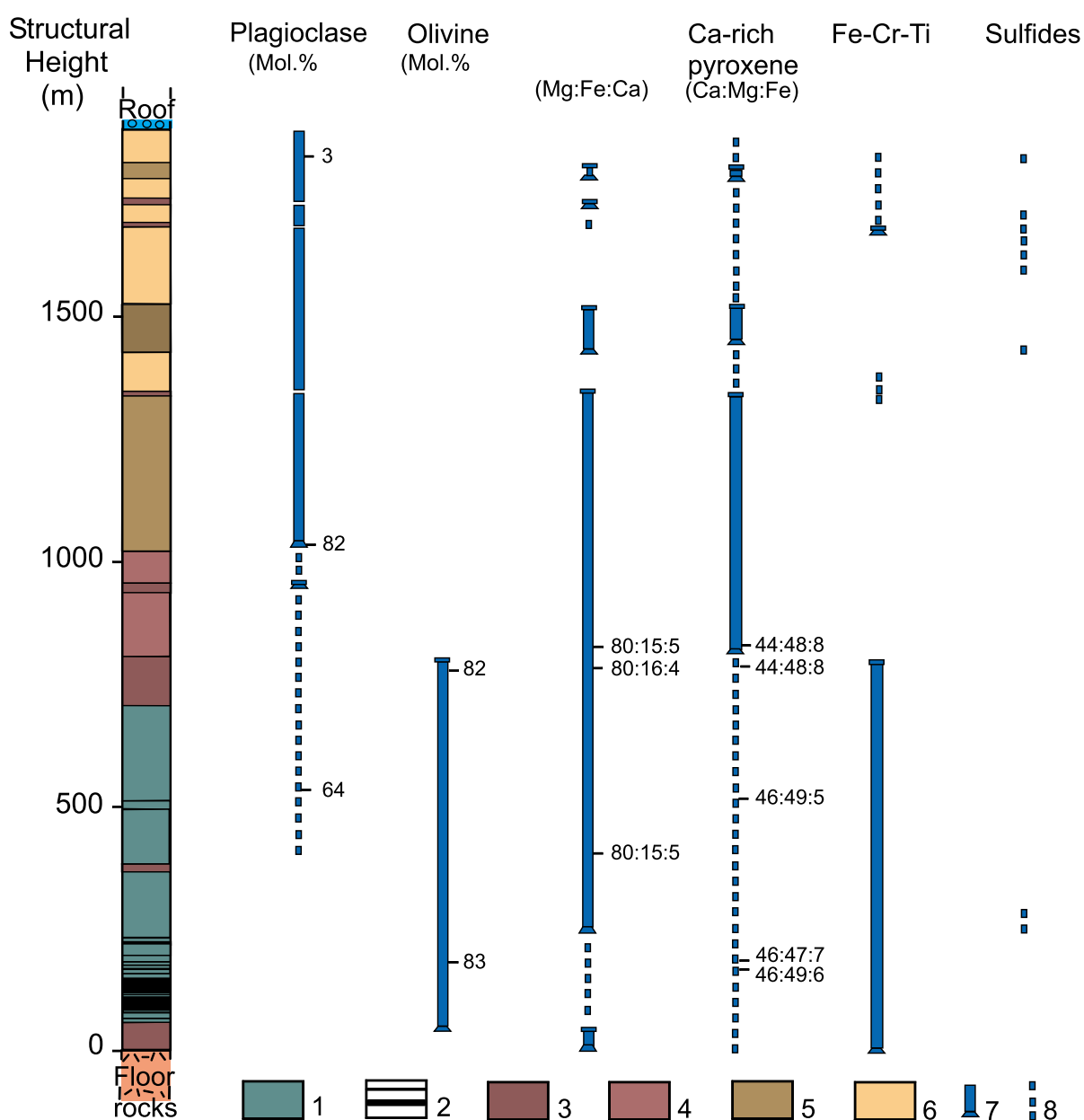


Fig. 3. Stratigraphic sequence and cryptic variation in minerals in the Kemi layered intrusion. 1. Peridotite ($o \pm b \pm sC$). 2. Chromitite ($s(o)C$). 3. Bronzitite and olivine bronzitite ($bo(s)C$). 4. Websterite and diallagite ($a \pm bC$). 5. Gabbronorite and gabbro ($pa \pm bC$). 6. Leucogabbro and anorthosite (pC). 7. Cumulus mineral. 8. Intercumulus mineral, after Alapieti *et al.* 1989a.



Fig. 4. 'Feeder channel' on the southeastern wall of the Kemi open pit.

recognized by means of pseudomorphs, thus enabling the cumulate sequences to be determined.

The complex basal contact series typically indicating reserved fractionation and being characteristic of the many other layered intrusions in northern Finland has not been observed in the Kemi Intrusion. Either no such series formed at all or else it was obliterated by erosion during the magmatic stage. Instead, a fine-grained, ultramafic marginal rock about 10 cm thick which has preserved its original texture occurs in borehole Eli-60 in contact with the basement granitoid. The silicate minerals in this ultramafic rock are completely recrystallized, whereas the chromite, which accounts for about 15 vol. percent of the whole rock, has been preserved and occurs as euhedral phenocrysts about

0.5 mm in diameter. This rock is overlain by a markedly altered sequence 50 to 100 m thick, the lower part of which is composed of a bronzite-chromite cumulate and the upper part of an olivine-chromite \pm bronzite cumulate, with chromitite interlayers from 0.5 to 1.5 m thick. The bronzitic cumulates are often characterized by gneissic xenoliths from the underlying basement complex.

The sequence described above is followed by the main chromitite layer, which in borehole Eli-83 (Fig. 2) is composed of two parts with a more silicate-rich rock between them. The total thickness of the main chromitite layer is almost 60 m in this borehole. Its cumulus minerals are chromite and olivine, and the intercumulus minerals comprise poikilitic bronzite and to a lesser extent augite. The abundance of cumulus olivine in relation to

chromite is relatively low in the upper part. Bronzite occurs temporarily as the cumulus phase in the more silicate-rich interlayer, which is typified by annular textures constituting accumulations of small chromite grains around the larger cumulus silicate minerals. The main chromitite layer is overlain by about 550 m of peridotitic cumulates with olivine, chromite and occasional bronzite as the cumulus minerals. This thick cumulate sequence contains about 15 chromite-rich interlayers varying in thickness from 5 cm to 2.5 m, the uppermost being about 370 m above the main chromitite layer. A 5 to 10 m thick pyroxenitic interlayer occurs around the core of the peridotitic sequence, and about 10 m below this a sodium-rich rock type is encountered which could also be a xenolith from the basement complex. This interpretation is suggested by the fine-grained chilled margins in

the surrounding ultramafic rock.

Bronzite becomes the dominant cumulus mineral about 700 m above the basal contact of the intrusion, with olivine and chromite as the other cumulus phases. Then, about 100 m higher up, augite becomes the dominant cumulus mineral alongside bronzite, but olivine and chromite disappear. Even bronzite is so low in abundance in places that the rock could be referred to as a diallagite.

At about 1,000 m above the basement, plagioclase becomes the cumulus phase alongside augite and bronzite. These rather monotonous plagioclase cumulates continue for about 800 m upward to the contact with the hanging wall. In the upper part of the sequence augite occurs as the intercumulus phase, however, and there is little or no Ca-poor pyroxene. In conventional terms, these rocks are therefore leucogabbros or anorthosites (Table 1)

Table 1. Rock-type nomenclature used

Conventional rock name	Cumulus mineral assemblage	Cumulate abbreviation
Peridotite	Olivine \pm bronzite \pm chrome spinel	$o \pm b \pm sC$
Chromitite	Chrome spinel (\pm minor olivine)	$s(o)C$
Bronzitite and olivine bronzitite	Bronzite-olivine (\pm minor chrome spinel)	$bo(s)C$
Websterite and diallagite	Augite \pm bronzite	$a \pm bC$
Gabbronorite and gabbro	Plagioclase-augite \pm bronzite	$pa \pm bC$
Leucogabbro and anorthosite	Plagioclase	pC

MINERALS AND MINERAL CHEMISTRY

Olivine: Olivine is a typical cumulus mineral of peridotitic and pyroxenitic rocks, the augite cumulates excluded (Fig. 3). It has been completely altered in the lowermost cumulates, however. The olivines analyzed were of constant composition, Fo_{82} - Fo_{83} .

Ca-poor pyroxene: Ca-poor pyroxene is present as a cumulus phase practically throughout the intrusion, although it occurs typically in the form of largish oikocrysts in the chromite-rich layers. It, too, is fairly constant in composition, the $100 \times \text{Mg}/(\text{Mg} + \text{Fe}^{2+} + \text{Mn})$ ratio being about 83 and the Cr_2O_3 content quite high. The orthopyroxenes analyzed represent cumulus minerals in olivine-bronzite-(chromite), bronzite-olivine, and bronzite-augite cumulates, their Cr_2O_3 content varying from 0.41 to 0.60 wt. percent with a mean value of 0.51 wt. percent.

Ca-rich pyroxene: Augite exists as an intercumulus mineral in the lower half of the intrusion but becomes a cumulus mineral in the clinopyroxenites. It continues upward as a cumulus phase, reverting to an intercumulus mineral in the leucogabbros and anorthosites of the upper part. Like the bronzite, it has a surprisingly high chromium content. The lowermost, poikilitic augite, which is located about 30 m above the main chromitite, contains around one wt. percent Cr_2O_3 . The highest content, 1.18 wt. percent, was found in the poikilitic augite in the uppermost chromitite layer, 370 m above the main chromitite. The uppermost intercumulus augite occurring in the bronzite-olivine-(chromite) cumulate about 650 m above the main chromitite,

contains 1.1 wt. percent Cr_2O_3 and the lowermost cumulus augite in the bronzite-augite cumulate 0.83 wt. percent.

Plagioclase: Plagioclase, with an anorthite content of about An_{65} , occurs as an intercumulus phase above the pyroxenitic interlayer in the peridotitic cumulates. It appears as a cumulus mineral around the middle part of the intrusion, where it increases sharply in abundance and its anorthite content rises to An_{82} . From this point it continues as a cumulus phase up to the upper contact of the intrusion. Microanalyses show that the plagioclase is albitic in composition close to the roof of the intrusion, with some evidence of saussuritization.

Cr-Fe-Ti oxides: Chromite is by far the most prominent Cr-Fe-Ti oxide in the Kemi Intrusion, occurring as a cumulus mineral throughout the lower part, up to the level at which augite appears as the cumulus phase, 800 m above the base.

Especially in the silicate-rich rocks, the chromite grains are frequently altered at the rims, usually with a sharp drop in aluminium from the core of the grain outward, this being replaced by ferric iron. On the other hand, the chromium content declines only slightly in an outward direction (Table 2), the difference in Cr_2O_3 content between the core and the outer rim being only 3.5 wt. percent, whereas the Al content decreases about 16 wt. percent at the same time. Magnesium, like aluminium, also declines abruptly, whereas the nickel content increases distinctly toward the rim, as

Table 2. Analyses of selected chromites from the Kemi Intrusion

Sample	1	2	3	4	5	6	7	8
Weight percent								
TiO ₂	0,39	0,96	0,4	0,41	0,61	0,57	0,42	0,62
Al ₂ O ₃	14,17	9,63	15,43	14,51	16,98	2,3	0,84	16,79
Cr ₂ O ₃	51,32	42,18	49,03	48,63	42,94	39,65	39,43	45,1
Fe ₂ O ₃	3,90	10,81	5,29	5,69	5,89	23,7	26,49	7,82
V ₂ O ₃	0,22	0,21	0,11	0,15	0,13	0,13	0,14	0,2
FeO	15,52	29,57	18,09	19,06	28,6	29,73	30,36	17,16
MnO	0,31	0,67	0,3	0,32	0,26	0,28	0,26	0,32
MgO	11,71	0,14	10,54	9,67	4,06	1,18	0,78	11,45
ZnO	0,00	3,40	0,08	0,06	0,05	<0,05	0,07	<0,05
NiO	0,17	<0,05	0,11	0,1	0,05	0,17	0,18	0,09
Sum	97,70	97,57	99,34	98,6	99,57	97,71	98,97	99,58
Number of ions on the basis of 32 oxygen atoms								
Al	4,38	3,333	4,719	4,512	5,385	0,82	0,299	5,067
Cr	10,645	9,794	10,059	10,144	9,135	9,477	9,419	9,128
Fe ³⁺	0,77	2,389	1,025	1,13	1,193	5,392	6,023	1,506
Ti	0,077	0,212	0,078	0,081	0,123	0,13	0,095	0,119
V	0,046	0,049	0,028	0,032	0,028	0,032	0,034	0,043
Mg	4,577	0,061	4,076	0,803	1,628	0,532	0,351	4,37
Ni	0,035		0,023	0,021	0,011	0,041	0,044	0,018
Fe ²⁺	3,404	7,262	3,926	4,205	6,425	7,516	7,671	3,673
Zn	0	0,737	0,015	0,012	0,01		0,016	
Mn	0,068	0,167	0,066	0,072	0,059	0,041	0,067	0,07
Mole percent								
(Fe,Mg)Cr ₂ O ₄	67,4	63,1	63,6	64,3	58,1	60,4	59,8	58,1
(Fe,Mg)Al ₂ O ₄	27,7	21,5	29,9	28,6	34,3	5,2	1,9	32,3
Fe ₃ O ₄	4,9	15,4	6,5	7,1	7,6	34,4	38,3	9,6
Cr/Fe	2,37	0,94	1,88	1,77	1,11	0,68	0,64	1,64

1 'Feeder channel'

2 Fine-grained ultramafic marginal rock, borehole Eli-60 128,00 m

3 Average composition of chromites in the lower part of the main chromitites (6 samples)

4 Average composition of chromites in the upper part of the main chromitites (5 samples)

5 Homogeneous core of a rimmed chromite in silicate-rich rocks just below the main chromitite layer

6 Inner rim of the rimmed chromite mentioned above

7 Outer rim of the rimmed chromite mentioned above

8 Uppermost chromitite-rich layer (0.5 m thick) located 370 m above the main chromitite layer

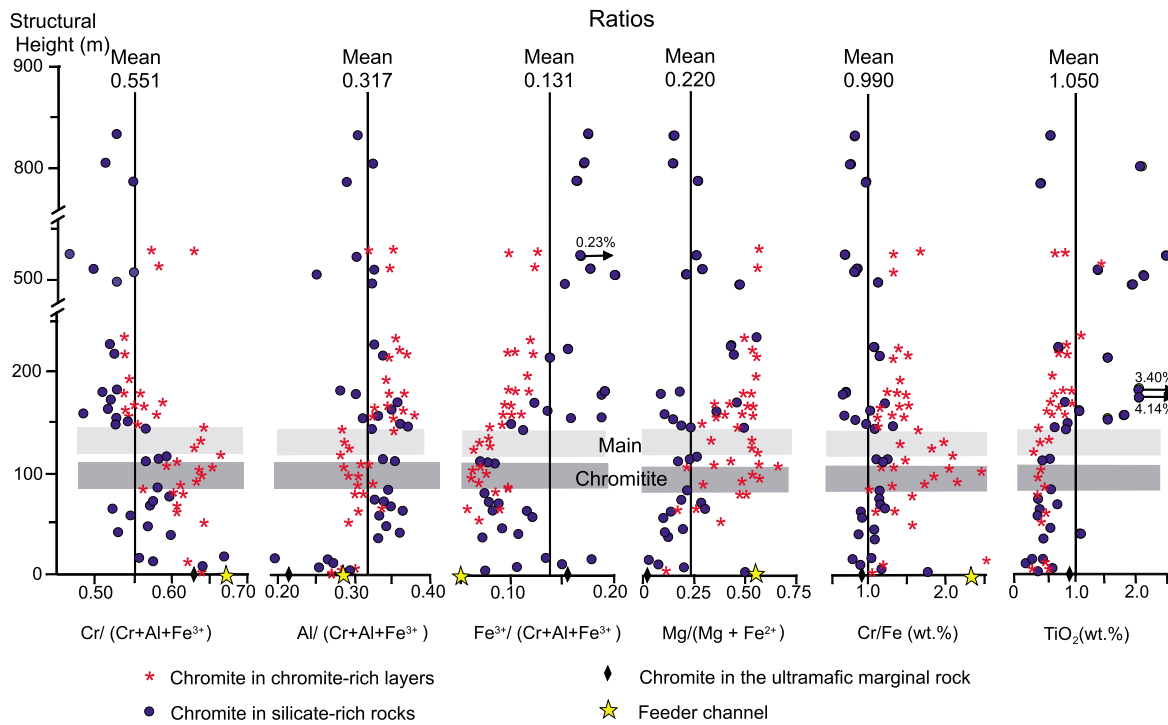


Fig. 5. Selected cation and Cr/Fe ratios and TiO_2 content for chromites in the Kemi Intrusion, after Alapieti *et al.* 1989a.

the altering chromite probably absorbs nickel from the surrounding mafic silicates, thereby increasing the mole fraction of trevorite. In addition, the chromite grains have also altered to ferrichromite in places, and then the chromium content can be higher than 65 wt. %, while aluminium and magnesium are distinctly lower than in the main chromitite.

The highest Cr-content in the Kemi chromitites was encountered in the probable feeder channel (Table 2). Similarly the Cr/Fe ratio is there distinctly higher than in the main chromitite (Fig. 5).

The chromite in the fine-grained ultramafic rock at the basal contact of the intrusion has an anomalously high zinc content, containing an average of 3.4 wt. percent ZnO, whereas a sample taken 0.5 m above the boundary of this rock type showed the ZnO content to have dropped to only 0.11 wt. percent, a

value characteristic of the other chromites of the Kemi Intrusion. The fine-grained contact rock also contains galena, as found in the granitoid below the Penikat intrusion and in the pyrrhotite-dominated mineralization in the marginal series of the Suhanko intrusion in the Portimo area, where it is associated with sphalerite and has been shown by isotope determinations to be derived from the rocks of the Archean basement (Alapieti *et al.*, 1989b). Thus the chromite enriched in the gahnite molecule may be the product of a reaction between sphalerite and chromite, and the sphalerite itself may be a result of contamination from the basement complex.

The Cr content of the chromites in the chromite-rich layers below the main chromitite layer and in the main chromitite layer itself is fairly constant, whereas a declining trend sets in above this (Fig. 5). The highest values are encountered in the main chromitite, however.

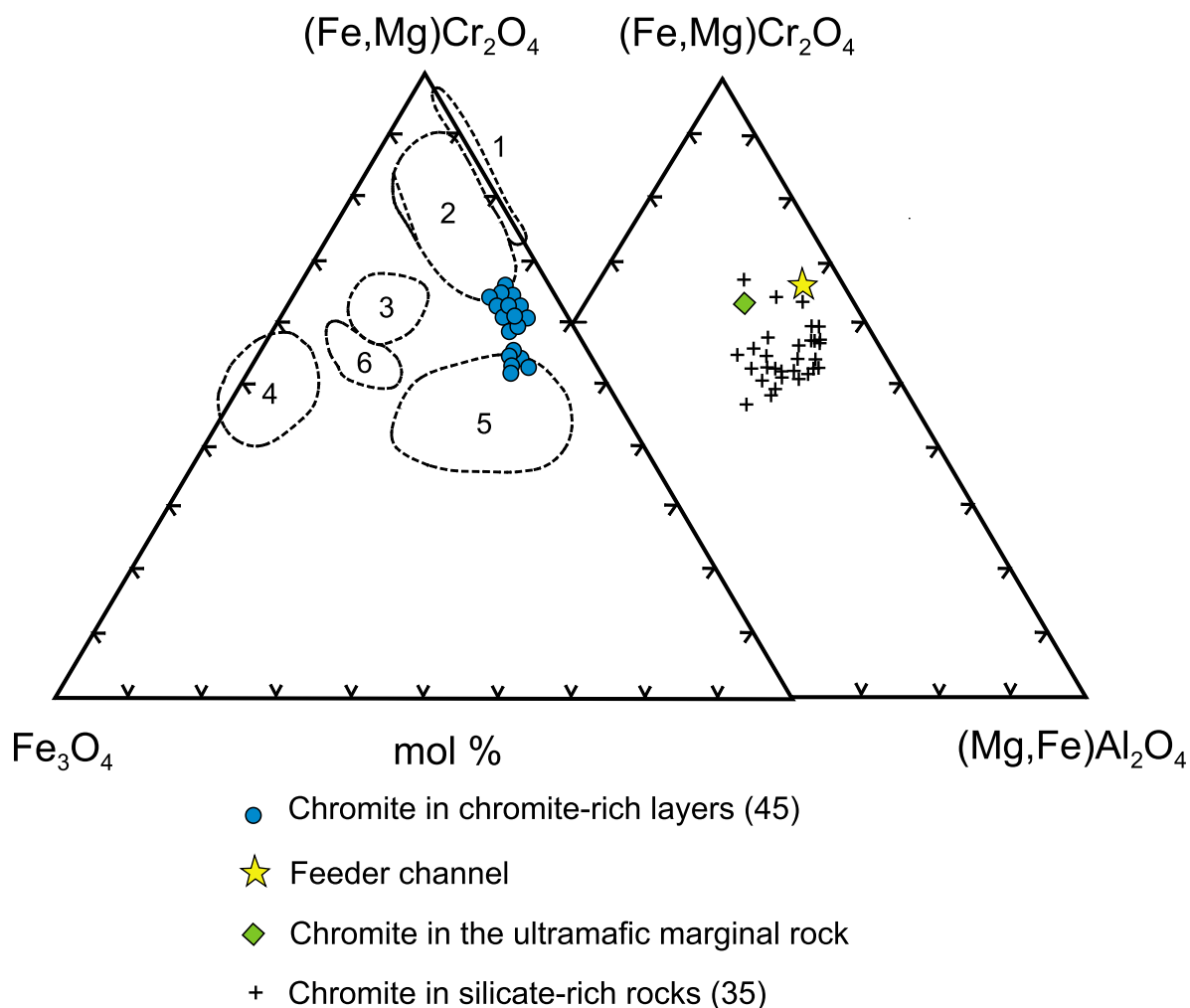


Fig. 6. Chromite-spinel-magnetite ternary diagram, showing the composition of the minerals of the spinel group in the Kemi Intrusion (numbers of samples in parenthesis). The provinces of the chromite deposits after Weiser (1967) and Ghisler (1976) are also shown. 1. Southern Europe and Asia. 2. Bushveld and Great Dyke complexes. 3. Chromites in Bushveld anorthosites. 4. Western Norway. 5. Fiskenaasset chromites. 6. Kemi chromites after Weiser (1967).

The Al, Fe³⁺, and Ti concentrations behave in the opposite manner, and the vanadium content (not shown in Fig. 5) also increases from the main chromitite upward. The Mn content remains more or less stable (MnO = 0.3-0.6 wt. %), except in one Cr-rich layer below the main chromitite, where it exceeds two wt. percent.

Comparison of the chromite compositions of the chromite-rich layers with those of the chromite-poor silicate rocks (Fig. 5) shows the former to have higher Cr/(Cr + Al + Fe³⁺),

Mg/(Mg + Fe²⁺) and Cr/Fe ratios and lower Al/(Cr + Al + Fe³⁺) and Fe³⁺/(Cr + Al + Fe³⁺) ratios than the chromites in the stratigraphically associated chromite-poor silicate rocks. These findings are in agreement with the observations of Cameron (1977) on the Bushveld Complex, with the exception of the Al/(Cr + Al + Fe³⁺) ratio, which is distinctly higher in the Bushveld chromitites than in the silicate-rich rocks. The Ti concentrations in the chromites of the chromite-poor silicate rocks (Fig. 5) increase upward considerably more than do the corresponding concentra-

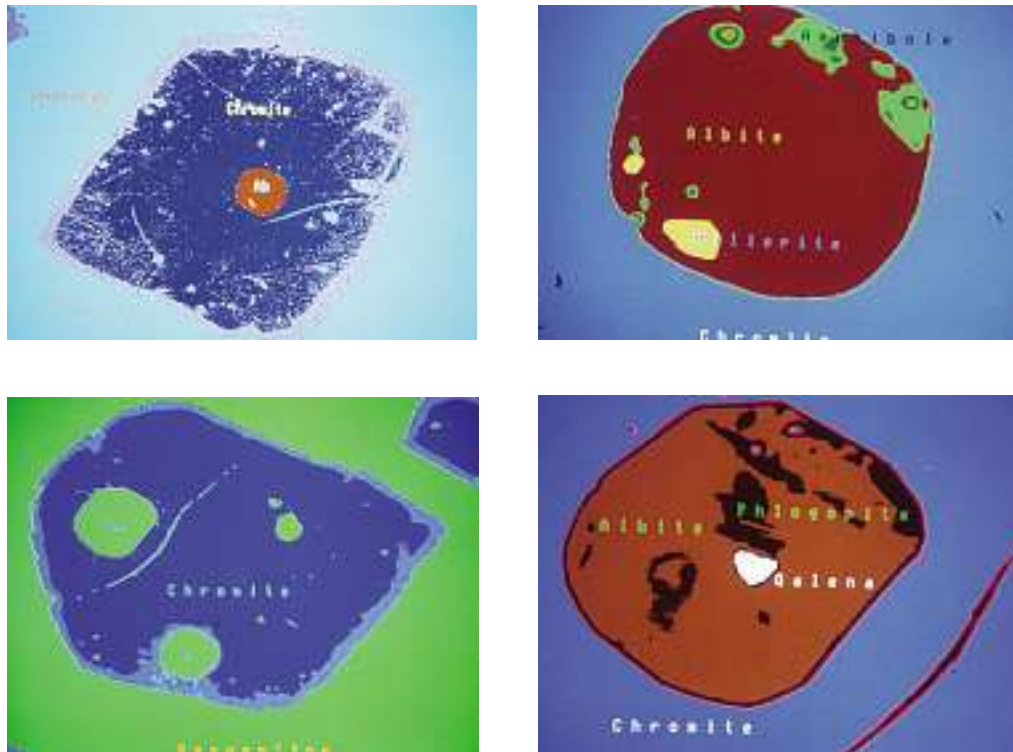


Fig. 7. Backscattered electron image showing silicate inclusions in chromite grains in the Kemi chromitite layers after Alapieti *et al.* 1989a.

tions in the chromite-rich layers, to the extent that some samples above the main chromitite layer have TiO_2 concentrations of up to 3 to 4 wt. percent.

The first intercumulus ilmenite makes its appearance in the upper part of the bronzite-olivine cumulate, about 770 m above the base of the intrusion, and ilmenite becomes a cumulus phase in the anorthosite of the upper part, at about the same level at which apatite emerges as a cumulus mineral. No cumulus magnetite is found at any level.

The chromite grains are in many places characterized by spherical silicate inclusions 5 to 100 μm in diameter, so that those in some of the lowermost chromite-rich layers commonly resemble Emmenthal cheese. The most common inclusions, and usually also the largest ones, are composed of mafic

silicates similar to those in the surroundings of the chromite grains, whereas many other inclusions are completely different in composition (Fig. 7). The most common among these latter are the albite-bearing inclusions.

Chromites in one 1.8 m thick chromitite layer about 60 m above the basal contact of the intrusion contained an exceptionally large number of silicate-rich inclusions characterized by a variety of minerals. One of these contained potassium-bearing pargasitic amphibole, hornblende, albite and millerite (Fig. 7), while another chromite grain in the same sample was composed of three silicate inclusions (Fig. 7). The largest of these inclusions contained albite, phlogopite and galena. The occurrence of the last-mentioned mineral in this connection is interesting, because it has also been found in fine-grained border rock, as mentioned above.

Silicate-rich inclusions resembling those presented above have also been described by McDonald (1965) in the Bushveld chromitites, by Jackson (1961, 1966) in the Stillwater chromitites, and by Irvine (1975) in the Muskox chromitites. An albite-bearing inclusion has also been found by Alapieti (1982) in an olivine-bronzite-chromite cumulate in the Näränkäväära intrusion, north-eastern Finland, which belongs to the same age group as the Kemi Intrusion.

Sulfides: Although no more than a weak dissemination, the sulfide assemblage pyrrhotite-pentlandite-chalcopyrite is most abundant in the silicate-rich rock in the middle part of the main chromitite and on both sides of a 2.5 m thick chromite-rich layer situated above the main chromitite. Some chalcopyrite also

occurs in the lower part of the augite-bronzite cumulate and in the anorthosite of the upper part of the intrusion. In the anorthosite it is accompanied by pyrite.

Phlogopite: Abundant phlogopite is present as an intercumulus mineral in the upper part of the peridotitic cumulates, its mode fraction being as high as 10 vol. percent in some samples.

Platinum-group minerals: Platinum-group minerals are quite common in chromitites. They are mostly represented by Os, Ir and Ru minerals, especially laurite. On the other hand, in the sulphide-bearing silicate rich rock in the middle of the main chromitite, which is palladium-rich (Fig. 9), the Pd-Pt minerals are dominating.

GEOCHEMISTRY OF THE KEMI INTRUSION

Variations in the CIPW norms within the intrusion are given in Fig. 8. Note that the relatively high plagioclase abundances assigned to the ultramafic rocks are due to the Al of chromite and the Ca of augite. The diagram illustrates well the high incidence of chromite-rich layers in the intrusion. The emergence of plagioclase as a cumulus phase, a feature which divides the whole intrusion into an upper and a lower part, is also conspicuous.

Of the individual oxides (Table 3), mention should be made of the steep increase in the Al_2O_3 content above the contact between the pyroxenitic and gabbroic cumulates. MgO concentrations remain relatively constant up to the upper part of the peridotitic cumulates, above which they decline steadily toward the

roof of the intrusion. A sharp rise in CaO content is seen where augite becomes a cumulus mineral of the clinopyroxenites, after which it decreases gradually toward the roof of the intrusion. Na_2O concentrations increase steadily throughout the intrusion. K_2O is highest in the anorthosites of the upper part, although it increases to over 3 wt. percent in one chromite-rich layer, mentioned earlier, immediately below the main chromitite and below another chromite-rich layer 5 cm thick located above the main chromitite. The latter chromite-rich layer also has high La and Ce concentrations of 130 and 300 ppm, respectively, suggesting the presence of loweringite, although this mineral has not been encountered so far in the Kemi Intrusion (cf. Alapieti, 1982; Tarkian and Mutanen, 1987). The highest Pd, Pt,

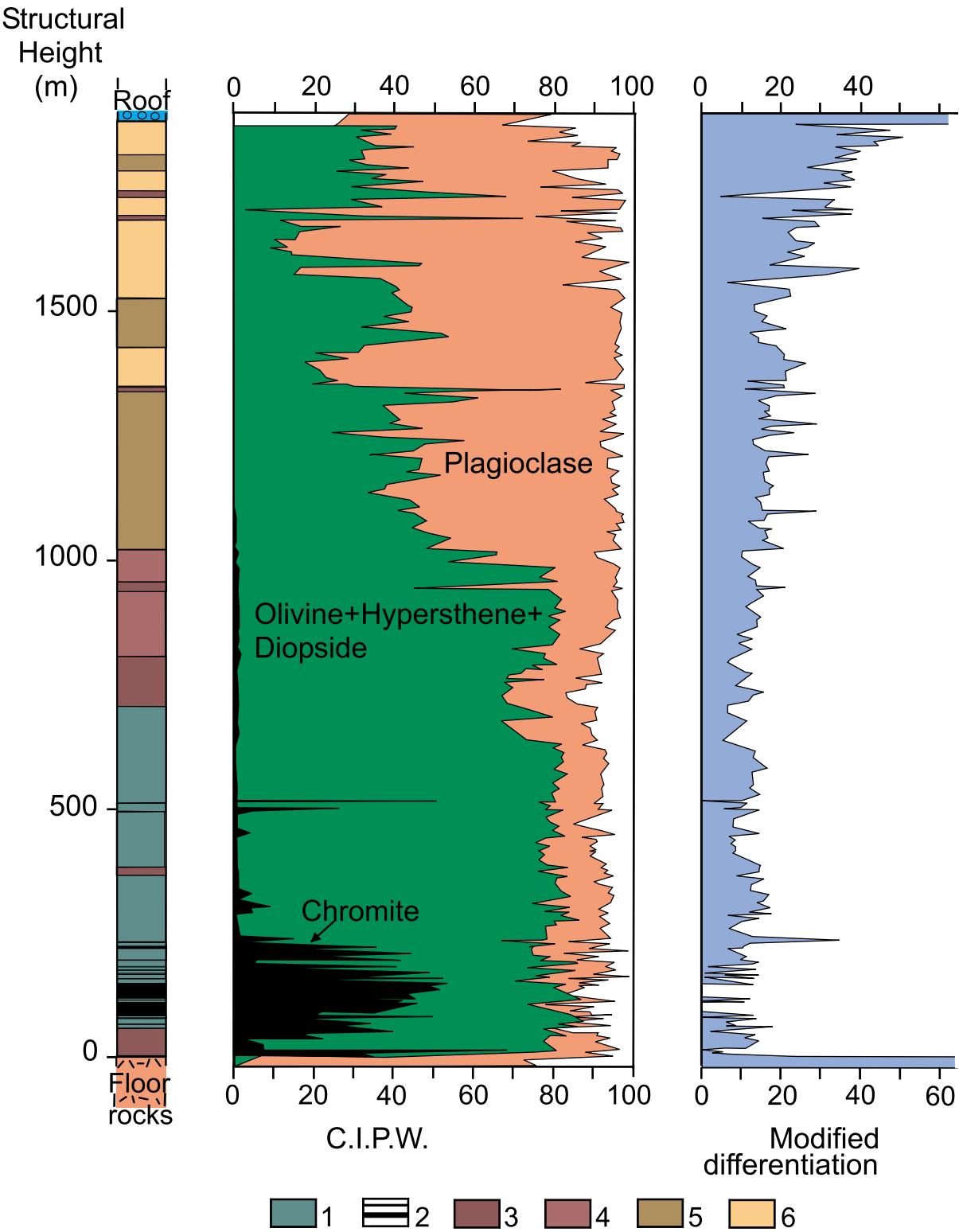


Fig. 8. Variations in the CIPW norm and modified differentiation index (von Gruenewaldt, 1973) in the Kemi Intrusion. The chemical analyses were recalculated in volatile-free form before computing the norms and the differentiation index.

Table 3. Representative analyses of rock types in the Kemi Intrusion (recalculated volatile-free)

Sample	1	2	3	4	5	6
SiO ₂	52,17	28,44	10,30	6,56	48,21	47,30
TiO ₂	0,49	0,64	0,36	0,43	0,14	0,18
Al ₂ O ₃	10,80	15,81	12,09	12,98	27,10	12,00
Fe ₂ O ₃		4,16	3,72	4,59	0,95	
Cr ₂ O ₃	0,64	11,22	41,91	41,62	0,01	2,56
FeO	10.39*	14,96	13,42	16,52	3,09	7.80*
MnO	0,15	0,27	0,27	0,25	0,05	0,15
MgO	17,06	19,73	17,25	16,67	5,92	19,50
CaO	3,33	4,24	0,62	0,37	10,41	9,08
Na ₂ O	0,00	0,23	0,06	0,00	3,83	1,11
K ₂ O	4,89	0,25	0,00	0,00	0,27	0,27
P ₂ O ₅	0,08	0,04	0,00	0,00	0,01	0,02
S	0,01	0,01	0,00	0,00	0,01	0,04

1 'Feeder channel'

2 Fine-grained ultramafic rock at the contact of the Kemi Intrusion (includes Zn = 0.70 and Pb 0.25 wt. %)

3 Chromite mesocumulate (heteradcumulate), with poikilitic postcumulus augite as the intercumulus material, lower part of the main chromitite

4 Chromite mesocumulate (heteradcumulate), with poikilitic postcumulus bronzite as the intercumulus material, upper part of the main chromitite

5 Plagioclase mesocumulate, with augite and quartz as intercumulus crystals (anorthosite) about 300 m below the roof of the intrusion

6 Average composition of the borehole profile A-A' in Fig. 1, based on 375 samples; weighted mean, weighted by the thickness and density of the layer represented by each sample

* total iron as FeO

and Rh concentrations recorded in the Kemi Intrusion, 50, 180, and 120 ppb, respectively, are from immediately above this Cr-rich layer (Fig. 9). The chromium content is unusually high throughout the intrusion. The chromite-rich layers generally contain more than 20 wt. percent Cr, and the Cr content of the peridotitic and pyroxenitic cumulates is relatively constant, varying between 0.2 and 0.6 wt. percent. Only in the lower part of the gabbroic cumulates does the Cr content fall below 0.1 wt. percent, and values below 600 ppm are encountered only in the plagioclase cumulates of the upper part of the intrusion.

The Cr content rises above the 600-ppm level again close to the roof. The nickel content is quite constant, about 0.1 wt. percent in the lower part of the intrusion. The decline in Ni begins in the upper part of the peridotitic cumulates and continues almost linearly toward the roof of the intrusion. Zn is highest in the chromite-rich layers and diminishes gradually toward the uppermost anorthosites, where it begins to increase again. Sr behaves in much the same way as Na₂O, i.e., it increases gradually from the lower parts of the intrusion upward.

THE CHROMITE ORES

The chromite-rich layer which parallels the basal contact zone of the Kemi Intrusion is known over the whole length of the complex, beginning from the town of Kemi and extending 15 km northeast to the northern side of Lake Kirvesjärvi (Fig. 1). The chromite-rich layer varies in thickness from a few centimeters up to 160 m in the Elijärvi area, where the whole complex is at its thickest (Fig. 10). Economically the most important portion of the chromitite layer extends from the Elijärvi orebody in the west to the Pohjois-Viia orebody in the east. Average thickness of the chromitite layer is about 40 m in this area. The total length of the mineable portion of

the layer is about 1.5 km. The chromitite layer is cut into several ore bodies by numerous faults, and these are treated as separate units for the purposes of mining, beneficiation, and metallurgy. The whole ore field with its nine orebodies is depicted in Figure 10. The chromite-rich unit has an average dip of 70° to northwest.

The mine's proven ore reserves total some 50 million tons. In addition, it is estimated that there are 90 million tons of mineral resources. The average chromium oxide content of the ore is 26 percent and its chrome-iron ratio is 1.6.

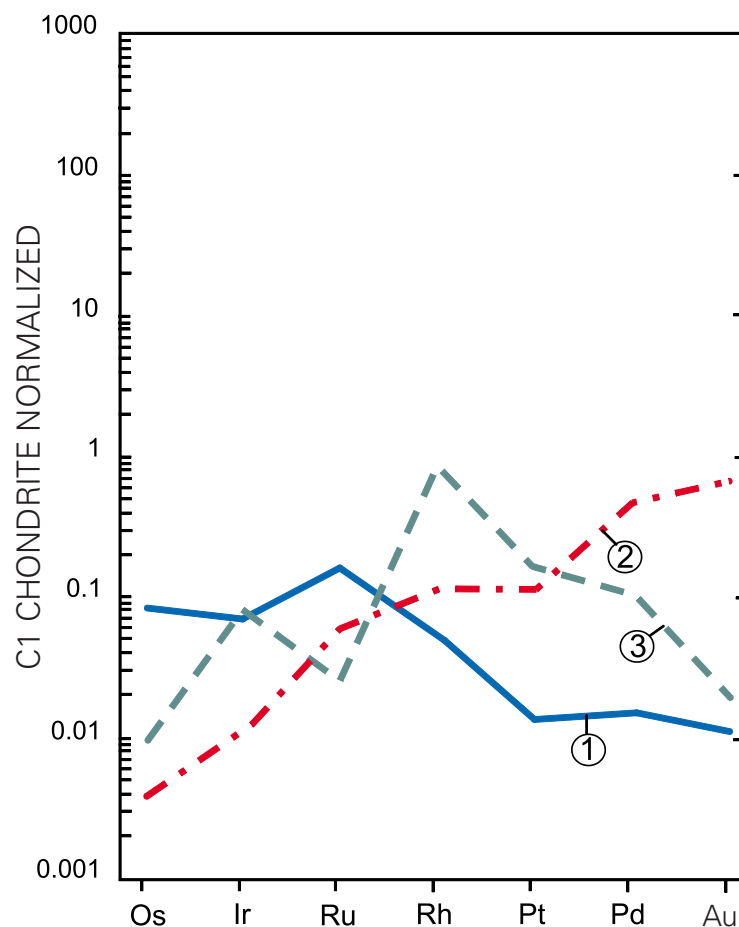


Fig. 9. Chondrite normalized metal patterns for the Kemi rock samples. 1, The main chromitite, average of three samples; 2, A sulfide-bearing, chromite-poor rock type in the middle of the main chromitite; 3 A chromitite-rich layer about 130 m above the main chromitite, average of two samples.

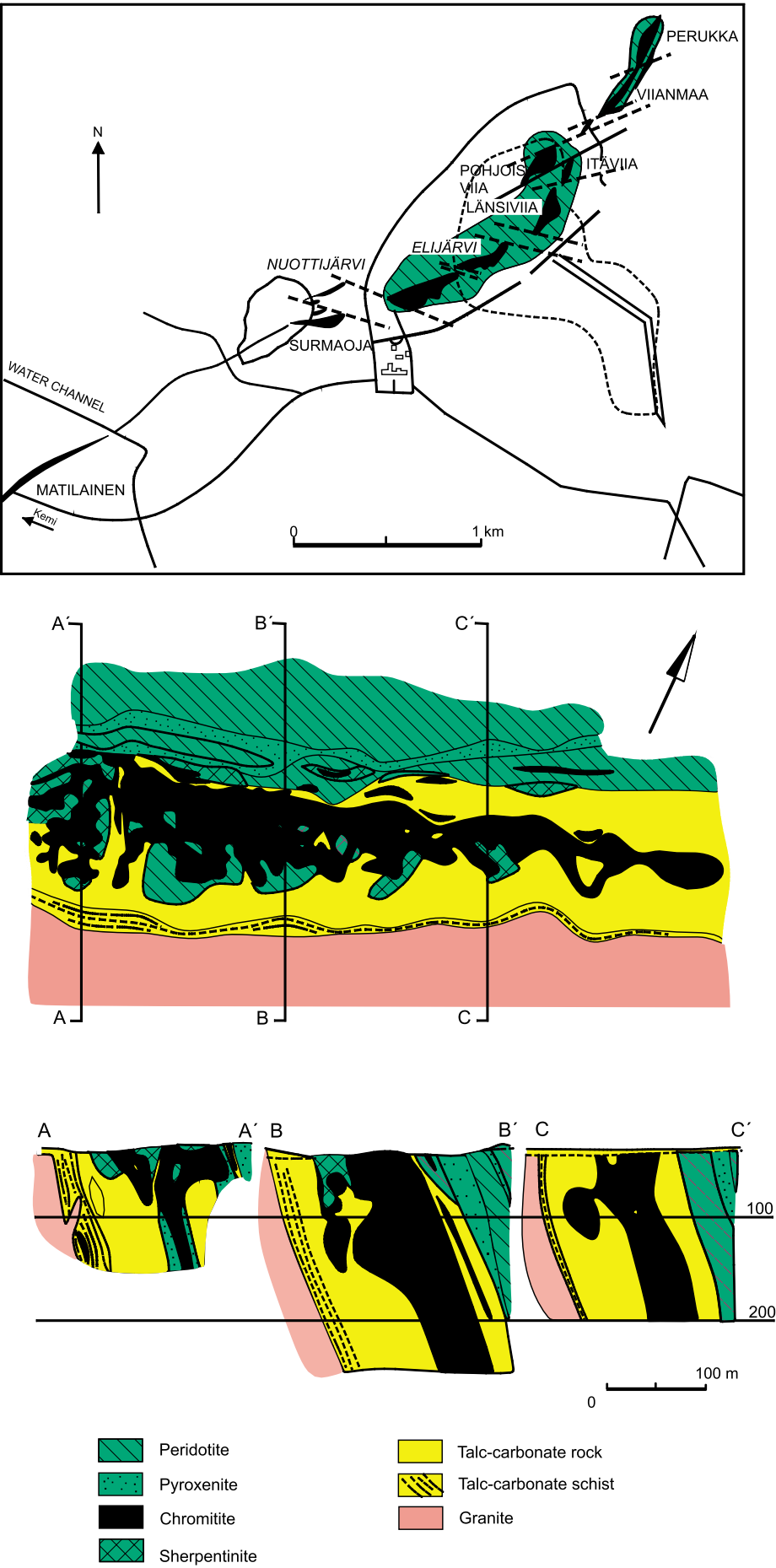


Fig. 10. Surface plan and three cross-sections of the Elijärvi orebody, after Alapieti et al. 1989a.

STRUCTURE AND TEXTURE OF THE CHROMITE ORES

In the central part of the Kemi Intrusion the basal chromitite layer widens into a thick chromitite accumulation, which can be divided into three structurally different units. From bottom to top, these are the main chromitite unit, the altered unit, and the uppermost unit.

The basal contact with the Archean basement is tectonic, and a mylonitic talc-chlorite-carbonate schist, varying in thickness from 5 to 50 m, is the lowest rock type of the layered complex. The main chromitite unit is locally in contact with the remobilized granitoid, which intersects and brecciates the chromite ore.

The thickness of the main chromitite unit averages 40 m, but it varies from a few meters to 160 m. The upper contact with the altered chromitite unit lies stratigraphically 100 to 150 m above the basal contact of the complex, but its position has been altered by several strike-slip faults. The top of the main chromitite unit is layered in structure, but the lower part is non-layered and brecciated and the chromite ore contains abundant barren ultramafic inclusions. The best preserved structurally is the part of the layered unit between the Matilainen and Surmanoja orebodies where its thickness varies from a few meters to 30 m. The inhomogeneous Elijärvi orebody is depicted in Figures 10.

An intensely altered ultramafic rock with abundant thin chromite layers exists above the main chromitite unit. This rock type was primarily pyroxenite but now consists of talc and carbonates. Some of the chromite layers

can be traced for several tens of meters, but most of the layers extend for only a few meters. Innumerable small faults cut the layering and make it difficult to trace individual layers.

Sparse chromitite layers occur in the well-preserved peridotitic cumulate above the intensely altered ultramafic rock. The uppermost chromitite layer in the stratigraphy, about 0.5 m thick, exists as high as about 500 m above the basal contact of the intrusion.

In addition to the thick chromitite layer, the Cr content is also high in the pyroxenes in the middle part of the intrusion. This is surprising, since a vast amount of chromite must have crystallized out from the magma before these pyroxenes. One explanation for this is the entry of fresh magma pulses into the crystallizing chamber, mixing with the earlier, more or less contaminated liquid. According to the model proposed by Huppert *et al.* (1986), the new magma pulse would have been able to form a plume in the earlier liquid, resulting in the formation of chromite crystals during mixing. These crystals would have been taken up in the plume and would have spread sideways at the top of the liquid layer. After the discovery of the granophyre in the Penikat Intrusion, it would seem probable that it has also occurred above the Kemi Layered Series, and the plume has also reached this granophyric layer, where the salic contamination has triggered the chromite precipitation. The chromite grains will then have rained out of the plume to form the chromite pile at the base, preferentially around the vent, which would explain the



Fig. 11. Aerial photo of the Kemi open pit.

great thickening of the main chromitite in the central part of the intrusion. In addition, quite thick vertical chromitite has also been encountered in the probable feeder channel in the granite gneiss about 100 m below the intrusion, as mentioned earlier. The occurrence of this chromitite could be explained by flow differentiation, i.e. when the liquid with suspended chromite crystals flowed through this conduit, the chromites must have migrated into the region of higher velocity flow and concentrated in the center of the dike. The significance of the small spherical silicate inclusions rich in alkalis which commonly oc-

cur in chromite grains for the formation of the chromite-rich layers still remains poorly understood, although they could be indicative of sodium-rich fluids occurring during the crystallization of chromite.

The Kemi chromitite mine is a good example of the exploitation of a low-grade ore, distinctly lower in grade than in the stratiform deposits in southern Africa. The success of the operation is due to the convenient location of the deposit combined with advanced mineral processing and ferro-chrome production technology.

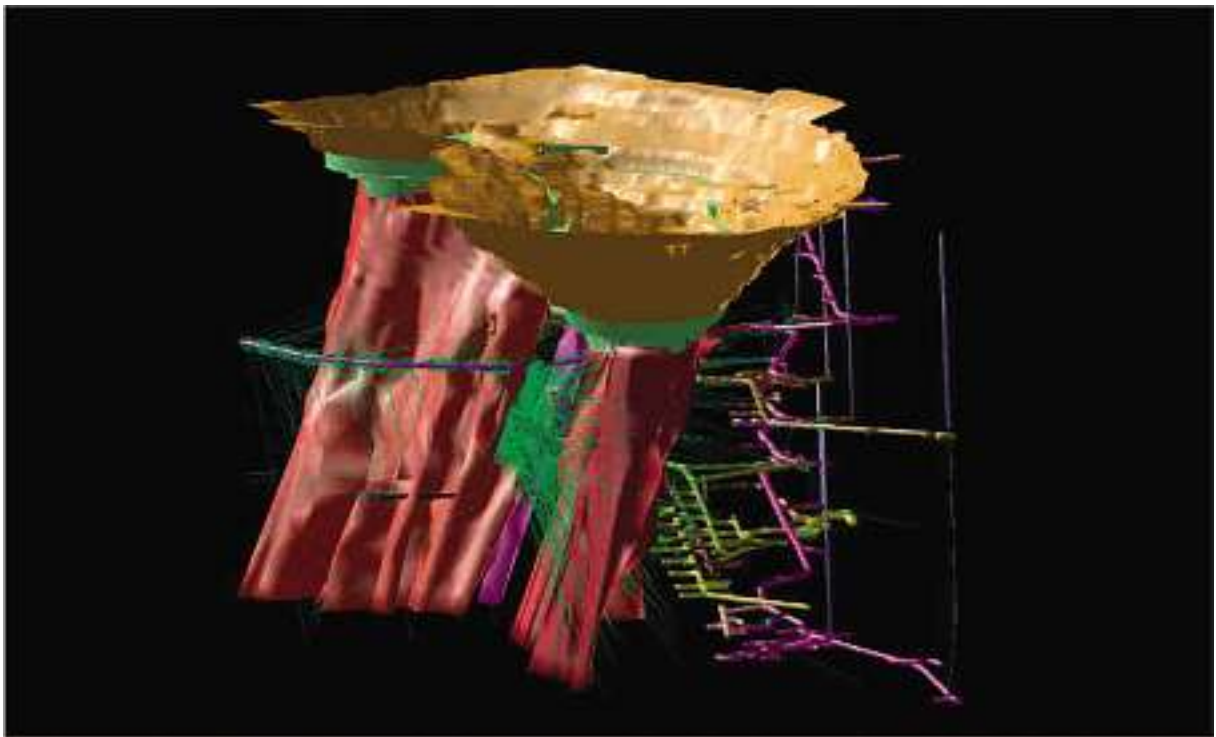


Fig. 12. 3-D model of the Kemi Mine

EXCURSION SITES

1. The Kemi open pit
2. Underground mine
3. Upper contact of the Kemi Intrusion

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