GEOLOGINEN TUTKIMUSLAITOS

BULLETIN
DE LA
COMMISSION GÉOLOGIQUE
DE FINLANDE

N:o 194

ON THE PROSPECTING AND GEOLOGY OF THE KEMI CHROMITE DEPOSIT, FINLAND

A PRELIMINARY REPORT

BY

AARNO KAHMA, TOIVO SIIKARLA, VALTO VELTHEIM,
OKE VAASJOKI AND AULIS HEIKKINEN

WITH 40 FIGURES AND 11 TABLES IN TEXT AND 8 PLATES

HELSINKI 1962

GEOLOGINEN TUTKIMUSLAITOS
BULLETIN DE LA COMMISSION GÉOLOGIQUE DE FINLANDE N:o 194

ON THE PROSPECTING AND GEOLOGY OF THE KEMI CHROMITE DEPOSIT, FINLAND

A PRELIMINARY REPORT

BY

AARNO KAHMA, TOIVO SIIKARLA, VALTO VELTHEIM,
OKE VAASJOKI AND AULIS HEIKKINEN

WITH 40 FIGURES AND 11 TABLES IN TEXT AND 8 PLATES

HELSINKI 1962

Helsinki 1962. Valtioneuvoston kirjapaino

CONTENTS

INTRODUCTORY NOTES

BY

AARNO KAHMA

The results of the investigations carried out by the Ore Department of the Geological Survey during the period between June 30, 1959 and May 30, 1960 in the region of the Kemi chromite occurrence, situated a few kilometers northeast of the town of Kemi — shown in the map (Fig. 1) — are presented in the papers included in this volume.

The starting point for the investigations was provided by the pyrite-bearing samples sent to the Geological Survey in June of 1959 by Mr. M. Matilainen, a diver, residing in the town of Kemi. In connection with trips of inspection to the scene of the finds, Mr. Pentti Ervamaa, M. A., examined other samples collected by the diver in the vicinity of Kemi. Among them one nonmagnetic sample attracted his attention, and it was identified in laboratory examinations supervised by Dr. Oke Vaasjoki as chromite. This chromite sample proved to have originated from small chromite lenses 20—50 cm thick occurring at the bottom of a water channel dug for a local paper mill.

Since, on the evidence of these chromite lenses and the general geological mapping carried out in 1949 by Dr. M. Härme, the area had to be considered promising also from the point of view of discovering chromite deposits on a larger scale, it was decided to conduct detailed gravimetric, magnetic and electromagnetic surveys of the soil-covered surroundings of the channel during the autumn of 1959. The measurements led to the discovery of a separate positive (0.3—1.2 mgal) gravimetric anomaly zone several kilometers long on the southeastern side of the chromite lenses met with in the beginning, and a negative (1 000—2 000 γ) magnetic anomaly associated with it. After density and susceptibility determinations of the narrow chromite lenses and the surrounding slightly magnetite-bearing serpentine rocks, it was considered highly probable that the anomaly sequence was caused by a chromite formation within the serpentine rock.

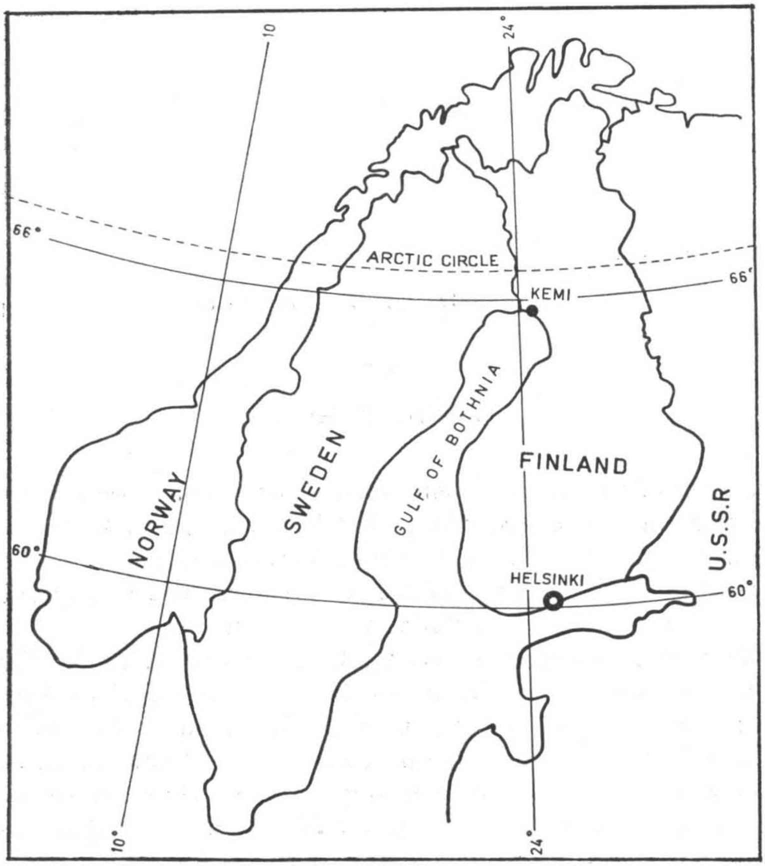


Fig. 1.

This interpretation was observed to be correct when, on November 5, 1959, the first hole drilled into the western end of the zone pierced a chromite deposit twenty meters thick; and it was further verified in other parts of this long and narrow anomaly zone, as all twenty-six drillholes made by the Geological Survey within the anomaly zone have proved the occurrence of chromite.

On the basis of the drillings carried out by the Ore Department between October 25, 1959 and April 30, 1960, the thickness of the chromite deposit included in the geophysical anomaly sequence varies between twenty and 100 meters and it may be estimated to contain 17.5 million tons of over 20 % and 4.4 million tons of over 30 % chromium ore. On the basis of analyses performed at the Geological Survey, the chromium—iron ratio of the portions investigated is relatively low, varying around 0.84—1.87.

With an eye to the speedy clarification of the economic potentialities of the occurrence, the Council of State, through an agreement made on April 7, 1960, handed over the task of further exploring the chromite occurrence of Kemi, together with the research material, to the Outokumpu Company.

The following articles were written on the basis of the reports of the Ore Department delivered in accordance with the afore-mentioned agreement on May 30, 1960, to the Outokumpu Company. Mr. Valto Veltheim was the geologist in charge of the area under investigation from August, 1959; Mr. Toivo Siikarla directed the geophysical measurements carried out in the area; and Dr. Oke Vaasjoki was in charge of the mineralogical investigations of the chromite, the chemical analyses involved having been performed by Mr. Aulis Heikkinen in the Chemical Department.

On account of the limited research material and time, the articles included in the present volume must be regarded principally as preliminary reports, which the further investigations to be carried out in years to come by the Outokumpu Company will doubtless complement and enlarge in many ways.

Geological Survey of Finland, Otaniemi, December 1960

1

ON GEOPHYSICAL INVESTIGATIONS OF THE KEMI CHROMITE OCCURRENCE

BY

TOIVO SIIKARLA

ABSTRACT

The paper deals with the magnetic, gravimetric and electromagnetic surveys carried out in the vicinity of Kemi in northern Finland. The magnetic and gravimetric measurements led to the localization of an extensive chromite occurrence in an area where the bedrock is entirely overlain by overburden. The general features of the geophysical anomalies noted are presented, and the magnetic and gravimetric anomalies in two profiles are compared in detail. The geophysical anomalies are also interpreted geologically. In conjunction with the magnetic measurements, the results of the susceptibility determinations are given. In conjunction with the gravimetric measurements, a method is described for performing density determinations from drill cores as well as for computing residual anomalies. The point is made that an interpretation calls for a detailed comparison of the results obtained by different methods one with another, as well as with certain physical constants determined from samples, and close collaboration between geophysicist and geologist.

CONTENTS

INTRODUCTION

Previously, chromite had been met with in Finland only as a sporadic additional component of serpentine rocks. In the summer of 1959 the Geological Survey received for examination a boulder found by an amateur prospector on the shore of the channel situated on the northeastern side of the town Kemi. The boulder was found to contain chromite in considerable abundance. An exploration of the locality where it had been picked up led to the discovery of several narrow chromite veins at the bottom of the channel, where the bedrock had become exposed during the digging of the channel. Since the bedrock in the vicinity of the discovery was everywhere overlain by overburden and, accordingly, it was not possible to investigate the matter further by means of direct geological observations, geophysical investigations were undertaken in the area and aimed toward tracing possible chromite occurrences of greater extent. The susceptibility and density determinations made of samples taken from the veins and the country rock indicated that magnetic and gravimetric methods would be feasible provided the dimensions of the occurrences sought were great enough. The results presented in the following are based on the explorations carried out by the Geological Survey in the region during the fall of 1959 and the late winter of 1960.

Systematic magnetic, gravimetric and electromagnetic measurements were performed over an area of seven square kilometers, which, six kilometers long and 1—1.5 km broad, covers an anorthosite-serpentine intrusion and a granite contact. The number of observation points is about 5 000, or 715 points per square kilometer.

Field operations were in charge of Messrs. O. Kinnari and N. Puranen, research assistants, who were assisted by Messrs. J. Kankaanpää and A. Salo, work foremen. Messrs. O. Kinnari and J. Kankaanpää also performed the calculations involved in the magnetic and gravimetric work.

By means of the geophysical measurements, particularly the magnetic and gravimetric ones, an extensive chromite occurrence was localized beyond the narrow veins first discovered, in an area where there was not a single bedrock exposure.

LOCATION, GEOLOGY AND TOPOGRAPHY OF REGION

Kemi, the most important industrial town in the province of Lapland, is situated on the northeastern shore of the Gulf of Bothnia at about 65° 45′ north latitude and 24° 30′ east of Greenwich.

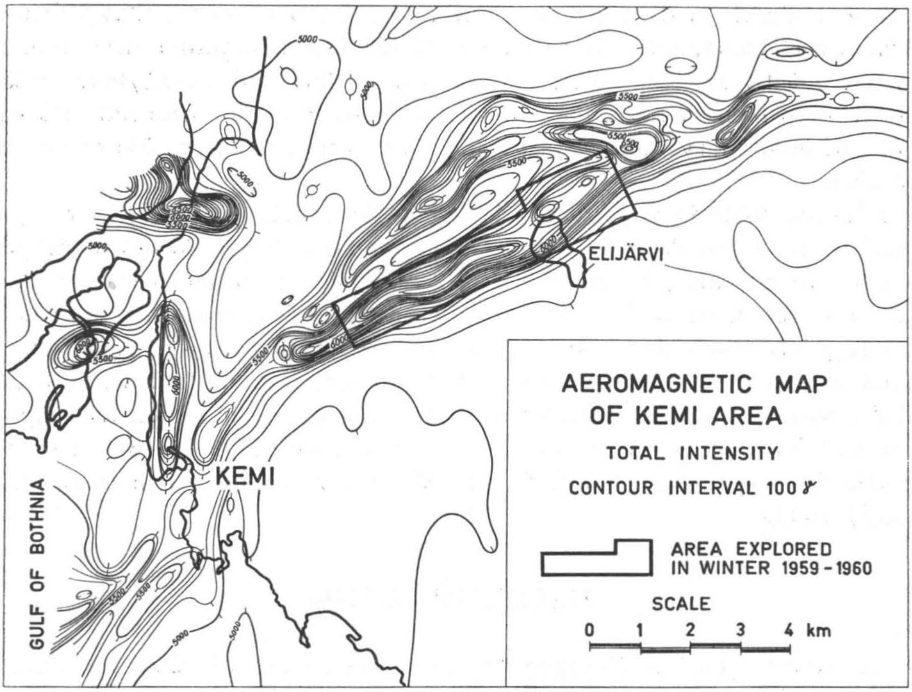


Fig. 1. Simplified aeromagnetic map showing the location of the Kemi exploration area.

The general geology of the Kemi region was described by Dr. M. Härme in his study dating back to the year 1949 (Härme 1949). According to Härme, in the vicinity of the town of Kemi the anorthosite-serpentine series includes an intrusion which, measuring some twelve kilometers in length and 1—3 km in breadth, extends from the coast in a northeasterly direction. Toward the southeast this intrusion is bounded by a broad area consisting of migmatite granite, and toward the northwest and west by greenstones and quartzites.

The chromite occurrence is associated with the anorthosite-serpentine intrusion near the contact of the migmatite granite. The breadth of the ore zone varies between fifteen and 100 meters and its dip averages 60° NNW.

The area on which the geophysical investigation concentrated consists principally of woods and bogs. Across the southwestern part of the area runs the previously mentioned channel and in the central and northeastern part there are two small lakes, Nuottijärvi and Elijärvi. The maximum variation in altitude in the entire area amounts to about twenty meters and the mean elevation is 25 m above sea level.

The bedrock is everywhere overlain by loose deposits. The thickness of the overburden, according to diamond drillings and probe measurements carried out by L. Kauranne, varies between one and twentyfour meters, the avarage being 7.5 m. The thickest beds of loose deposits are met with south of Nuottijärvi and Elijärvi and on the northeastern side of the latter lake.

Also available to supplement the geological picture of the Kemi region based on M. Härme's earlier studies were the aeromagnetic maps compiled from measurements performed in 1951. The measurements were carried out from aircraft with a flux-gate magnetometer of Canadian manufacture. The flight altitude was 150 m (measured from the ground) and the distance traversed was 400 meters. Fig. 1 presents a simplified aeromagnetic total intensity map, on which the contours have been drawn at 100γ intervals. The map clearly shows the aeromagnetic anomaly caused by the anorthosite-serpentine massif, the maximum value of which is approximately 1900γ.

GEODETIC FRAME

In order to position the geophysical observations, a basic set of parallel lines spaced 500 m apart was set up in the area under investigation and marked by piles driven into the ground. This grid was oriented so as to correspond to the mean trend of the contact of the ultrabasic massif and the granite. The coordinate axis representing this trend is provided with the symbol »K». The measurement profiles are at right angles to this basic grid and likewise marked by piles driven into the ground, the marked points being intended mainly for gravitational observations. The axis of this direction is marked by the symbol »L». The basic grid has been linked to the national triangulation network by means of polygonal measurements. The height of the observation points has been determined by levelling. In the ore belt the measurement profiles, which are thus orientated approximately at right angles to the trend of the ore, are spaced 50 m apart, elsewhere 100 m. The interval between the observation points along a profile is either 10 or 20 m. The various geophysical measurements have been made at these piles, so that they correspond to each other fully as regards location.

MAGNETIC SURVEYS

The magnetic measurements have been performed with the Finnish ARM-magnetometer. The observation point density varies somewhat in the

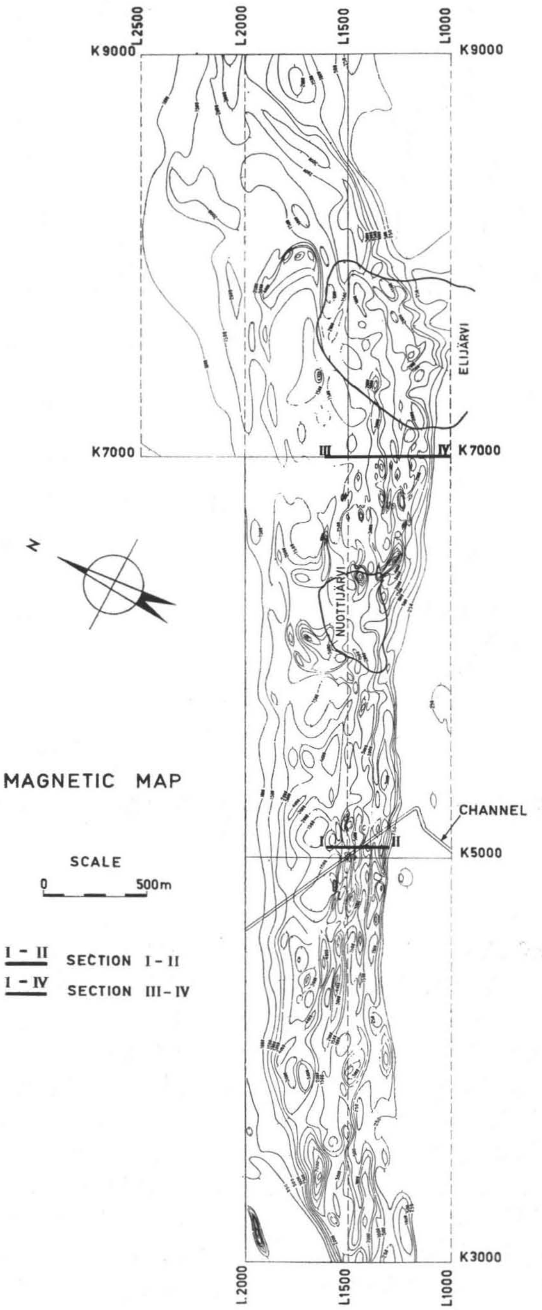


Fig. 2. Vertical component magnetic field map of the Kemi exploration area. Contours at 250, 500, 1 000, 1 500, 2 000, 3 000, 4 000γ, etc.

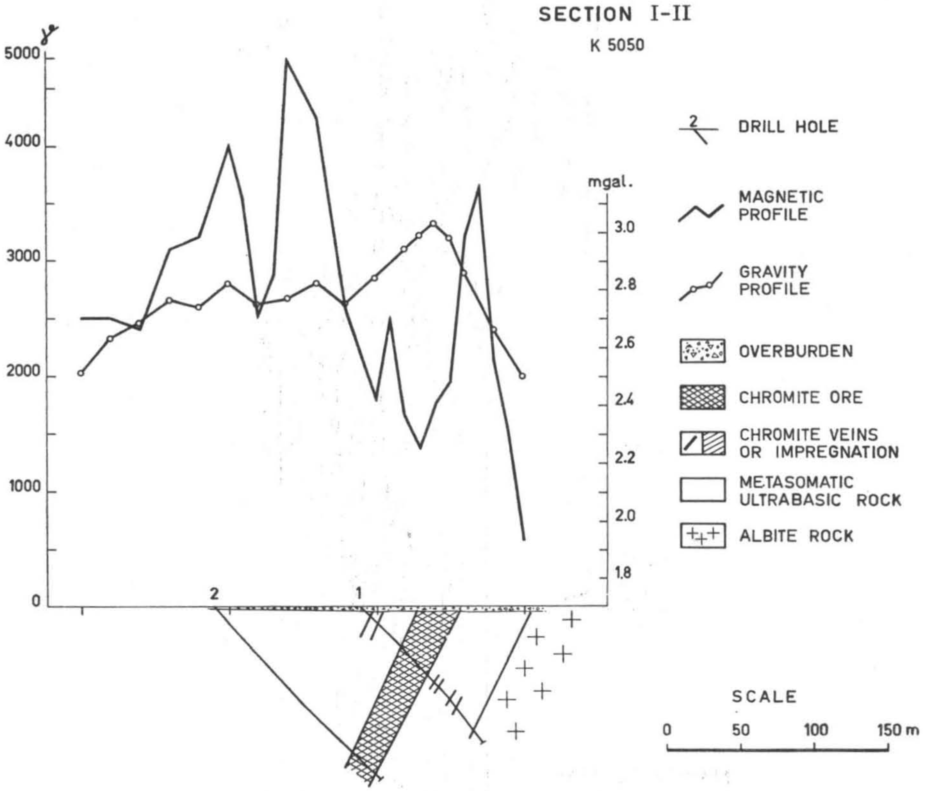


Fig. 3. Combined magnetic and gravimetric profile I—II.

different parts of the region. In the ore belt the distance between profiles is 50 m, and between the observation points along each line 10 m, while elsewhere the corresponding spacing is 100 m, and 20 m respectively. The map presenting the Z-component brings out the contact of the ultrabasic rocks and the granite quite distinctly and sharply (Fig. 2). The strength of the anomaly induced by the ultrabasic rocks varies between 1 500 and 7 000γ. The typical features of the anomaly picture appear best in the magnetic profiles, examples of which are show in Figs. 3 and 4. The relative location of these profiles, which are approximately perpendicular to the rock contact, is shown in Figs. 2 and 8. Figure 3 presents a profile at the edge of the channel in the southwestern part of the area under investigation. It shows how the magnetic anomaly, starting from the granite contact, and running to the ultrabasic rock, at first increases to the value of 3 500γ and then diminishes to 1 200γ, after which the anomaly

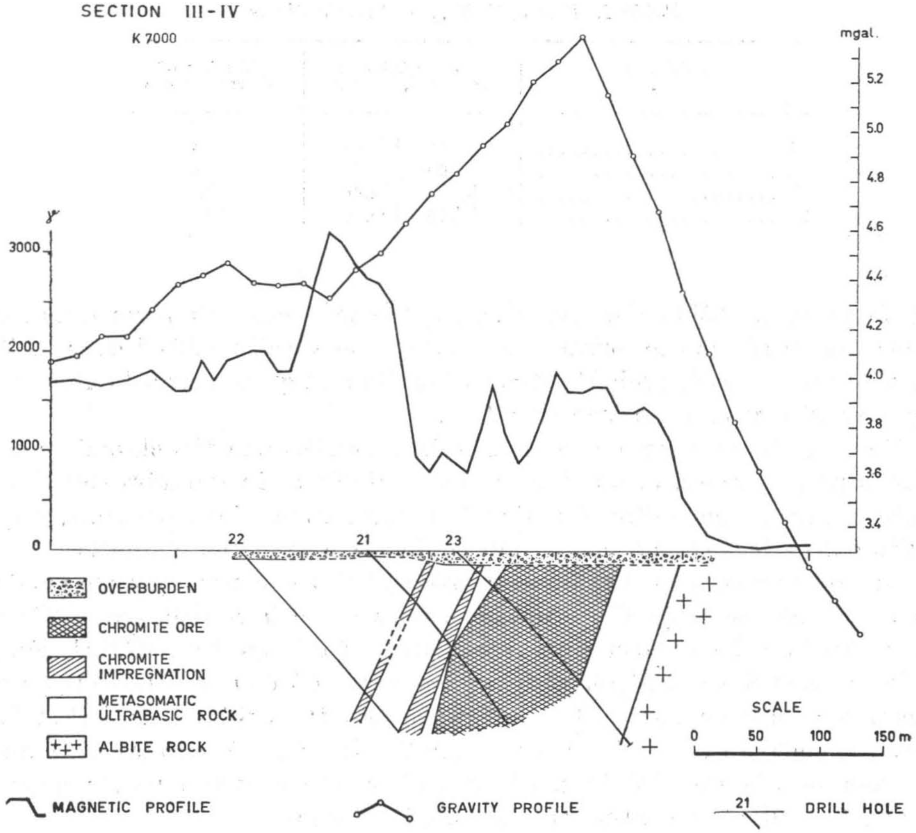


Fig. 4. Combined magnetic and gravimetric profile III—IV.

increases again to reach its maximum of 5 000γ. Thereafter the anomaly weakens. Fig. 4 presents a profile situated 1 950 m to the northeast from the foregoing one, and is analogous to it. First there is a marginal anomaly measuring about 1 750γ near the contact, then a twin hollow, the value of the Z-component of which is 800—1 000γ. The hollow is followed by a 3 000γ maximum and this, further on, by a relatively level 1 600—1 800γ anomaly zone. This same anomaly sequence recurs in several different profiles and reflects fairly faithfully the geological picture observed in them. The granite rock possessing a low susceptibility (albite rock) is followed by a serpentinized, magnetite-bearing rock, which induces the first anomaly maximum. Thereafter follows the minimum caused by chromite with low susceptibility, and then comes the maximum induced by the ultrabasic rock. The narrow maxima in the chromite »hollow» divide it into several parts, and are due chiefly to intermediate layers or inclusions of

Table 1. Susceptibility determinations

Drill-hole No.	Depth interval measured, meters	Number of determinations
1	6.50—131.20	113
2	4.00—137.80	121
19	51.20— 74.00	23
21	89.40—195.50	114

ultrabasic rock within the ore. Further the magnetic minimum does not occur wholly above ore outcrop but has systematically shifted over to its hanging wall. This is probably due to the dip and great vertical extension, together with transverse magnetization.

The correlation between the magnetic anomalies and the chromium ore zone is not, however, everywhere so indisputable as in the afore-described profiles. This is due to the fact that in certain parts of the ore zone, magnetite occurs in varying amounts in conjunction with the chromite.

In order to confirm the interpretation of the magnetic measurements, numerous susceptibility determinations were made from drill cores. These determinations have been carried out using the American »G.S.C. Magnetic Susceptibility Bridge», with a frequency of 1 000 cgs. The measurements were carried out at 1 m intervals, and the drill-holes selected for measurement: Nos. 1 and 2 from profile I—II (Fig. 5), and Nos. 21 and 19 from profile III—IV (Fig. 6). The distribution of the measurements among the different drill-holes is shown by Table 1.

All told, 375 susceptibility determinations were made from the four drill-holes, and covering a length of 387 meters. The results were computed on the basis of the mean diameter of the drill cores by using constants given by the manufacturer of the instrument.

Figs. 5 and 6 present susceptibility values for samples from drill-holes 1 and 21. The abscissa is the depth of the hole and the ordinate the susceptibility value represented on a logarithmic scale in units of 10^{-6} cgs. The Cr_2O_3-content of the samples has been marked in the upper part of the drawing. The length of a column gives the Cr_2O_3-content in percent, and the width shows the length of the drill-core sample analyzed. The results presented in both figures are in close agreement. The country rock, depicted by the chemically unanalyzed portions at the upper margin of the figure, has a susceptibility varying between 2 000 and 12 000 $\times 10^{-6}$ cgs, whereas for the ore it averages 100 $\times 10^{-6}$ cgs. The low susceptibility values met with at the bottom end of each hole, amounting to 20 $\times 10^{-6}$ cgs, represent albite rock. Table 2 shows the variation of the susceptibility values within unified ore zones in these profiles.

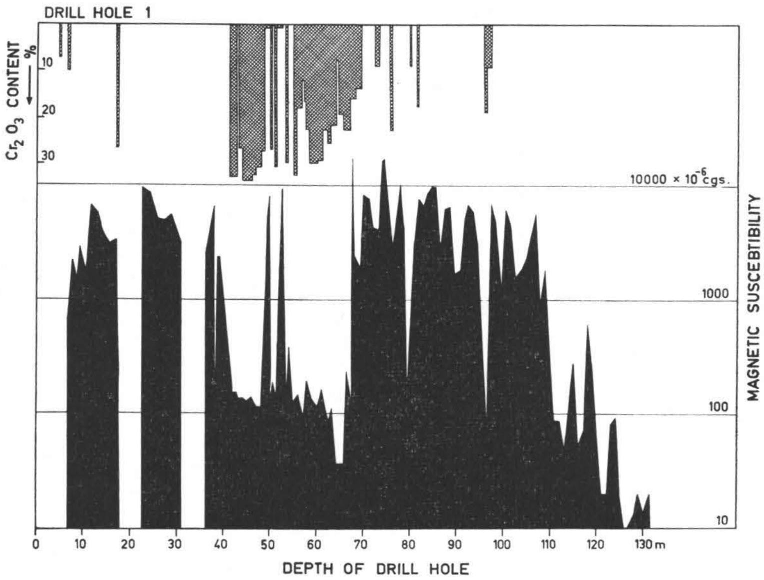


Fig. 5. Susceptibility values and Cr_2O_3 content for core samples from borehole n:o 1.

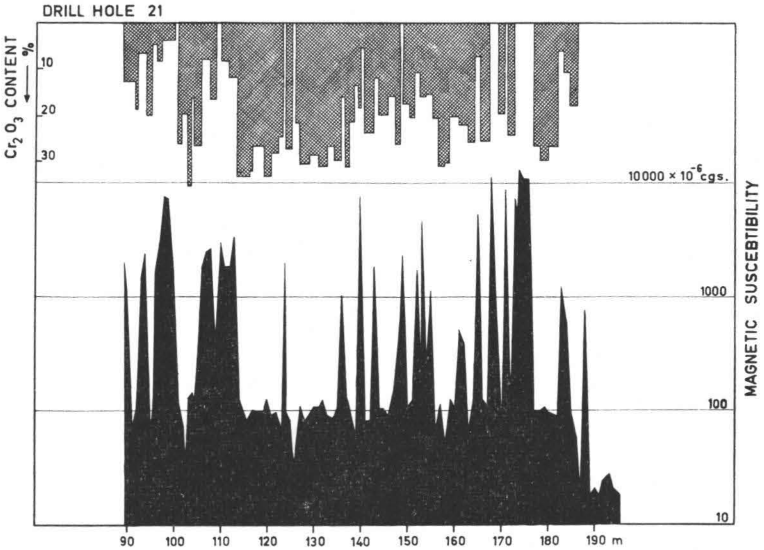


Fig. 6. Susceptibility values and Cr_2O_3 content for core samples from borehole n:o 21.

Table 2. Susceptibility determinations of chromite ore.

Hole No.	Depth interval, m.	Value range 10^{-6} cgs.	Mean 10^{-6} cgs.	Number of determinations
1	41.80— 51.10	114—154	136	11
1	53.60— 65.50	37—194	119	12
21	115.00—135.00	43—135	95	23
21	177.00—185.00	60—106	92	8

Weighted mean 108 × 10^{-6} cgs.

The chromite-bearing portions of drill-hole 19, situated between Nuottijärvi and Elijärvi 200 meters southwestward from profile III—IV, have yielded quite high susceptibility values, including the several examples below:

Susceptibility × 10^{-6} cgs.	Cr_2O_3-content %
4 500	16.8
15 400	16.8
10 150	21.9
11 650	16.9
20 300	16.9
9 960	7.1
13 700	7.1
11 660	17.0
7 800	17.0

For the country rock, the values in drill-hole 19 vary between 14 000 and 22 000 × 10^{-6} cgs. The high values measured from the ore are due to the fact that magnetite occurs in conjunction with the chromite in the form of narrow veinlets, or as an impregnation. On the basis of the magnetic map, the more abudant occurrence of the magnetite in conjunction with chromite would appear to be limited to particular sections of the ore belt as for example the Nuottijärvi area and the northeastern part of Elijärvi.

GRAVIMETRIC SURVEYS

BOUGUER ANOMALIES

The gravity measurements were performed with the American Worden gravimeter No. 231. The density of observations was the same as in the case of the magnetic measurements, the distance between profiles in the

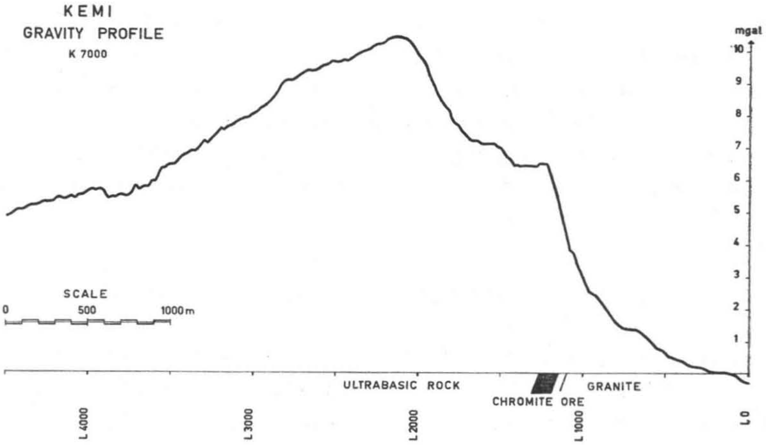


Fig. 7. Bouguer anomaly from the anorthosite-serpentine massif over section K = 7 000.

ore zone being generally 50 m and elsewhere 100 m, the spacing between the observation points along each profile being 10—20 m. The heights of the observation points were determined by levelling. The gravitational values were reduced to that prevailing at sea level by means of free-air and Bouguer corrections. The density value of 2.60 was applied in the Bouguer correction. The latitude correction was taken into account.

Five gravity profiles were measured at one-kilometer intervals across the entire massif in order to study the regional gravity anomaly caused by the anorthosite-serpentine massif as a whole. The length of these profiles varies between 3 000 and 4 500 meters and they are situated as follows:

K 5 000.	Profile	measured	between	L 1 000	and L 4 000
K 6 000.	»	»	»	L 1 000	and L 4 000
K 7 000.	»	»	»	L 1 000	and L 4 500
K 8 000.	»	»	»	L 1 000	and L 4 500
K 9 000.	»	»	»	L 0	and L 4 500

From these profiles it will be seen that the total anomaly produced by the anorthosite-serpentine rocks is 8—11 milligals. The maximum occurs in the co-ordinate interval L 2 000—L 2 500. Fig. 7 presents the gravity profile K 7 000.

It is only in the vicinities of Nuottijärvi and Elijärvi that the anomalies induced by the ore can be clearly observed on the Bouguer anomaly contour map. Elsewhere the strong regional anomaly masks the local anomaly induced by the ore almost completely.

As the geophysical investigations were begun in the vicinity of the channel, where the anomaly caused by the ore is comparatively weak, efforts were made to eliminate the effect of the regional anomaly. This was done by means of a linear rectification of the Bouguer-gravity-values, which made it evident that the remaining local anomalies had a distinct connection with the hollow revealed by the magnetic measurements.

LINEARLY RECTIFIED BOUGEUR ANOMALIES

The horizontal gradient of the regional anomaly induced by the anorthosite-serpentine massif is quite uniform throughout the area where measurements were performed. Its magnitude in the direction of the K axis is 5 milligals per kilometer. This horizontal gradient was eliminated linearly by subtracting from the Bouguer-gravity-values 5 mgals per km (0.1 mgal/20 m) in the direction of increasing K-ordinate. The rectification was carried out relative to grid line L 1 000.

The gravity values thereby obtained are presented in Fig. 8, where the contours are drawn at intervals of 0.1 mgal. On the map there is to be seen a uniform anomaly zone, which becomes quite distinct starting from line K 4 700 and then continues on in the dicection of the rock contact across the channel, running via Nuottijärvi to Elijärvi, where it turns more sharply northeastward and extends nearly as far as line K 9 000. This anomaly is at its strongest on the western side of Elijärvi, where it rises about 1.2 mgal above the immediate surroundings, the corresponding figure on the eastern side of Elijärvi being approx. 0.9 mgal. This anomaly zone has been explored by drillings on both sides of the channel between K 4 700 and K 5 250 and at Nuottijärvi along lines K 6 200 and K 6 500 as well as at Elijärvi between K 6 800 and K 7 900. Since the drillings have shown a clear correlation between the ore and the gravity anomalies everywhere, it is quite probable that the anomalies observed in this zone — also those in undrilled areas — are connected with the occurrence of chromite. A more detailed picture of the inter-relation between the gravity anomalies and the ore is provided by profiles I—II (Fig. 3) and III—IV (Fig. 4). The gravity values presented for these profiles are linearly rectified Bouguer-anomaly values. The gravity anomaly occurring in profile I—II (Fig. 3), the magnitude of which, as computed from the granite side, is approx. 0.8 mgal and, from the side of the ultrabasic rock, 0.3 mgal, is due to a chromite zone approx. 20 m thick whose density difference relative to the ultrabasic rock is 0.7—0.8 g/cm^3 and relative to the granitic rock 0.9 g/cm^3. The distribution of the density in drill-hole No. 1 belonging to the profile is shown in Fig. 14. The profile makes evident

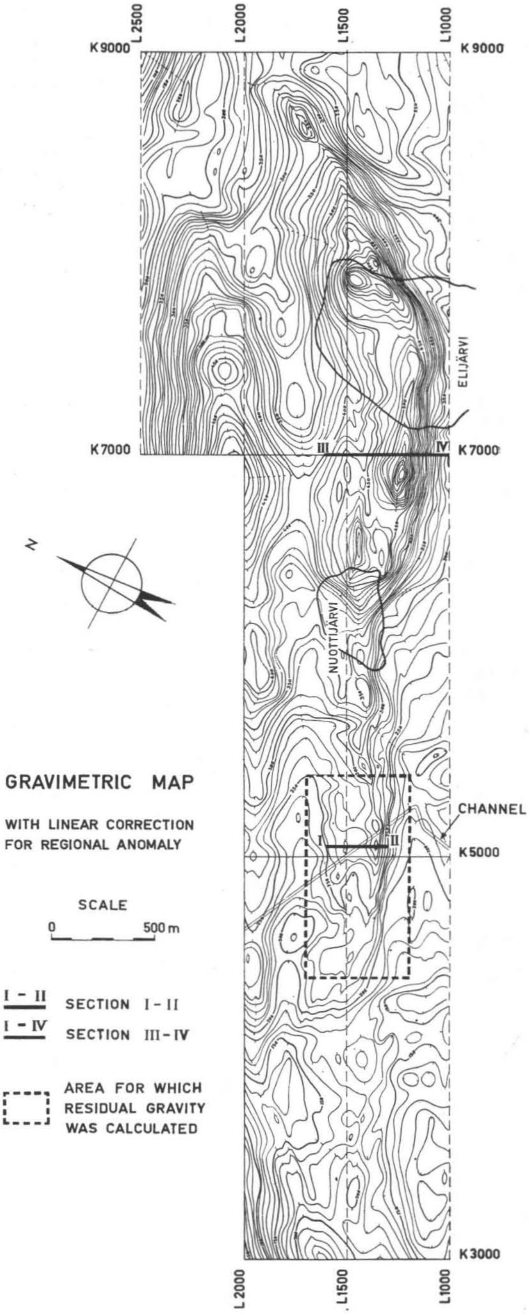
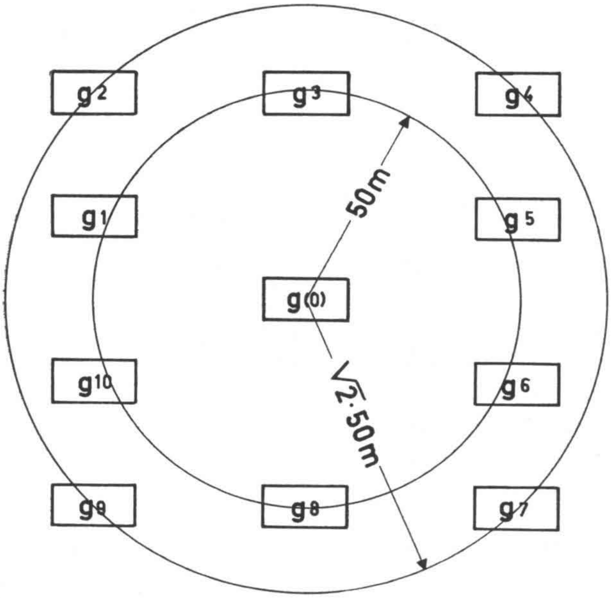


Fig. 8. Bouguer anomaly map of the Kemi exploration area with linear correction for elimination of regional anomaly.

the fact that the gravity maximum corresponds to the position of the ore established by means of drillings and coincides with the magnetic minimum, although slightly displaced in relation to the magnetic minimum. Fig. 4 presents a corresponding profile from Elijärvi, 1950 m northeast-ward from the preciding profile. The gravimetric anomaly is here much stronger, owing to the greater thickness of the chromite zone. This profile likwise exhibits a shift between gravity maximum and magnetic minimum corresponding to that of the preceding profile.

RESIDUAL ANOMALIES

In the vicinity of the channel, where the anomalies induced by the ore are comparatively weak, the residual anomalies proper were also calculated. The computation method used departs somewhat from that given



$$\Delta g = g(0) - \frac{g_1 + g_2 + \cdots + g_9 + g_{10}}{10}$$

Fig. 9. Template for calculation of residual gravity.

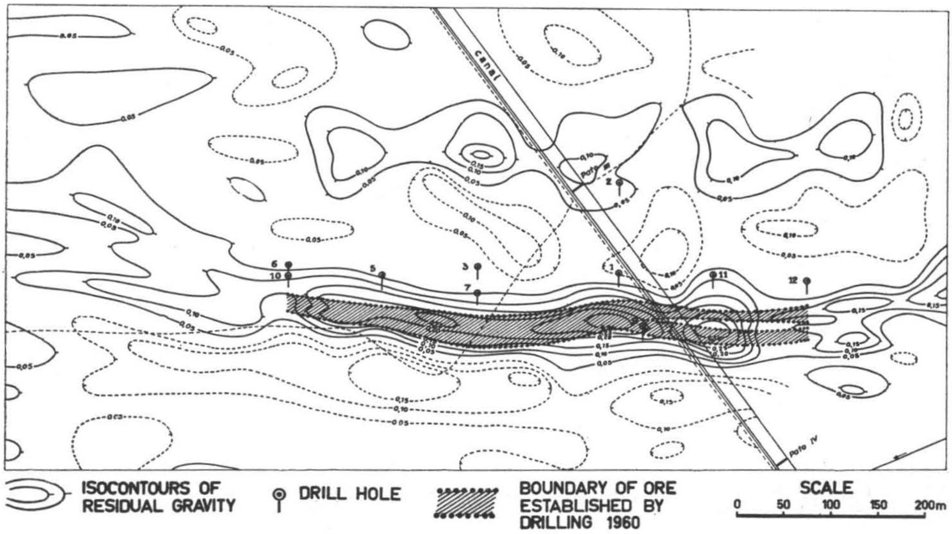


Fig. 10. Residual gravity map for the vicinity of the channel calculated from Bouguer values. Boreholes are marked on the map. The outline of the ore outcrop was gotten from the borehole findings.

by Griffin (1949) in which the residual gravity is computed from the formula:

$$\Delta g = g(O) - \bar{g}(r), \text{ where}$$

Δg = residual gravity
$g(O)$ = measured gravity at point of calculation
$\bar{g}(r)$ = mean gravity over the circumference of a circle of radius r, the center of which is situated at the point of calculation.

In determining $\bar{g}(r)$ a template slightly deviating from the usual has been used in order to make the work of computation more mechanical. The template has been provided with gaps, which have been placed in such a way that they fall on numerical values marked on the map. The structure of the template is presented in Fig. 9. There are ten gaps in order to avoid division in computing the mean value. Six are located along the circumference of a circle of radius 50 m, and the remaining four around a circle of radius $\sqrt{2} \cdot 50$ m. This template has been planned in correspondence with observation point density to yield g-values (gl, $g2$, etc.) from the map directly. Bouguer-values have been used to compute the residual anomaly. Fig. 10 presents the residual map calculated from the Bouguer-values. For comparison, Fig. 11 gives a map obtained from the Bouguer map by

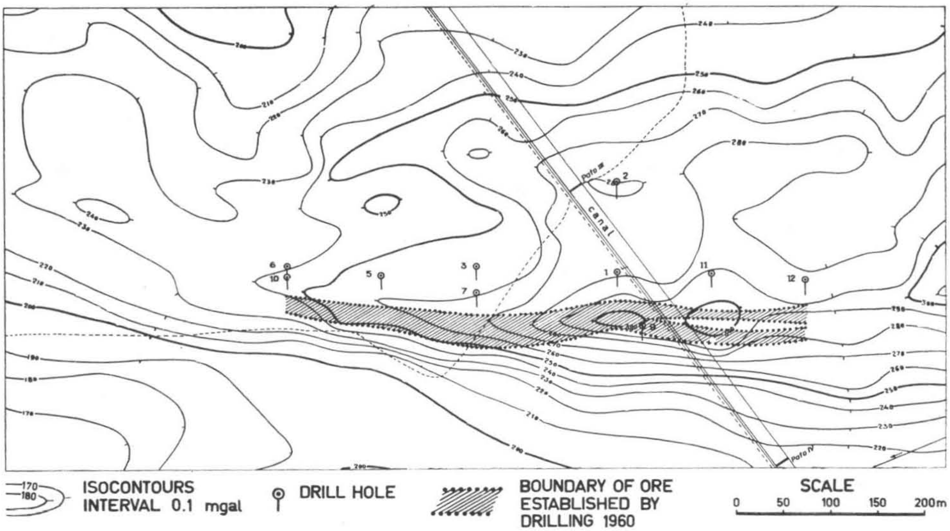


Fig. 11. Bouguer anomaly map with linear correction for regional anomaly and covering the same area as that of fig. 10.

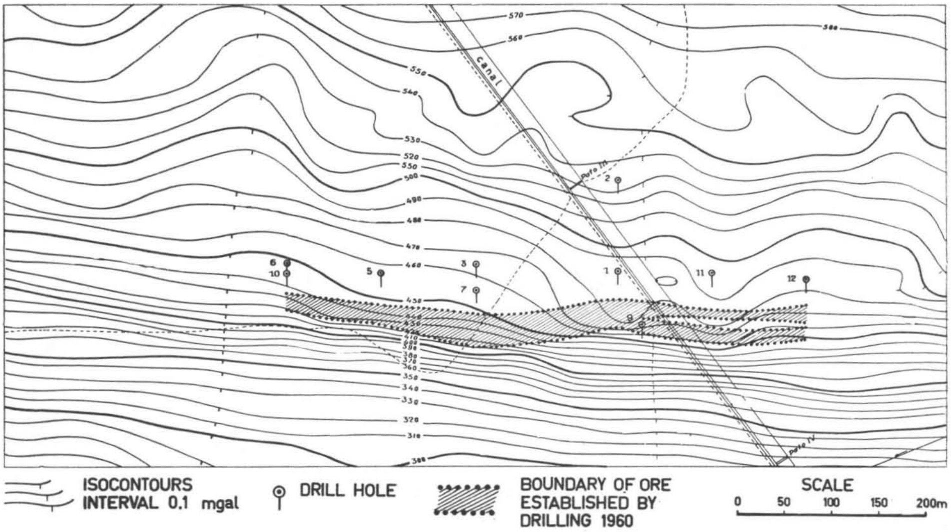


Fig. 12. Original Bouguer anomaly map of the same area as that of fig. 10.

eliminating the linear horizontal gradient while Fig. 12 shows the original Bouguer-anomaly map. The boundaries of the ore determined by means of diamond drillings have been marked on all the maps.

It is difficult to detect the local anomaly caused by the ore from the original map, as it is masked by the strong regional anomaly resulting from the basic massif.

The linear elimination of the regional anomaly, as shown in Fig. 11, has fairly clearly brought out the effect of the ore and the situation of the ore can be determined quite easily by means of this map. The effect of the ore appears far more distinctly in the residual map proper, Fig. 10. In addition, it brings out another zone running parallel with the main one 150 m to the northwest and corresponding to the chromite veins met with at the bottom of the channel.

DENSITY DETERMINATIONS FROM DRILL CORES

In order to verify the interpretation of the results given by the gravity observations, a large number of density determinations were made from the drill cores.

As is well known, it is rather difficult to obtain a picture of the mean density through density determinations made from individual samples, particularly in the case of non-homogeneous rocks or ore-bearing zones. Upon the density's changing at short intervals within a relatively large range, a poorly selected group of samples is liable to lead to erroneous results. In order that the determinations might give a more reliable average picture of the distribution of the density, the Geological Survey starting in 1954 has used a device, in which the density of the drill core can be determined over a length of 80 cm at one and the same time. In this way, a continuous spectrum of the distribution of the density can be obtained, whenever desired, throughout the length of the drill hole by measuring the cores of the entire hole in a single continuous operation. This device is represented in Fig. 13.

The device consists of a balance equipped with effective eddy current damping, and with a range of 0—2 kg, the sensitivity being 0.2 g. The drill cores are stacked in an aluminum trough 80 cm in length, and the weighing is performed first in air and then in water. Several troughs are used and they are identical so that their loss of weight in water can be compensated for by a single constant additive weight.

Density determinations have been made from the cores of six drill-holes over a total length of some 1 040 meters. These determinations are concentrated mainly in the drill-holes of profiles I—II and III—IV. The density of the ultrabasic rock occurring as the country of the ore varies between 2.73 and 2.90 and that of the albite rock between 2.60 and 2.65.

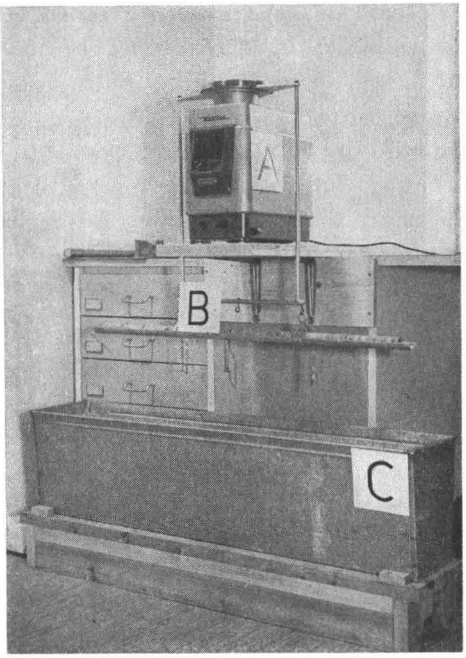


Fig. 13. Apparatus for density determinations from cores.

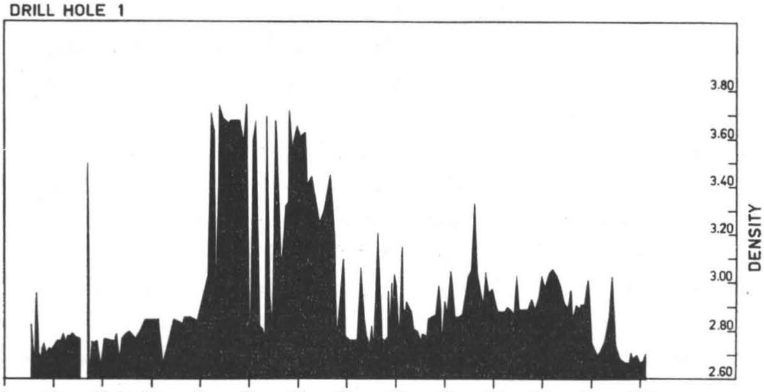


Fig. 14. Density values for samples from borehole n:o 1.

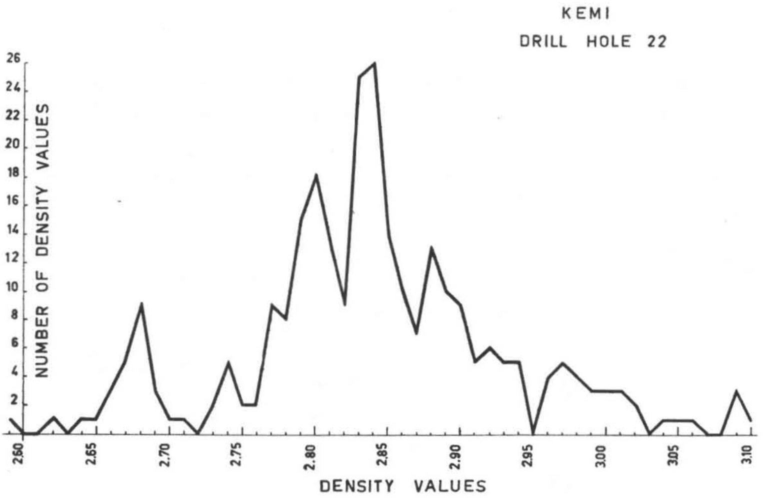


Fig. 15. Frequency spectrum for density values of the country rock from borehole n:o 22. The figure represents 274 determinations over a total borehole length of 220 m.

The distribution of the density in profile I—II is represented by the density diagram of drill-hole 1 in Fig. 14.

The frequency of occurrence of the different density values obtained from the cores of drill-hole 22 is presented in Fig. 15. The measurements have been performed from the country rock over the roof side of the ore, between the depth intervals of 11.30 and 231.60 m. They represent 274 density determinations over a length of 220 m. The abscissa of the figure gives the numerical values of the densities measured, and the ordinate the frequency of occurrence of the different density values. A distinct frequency maximum occurs between density values 2.83 and 2.84.

ELECTROMAGNETIC SURVEYS

Electromagnetic measurements have been carried out in the region investigated with the loop-frame method. The frequency of the primary field was 3 600 cps and the coil separation 40 m. In the measurements carried out no electrical indications were met with, such as might indicate the occurrence of sulphide ores.

SUMMARY

The Kemi chromite occurrence offered quite a favorable object for the application of geophysical methods to ore prospecting. In geological structure the occurrence is quite regular, and it is of sufficient dimensions to induce anomalies large enough to exceed the limits of error of the measurements considerably.

It was possible to determine the contact of the serpentine rock and the granite accurately reliably by means of magnetic measurements. Inasmuch as the chromite ore was bounded on both sides by ultrabasic rock possessing a considerably greater susceptibility, the ore itself could also be detected magnetically. In part of the area investigated, however, magnetite could be observed in addition to the chromite and, on the other hand, the country rock contained relatively weak magnetic zones. Accordingly, the results of magnetic measurements generally cannot be interpreted without a detailed comparison with the gravimetric measurements.

In order to determine the local gravity anomaly induced by the ore, it was necessary first to eliminate from the measurements the strong regional anomaly resulting from the anorthosite-serpentine massif. Owing to the regular form of the regional anomaly, the elimination was carried out by means of a rapid and simple linear rectification, whereby the local anomaly by the ore became quite distinctly evident. However, a residual gravity map was observed to give an even more detailed picture of the ore, at least in the vicinity of the channel.

The investigations carried out in the Kemi region convincingly demonstrated the applicability of geophysical methods to prospecting for chromium as well as the decisive importance of these methods in prospecting for ore in areas poor in rock exposures.

Furthermore, they demonstrated importance of comparing the results obtained by different methods one with another, as well as with physical constants as determined from samples. A correct interpretation of results also requires frictionless collaboration between geologist and geophysicist.

ACKNOWLEDGEMENTS

The author wishes to extend thanks to Mr Valto Veltheim, Ph. Lic., geologist of the Kemi survey area, for his excellent co-operation during the field work. I also wish to acknowledge the assistance I received in the form of chemical analyses and the geological data yielded by diamond drilling operations. It is further my pleasant duty to thank Miss Sisko Lehtiniemi for the maps she skilfully drew for me as well as Mrs. Siiri Kinnari and Mr. M. Huuskonen for the density determinations they carried out with commendable care.

Special credit is due the assistant research workers and labor foremen mentioned in the text. It was their skill and energy that made possible the speedy performance of the field investigations under difficult wintry conditions.

Finally, Mr. Paul Sjöblom deserves a word of thanks for translating my manuscript into English.

REFERENCES

GRIFFIN, W. R. (1949) Residual gravity in theory and practice. Geophysics 14, n:o 1, pp. 39—56.

HÄRME, M. (1949) On the stratigraphical and structural geology of the Kemi area, northern Finland. Bull. Comm. géol. Finlande 147.

2

ON THE GEOLOGY OF THE CHROMITE DEPOSIT AT KEMI, NORTH FINLAND

BY

VALTO VELTHEIM

ABSTRACT

The chromite deposit is associated with a zone of ultrabasic rocks. The continuous ore belt is approximately 3.5 km long. The thickness of the belt varies considerably measuring at its thickest well over a hundred meters. The dip of the ore body averages 65° NW. The ore is known to continue at least to a depth of 250 m in roughly the same thickness.

The chromite occurs in the ore as either dense or sparse impregnations. The impregnations are generally evenly distributed, although there are also ore types in which oreless flecks of former olivine grains appear in an evenly distributed impregnation. The grain-size of the chromite remains within a few tenths of a millimeter. At its richest the ore contains ca. 40 % Cr_20_3.

It is assumed that a portion rich in chromium separated from the parent magma at an early stage. The parent magma penetrated into its present sill-like position where it differentiated into anorthosite and peridotite. The chromium-rich portion then penetrated into the peridotite. After the placement of the ore, hydrothermal solutions penetrated into the same zone producing a metasomatic change in the parent rock of the ore and on both sides of the ore zone.

CONTENTS

THE GENERAL GEOLOGY OF THE REGION

The stratigraphy and structural geology of the Kemi area has been investigated by Härme (1949). The geological map (Fig. 1) appended to Härme's publication shows the zone of intrusive rock running northeast from the town of Kemi. This »anorthosite-serpentine series» is about twelve kilometers long and, in its southwestern part, about a kilometer wide, the width increasing toward the northeast so that near the other end of the formation, at Elijärvi, it is approximately three kilometers. Another formation described as consisting of the same rock occurs, however, at a distance of some eight kilometers to the northeast from Elijärvi, where it runs in a northeasterly direction as a belt two or three kilometers wide and about twenty-one kilometers long.

The Kemi-Elijärvi anorthosite-serpentine sequence borders at its southeastern end, as shown in the map, on a broad stretch of migmatite granite. Facing the formation on its northwestern side there is greenstone as well as, at about the middle of the sequence, quartzite. According to Härme, the different rocks mentioned would rank in the following order, starting with the oldest: the older component of the migmatite granite (gneiss granite) — quartzite — greenstone — anorthosite-serpentine sequence — the younger component of the migmatite granite (potash granite). The greenstone occurs in two varieties: amygdaloidal and hypabyssal. Judging by the primary structures, the trend of the base of the quartzite is toward the southeast. The general dip of the formation is NW.

On the basis of Härme's presentation, the main geological features of the region may be summed up as follows:

1- The weathering sediment (quartzite) has been deposited on a basis of gneiss granite.

2- During volcanic action, which took place in part also while the sedimentation process was still going on, basic supracrustal layers (amygdaloid

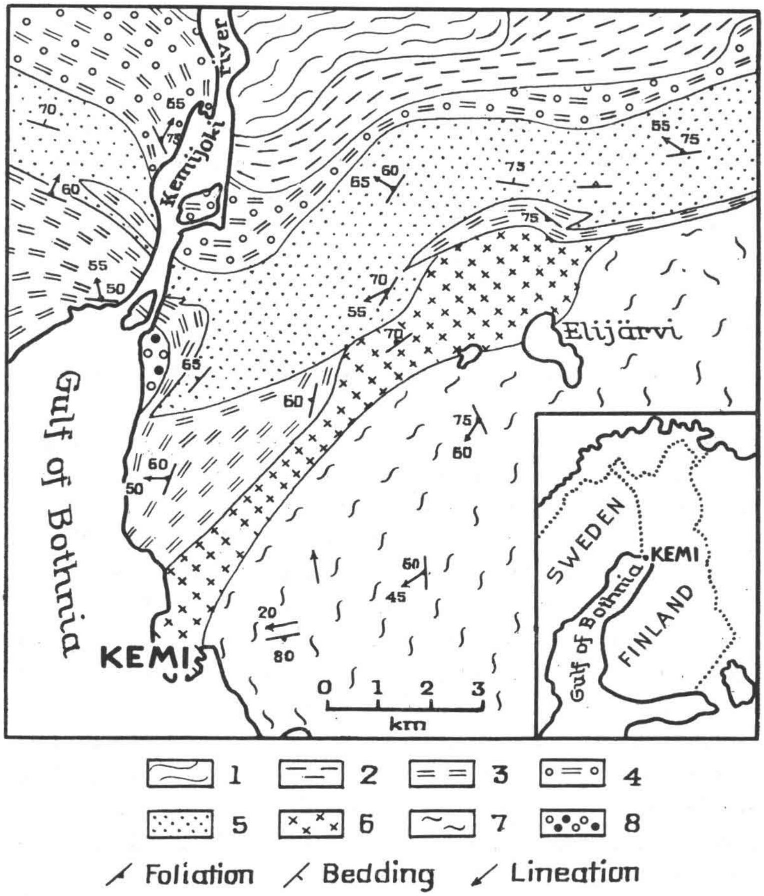


Fig. 1. Geological map of the Kemi area. According to Härme, 1949. 1 — slate, 2 — basic schist, 3 — greenstone, 4 — amygdaloidal greenstone, 5 — quartzite, 6 — anorthosite-serpentine series, 7 — migmatite granite, 8 — diorite.

greenstone) settled on top of the weathering sediments, while hypabyssal parts intruded between the gneiss granite base and the quartzite.

3- A sill-like intrusive, corresponding in composition to ossypitic gabbro, thrust itself, still in an almost horizontal position (information received by word of mouth), underneath the supracrustal formation, where it became differentiated into anorthositic and peridotic components.

4- In connection with the domelike elevation of the migmatite granite, the foregoing stratigraphic composition received its present inclined position. During the same tectonic period, dislocations occurred in the hard layers in a direction nearly at straight angles to the granite contact.

The differentiated peridotitic rock appearing in the present map at the southeastern margin of the ultrabasic zone contains ingredients predominantly olivine and pyroxene by origin.

Mention should be made of the older view, presented by Hausen and Väyrynen (Härme, op. cit., p. 46), according to which the vertical position of the supracrustal complex was due to a north-south overthrust against the resistant gneiss granite, in conjunction with which also the ultrabasic intrusive was intruded into place.

THE GEOLOGY OF THE MINERALIZED ZONE

The mineralized zone, comprising the chromium ore belt and the country rock on both sides of it, which, in respect to its special geological features is associated either primarily or secondarily with the ore, liest at the northeastern end of the Kemi—Elijärvi anorthosite-serpentine series parallel to its southeastern border. The length of the zone, which is here restricted to include only the part explored by drillings, is 3.3 km, starting from a channel about 7 kilometers northeast from Kemi and extending to the northeastern end of Elijärvi lake. The breadth varies between 200 and 400 meters. The trend of the zone follows quite faithfully that of the southeastern contact of the ultrabasic rock sequence — even to the extent that at the northeastern end of the sequence, where the contact referred to curves northward, the same kind of change in direction is observable in the zone.

The drillings have given a fairly detailed geological picture of the zone, though naturally limits have been imposed by the fact that the research material consists exclusively of drillcores. Three series of drillholes, one at the site of the channel and the other two in the vicinity of Elijärvi, illuminate the geological conditions prevailing farther on at the northwestern side of the ore belt.

The profiles made reveal that at the northwestern side of the zone, some 50 to 150 meters from the ore, there apparently exists a continuous olivine- and/or pyroxene-bearing rock wall. Depending on the relative amounts of olivine and pyroxene, the rock belongs in the categories from dunite to pyroxenite.

Some thirty to eighty meters away, on the opposite side of the ore, there is a continuous wall of coarse-grained albite rock which runs parallel to the ore belt. Albite rock has been reached with numerous drillholes, and its contact can also be clearly interpreted from geophysical profiles (see the paper by Siikarla in this volume), which reveal that this variety of rock extends several hundreds of meters farther to the southeast.

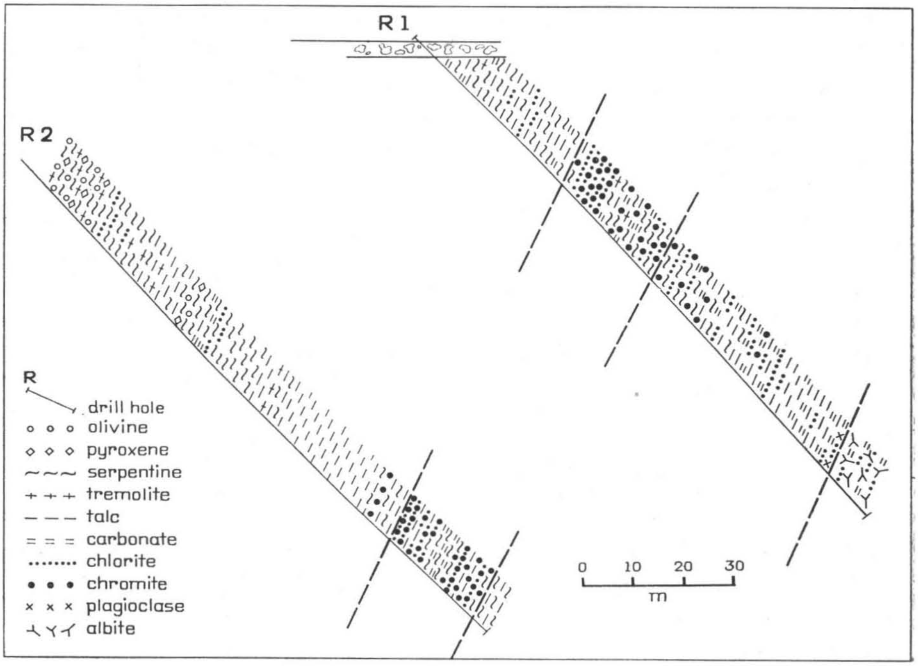


Fig. 2. Mineralogical composition in the vertical section R 1 — R 2, West End Ore.

The zone situated between the olivine- and/or pyroxene-bearing rock and the albite rock, in the middle of which the ore belt proper occurs, is characterized by strongly metasomatic rocks. The dominant mineral components in this metasomatic zone are serpentine, tremolite, chlorite, talc and carbonate. It would appear, roughly speaking, that the rock types marked by a predominance of talc and carbonate are situated primarily in the central part of the zone, whereas the types rich in serpentine and tremolite lie chiefly in the marginal parts of the zone. When examined in closer detail, the rock sequence within the zone exhibits quite frequent changes of the dominant mineral component, however. Thus, e.g., hard portions of serpentine rock of varying thickness occur quite often within the soft talc-carbonate rock. In certain cases, even olivine-bearing rock has been met with inside metasomatic rocks.

No differences of a fundamental nature could be detected between the metasomatic rocks situated on either side of the ore belt.

The change of rock types observed in the horizontal picture given by the drill cores evidently continues in the direction of the dip. Nevertheless, it has been difficult to connect the occurrence of the different rock types in drillholes of the same vertical plane at different depths.

At two points, in the southwestern part of the zone and at Elijärvi, in both cases a few meters beyond the margin of the ore, the drillcore shows for a distance of six to ten meters a rock type deviating from its surroundings in the respect that its mineral components include feldspar. The rock is relatively fine-grained and has an ophitic structure. In addition to plagioclase, the rock contains amphibole as another essential mineral. Judging by its mode of occurrence and structure, the rock might be regarded as gabbro, which may be a foreign substance in the entire ultrabasic rock zone.

In addition to the uniform area mentioned on the southeastern side of the zone, albite rock is met with in drill cores as portions of varying thickness averaging a few meters contained within the metasomatic zone outside the ore belt, and in a few instances also within the ore. In such cases the albite rock is notably finer of grain. No direct connection between these and the albite rocks of the southeastern side has been perceived.

A fairly regular feature is the occurrence of a fine-grained chlorite-carbonate-plagioclase rock facing the albite rock on the southeastern side. The thickness of this zone is a few meters, and it must apparently be considered a reaction zone between the ultrabasic and albite rock.

As pointed out in the foregoing, the ore belt runs through the middle of a zone of metasomatic rock. Accordingly, it parallels the trend of the metasomatic zone and curves in line with it northward at the northeastern end of the zone. Geophysically interpreted, it is most probable that the ore-bearing belt is continuous throughout the length of the mineralized zone dealt with in this report and even extends beyond it. On account of its varying thickness, the diamond drilling operations were concentrated on sites deemed most promising economically. In the areas explored by drillings, the ore belt is narrowest at its southwestern end, where the thickness of the ore (Cr_2O_3-content more than 20 %) averages 20 meters over a distance of 550 meters. It is at Elijärvi that the ore belt reaches its maximum thickness averaging 71 meters across a stretch of half a kilometer. It is highly probable that between the investigation sites the ore belt in many cases narrows down to only a few meters, At Nuottijärvi, where there was time to carry out only a very tentative survey, two separate, parallel, comparatively thick ore occurrences apparently exist. In the northern part of Elijärvi, where the investigation likewise did not get beyond the initial stage, two separate ore occurrences were also observed, though they do not run parallel. At the time of writing, the situation in this particular area is still to be clarified.

Examining the horizontal map of the ore belt, attention is drawn, first of all, to the general feature that the northwestern (hanging wall) contact of the ore is continuous and distinct, whereas, contrarywise, on the southeastern (foot wall) side the ore breaks up into numerous parts of varying thickness. However, it should be added that also within the hanging wall part of the ore belt there occur oreless and/or chromite-poor zones.

A more detailed exposition of the occurrence of the chromite can be found in connection with the petrographic description.

The observations made of the dip in the mineralized zone are confined to the ore belt and the dip of the contact with the albitic rock. The definition of the dip of the ore belt is based on the connections of the sections made at different depth levels, in which the contact of the hanging wall of the ore, by virtue of its continuity, has been determinative. The dip in the southwestern part of the ore belt has been measured as being 65° NW. In the vicinity of Elijärvi it is possibly a bit steeper in places, or about 70°, though there, too, the majority of observations give the same figure of 65°. In the northern part of Elijärvi, after the northern arching of the ore belt, a single observation indicates a marked grading down of the dip.

The contact on the surface between the ultrabasic and the albite rock could be determined quite accurately from the geophysical profile. Connecting this with the albite rock met with deeper in the drillhole, the dip of the contact yields a value of approximately 65° NW.

Common throughout the entire metasomatic zone are sheared zones. Their occurrence is most frequently to be observed along the hanging wall margin of the ore belt, but they are to be found also at greater distances from the ore as well as within the intercalating zones of oreless rock inside the ore belt. The ore itself contains no sheared zones, although the adjacent sheared zones are quite likely to have caused shearing at the edges of the ore-bearing rock.

THE ORE OCCURRENCES INVESTIGATED

Drilling operations were concentrated in four different areas in the anomaly zone, these having been interpreted in the light of geophysical indications to be most promising from the economic standpoint. An ore occurrence was also discovered in each area, and they were named as follows:

West End ore (Länsipään malmi),
Nuottijärvi ore,
Elijärvi ore, and
Viianmaa ore.

WEST END ORE

The West End ore is situated at the southwestern end of the zone investigated. The whole regional survey was first concentrated on the site of this occurrence. The ore belt was pierced by seven drillholes, of which six, at intervals of 100 m from each other, pierced the ore at a depth of 40—50 m and one at 110 m. The general trend of the ore is N 65° E, or the same as that of the ultrabasic formation. Longitudinally, a very gentle S-curve can be detected in the trend of the ore. The length of the ore explored (the distance between the extreme drillholes) is 550 m. The dip of the ore, obtained by connecting the ore in the aforementioned deep hole and in the shallower hole in the same vertical plane, is 65° NW. The thickness of the ore belt varies between 19 and 30 m, the average thickness being approximately 21 m. In the vertical profile formed by the two holes, the ore may be observed to have narrowed down from 26 m (at a depth of about 40 m) to 21 m (at a depth of 110 m).

The oreless interpart met with in a number of holes in the central part of the ore belt indicates a division in twain of the ore body longitudinally and parallel to the dip. This feature occurs quite distinctly in the two centermost holes, where the thickness of this interpart is about 5 m. Quite a consistent feature of the West End ore throughout its length is a zone of shearing, some 10—20 m wide, met near the contact of the hanging wall. The shear zone consists of a fine-grained mass rich in talc and so soft in

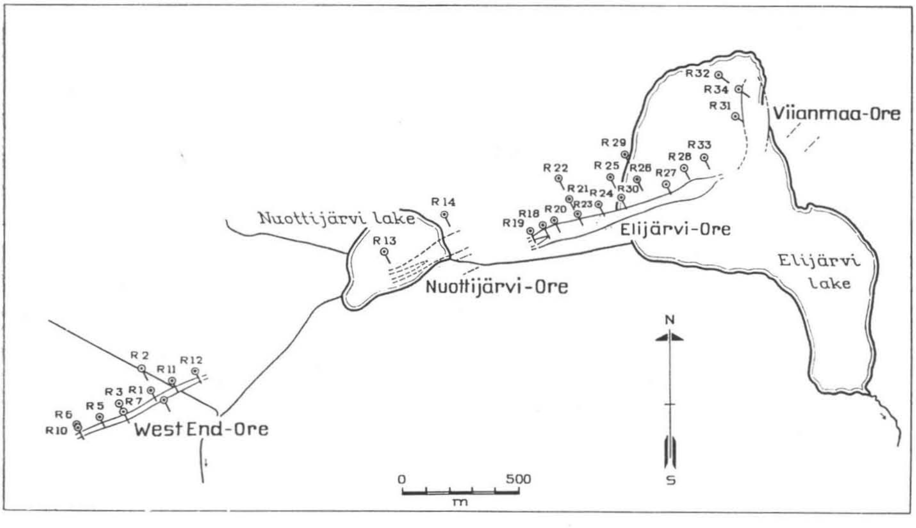


Fig. 3. The investigated ore deposits.

places that a drill will penetrate it without being rotated. This zone runs very close to the ore and even touches it at many points, but at many other points a thin layer (1—2 m) of harder rock lies between the ore and the shear zone. The same sort of shearing has also been met with in a deeper section, 110 meters below the surface of the earth, though it was only a few meters thick there.

The mean content of the West End ore, taking into account the entire ore belt excepting, however, the more scattered portion at the northeastern end, is 21.9 % Cr_2O_3. Portions with continuously higher percentages, Cr_2O_3-content over 30 %, can be distinguished, however, in a longitudinal direction. The most unified of them, with a thickness varying between 1.3 and 6.8 m, occurs uppermost on the hanging wall side of the ore. The highest Cr_2O_3-content analyzed in the area of the West End ore is 38.1 %, the length of the analyzed interval being 3.06 m, which percentage also comes close to the maximum values established in analyses of other ores.

NUOTTIJÄRVI ORE

About one kilometer from the West End ore toward the northeast, two holes were drilled toward the final stage of the investigation at Nuottijärvi, more precisely at the site of the strong geophysical indication met with on the northeastern side of the lake. The distance between the holes was 300 m.

The drillhole toward the southwest showed the ore to be scattered. In the ore zone, measuring a total of some 130 m in thickness, there occurred four different portions with a richer content of ore and approximately equidistant from each other. Only the two situated in the middle contained ore uniformly, whereas the other two contained ore and oreless zones in alternation. The thicknesses of the two ore zones in the middle were 12 and 11 m respectively, with the corresponding Cr_2O_3-contents being 20.1 % and 30.5 %.

The drillhole to the northeast pierced two more uniform ore zones, between which occurred an oreless intercalation some 48 m thick. The first ore is quite uniform. Its thickness is about 52 m and its Cr_2O_3-content 23.9 %. In this ore the chrome-oxide content diminishes comparatively evenly from 36.1 % on the side of the hanging wall to 12.1 % on the footwall side.

A scattering of the ore can be observed in the lower ore zone of the drillhole. At the end of the drillhole there occurs, however, a uniform ore zone the thickness of which is 29 m and the Cr_2O_3-content 31.7 %.

Connecting the ore from one drillhole to the other is difficult. The two separate ore zones of the latter drillhole possibly indicate the occurrence of two separate, parallel ore bodies, in which case the uppermost one would probably be an extension of the West End ore while the lower one would be associated with the ore zone trending northeastward, toward Elijärvi.

ELIJÄRVI ORE

The very strong geophysical anomaly met with in the vicinity of Elijärvi proved an indication of the greatest continuous ore occurrence in the entire area surveyed. Fourteen holes were drilled into the occurrence, four of them piercing the ore underneath the shorter holes. The general trend

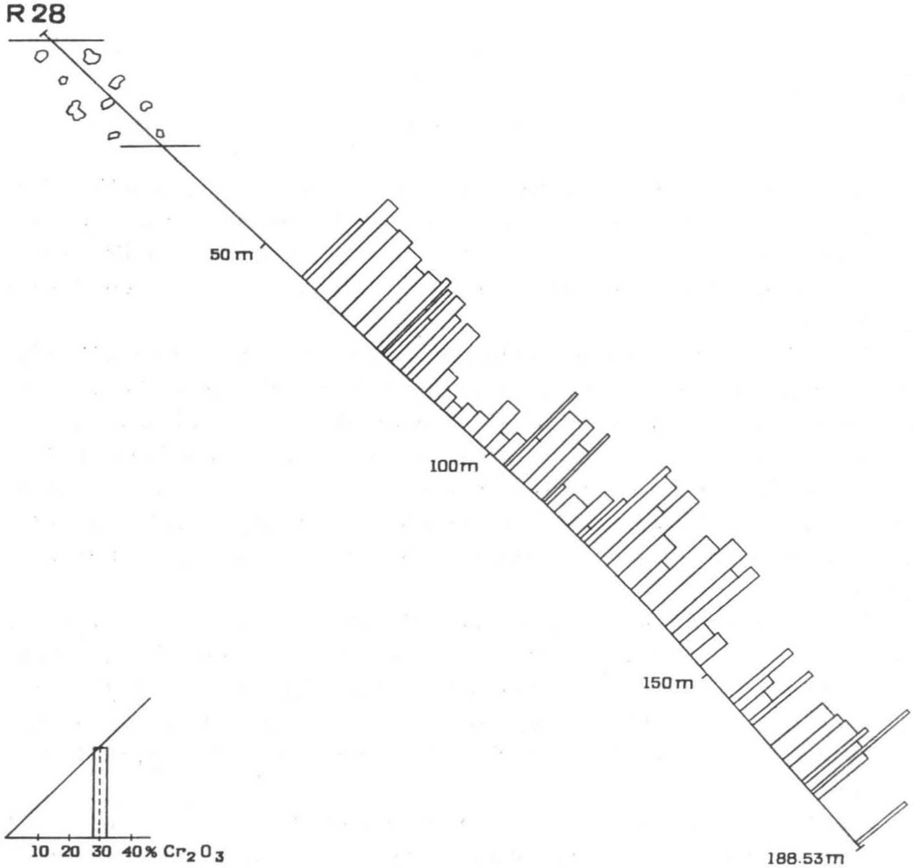


Fig. 4. Cr_2O_3 content in the drillhole R 28 in the Elijärvi ore.

of the ore is N 72° E, which means that it deviates somewhat from that of the West End ore. The length of the ore probed by drillings is 800 m. The dip of the ore, obtained by connecting it in the same vertical plane in profiles at different depths, varies between 65 and 70 degrees (NW). The average thickness of the whole ore zone is slightly over 100 m. After eliminating the more scattered portions of the ore from the foot wall side, the average thickness of the reduced, more unified ore is about 71 m, the range being from 33 to 101 m. Depthwise the ore has been observed in some profiles to narrow down and in others to broaden out. The deepest profile made of the ore pierces it at a mean depth of about 210 m. The ore is quite dispersed toward the foot of it. Also in the more unified hanging wall part of the ore there occur oreless intercalations in abundance. It is not generally possible to connect with each other these intercalations any more than the portions rich in ore even in the case of neighboring drillholes (spaced 100 m apart). In a typical cross-section, like the one shown in Fig. 4, there occur within the total thickness of the occurrence, four or five parts , rich in ore divided by barren or ore-poor rock. In all likelihood, the unified, high-percentage zone extending throughout the length of the occurrence reappears in the hanging wall of the ore. The thickness of this zone varies between 2 and 42 m, the mean thickness being approximately 15 m.

The mean Cr_2O_3-content of the Elijärvi ore zone, considering the aforementioned, reduced thickness of 71 m, is 20.3 %. The chrome-oxide content of the higher percentage ore zone occurring in the hanging wall is 30.9 %.

VIIANMAA ORE

Only three holes were drilled in this area, two of them in the same vertical plane. On the basis of the geophysical interpretation it could be assumed that the trend of the ore belt had turned more northward at this point. This also caused a shift eastward of the drilling direction. Two holes drilled in the same vertical plane indicated the dip of the ore as being more gentle than in the ones described in the foregoing.

The southern hole (R 31) in the area pierced a relatively unified ore body, the thickness of which was approximately 75 m and the mean content 24.5 % Cr_2O_3. High chrome-oxide values occur here evenly distributed throughout the thickness of the entire ore body.

The pair of holes (R 32, R 34) drilled farther to the north pierced an ore body probably joined to the one referred to above, its mean thickness here being about 68 m and mean content about 23 %.

The more eastern of the pair of holes pierced another ore zone after passing through a bed of rock about a hundred meters thick; this zone proved to be comparatively continuous, with a thickness of about 56 m and a mean content of 17.5 %.

Thus, in the Viianmaa area, two separate ore zones were observed situated relatively far apart. It is possible that the zones do not run parallel to each other but that the ore belt at this point has two branches: the shorter one, trending north and the other branch, evidently of greater length, extending northeastward.

PETROGRAPHIC DESCRIPTION

Owing to metamorphosis, the ultrabasic rocks occurring in the area under consideration are not met with wholly in their original, unaltered composition. It has been possible, however, on the basis of relictic mineral grains and structural features to determine fairly confidently the original mineralogical composition of less altered rocks — and it has also been possible, by following the alteration process step by step, to decide the origin to a high degree of probability even when the features indicative of the origin of the rock have almost totally disappeared. In this respect it is notable that the structural features suggesting the origin of a rock are generally in evidence in rocks that have undergone metamorphosis to a far-reaching extent. Since a classification of the rocks situated in the mineralized zone according to their present mineral composition would lead to a great multitude of variations, the rocks are arranged in the petrographic description in accordance with their original mineral composition, whether indicated or assumed.

PERIDOTITE

Rocks still containing *olivine* are most prevalent in the southwestern part of the area, where they seem to form a continuous wall on the northwestern side of the strongly metamorphosed zone. Variations in coarseness are to some extent to be observed in the rocks, but on the whole they are relatively coarse of grain. In color the rock is dark green. The poikilitic structure characteristic especially of the harzburgitic type appears as pyroxene grains which reflect light in spots measuring 1—1.5 cm in diameter and in which the olivine grains occur as inclusions. Although the amount of olivine may vary somewhat, it is nevertheless the predominant component in the original peridotitic rock.

In the microscopic picture, the former olivine grains appear as idiomorphic pseudomorphs. The remaining olivine content varies, occurring either as quite small grains in the middle of the pseudomorphs or as crys-

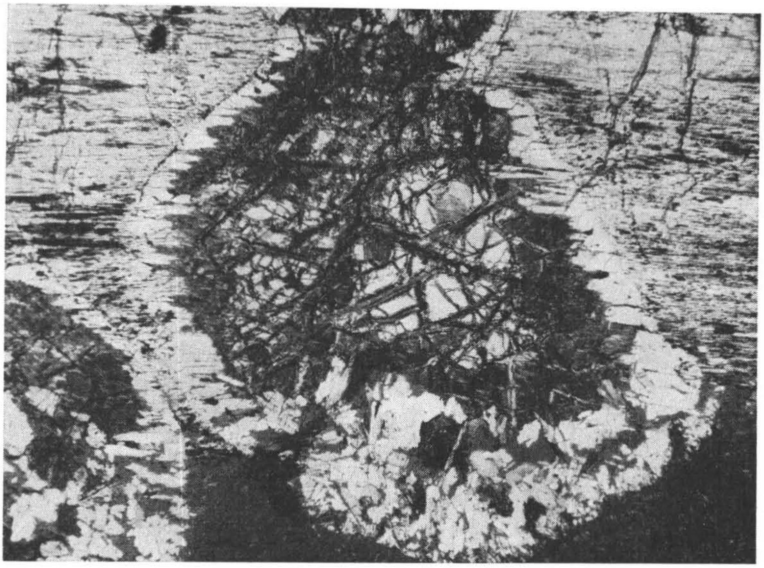


Fig. 5. Olivine pseudomorph in peridotite. In the middle of the pseudomorph are olivine relicts, surrounded by lamellar serpentine. Around the margin of the pseudomorph, a continuous tremolite rim. Chlorite (dark area in lower part of picture) and tremolitized monoclinic pyroxene occur as interstitial mineral in relation to olivine pseudomorphs. Distinct structural and density difference noticeable in tremolite rim, depending on the interstitial mineral. About 30 ×

tals of nearly their original size. To judge by its optical properties, the composition of the olivine is forsteritic (Fo approx. 80 %).

The first visible alteration product of olivine is serpentine. Particularly when olivine is still met with as largish grains, the serpentinization is to be observed as a fine-grained, darkish mass which usurps the parent mineral along its margins and from the edges of the segmental cracks. The segmental cracks consist of fine-grained, cross-fibered serpentine. The serpentine surrounding the relictic olivine grains is scaly and somewhat coarser.

Another metasomatic alteration product occurring almost consistently in the olivine pseudomorphs is tremolite, which in the majority of cases forms a continuous frame around the edge of the pseudomorphs (Fig. 5). The acicular amphiboles have in many instances grown perpendicularly from the margins of the pseudomorphs toward their center.

The relative content of *rhombic pyroxene*, occurring in the microscopic picture as an interstitial mineral in relation to the olivine pseudomorphs, varies in the different types of peridotitic rocks found in the area. The poikilitic texture appears as a simultaneous extinction of the pyroxene portions even when these are found separately in the interstices of the quantitatively dominant olivine pseudomorphs. On the basis of the optical properties of the pyroxene, as measured from certain unaltered grains, the enstatite content of the rhombic pyroxene is 83—85 %, according to which the mineral is bronzite. In general, the mineral is largely serpentinized.

Among the peridotitic rocks of the zone, in addition to the aforementioned rhombic pyroxene, one also meets with *monoclinic pyroxene*, though regional variations may be observed in that it occurs in the southwestern part of the zone mostly only as an accessory component, whereas toward the northeast it is likely to constitute the fundamental mineral of the peridotites. The monoclinic pyroxene has in general become tremolitized throughout, though the pyroxenic origin of the mineral could be noted on the evidence of the relicts met with here and there. Judging by the optical properties ($c \wedge \gamma = 43°$), the pyroxene should be diopside.

In peridotites the monoclinic pyroxene occurs in relation to the olivine as an interstitial mineral. Only in exceptional cases has it been observed to form idiomorphic crystals. The possibility that the chlorite of the peridotite might be partially monoclinic pyroxene by origin will be considered in more detail later on.

Chlorite constitutes at present a fundamental mineral component of the peridotitic rocks of the area. In relation to the olivine, the chlorite occurs as an interstitial mineral, and in this respect it is comparable to the aforementioned pyroxenes.

On the basis of microscopic observations, at least two different varieties of chlorite are to be found. The quantitatively dominant type of chlorite appears under the microscope as a fine-grained unoriented mass. It is colorless or, in spots, pale yellowish green, in which case the mineral is weakly pleochroic. In polarized light the mineral possesses a peculiarly darkish olivegreen color. The fine-grain of the chlorite prevents determining its optical properties in closer detail. Outwardly very similar chlorite is met with, however, as somewhat coarser-grained, monomineral portions here and there in the metamorphic zone, and the mineral is described more closely in connection with this rock on p. 53. In conjunction with the aforementioned chlorite, especially in the middle of clusters, there often occurs likewise fine-grained though in appearance elongated and oriented chlorite, which has a bright-blue interference color and which could, on the basis of this property, be pennine.

Since it is improbable that chlorite would constitute the primary mineral component of the peridotitic rock, particular attention was paid to the possibility that in conjunction with the chlorite there might occur relictic grains or structural features that might reveal the original mineral. No relict grains could, however, be discovered. Yet, the interstitial chlorite of the

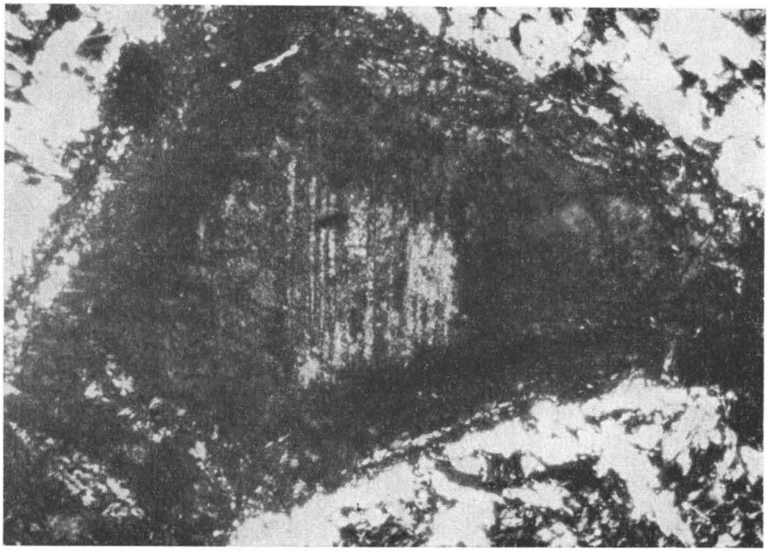


Fig. 6. Lamellar relicts in fine-grained chlorite, occurring as interstitial mineral of olivine pseudomorphs. About 50 ×

peridotites containing the monoclinic pyroxene present in the northeastern part of the zone — chlorite which in this case consists mostly of pennine — exhibits a lamellar appearance of a distinctly relict character (Fig. 6). It is noteworthy that wherever such an interstitial chlorite is linked to a tremolitized interstitial monoclinic pyroxene the contact between these two minerals is not sharp, instead small chlorite particles are to be seen among the amphibole laminae (see Fig. 5). One gets the impression that the original mineral of both secondary minerals is the same, namely monoclinic pyroxene. If this observation were to prove correct, it would mean, from the standpoint of the chloritization process of the pyroxene, the total elimination of the calcium contained by the original mineral. This, in turn, would be in harmony with the observed fact that the tremolite rim appearing at the edges of the olivine pseudomorphs is markedly stronger at the points bordering on the chlorite than at points where the olivine borders on tremolitized interstitial pyroxene, as shown in Fig. 5. This phenomenon would likewise be an indication of an alteration process representing two different, simultaneously observable stages, of which the latter, the chloritization, should be regarded as belonging to a separate, powerful hydrothermal metasomatic process later affecting the zone. The hypothesis advanced would, however, explain the origin of the chlorite only in part. In respect to the peridotitic rocks in the southwestern part of the zone, in which monoclinic

Table 1. Chemical composition of the serpentine peridotite. Anal. H. B. Wiik. (Härme, 1949)

	%	Norms.	
SiO_2	41.01	or	1.28
TiO_2	0.23	ab	1.84
Al_2O_3	5.22	an	12.63
Fe_2O_3	4.76	en	27.58
FeO	5.94	hy	2.64
MnO	0.16	fo	31.25
MgO	29.00	fa	3.29
CaO	4.00	wo	2.78
Na_2O	0.22	mt	6.90
K_2O	0.22	il	0.44
P_2O_5	0.09	ap	0.20
H_2O+	8.56		90.83
H_2O-	0.56	H_2O	9.12
CO_2	0.11		
	100.08		99.95

pyroxene seems to be very rare, the origin of the chlorite remains an open question, and this applies likewise to the origin of the calcium required by the tremolite occurring as a rim around the edges of the olivine pseudomorphs.

The most general accessory minerals of the peridotitic rocks are chromite and biotite. The chromite has primarily concentrated in association with the chlorite and with rhombic pyroxene occurring as an interstitial mineral, where it is present as somewhat deformed octahedrons. The occurrence of chromite crystals in olivine pseudomorphs is exceedingly rare. Biotite is met with here and there as isolated, in some instances fairly large grains with abundant black ore pigment.

In his publication Härme (op. cit.) has presented the analysis (Table 1) of the serpentine peridotite occurring in the exposure situated about half a kilometer to the west from Elijärvi. This spot is directly attached to the area under investigation. Dr. Härme kindly made available to the present writer an analyzed original sample, a thin section from which indicates that in mineral composition the rock represents peridotite typical of the area on the northeastern side. (Olivine relicts are met with in the middle of the dominant olivine pseudomorphs, and a typical tremolite rim occurs around the margins. As an interstitial mineral there occurs rhombic and monoclinic pyroxene, of which the latter has become tremolitized almost throughout. As supplementary minerals there occur some largish biotite grains as well as, somewhat exceeding the average content, accumulations of magnetic ore. Chromite grains are not met with in thin section.)

In addition to the aforedescribed peridotitic rocks, olivine has been found in the vicinity of Elijärvi, as an intercalation in the ore, on the foot wall side of the ore belt.[1] The rock consists of serpentine and olivine, the former occurring as an unoriented mass, in which the olivine is present in the form of small, round grains. The simultaneous extinction in groups of the olivine grains in polarized light and the figures formed by chromite present in accessory amounts indicate the rock to have originally been relatively coarse-grained dunite. The higher interference color of the olivine points to its larger faialite content in comparison with the olivines of the aforementioned peridotitic rocks.

As the degree of metamorphism increases, *serpentine* becomes the dominant mineral of the peridotitic rocks. Rocks dominated by serpentine occur as harder intercalations in the strongly metamorphosed zone of the area. Although the increasing serpentinization cannot be followed as a gradual alteration process in a transverse direction in relation to the zone, it is nevertheless possible, on the basis of samples taken from various points, to obtain a series in which, starting with the aforedescribed olivine-bearing rocks, the rocks gradually become richer in serpentine. The next degree after the aforementioned peridotites is the total serpentinization of the olivine content of the rock. The rhombic pyroxene has likewise become throughout transformed into fine-grained, oriented serpentine. The relictic structural feature deriving from the different mode of occurrence of serpentine easily reveals, on the one hand, the originally olivinic and, on the other, the bronzitic portions. Tremolite, to which we shall return in the following, is the prevalent mineral component, along with serpentine, of the majority of the metamorphosed rocks of peridotitic origin. Likewise, the chlorite occurring as an interstitial mineral, referred to already in connection with the less metamorphosed peridotites, remains unaltered in considerably metamorphosed rocks, thereby in part also exhibiting the texture of the original rock.

Relatively common in the metamorphic zone are, furthermore, serpentine rocks, in which other mineral components occur only in accessory amounts. In numerous instances their peridotitic origin can be noted from the relictic structural feature reflecting the different appearance of serpentine (Fig. 7). However, in a large number of such serpentinites, no such structural features can any longer be seen, but the entire rock consists throughout of homogeneous, unoriented serpentine. Considering their origin, one is inclined to identify them as alteration products of dunites.

---

[1] It is, however, most probable that the prevalence of rocks containing olivine is greater than that observed. In the examinations of drillcores carried out in routine fashion, such rocks, being almost impossible to identify macroscopically, could easily have passed unnoticed.

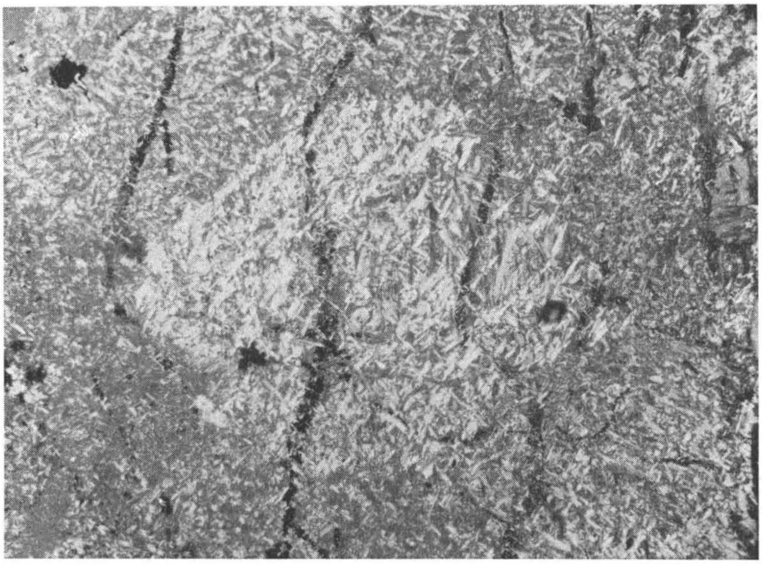


Fig. 7. Serpentine rock in which parts formerly occupied by olivine grains are observable as coarser-grained areas. About 35 ×

Table 2 presents the result of an analysis of a serpentine rock containing as accessories chromite and carbonate, which to a small degree occurs nearly without exception in predominantly serpentine rocks.

In connection with the foregoing reference (p. 43) to the metamorphic alteration of olivine, mention was made of the rim consisting of *tremolite* laminae, which is quite common along the edges of olivine pseudomorphs. Mention was also made of the apparent causal connection prevailing between the tremolite rim and the chlorite occurring as an interstitial mineral, which must be interpreted in all probability in the light that the chlorite in question is an alteration product of a calciumbearing mineral, the calcium of which metasomatically caused the formation of tremolite in the marginal zone of the olivine. On the other hand, as became evident in reference to the monoclinic pyroxene (p. 44), this is seen to have metamorphosed directly into tremolite. In the cases where the monoclinic pyroxene and the olivine have bordered on each other, the tremolite laminae present as an alteration product of pyroxene may be observed to continue into the olivine pseudomorphs and to form part of the tremolite rim, as shown in Fig. 1. The optical properties of tremolite are in all cases, however, the same: $c \wedge \gamma = 18°$, $\gamma—\alpha = 0.027$, 2 V approx. 90°. As for the process of tremolitization as such, it probably belongs to a very early stage of the metamorphic history. It apparently coincides with the initial stage of serpentinization, in part possibly

Table 2. Chemical composition of the serpentine rock.
Anal. Irja Huhta and A. Löfgren (Ni, Pt, Rh, Pd).

	%	1 000 × mol. prop.	Norms	
SiO_2	37.97	633	$FeO. Cr_2O_3$	1.40
TiO_2	0.00		$CaCO_3$	3.20
Al_2O_3	1.68	17	H_2O	11.09
Fe_2O_3	5.78	36	ab	1.57
FeO	6.15	86	an	3.89
MnO	0.05		en	29.70
MgO	31.14	779	hy	2.24
CaO	3.71	66	fo	33.74
Na_2O	0.21	3	fa	2.65
K_2O	0.05		wo	2.32
P_2O_5	0.02		mt	8.35
CO_2	1.38	32		
H_2O+	9.30			100.15
H_2O-	1.79			
Cr_2O_3	0.97	7	Pt	0.03 g/t
NiO	0.15		Rh	0.01 »
	100.35		Pd	0.01 »

antedating it, as in certain cases the olivine pseudomorphs are likely to exhibit a tremolite rim directly around the olivine grains.

The mineral association serpentine-tremolite (+chlorite) constitutes quite a common rock type in the metamorphic zone. The original structure of the rock is thus quite often reflected by the aforedescribed outward features of the tremolite. One does, however, come across serpentine-tremolite rocks in which such a structure is not evident and in which long tremolite laminae are scattered over an unoriented serpentine grain base.

Talc and *carbonate* are extremely common mineral components of rocks of peridotitic origin in the metamorphosed zone. Along with serpentine and tremolite as well as with the primary mineral components of the rock, they are likely to bring about the most varying mineral compositions.

Talc occurs principally as an alteration product of serpentine. In serpentine rock, talc forms, in its initial stage, fine-grained accumulations scattered here and there. Proceeding farther in the metamorphic process, the talc occurs as the dominant component of the rock. In such cases it is a common feature for the finer-grained serpentine portions (former bronzitic portions) to be more talcose than the coarser-grained, originally olivinic portions, which are often likely to occur as ideal olivine pseudomorphs (Fig. 8). In the strongly metamorphosed zone, however, there occur quite abundantly also totally talcose rocks, in which features suggesting the ori-

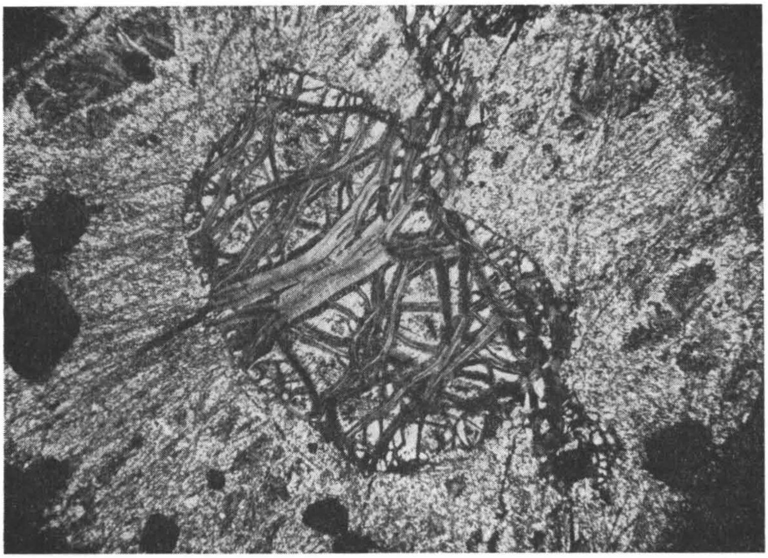


Fig. 8. Olivine pseudomorph on base of fine-grained serpentine-talc mass. About 35 ×

gin of the rock can by now scarcely be detected. Nevertheless, in cases where chromite occurs as an abundant accessory of the talcose rock, these grains might form figures appearing to reflect the shapes of the primary minerals, specifically olivine (Fig. 9).

The occurrence of carbonate is closely associated with that of talc, although carbonate is also met with in small amounts in non-talcose types of rock. Carbonate occurs in conjunction with talc as either a fine-grained or coarser aggregate, as small roundish grains or as rather large crystals. In general, the amount of carbonate is less than that of talc. An X-ray determination of the carbonate contained in talcose rock proved it to be magnesite.

PYROXENITE

This rock type is not met with in the area in its original composition, either. The pyroxenitic origin of the rock has, however, been established on the basis of its mineral relicts and relict structures.

In the vicinity of Elijärvi there occurs, as revealed by diamond drillings, even-grained, rather coarse (diameter of grain approx. 3 mm), greenish-gray rock, which is spread over a fairly large area. Under the micro-

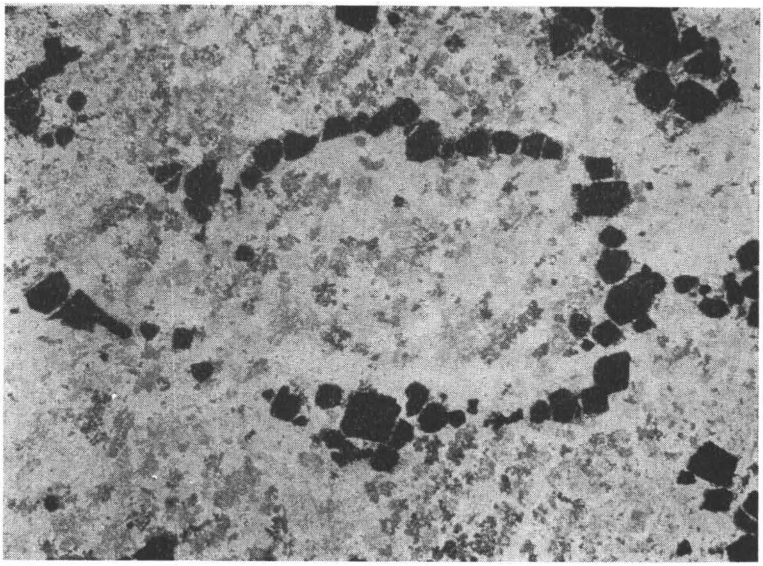


Fig. 9. Talc-carbonate rock in which chromite crystal figure indicates location of former olivine grain. About 20 ×

scope, the grains appear to be practically hexagonal, elongated, crystallized pseudomorphs, the present mineral composition of which consists mostly of tremolite. Amphibole occurs most generally as narrow laminae, arranged to some extent parallel to the long side of the pseudomorphs (Fig. 10). It may also form larger grains, even to the extent that an entire pseudomorph is likely to consist of but a single tremolite grain. In cases of the latter kind, pyroxene grains appearing as small relicts may be seen distributed here and there in the middle of the amphibole. In certain amphibole grains relict zoning typical of pyroxene has also been noted. It was possible to measure the angle of extinction of the pyroxene relicts: $c \wedge \gamma$ approx. 45°, according to which the mineral might be diopside. The optical properties of the tremolite are as follows: $c \wedge \gamma = 18°$, $\gamma - \alpha = 0.027$, 2 V approx. 90°.

Fine-grained chlorite occurs as an interstitial mineral of the pseudomorphs. Chlorite is likely to be present, furthermore, within the pseudomorphs, in conjunction with the lamellar tremolite. The most common accessory mineral is mica, which is consistently blackened by the abundant ore pigment. Only sporadically does the typical pyroxene contain serpentine as well as, probably, its alteration product, talc. Ore grains, specifically those of chromite, are scarce.

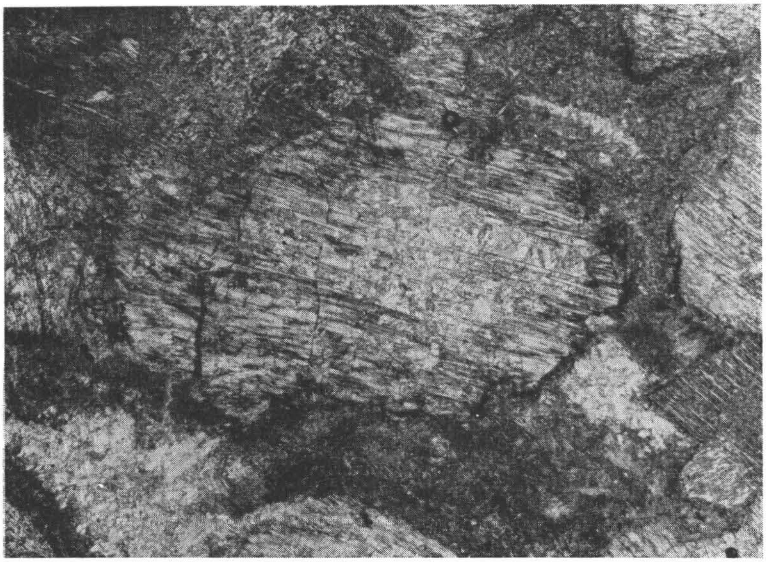


Fig. 10. Originally pyroxenite, in which the pyroxene has become tremolitized throughout. About 25 ×

The chemical composition of the tremolite rock of the Elijärvi area is as follows:

Table 3. Chemical composition of the tremolite rock. Anal. Irja Huhta and A. Löfgren (Ni, Pt, Rh, Pd).

	%	1 000 × mol. prop.	Norms.	
SiO_2	50.12	835	$FeO. Cr_2O_3$	0.50
TiO_2	0.29	4	$CaCO_3$	1.10
Al_2O_3	4.22	41	H_2O	3.70
Fe_2O_3	1.25	8	or	5.00
FeO	7.01	97	ab	6.81
MnO	0.21	3	an	5.28
MgO	21.19	530	en	38.00
CaO	9.63	171	hy	10.43
Na_2O	0.76	13	fo	11.90
K_2O	0.76	9	fa	0.61
P_2O_5	0.02		wo	16.36
CO_2	0.52	11	mt	1.86
H_2O+	3.64			100.16
H_2O-	0.06			
Cr_2O_3	0.36	3		
NiO	0.04		Pt	0.12 g/t
			Rh	0.01 »
	100.08		Pd	0.02 »

One must regard as a link between the olivine-bearing peridotites and the foregoing pyroxenites the rocks occurring in the northeastern area in which, besides the prevailing pyroxene, there is a scattering of roundish flecks composed of serpentine which, to judge by their mode of occurrence, most probably represent olivine pseudomorphs.

GABBRO

In one drillhole (R 11) in the southwestern part of the mineralized zone, the country rock in the hanging wall side of the ore contains plagioclase-hornblende rock whose genetic kinship to the ultrabasic rock types of the zone remains, for the time being, unclear. The said rock occurs in the drillhole over a distance of about ten meters. It is not met with in the neighboring drillholes, situated 100 meters away on each side.

The rock is of medium coarseness, and in structure it is ophitic-hypidiomorphic. The principal components are plagioclase and hornblende. The hornblende is for the most part chloritized. The feldspar is relatively unaltered and it is close to andesine in composition. As an abundant accessory, the rock contains dark, fine-grained accumulations closely resembling leucoxene. In thin section narrow, intersecting fissure veins consisting of fine-grained chlorite may be found.

CHLORITE ROCK

The drillcore material includes fine-grained chlorite rock, which occurs quite generally in the metamorphic zone, in association with originally peridotitic varieties of rock. By and large, the length of occurrence of this rock in drillcores is only a few meters, in many instances only a few dozen centimeters.

Especial attention was drawn to this chlorite because, insofar as the eye could tell, it resembles the chlorite (p. 44) met with as an intermediary mineral of the peridotitic rocks and because the same chlorite, apparently, occurs in part quite commonly as a parent mineral of richer ores (p. 57).

Under the microscope, the rock is seen to be composed almost exclusively of unoriented, flaky chlorite. The only other mineral component observed is rutile, which occurs as occasional tiny grains. The chlorite is either colorless or pale yellowish green, in which case the mineral is weakly pleochroic. The interference color is a peculiarly dark olive green. The following optical properties of the mineral have been determined: longitudinal direc-

Table 4. Chemical composition of the chlorite rock.
Anal. Irja Huhta

	%	1 000 × mol. prop.	At. n.			
SiO_2	30.92	516	Si	516	3 × 172	4 × 172
TiO_2	0.23					
Al_2O_3	15.28		Al	300	172	
Fe_2O_3	1.92	150			128	
FeO	9.80	12	Fe^{+3} ...			
MnO	0.14	136	Fe^{+2} ...	136		
MgO	29.28	2	Mn	2		
CaO	0.11	726	Mg	726		
Na_2O	0.0					
K_2O	0.0					
P_2O_5	0.08					
H_2O+	12.37	687	OH	1374	8 × 172	
H_2O-	0.08					
	100.21					

tion —, optical nature +, angle of axis 15—20°, coefficient of refraction approx. 1.593, double refraction below 0.003. The pleochroic haloes observed around the roundish rutile grains appear in polarized light as bright blue, round specks.

The result of the chemical analysis of the chlorite rock is presented in Table 4.

When the small amount of TiO_2 appearing in the analysis is separated into microscopically observed rutile, the remainder represents the chemical composition of chlorite, from which the following mineral formula can be computed:

$$Mg_{4,22}\ Fe^{+2}_{0,79}\ Fe^{+3}_{0,14}\ Al_{0,74}\ (Si_{3,00}\ Al_{1,00})\ O_{10}\ (OH)_8.$$

In the diagram drawn up by Brindley & Gillery (1956) on the basis of Winchell's chlorite classification to depict the distribution of the different species, the chlorite corresponding to the above in composition happens to fall exactly on the borderline of clinochlore and pennine near the areas of rumptite and delessite.

The X-ray determination of the rock gave a typical chlorite pattern. It was hoped, in this connection, that the X-ray might reveal features suggesting the crystal structure of the original mineral.

CHROMITE-PERIDOTITE AND CHROMIUM ORE

The occurrence of the chromite mineral in the ore zone is, on the whole, quite monotonous. In general, the chromite appears to be fairly even-

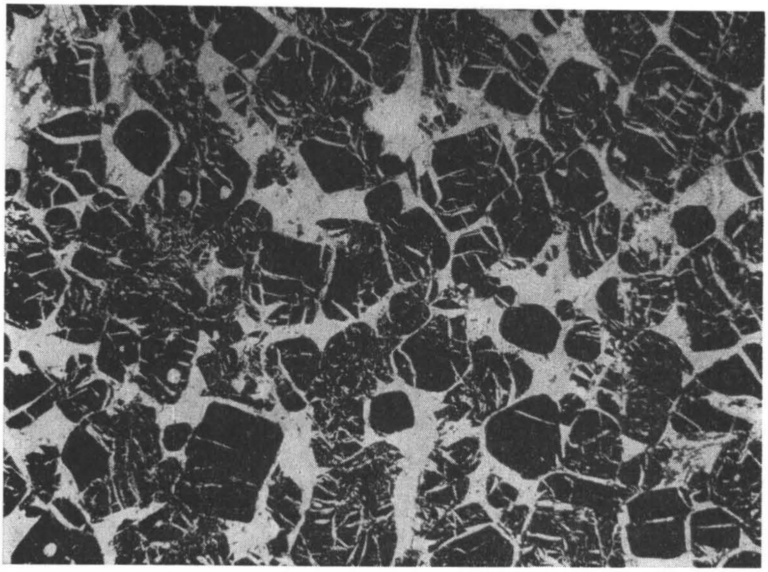


Fig. 11. Broken chromite grains. About 20 ×

grained, the average grain size being a few tenths of a millimeter. In certain coarser-grained portions of the ore, the grain size is likely to approach one millimeter in diameter. In thin sections, the chromite appears as rather idiomorphic octahedrons. Fracture cracks running through the mineral are, however, relatively common. In some cases, far-gone fractures divide the mineral into several fragments (Fig. 11). At the contact of the hanging wall of the ore, at the West End ore zone, the ore grains are liable to be crushed wholly into fine fragments. In many cases, the chromite contains round inclusions, which generally consist of the rock material prevailing around the chromite grains. The chromite crystals consistently occur as separate grains, mostly distributed at even intervals. In one instance (drillhole R 14) has the linkage of grains been observed as a chain structure (Sampson 1932) made up of several crystals (Fig. 12). In the instance cited there is also the unique feature of the chromite being divided into two grain sizes.

In penetrating light, the chromite is generally opaque, but in certain instances it has a reddish brown appearance. The analytical results in Table 5 are of two separated chromites, the first representing a homogeneous, high-percentage ore type and the latter a poorer, spotted one.

The ore belt is contained *in toto* within a strongly metamorphosed zone. In the determination of the original silicate minerals contained in the rocks, one can in this respect largely follow the same lines as in the case of the

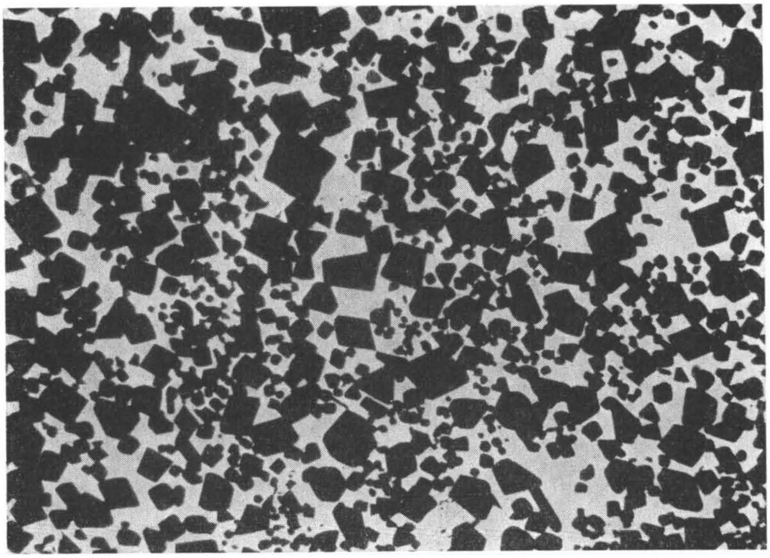


Fig. 12. Chromite showing chain structure. Note two grain sizes of chromite. About 10 ×

aforedescribed oreless rocks. In spite of the multiplicity of mineral compositions likely to occur in the parent rock of the ore, the chromite-rich types of rock can nevertheless be classified according to the following main combinations:

chromite — serpentine
» — talc — carbonate
» — chlorite

It is noteworthy that, although tremolite plays an important part in the country rock of the ore zone, its occurrence in the ore proper is limited.

The association *chromite-serpentine* does not belong among the most common ore rocks and this association does not include the very highest percentage ore contents. During the initial stage, as already pointed out, the chromite grains are situated in the interstices of the olivine pseudomorphs of the peridotitic rock. (Incidentally, it should be noted that the fine-grained chlorite often tends to appear wholly isothropic around the ore grains.) The feature mentioned appears also in rocks in which the quantity of chromite is essential. The chromite accordingly forms a netlike impregnation structure occurring throughout the rock (cf. Fig. 13). When the chromite content becomes dominant, the olivine pseudomorphs appear as oreless specks on the homogeneous chromite impregnation base (cf. Fig. 14). The last-mentioned

Table 5. Chemical composition of two separated chromites.

Anal. A. Heikkinen.

	I	II
SiO_2	1.64	0.48
TiO_2	0.51	0.73
Al_2O_3	16.30	18.20
Fe_2O_3	4.28	5.20
FeO	22.31	25.83
MnO	0.30	0.31
MgO	8.89	6.58
CaO	0.05	0.05
H_2O+	0.63	0.21
H_2O-	0.00	0.00
Cr_2O_3	45.67	42.42
	100.58	100.01
	Cr/Fe = 1.54	Cr/Fe = 1.22

feature has led to the adoption of the term »spotted ore.» In certain cases, however, the chromite is likely also to occur rather densely, as an evenly distributed impregnation in rock with serpentine base.

The most common accessory mineral in the chromite-serpentine rocks is the aforementioned chlorite. Tremolite may occur in varying amounts in olivine pseudomorphs.

The *chromite-talc-carbonate* rock is an alteration product of the afore-described chromite-serpentine rock and it is thus analogous to it in many respects. As in the case of serpentine rock, chromite grains are likely to form figures also on a talc base that reflect the former olivine grains (Fig. 9). One likewise meets with netlike impregnations (Fig. 13) and spotted ore (Fig. 14) formed by chromite on a talc base; moreover, an even chromite impregnation may also occur on a talc base. Carbonate occurs rather commonly in connection with talc. The most common accessory mineral is chlorite, which, starting with olivine-bearing peridotites seems to be capable of quite stubbornly resisting metamorphic change.

The association *chromite-chlorite* is the most noteworthy from the standpoint of chromium ore, inasmuch as it represents the highest chromium contents and quantitatively also accounts for a prominent portion of the ore zone.

Chromite occurs on the chlorite base as an evenly distributed impregnation. Macroscopically, the rock appears to be pseudo-coarse-grained and poikilitic insofar as the chloritic parent rock forms roundish, light-reflecting specks measuring 1—1.5 cm in diameter in which small chromite grains are present as densely packed inclusions. Owing to the partially strong

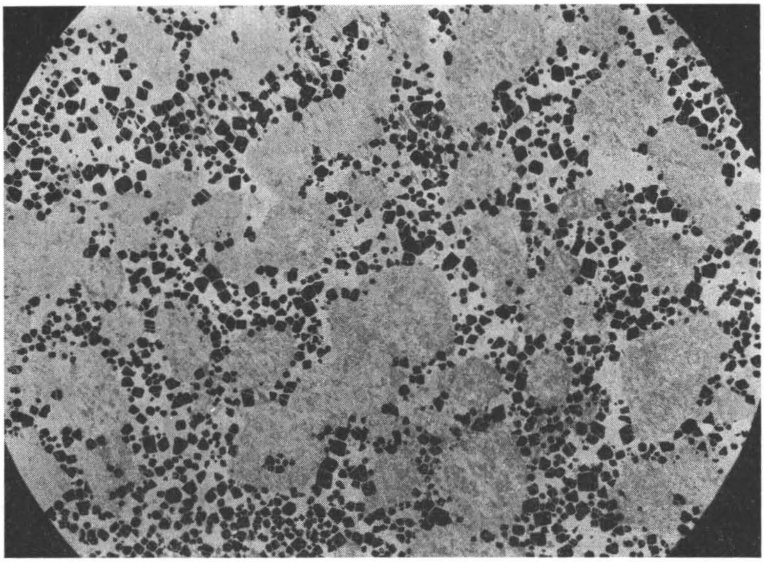


Fig. 13. Netlike chromite impregnation. Oreless, roundish areas (gray in picture) are olivine pseudomorphs consisting of talc and carbonate. Pale background of chromite grains is fine-grained chlorite. About 5 ×

violet color of the chlorite, the entire rock has a distinctly violet tinge. By using a binocular microscope, it was possible to separate from the rock a small amount of violet chlorite, and the spectrum analysis made from it gave an unmistakably positive chromium indication, which presupposes a content of several per cent Cr_2O_3.

In thin section one may observe that in addition to the aforementioned chromium chlorite[1], the rock almost invariably contains also the flaky chlorite of an olive-green interference color mentioned several times in the foregoing. As for the proportional content of the two chlorites, the chromium chlorite is quantitatively dominant, forming in thin section fairly large, clearly bounded areas in which the mineral occurs as elongated, oriented laminae. Under the microscope, the chromium chlorite is colorless. In polarized light it is an intense blue, tinged with violet. Oriented narrow tremolite laminae are likely to occur here and there in conjunction with the chromium chlorite. In typical chromite-chlorite ore rock, chromite octahedrons occur as a dense impregnation on the chlorite base without any appreciable difference appearing in this respect between the two chlorites.

---

[1] According to Lapham's recommendation (1958), the general designation »chromiun chlorite» is applied to »pink to rose-violet chlorite», for the term »kämmererite», which is often used, should be restricted to apply to »octahedral chromium chlorite» with more than 2 % Cr_2O_3.

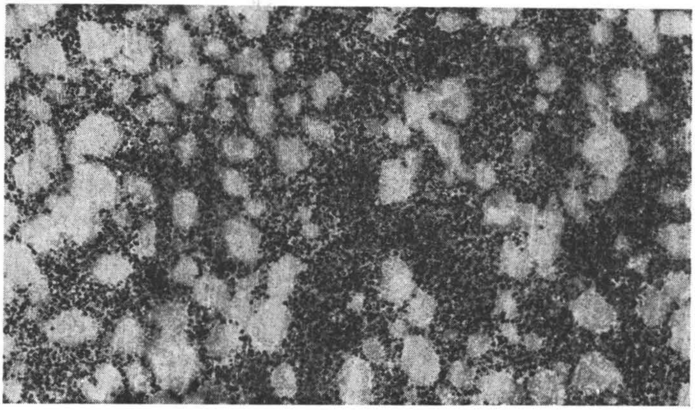


Fig. 14. Spotted chromium ore. White specks are olivine pseudomorphs now consisting of talc. About 2 ×

Seeing the mode of occurrence of the chromium chlorite, it is evident that it is the alteration product of quite a coarse-grained mineral, although no conclusive proof of the original mineral has been obtained. In this connection, however, one is reminded of the close similarity prevailing between the chromium ore type dealt with here and the chromitite of Bushveld described by Sampson (1932), which constitutes the richest ore portions there[1]. The African chromitite contains large bronzite crystals, which poikilitically envelope idiomorphic chromite grains.

ALBITE ROCK

As mentioned previously, on the southeastern side of the mineralized zone there occurs a probably continuous wall of albite rock, the contact of which can be interpreted from the geophysical profiles. This rock has been reached by numerous drillholes.

Macroscopically, the albite rock is coarse, relatively even-grained, pale of color or reddish in spots. Near the contact of the basic rock, there occur in places darker portions, caused by the chlorite content. Under the microscope, the feldspar appears as large grains lacking distinct crystal forms. The mineral is blurred by an abudant saussuritic alteration product. Three X-ray determinations (basis of determination: J. V. Smith, Min. Mag., Vol. 31, pp. 47—68, 1956) yielded the following An-contents: 2 %,

---

[1] The resemblance came to the fore also in discussions with Prof. Sampson when he visited Finland after the International Geological Congress held in Copenhagen, as well as in comparing samples which he was kind enough to the send to the present author later.

Table 6. Chemical composition of the albite rock.
Anal. Irja Huhta and A. Löfgren (Pt, Rh, Pd).

	%	1 000 × mol. prop.	Norms.	
SiO_2	59.84	998	$CaCO_3$	6.60
TiO_2	0.01		H_2O	0.96
Al_2O_3	21.49	211	Q	5.70
Fe_2O_3	0.38	3	C	5.51
FeO	0.74	10	or	5.00
MnO	0.04		ab	69.17
MgO	0.66	17	an	4.45
CaO	4.61	82	en	1.70
Na_2O	8.22	132	hy	0.92
K_2O	0.78	9	mt	0.70
P_2O_5	0.00			100.71
CO_2	2.88	66		
H_2O+	0.88			
H_2O-	0.08		Pt	<0.01 g/t
Cr_2O_3	0.00		Rh	<0.01 »
	100.61		Pd	<0.01 »

0.5 % and 0 %. The most common extra component, which in places occurs in more than accessory amounts, is carbonate, and it is met with in the interstices and fracture cracks of feldspar grains. Quartz and chlorite are likely to be present in the rock, furthermore, in accessory amounts. An analysis made of albite rock is presented in Table 6.

The relation between the albite rock on the southeastern side and the portions of albite rock met with in conjunction with peridotitic rocks and even in the ore zone, and which are found in drillcores in lengths measuring between 0.5 and 10 meters, is not clear. The latter differ from the former particularly by being finer of grain. Neither do alteration products occur in the feldspar. The composition of the feldspar is comparable to the preceding, three X-ray determinations having given the following An-contents: 0 %, 1 % and 3 %. As accessory components, the fine-grained albite rock includes sphene and tremolite amphibole, which forms long, laminated crystals.

Owing to lack of evidence, it is not possible to probe deeper into the problem of the occurrence of albite rock. In considering the origin of the rock, two possibilities deserve to be taken into account. The rock might be regarded as a product of albitization undergone by a feldspar rock originally richer in anorthite. In the event that an original anorthosite were in question, one would have to regard the rock as being part of the region's ultrabasic rock complex and, accordingly, comparable to the anorthosites situated on the northwestern side of the peridotites (Härme, op. cit.). However, in composition they have very great differences, which, taking also the metamorphosis into account, are difficult to interpret (cf. anal. ,Härme, op. cit.). Another possibility, which would, perhaps, also be easier to understand, is that the albite rock is associated with the southeasterly country rock of the ultrabasic formation, the migmatite granite, which had metamorphically suffered from the effect of the intrusion.

At the contact of the albite rock and the ultrabasic rock — on the side of the peridotitic rock — there is a zone measuring a few meters in thickness and occurring quite regularly, which consists of the mineral association chlorite-carbonate-plagioclase. The plagioclase, which is oligoclase in composition, occurs as rounded grains in conjunction with the chlorite. The carbonate forms rather large, relatively idiomorphic crystals.

DISCUSSION

Thanks to their lower degree of metamorphism, the olivine-bearing rocks at the northwestern margin of the mineralized zone give the most certain picture of the original mineral composition of the peridotites. The essential mineral components have been olivine and rhombic and monoclinic pyroxene, the proportionate contents of which vary in such a way that it is possible, on the basis of this variation, to designate the following peridotitic types of rock: dunite (olivine), harzburgite (olivine, rhombic pyroxene), lherzonite (olivine, rhombic and monoclinic pyroxene). With the exception of dunite, the aforementioned peridotites contain quite commonly and even as a fundamental component chlorite as well, the origin of which is not altogether clear. The most common accessory mineral is chromite. The crystallization sequence of the minerals is as follows: olivine — chromite — pyroxene.

In the strongly metamorphosed zone, the silicate minerals of the original rock have become wholly altered. Nevertheless, it has been possible to determine the original mineral composition of the rocks to a high degree of probability on the basis of the existing structural features, notably the olivine pseudomorphs. In this respect, nothing has come to the fore to refute the conclusion that the aforementioned peridotites are not also original rocks belonging to the metamorphosed zone.

Besides peridotites, the metamorphosed zone — particularly the northeastern part of it — contains pyroxenites, by now tremolite rock, as well as, in smaller amounts, plagioclase-bearing rocks of the gabbro class.

Associated with the metamorphic zone formed by the aforementioned, originally ultrabasic rocks is a continuous chromite-rich zone which parallels the general trend of the ultrabasic formation as a whole. Longitudinally, the ore zone curves gently and varies considerably in thickness.

Petrographically the ore zone is quite unified throughout its length, and in this respect it differs from the complex of ultrabasic rock outside the zone. As pointed out, the strongest concentration of chromite is associated across the entire length of the ore zone with chlorite. The chlorite occurs in two varieties, one of which, chromium-chlorite, resembles an alteration product in its mode of occurrence suggesting that the primary mineral could possibly have been rhombic pyroxene. No rock like this parent rock of the ore has been met with outside the ore zone.

In the crystallization process, the chromite can be placed fully on a par with the other crystallizing minerals; in this respect, no signs of movement resulting, e.g., from the mineral's higher specific weight, have been detected.

Accordingly, it appears to the present author most likely that there is no direct genetic connection between the ore zone and its ultrabasic country rock. In other words, it is scarcely probable that the enrichment of the chromite into the ore zone had taken place *in situ* from the surrounding ultrabasic rock complex.

The geological evolution could, accordingly, be outlined as follows:

One may assume that at a very early stage, before the intrusion, in the primary »magma chamber,» there took place a differentiation that led to the separation of the portion of the magma rich in chromite.

The main portion of the divided primary magma, corresponding in composition to ossypitic gabbro, was intruded like a sill underneath the supracrustal rocks and there differentiated into two, anorthositic and peridotitic main components (Härme, 1949).

In the peridotitic component, one might, in addition, observe a differentiation into various classes of peridotitic rocks, with which are associated pyroxenitic rocks as well.

Evidently, as early as the crystallization stage, there had started in the ultrabasic rocks a process of metamorphic (autometamorphic) change, manifested principally through the partial serpentinization of the olivine as well as through the formation of tremolite, mostly at the expense of monoclinic pyroxene.

Following the differentiation, the ultrabasic rock complex was intruded by the chromium-rich magma portion that had separated from the primary magma. Whether this penetration occurred while the sill was still in its original horizontal position or later, when it had turned into a vertical position (Härme, 1949), is not clear. Since the point in the ore zone involved does not seem to represent any original geological boundary zone, the reason for the opening of the space required by the intrusion at precisely the point of the present ore zone is not clear either.

The intrusion of the chromium-rich magma portion is assumed to have taken place over a long period of time, during which a change in the composition of the magma toward increasing richness in the chromium content went on. At first, a relative abundance of olivine crystallized, but gradually it diminished in quantity so that at a later stage the chromite emerged as the dominant crystallization product. After the crystallization of the chromite, the residual solution in both the olivine-producing and the chromite-rich portions poikilitically enveloped the chromite crystals and also, in part, the olivine while undergoing crystallization. Into what mineral this latest crystallization product, now appearing as chlorite, had crystallized in the beginning is still largely a matter of conjecture. The chromium chlorite might have been rhombic pyroxene, in which case the ore type would be comparable to chromitite (Bushvelt, Sampson, op. cit.).

After the crystallization of the ore zone, the area situated in the direction of the zone underwent a conspicuous metamorphic change caused by hydrothermal solutions. This process which affected both the ore zone and its country rock to a breadth of about 50 to 150 meters on both sides, almost totally altered the original mineral composition of the rocks. Only the chromite underwent this phase without any noteworthy change. The minerals of the former ultrabasic rocks are represented at the final stage principally by talc, chlorite and carbonate. The fact that the metamorphic zone follows the ore zone closely indicates that the metamorphosis has a causal relationship to the ore zone. However, in this respect two alternatives are involved: there is the possibility that the hydrothermal solutions that brought about the metamorphosis had followed the ore intrusion more or less directly, on the other hand, this may have taken place only subsequently, in connection with the orogenic movements in which, on account of the physical differences prevailing between the ore and the country rock, expressly the position of the ore zone might well be critical. The fact that at the contact of the ore and the country rock, there occurs a shear zone, noticeable on both ore and country rock sides, indicates that movements took place also after the intrusion of the ore.

SUPPLEMENTARY NOTE

Subsequent to the completion of the aforegoing article the author was given the opportunity to see the exploration work done by the Outokumpu Company in the Elijärvi region (close to the drillhole R 18), where rock has been laid bare for a distance of some 80 meters across the ore zone. On the walls of the pit many such features could be seen as were not observable in the drillcores.

Fig. 15. The northeastern wall of the open pit. In the center a big barren fragment.

Between the hanging wall contact of the ore and the side rock, which in this case is altered pyroxenite, a narrow shearing zone could be seen. A banded structure, which in drillcores has been observed in only a few and somewhat doubtful cases, is to be found in a width of several meters on the hanging wall side against the side rock. The direction of the structure is parallel to the direction of the contact between the ore zone and the side rock. The thickness of the chromite bands varies between a few millimeters and a couple of centimeters. The oreless intercalations are generally somewhat greater in thickness. The boundary between the chromite bands and the oreless intercalations may alternatively show gradual change on one or on both sides. In addition to the bands of the thickness referred to above, there are, however, also thicker (10—20 cm) layers composed of compact chromite ore. The boundaries of these are generally sharp.

When the banded ore-bearing rock on the hanging wall side is not included, the actual ore zone is characterized by very heavy brecciation. As a general feature it may be stated that ore poorer in chromite content is successively brecciated by ore of higher degree. The latest brecciating component is represented by high grade compact ore, the chromite-chlorite ore. In the breccia ore-less country rock may be found as fragments, as well as fragments showing the banded structure and, further, as fragments of the spotted ore type. The size of the fragments varies from a couple of centimeters to several meters (Fig. 15).

As a special feature in compact ore should be mentioned the occasional concentration of more coarse grained chromite into aggregates 3—5 cm in diameter. On the weathered rock surface these aggregates appear as raised knobs.

The assumption presented in this study to the effect that the ore had intruded into the ultrabasic rock complex, is, in the opinion of the author, strengthened by the observations made on the outcrop, with the additional feature, however, that heavy brecciation appears to characterize the different successive phases of the intrusion, and that in the intruded ore portions signs of an activity may be observed, which has caused an inhomogeneity in the chromite-bearing intruded mass.

ACKNOWLEDGEMENTS

The author has received help in the different branches of the investigation from the following specialists: Mr. A. Vorma, Phil. Lic., has carried out the X-ray powder analysis of the minerals as well as computed the mineral formula of the chlorite described on p. 54. Mr. A. Löfgren, Mag. Phil., has by means of a spectroscope determined the chromium content of the separated chromium chlorite. The optical properties of silicates have been determined by Mrs. Marjatta Virkkunen, Mag. Phil. The microscopic photographs have been taken by Mr. E. Halme. The manuscript has been translated into English by Mr. P. Sjöblom, Mag. Phil.

REFERENCES

Brindley, G. W. and Gillery, F. H. (1956) X-ray identification of chlorite species. Amer. Mineralogist 41, p. 169—186.

Dunham, K. C. and others (1958) The chromiferous ultrabasic rocks of eastern Sierra Leone. Geol. Surv. Dept. Sierra Leone, Short Paper N:o 4.

Du Rietz, Torsten (1955) The content of chromium and nickel in the Caledonian ultrabasic rocks of Sweden. Geol. Fören. i Stockholm Förh. 78, p. 233—300.

Härme, Mauno (1949) On the stratigraphical and structural geology of the Kemi area, northern Finland. Bull. Com. géol. Finlande 147.

Hess, H. H. (1960) Stillwater igneous complex, Montana. Geol. Soc. America, Memoir 80.

Hiessleitner, Gustav (1951) Serpentin- und Chromerz-Geologie der Balkanhalbinsel. Jb. Geol. Bundesanstalt, Wien. Sonderband 1.

Lapham, Davis M. (1958) Structural and chemical variation in chromium chlorite. Amer. Mineralogist 43, p. 921—956.

Sampson, Edward (1932) Magmatic chromite deposits in southern Africa. Econ. Geol. 27, p. 113—144.

Schneiderhöhn, Hans (1958) Die Erzlagerstätten der Erde, Band I. Die Erzlagerstätten der Frühkristallisation. Stuttgart.

Smith, Charles (1953) Origin of the chromite deposits of the Bay of Islands igneous complex, western Newfoundland. Econ. Geol. 48 p. 408—415.

Zealley, A. E. V. (1914, 1915) The geology of the chromite deposits of Selukwe, Rhodesia. Trans. Geol. Soc. South Africa 17, p. 60—74.

3

ON THE CHROMITES OF THE KEMI DEPOSITS, NORTH FINLAND

BY

O. VAASJOKI AND AULIS HEIKKINEN

ABSTRACT

The paper deals with results obtained by detailed ore microscopic and analytical investigations of the chromites from the Kemi deposits. The main composition of the chromites investigated corresponds to that of alumoberezowskite. In places the chromite is characterized by abundant alteration bands, the composition of which has been studied by means of electronic X-ray microanalyzer. Besides the altered bands exsolution products have been described. The exsolution products most probably comprise titaniferous material corresponding to ilmenite or ulvöspinel in composition.

Based on the chemical properties on the chromites and the paragenic succession in the ore studied some comments on the temperatures of the crystallization of the Kemi chromite and on the origin of the deposits are presented.

CONTENTS

INTRODUCTION

The exploration carried out in 1959—60 by the Geological Survey of Finland have revealed chromite deposits of economic dimensions in vicinity of the city of Kemi in northern Finland. According to the explanatory text for the geological map of Finland, sheet Oulu — Tornio (Enkovaara *et al.*, 1953), a zone of Precambrian subsilicic rocks measuring 2—3 km in width and 20 km in length runs approximately in the direction ENE from the city of Kemi. The formation seems to be composed mainly of coarse grained, ossipitic gabbro, including zones of anorthosite rocks, gabbro-peridotite and serpentine-peridotites. Owing to the obviously gradual change from one rock type to another, the suite of subsilicic rocks under consideration has been explained as a representative of a differentation series. Subsequently ultrabasic rocks forming the host for the chromite deposits belong to the previously known zones of the subsilicic segregations, although the widely distributed and, in places, heavy overburden has impeded a detailed geological mapping of the basement rocks, especially in the areas now of utmost ore geological interest.

From the very beginning, the authors have participated in the laboratory investigations concerning the new prospect. Accordingly, the emphasis in this paper is on aspects developed from the said basis. Undoubtedly, the results as here presented are still preliminary in character. The mining and exploration in the Kemi area will surely bring to light new material and at some more advanced stage of the research, additional phenomena as regards the properties of the ores under consideration may well be indicated. However, the results already obtained, while of general interest for the researchers of the chromium ores, are worth summarizing. Especially the alteration products and other microstructures observed in the chromite of the Kemi deposits offer fascinating instances augmenting the previous knowledge of analogous phenomena gained from several other chromite-bearing occurrences.

The first author stands for the ore microscopic study and the text whereas the second author is responsible for the analytical work included.

ORE MICROSCOPIC OBSERVATIONS

The material investigated includes specimens collected from diamond-drill cores representing two sections through the massive and strikingly uniform ore zone. The first section is represented by specimens from three drill holes and by channel specimens from a 32-meters-long stripped outcrop. The second section, situated 1950 m from the first section, is represented by specimens of three drill holes penetrating the ore zone on different levels in a vertical direction. Both sections are presented in Fig. 1.

Under the ore microscope the specimens studied show variation of properties as regards grain size, fracturing of grains, occurrence of alteration or exsolution products in the chromite or the presence of other ore minerals. Some specimens are distinguished by remarkable effects of corrosion of the oxide ore minerals or by the presence of abundant silicatic inclusions in the chromite grains. The silicatic matrix in the ore specimens studied consists mainly of serpentinized olivine and serpentine accompanied by chlorite or chromium-chlorite kaemmererite. In specimens poor in chromite the pyroxenes followed by anorthitic feldspar are the dominating silicatic constituents in the matrix material. The chlorite and talc are typical constituents in the specimens showing an increasing content of sulphide minerals.

According to the grain size, the following three types of ore have been defined:

Coarse grained ore (Fig. 1, Pl. I). The diameter of the grains averages about 0.5 mm. The grains are generally rounded at the corners, although they otherwise show distinctly idiomorphic features. The ore is characterized by more or less intensive, cataclastic fracturing of the grains, as in the case of numerous other chromite ores (see Ramdohr, 1955, Abb. 486 a).

Medium grained ore (Fig. 2, Pl. I). The diameter of the grains varies between 0.1—0.3 mm on the average. The grains are weakly rounded and often show pronounced idiomorphism whereby the grains are fractured only slightly or not at all. A chain texture, which is commonly detectable in the medium grained ore, may exhibit a simultaneous crystallization of the chromite and surrounding silicates resembling the chain textures displayed by the pyroxenite seams in the deposits of the eastern part of the Bushveld Complex, as described by Cameron and Emerson (1959).

The rounding of the corners of the individual chromite grains is obviously a result of corrosion, the influence of which may also appear in textures of the other oxidic minerals in the ores under study. According to de Vijkerslooth (1943) and Krause (1958), the phenomena of corrosion as observed in connection with the chromites of the Anatolian ores probably

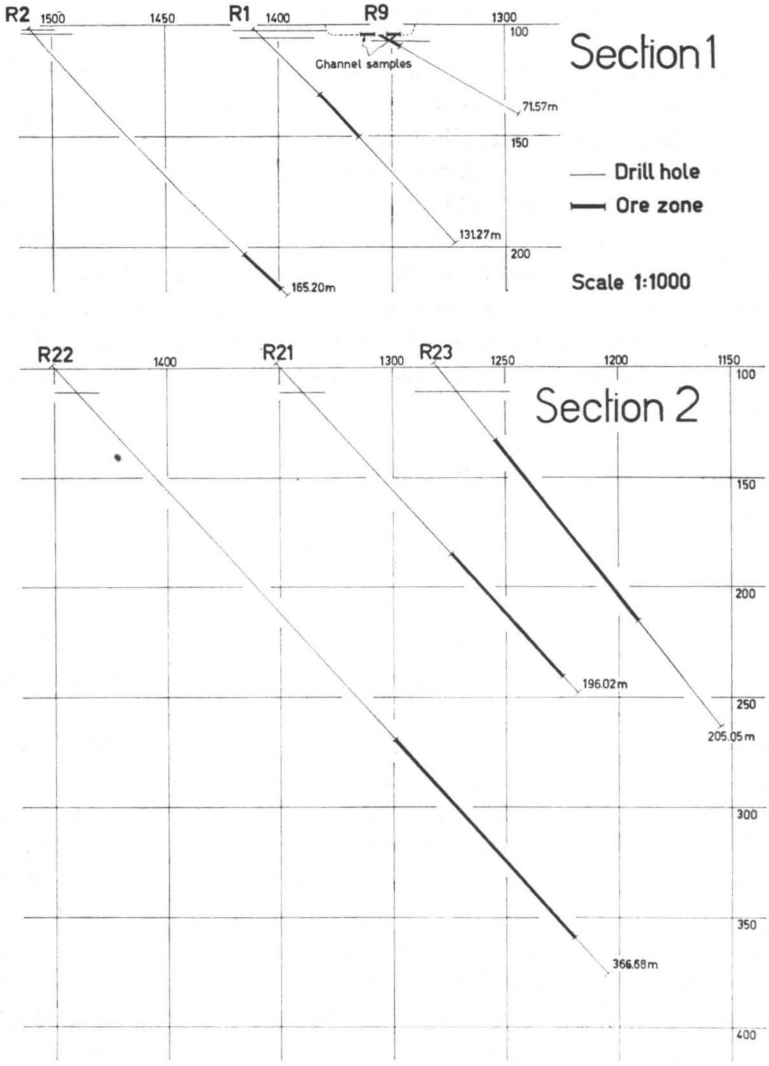


Fig. 1. The diamond drill profiles in sections 1 and 2.

has been produced during different stages of the ore-forming processes. Conjoining with this concept, the rounded forms, as displayed particularly by the grains of the coarse and medium grained ores of the Kemi deposits, were caused rather by magmatic corrosion, operating during a process of gravitative differentation. A texture shown in Fig. 1, Pl. II, illustrates another type of corrosion which has attacked, in particular, the magnetite surrounding the chromites. In connection with these textures, there may exist along the borders of the cracks in chromites a slight porosity, which might likewise be a result of corrosive action.

Fine grained ore (Fig. 1, Pl. III). The diameter of the grains averages 0.05 mm. The outlines of the individual grains are irregular and the grains subsequently have the shape of breccia fragments.

The textural features of the fine grained ore suggest a process by which the individual grains of the coarse grained ore have been split under considerable tectonic movements. The different products of this process are illustrated by Fig. 2, Pl. III and Fig. 1, Pl. IV. It may be pointed out that, according to the field evidence, the fine-grained ore ultimately follows the zones where strongly tectonized portions have been indicated in the wall rock.

According to the present knowledge, the chromite appears to be the only mineral of economic importance in the Kemi deposits. In the ore mineral assemblage so far identified, the magnetite is a most common associate and undoubtedly is not without practical significance, as has been emphasized in several connections, *i. e.*, most recently by Jenness (1959). The ilmenite occurs here and there accessorily, usually having intermingled as small grains with the silicate minerals (Fig. 2, Pl. IV). Sulphide minerals sometimes occur as very tiny spots in the chromite. Commonly they occur in the matrix between the chromite grains, in the fractures of the chromite, or often, partly surrounding the individual chromite grains. Besides chalcopyrite, pyrite and pyrrhotite, some Ni- and/or Co-minerals like pentlandite, linneite, millerite and maucherite have been identified.

A later, secondary alteration of varying intensity along the grain borders and cracks of the chromite is a common phenomenon, especially within the zones of low grade ore (Figs. 1 and 2, Pl. V; Figs. 1 and 2, Pl. VI). The altered portions vary in cross-dimensions approximately from 10 to 100 μ and usually comprise two kinds of opaque materials, both having a stronger reflectivity than the chromite. In his investigation of the chromites from Tampadel, in Silesia, Horninger (1941) called these two compounds true magnetite and »grey magnetite». Some investigators have determined the »grey magnetite« to be ferrite-chromite (*e. g.*, Spangenberg, 1943). Owing to the small dimensions of the altered portions, the attempts at mineralogical determination of these formations are handicapped if only the conventional microscopic, analytical or X-ray methods are applied. Subsequently, an approach for determining the compositional features of the »grey magnetite» was made by using the electron X-ray microanalyzer, as will be discussed later on in this paper (p. 84). In this connection, however, some attention may be called to the reflectivity and magnetic properties of the »grey magnetite». The higher reflectivity of this mineral as compared to that of the chromite may tentatively suggest an increased iron content in the »grey magnetite». Sometimes the specimens including chromite with altered portions indicate magnetic properties. On the other hand, specimens which include chromite showing an intense alteration, i. e., an abundance of the »grey magnetite», are not necessarily magnetic at all.

Besides the alteration products, distinct exsolution textures have often been observed in the Kemi chromites when using higher magnifications. Most usually a heterogeneity composed of hardly visible specks has been met with in the chromites investigated (*e. g.* Fig. 2, Pl. V and Fig. 2, Pl. VI). In some instances, a more highly developed pattern formed by the specks mentioned has been detected. The usual pattern is shown in Figs. 1 and 2, Pl. VII, in which probably plane sections of two different directions of the same pattern are to be seen. Often structures of a similar character have been found to follow the fractures in the chromite, as seen in Fig. 1, Pl. VIII. The exsolution structures in particular seem to occur in the coarse grained ores, simultaneously often including larger flecks obviously of a composition similar to the specks shown in the former figures.

METHODS AND ANALYTICAL DATA

SEPARATION OF THE CHROMITE FROM THE ORE

For the analytical and other determinations the chromite was separated from the ores in as pure a state as possible. Generally, the specimens were crushed to a grain size of 0.2—0.15 mm. The fine grained ore, however, was crushed to a grain size of 0.15—0.075 mm.

Some of the crushed specimens were run twice through a superpanner, the fractions obtained being cleaned by a Franz magnetic separator; the final process of removing the fine, powdered impurities was carried out by using an ultrasonic cleaner. Later on, the separation by the superpanner was replaced by a heavy liquid separation using the Clerici-solution with a specific gravity of about 4.0. The cleaning of the fractions was performed as before.

After controlling the results under a binocular microscope, it was realized that the purity of each fraction was satisfactory with silicatic constituents measuring less than 1 %.

X-RAY STUDY

Some tentative roentgenographic investigations of the chromite fractions were made at the Geological Survey of Finland by Dr. K. Neuvonen,

Table 1. Lattice Parameters, Specific Gravities and the Ratios Cr : Fe of Some of the Kemi Chromites

Specimen No.	a_0	Spec.gr.	Cr:Fe
1	8.300	4.45	1.54
2	8.300	4.55	1.22
3	8.300	4.46	1.56
4	8.304	4.52	1.41
6	8.307	4.54	1.36
7	8.301	4.48	1.51
8	8.306	4.46	1.44
9	8.301	4.45	1.46
5	8.303	4.55	—
14	8.298	—	0.90
16	8.292	—	1.07
19	8.296	—	1.72
22	8.302	—	0.81
26	8.296	—	1.70

in charge of the Mineralogical Laboratory. The results of this research, accompanied by specific gravity determinations, have been presented in Table 1, which also includes the values of the ratio Cr:Fe determined from the corresponding fractions. The numbers of the specimens refer to Table 2.

The variations shown in the specific gravities may be in part caused by the differences in the composition of the chromites measured. For the most part, the variations observed probably depend on the amount of impurities left in the chromite fractions after separation.

The present X-ray study has not revealed any features of significance as regards the variation of lattice parameters. According to the investigations carried out by Stevens (1958), the variations of a_0 are remarkable if the composition of the chromites shows variation. For example, if the Cr_2O_3-content in the chromite varies inside the limits of 9.28 %, the value of a_0 changes systematically 0.029 Å. As shown by Table 1, the values of a_0 measured from the Kemi chromite do not show any analogical tendency in spite of the fact that the chromium oxide content in the chromites investigated varies 8.7 %.

In this connection, a reference should be made to the recent results reported by Cameron and Emerson (1959). The authors cited have arrived at the conclusion that the lattice parameters of the Bushveld chromites have been controlled by the Fe : Mg ratio, the larger parameters being due to an increase in the number of the larger Fe^{++} ions in the lattice. As will be shown later on in this paper, there exists an analytically well-controlled, pronounced diadochy between the Fe^{++} and Mg in the Kemi chromites.

Yet, this phenomenon is not reflected as a change in the values of the corresponding chromites so far measured. Apparently, it must be presumed that in the case at hand the possible effect of the varying Fe^{++} and Mg contents on the unit cell dimensions has in some way been compensated by variations of the other ions incorporating the chromite lattice.

ANALYTICAL STUDY

Altogether 43 fractions of the separated chromite were analyzed as regards Cr_2O_3, total iron, MnO, V_2O_5, TiO_2, CoO, NiO and SiO_2. From the said fractions, FeO, Al_2O_3 and MgO were determined from 24 samples. The results of the analyses carried out are presented in Table 2. In the cases where the amount of chromium-oxide in the ore was determined, the values are reported in column 16 of Table 2.

The amounts of Fe_2O_3 were calculated on the basis of the analyzed values of total iron and FeO. The components SiO_2, MnO, TiO_2, V_2O_5, NiO and CoO were determined spectrographically, whereby SiO_2 was controlled by means of the colorimetric method using a silicomolybdate complex reduced to molybdenium-blue and a light transmission at 6 500 Å.

DETERMINATION OF THE MAIN COMPONENTS

Cr_2O_3 and total Fe_2O_3

0.5 g of the sample was fused with Na_2O_2 using an Alsint crucible (pure alumina). The melt obtained was dissolved in water and boiled for ½ hour, acidified by H_2SO_4, transferred into a 500 ml measuring flask and after cooling filled with water up to the mark (solution A).

For determination of Cr_2O_3, a permanganate-ferrous-ammonium-sulfate method was applied.

For determination of the total Fe_2O_3, 100 ml. of the solution A was measured, and heated to the boiling point, after which the group R_2O_3 (Al, Fe, Ti, etc.) was precipitated by NH_4OH. The precipitate was filtered, washed carefully and dissolved in hot HCl solution and collected in a 100 ml. measuring flask. After cooling, the flask was filled with water up to the mark. Five ml (= 5 mg) of this solution was transferred with a pipet to a 50 ml. measuring flask, which was filled with HCl sp. gr. = 1,142 up to the mark. From this solution the yellow color of ferric chloride was measured by using Uvispec spectrophotometer (4400 Å) and the standard solutions made from pure iron (Pinsl, 1944).

Fe_2O_3 might be as well determined directly from the solution A, whereby the Cr^{6+} has to be reduced by a drop of 3 % H_2O_2. The effect of $CrCl_3$ has to be eliminated by a correction, based on the determined Cr_2O_3 value, substracted from the total absorption value.

The percentage of Fe_2O_3 in the sample has been calculated in the usual way by subtracting the Fe_2O_3 equivalent of FeO from the value for total Fe as Fe_2O_3, *i. e.*

$Fe_2O_3\ \% = Fe_2O_3\ \text{tot}\ \% - 1.1114 \times FeO\ \%$.

FeO

0.25 g pulverized chromite was dissolved in phosphoric acid (sp.gr. 1.92) in a Vitreosil tube (pure quartz) at a temperature of 320 C° under CO_2 flow. From this solution, the FeO was titrated with 0.05-n $KMnO_4$, using Ferroin solution as an indicator (Caesar and Konopicky, 1939).

Al_2O_3, CaO and MgO

0.5 g of the sample was boiled with 30 ml perchloric acid in a quartz flask until the sample was completely dissolved (2—4 hours). The oxidized chromium was reduced by H_2O_2 and the group R_2O_3 precipitated twice with $NH_4Cl—NH_4OH$.

From the filtrate, CaO and MgO were determined complexometrically. CaO in pH 12 using Murexid as an indicator (CaO was not present in the sample) and MgO using a NH_4 — NH_4Cl buffer and Eriochrome Black T as an indicator. Trietanolamin, potassiumcyanide and hydroxylamin-hydrochlorite were used as eliminating agents.

Al_2O_3

The precipitate was dissolved in HCl and transferred to a 250 ml measuring flask filled up to the mark. Of this solution 50 ml = 100 mg was diluted to a volume of 300 ml. The solution was heated and precipitated with 10 % NaOH — an excess of 10 ml being added — boiled and cooled. 10 ml of 10 % potassium-oxalate solution and 2—2.5 ml of 1 : 1 HCl were added. The pH of the solution was adjusted to 10.1. An addition of 20 ml 30 % potassium-fluoride liberates OH^-—ions as follows:

$AlO_2^- + 2\ H_2O + 6\ F^- \rightarrow AlF_6^{---} + 4\ OH^-$

The free OH-ions were titrated with 0.1-n HCl until the pH in the solution came back to 10.1.

The Al_2O_3 titer of 0.1-n HCl was determined by using standars made from chemicals containing Cr_2O_3, Fe_2O_3 and Al_2O_3 in amounts corresponding to those of the samples analyzed (Watts, 1958).

GENERAL REMARKS ON THE COMPOSITIONAL FEATURES AND TRACE ELEMENTS OF THE CHROMITES ANALYZED

The contents of the chromium-oxide in the chromite under investigation vary inside the range of 39 % to 48.7 % and do not seem to depend on whether a high-grade or a low-grade ore is involved. For instance, specimen 13 shows a high content of Cr_2O_3, although the ore is relatively poor. On the other hand specimen 36 shows a low content of Cr_2O_3 in spite of the ore being relatively rich in chromite. Cameron and Emerson (op. cit.) have reported a similar experience as regards the composition of the chromites in the Bushveld Complex.

The ratio Cr : Fe, while generally low from the commercial point of view, shows, however, considerable variation. The minimum for the ratio Cr : Fe is 0.81 and the maximum 1.87.

The contents of alumina are relatively high, whereas the amounts of magnesia are mostly low in all the chromites analyzed from the Kemi deposits. More detailed examination of the behavior of both of these components will be given later on in this paper (p. 78) in connection with the compositional correlations of the chromites analyzed.

Silica commonly shows values between 0.3 — 1.5 %, which insure a satisfactory separation of the silicatic components. Analyses 40 and 43, however, indicate exceptionally high values of SiO_2, equaling 4.0 % and 5.0 % respectively. According observations of the specimen in polished section corresponding to analysis 40, there often occur in the chromite abundantly rounded silicatic inclusions (Fig. 2, Pl. VIII) which have not been separable from the fraction of the chromite analyzed. The high content of SiO_2 in analysis 43 as well is a consequence of the silicatic material present as fine needles in the chromite grains. In the case of five analyses the SiO_2 has not been reported because of a mistake during the grinding of material, whereby the amount of silica was considerably increased owing to impurities loosened from the SiO_2-bearing grinding tools.

The manganese-oxide amounts in all the analyses to less than 1 %. having a maximum content of 0.94 % and a minimum content of 0.46 % The manganese, as expected, replaces the ferrous iron in the chromite lattice and, accordingly, affects to a slight degree the ratio Cr : Fe.

The titanic-oxide is usually present in the chromite investigated in amounts of less than 1 %. Conceivably interstitial ilmenite (Fig. 2, Pl. IV) has been removed in association with the silicatic material by a separation process. Exceptional contents have been determined in analyses 11 and 35, in which TiO_2 equals 1.58 % and 1.14 % respectively. The specimen corresponding to analysis 11 represents an ore with an average chromite content and is characterized by an intense fracturing of the individual

Table 2. Chromite Analyses from the Kemi Deposits, Northern Finland

1	2	3	Chromite Analyses												16
N:o	Drill hole	Depth	4	5	6	7	8	9	10	11	12	13	14	15	Cr_2O_3 in the Ore
			FeO	Fe_2O_3	Cr_2O_3	Al_2O_3	MgO	Cr:Fe	MnO	V_2O_5	TiO_2	Co	Ni	SiO_2	
1	Channel sample	A	22.3	4.3	45.7	16.3	8.9	1.54	0.33	0.20	0.51	0.03	0.07	1.45	
2	»	B	25.8	5.2	42.4	18.2	6.6	1.22	0.30	0.18	0.73	0.03	0.11	0.62	
3	»	II, 32 m [1]	25.9 [2]		45.9			1.56	0.35	0.16	0.64	0.02	0.09	0.50	
4	»	IV, 28.5 m	23.6	5.5	45.7	15.0	6.8	1.41	0.60	0.20	0.68	0.03	0.05	0.72	
5	»	XV, 27.5 m	28.0	7.1	43.1	14.3	4.0	1.10	0.83	0.18	0.62	0.03	0.03	1.12	
6	»	VII, 21.5 m	29.4 [2]		45.4			1.36	0.60	0.16	0.49	0.02	0.06	0.61	
7	»	X, 19.5 m	27.2 [2]		46.5			1.51	0.32	0.16	0.52	0.03	0.08	0.36	
8	»	XII, 17.0 m	28.1 [2]		46.2			1.44	0.41	0.20	0.78	0.03	0.07	0.57	
9	»	XIII, 16.0 m	28.1 [2]		46.6			1.46	0.54	0.18	0.68	0.03	0.06	0.45	
10	R 1	41.54— 42.90	27.8	5.4	44.7	15.7	4.3	1.20	0.64	0.18	0.45	0.02	0.04	0.71	33.0
11	»	44.18— 45.80	24.6	2.9	47.1	14.7	6.6	1.52	0.34	0.20	1.58	0.03	0.05	1.20	34.1
12	»	50.58— 51.25	30.2 [2]		44.2			1.29	0.64	0.23	0.68	0.04	0.09	1.48	31.2
13	»	55.46— 56.06	24.7	6.1	44.6	15.4	6.5	1.30	0.40	0.18	0.52	0.03	0.08	0.82	18.1
14	»	71.71— 77.08	39.1 [2]		40.2			0.90	0.75	0.20	0.58	0.06	0.10	1.18	9.3
15	»	81.01— 81.40	29.0	9.6	41.0	13.4	3.10	0.96	0.94	0.18	0.53	0.04	0.05	0.73	17.9
16	R 2	65.45— 65.65	22.8	10.5	39.0	15.4	7.9	1.07	0.75	0.27	0.66	0.04	0.07	1.05	
17	»	141.38—142.24	31.8 [2]		45.3			1.26	0.40	0.18	0.46	0.03	0.04	0.77	32.2
18	»	155.03—156.12	27.8	7.9	42.3	15.1	4.0	1.07	0.30	0.16	0.62	0.03	0.05	0.55	11.2
19	»	157.22—160.28	19.4	5.6	47.7	15.0	9.4	1.72	0.52	0.16	0.53	0.02	0.07	0.56	38.1
20	»	160.28—161.64	24.5	6.4	45.1	15.5	6.5	1.31	0.61	0.16	0.56	0.03	0.06	0.69	25.5
21	R 21	103.02—103.90	25.4	5.4	44.7	16.4	5.9	1.30	0.58	0.21	0.76	0.03	0.05	0.69	35.6
22	»	110.19—111.88	30.0	13.6	39.0	12.8	2.2	0.81	0.31	0.21	0.96	0.04	0.05	0.59	8.2
23	»	113.80—116.40	28.7 [2]		47.5			1.46	0.49	0.18	0.58	0.02	0.04	0.62	33.5
24	»	123.50—124.00	38.3 [2]		41.8			0.96	0.20	0.14	0.52	0.03	0.07	1.04	8.0
25	»	140.28—142.39	21.4	6.9	46.7	15.9	8.0	1.50	0.29	0.14	0.52	0.03	0.07	0.53	24.2
26	»	156.80—158.30	19.9	6.4	47.4	15.4	9.3	1.63	0.30	0.16	0.50	0.03	0.07	0.37	30.6
27	R 21	184.72—186.40	29.7 [2]		45.4			1.35	0.33	0.14	0.56	0.03	0.07	0.77	17.6
28	R 22	229.21—232.31	20.3	4.6	48.6	13.5	9.0	1.75	0.32	0.18	0.52	0.04	0.10		35.0
29	»	240.50—241.80	26.8 [2]		48.2			1.59	0.22	0.16	0.64	0.04	0.10	0.49	14.1
30	»	259.53—260.69	22.4	6.2	47.4	14.7	7.0	1.49	0.34	0.18	0.55	0.05	0.08		18.0
31	»	267.50—269.86	25.4 [2]		45.9			1.59	0.30	0.16	0.59	0.03	0.07		30.5
32	»	292.48—293.34	23.0	7.3	46.4	14.5	7.2	1.38	0.56	0.14	0.46	0.03	0.06	0.48	14.6
33	»	306.20—308.38	21.2	7.2	47.9	14.7	7.5	1.53	0.46	0.14	0.44	0.03	0.06	0.41	25.2
34	»	356.95—357.45	29.0	5.4	45.7	13.6	2.9	1.19	0.83	0.14	0.60	0.03	0.04	0.40	22.3
35	R 23	20.62— 22.23	27.5	10.4	39.1	15.1	4.6	0.94	0.62	0.25	1.14	0.04	0.06	0.63	10.6
36	»	39.62— 40.43	26.0	7.2	43.0	15.5	5.2	1.17	0.72	0.23	0.60	0.03	0.05		32.6
37	»	46.10— 47.87	24.0 [2]		48.2			1.77	0.30	0.18	0.46	0.03	0.08	0.34	38.5
38	»	74.05— 75.21	18.1	4.9	47.8	14.2	10.0	1.87	0.24	0.12	0.41	0.03	0.07		35.0
39	»	87.10— 88.41	25.5 [2]		48.1			1.66	0.32	0.12	0.38	0.03	0.07	0.41	30.8
40	»	103.90—105.42	25.6 [2]		45.5			1.56	0.30	0.16	0.64	0.04	0.08	4.0	27.2
41	»	124.40—127.40	34.2 [2]		44.5			1.14	0.40	0.16	0.66	0.04	0.07	0.52	25.4
42	»	134.18—137.10	24.5 [2]		48.7			1.74	0.44	0.16	0.45	0.03	0.09	0.49	28.7
43	»	186.10—186.10	28.3 [2]		45.0			1.40	0.54	0.11	0.46	0.03	0.05	5.0	23.4

---

[1] The measures for channel samples represent horizontal distances.

[2] Total iron calculated as FeO.

chromite grains. Typical of this chromite is its spotted heterogeneity accompanied by small flecks, as already explained on page 7. The specimen corresponding to analysis 35 represents a low-grade ore, characterized by an abundant alteration of the chromite.

All the contents of the vanadic-pentoxide, cobalt-oxide and nickel-oxide appear to be quite constant in character. This probably indicates that the small amounts of sulphides containing, among other elements, nickel and cobalt, have been removed by the separation of the chromite from the specimens. Hence it may be assumed that the elements concerned evidently incorporate the chromite lattice in the small amounts indicated by the analytical results.

CORRELATION OF THE ANALYTICAL RESULTS

The foregoing analytical results well characterize the general compositional features of the chromium-bearing mixed crystals of the spinel group. The pure end members in the series of this group usually have been demonstrated by the following species:

$FeCr_2O_4$	ferrous chromite
$MgCr_2O_4$	picochromite
$MgAl_2O_4$	pleonast
$FeAl_2O_4$	hercynite
$MgFe_2O_4$	magnesioferrite
Fe_3O_4	magnetite

In Winchell's diagram (1941) characterizing the mineralogical composition of the chromites, the first four members of the series have been considered as the end members of the diagram while the fields of the diagram represent spinels of mixed composition. Applying the spinel names given for the different compositional fields of the diagram, the analytical characteristics of the Kemi chromite correspond to those of alumoberezowskite.

In order to illustrate the variations of the main components of the chromites analyzed, a correlation by means of triangular diagrams has been applied. The systems considered are Cr_2O_3—MgO—FeO, Cr_2O_3—Al_2O_3—MgO and Cr_2O_3—Al_2O_3—FeO, as shown by diagrams 1, 2 and 3 in Figs. 2, 3 and 4. The corrected FeO- and MgO- contents as well as other values used for plotting these diagrams are shown in Table 3. The corrections concern the amounts of FeO and MgO which are needed to form ilmenite ($FeTiO_3$) and serpentine ($3MgO \cdot 2SiO_2 \cdot 3H_2O$) corresponding to the amounts of TiO_2 and SiO_2 of the analyses in Table 2. The possible influence of the manganese oxide has not been considered in correcting the FeO- and MgO- contents because commonly the contents of MnO are relatively low and because it is difficult to decide to what degree the Mn replaces either Fe^{++} or Mg. Regarding diagrams 2 and 3, it must be reported that

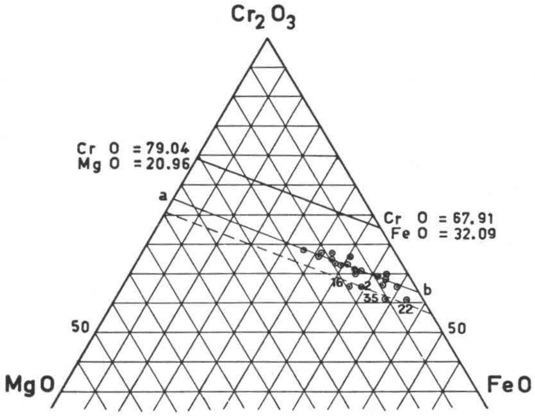
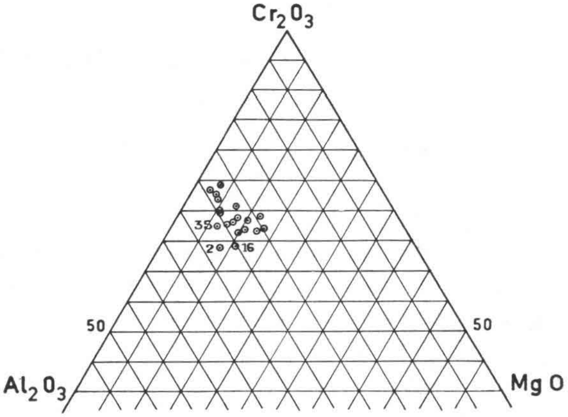


Fig. 2. Diagram 1. The system Cr_2O_3—MgO—FeO.

Fig. 3. Diagram 2. The system Cr_2O_3—MgO—Al_2O_3.



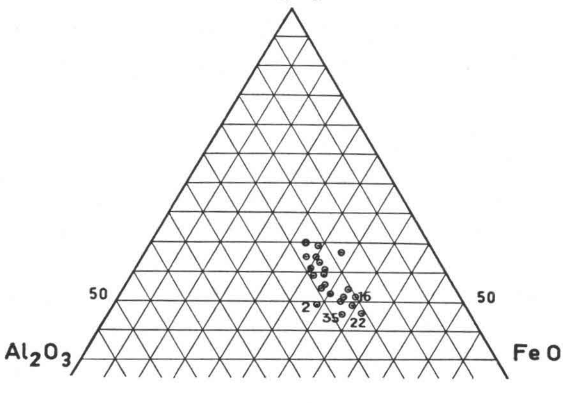


Fig. 4. Diagram 3. The system Cr_2O_3—FeO—Al_2O_3.

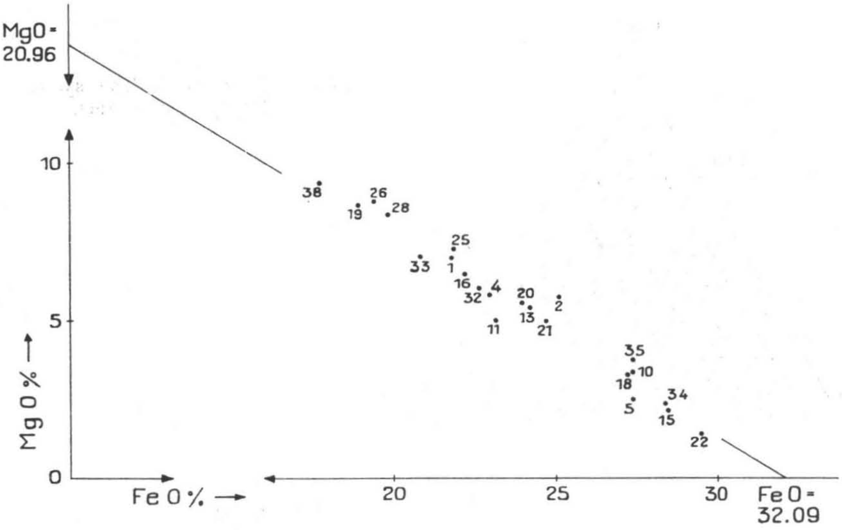


Fig. 5. Diagram 4. The variation of the ratio FeO : MgO.

all the analyses have not been plotted for the sake of the clearness of the figures. The maximum field of distribution has been illustrated, however, by the plotted points.

Diagram 1 represents a chromite of composition (Mg, Fe) O · Cr_2O_3. According to Krause (1958) the composition points of theoretically pure FeO · Cr_2O_3 and MgO · Cr_2O_3 have been connected by a line in the diagram. By drawing a parallel line (a — b) through the points corresponding to the composition of the Kemi chromites in the diagram, it is apparent that most of these points follow the trend of the line a — b. Points 2, 16, 22 and 35 show the most deviating position. The trend of these points, however, is parallel to direction a — b although a connecting line would run at a short distance beneath the line a — b. As revealed under the microscope, the specimens, including the chromites represented by the latter compositional points, commonly contain magnetite, whereby a pronounced alteration of the chromite towards the grey magnetite is a typical phenomenon. Presumably the deviating compositional properties of the chromites as indicated by specimens 2, 16, 22 and 35 in diagram 1 are a consequence of later effects, *e. g.*, in connection with a possible autohydratization which may have been instrumental in bringing about the serpentinization of the ore-bearing, ultrabasic horizon.

Moreover, the distribution of the points plotted in diagram 1 contribute the view that the chromites under investigation are characterized by a wide diadocic substitution between Fe^{++} and Mg.

Table 3. Corrected Values for Diagrams 1, 2 and 3 on the Composition of the Kemi Chromites

N:o	Original Determinations				Corrected Values		Diagram 1				Diagram 2				Diagram 3			
	1 C_2O_3	2 FeO	3 MgO	4 Al_2O_3	5 MgO	6 FeO	7 1, 5, 6	8 Cr_2O_3	9 MgO	10 FeO	11 1, 4, 6	12 Cr_2O_3	13 Al_2O_3	14 FeO	15 1, 4, 5	16 Cr_2O_3	17 Al_2O_3	18 MgO
1	45.7	22.3	8.9	16.3	6.95	21.8	74.45	61.38	9.34	29.28	83.80	54.53	19.45	26.01	68.95	66.28	23.64	10.08
2	42.4	25.8	6.6	18.2	5.75	25.1	73.25	57.88	7.85	34.27	85.70	49.47	21.24	29.29	66.35	63.90	27.43	8.67
4	45.7	23.6	6.8	15.0	5.83	23.0	74.53	61.32	7.82	20.86	83.7	54.60	17.92	27.48	66.53	68.69	22.55	8.76
5	43.1	28.0	4.0	14.3	2.50	27.4	73.00	59.05	3.42	37.54	84.8	50.83	16.87	32.31	59.90	71.95	23.87	4.17
10	44.7	27.8	4.3	15.7	3.35	27.4	75.45	59.25	4.44	36.32	87.8	50.91	17.88	31.21	63.75	70.12	24.63	5.25
11	47.1	24.6	6.6	14.7	4.99	23.2	75.29	62.56	6.63	30.81	85.0	55.41	17.30	27.30	66.79	70.52	22.01	7.47
13	44.6	24.7	6.5	15.4	5.40	24.2	74.20	60.11	7.28	32.61	84.2	52.97	18.29	28.74	65.40	68.20	23.55	8.26
15	41.0	29.0	3.1	13.4	2.12	28.5	71.62	57.25	2.96	39.79	82.9	49.46	16.16	34.38	56.52	72.55	23.71	3.75
16	39.0	22.8	7.9	15.4	6.49	22.2	67.69	57.66	9.59	32.80	76.6	50.91	20.10	28.98	60.89	64.05	25.29	10.66
18	42.3	27.8	4.0	15.1	3.26	27.2	72.76	58.14	4.48	37.39	84.6	50.00	17.85	32.15	60.66	69.73	24.89	5.37
19	47.7	19.4	9.4	15.0	8.65	18.9	75.25	63.36	11.49	25.12	81.6	58.46	18.39	23.16	71.35	66.86	21.03	12.12
20	45.1	24.5	6.5	15.5	5.57	24.0	74.67	60.40	7.46	32.14	84.6	53.31	18.32	28.37	66.17	68.16	23.42	8.42
21	44.7	25.4	5.9	16.4	4.97	24.7	74.37	60.11	6.68	33.22	85.8	52.10	19.11	28.79	66.07	67.66	24.82	7.52
22	39.0	30.0	2.2	12.8	1.41	29.5	69.91	55.79	2.02	42.20	81.3	47.97	15.74	36.29	53.21	73.29	24.06	2.65
25	46.7	21.4	8.0	15.9	7.29	20.9	74.89	62.36	9.73	27.91	83.5	55.93	19.04	25.03	69.89	66.82	22.76	10.43
26	47.4	19.9	9.3	15.4	8.80	19.4	75.60	62.70	11.64	25.66	82.2	57.66	18.74	23.60	71.60	66.20	21.51	12.29
28	48.6	20.3	9.0	13.5	8.33	19.8	76.73	63.34	10.86	25.80	81.9	59.34	16.48	24.18	70.43	69.00	19.17	11.83
30	47.4	22.4	7.0	14.7		21.9					84.0	56.43	17.50	26.08				
32	46.4	23.0	7.2	14.5	6.85	22.6	75.85	61.18	9.03	29.80	83.5	55.57	17.37	27.07	67.75	68.49	21.40	10.11
33	47.9	21.2	7.5	14.7	6.95	20.8	75.65	63.32	9.19	27.50	83.4	57.43	17.63	24.94	69.55	68.87	21.14	9.99
34	45.7	29.0	2.9	13.6	2.35	28.4	76.45	59.78	3.07	37.15	87.7	52.11	15.51	32.39	61.65	74.13	22.06	3.81
35	39.1	27.5	4.6	15.1	3.76	26.5	69.36	56.37	5.42	38.21	80.7	48.45	18.71	32.84	57.96	67.46	26.05	6.49
36	43.0	26.0	5.2	15.5		25.4					83.9	51.25	18.47	30.27				
38	47.8	18.1	10.0	14.2	9.33	17.7	74.83	63.88	12.47	23.66	79.7	59.97	17.82	22.21	71.33	67.01	19.91	13.08

Diagram 2 displays the compositional field of chromites corresponding to the form $FeO(Cr,Al)_2O_3$. In regard to the analyses of the Kemi chromites, it may be concluded that the scattering of the points plotted depends mainly on the variations in the FeO- and Cr_2O_3-contents, while the effect of the alumina is relatively negligible.

Diagram 3 includes the compositional field of chromites in the form $MgO\ (Cr, Al)_2O_3$. On the basis of this diagram, it may be noted that the substantial distribution of the plotted points, analogous to that of the former diagrams, occurs in a direction defined by the diadochy of Fe^{++} and Mg. For the reasons stated in connection with the first diagram here, too, analyses 2, 16, 22 and 35 are marked by a deviating character.

Diagram 4 (Fig. 5) was designed in order to correlate directly the variations of the FeO- and MgO-contentents in the analyses studied. On the axis of the diagram, the compositional points corresponding to both end members of a $(Fe,Mg)O \cdot Cr_2O_3$ mixed crystal have been plotted. This diagram particularly shows the wide diadochy existing between Fe^{++} and Mg in the Kemi chromites. The main trend of the plots strikingly conforms

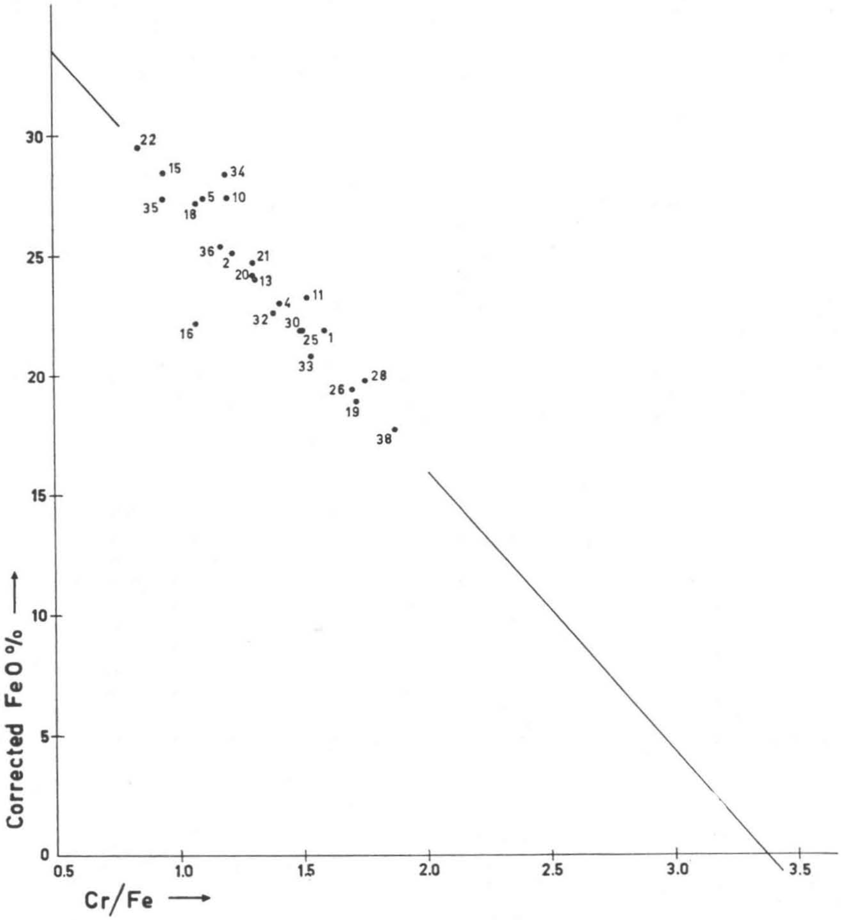


Fig. 6. Diagram 5. The relation of the amounts of FeO to the ratio Cr : Fe.

to the line connecting the theoretical points recorded on the axis of the diagram.

The ratio Cr : Fe of the chromite is of importance from a commercial point of view. As revealed in Table 1, in the present case this ratio is regularly low, varying between 0.81 and 1.87. The ratio is in the first place dependent on the amounts of FeO, Fe_2O_3 and Cr_2O_3, in the chromite. In Fig. 6 the dependence between the corrected amounts of FeO and the ratio Cr : Fe has been demonstrated. On the basis of this figure, it is apparent that the ratio Cr : Fe very smoothly follows the variations of the FeO-contents. On the other hand, the amount of FeO depends much on the diadochy between Fe^{++} and Mg, as shown in Fig. 5. The line drawn in Fig. 6

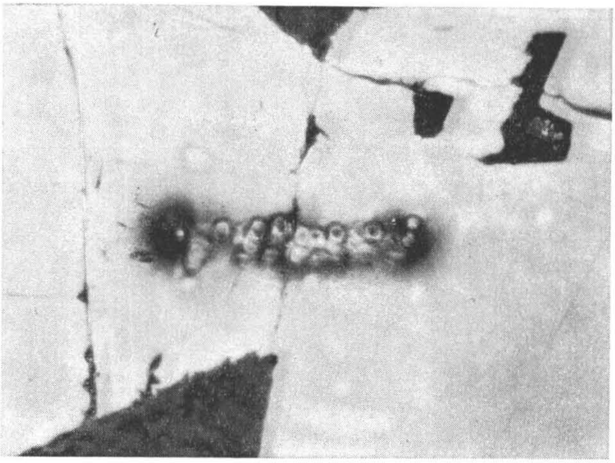


Fig. 7. The profile across an alteration band between two chromite grains analyzed by the electronic X-ray microanalyzer.

as well represents the trend of the MgO content in relation to the ratio Cr : Fe. The line further suggests that the ratio Cr : Fe might increase to a value approximately $3._{35}$ if all the ferrous iron would be substituted by magnesium and assuming that the amounts of the other elements in the respective chromites follow the normal compositional trend of the Kemi chromites. The foregoing concept presents a theoretical possibility that in some suitable horizon of the ore deposit there may exist chromites with a composition showing Cr : Fe ratios whose numerical values may exceed the values determined up to the present.

COMPOSITIONAL FEATURES OF THE ALTERATION AND EXSOLUTION PRODUCTS IN THE CHROMITES STUDIED

The alteration products and exsolutions in the chromites as observed in connection with the present microscopical study have brought up particular difficulties in identification and interpretation. As pointed out earlier in this paper, an attempt was made to resolve the compositional features of the said microstructures by using an electronic X-ray microanalyzer. An opportunity to carry out this research was opened to the first author through the courtesy of the Institute of Metallurgy in Stockholm and Dr. Kurt Fredriksson, Geological Survey of Sweden. While visiting the Institute mentioned, the author was able to make only one run with the Castaing-Guinier apparatus, as the work was interrupted when the

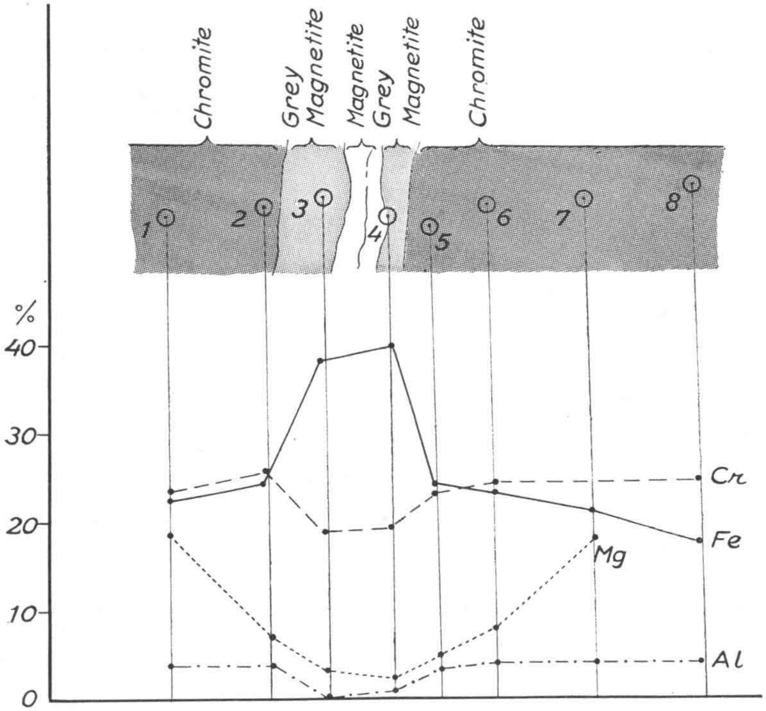


Fig. 8. The prelimary analytical results along the profile shown in Fig. 7. The numbers refer to the centres of the analysis spots.

scaler unit broke. After the apparatus was repaired, Dr. Fredriksson was kind enough to run the samples according to the original plans. A provisory, more or less qualitative summary of the essential results has been presented in Fig. 8, illustrating the compositional variations across an alteration band. Fig. 7 shows the traces of analysis points on the surface of a polished section.

According to the tentative results, it is confirmed that, in comparison to the composition of the chromite, the iron considerably increases in the band composed of the »grey magnetite.» The contents of aluminum, chromium and magnesium all decrease in the area of alteration band. The most pronounced drop in the contents of the last-named elements appears in the central part of the structure analysed. This coincides well with the microscopic result that the higher reflecting bands inside the »grey magnetite» are composed of true magnetite. The exact composition of the »grey magnetite», however, cannot be defined on the basis of the provisional determinations at hand. It might be tentatively suggested that, according to the diagram published by Winchell (1941), the mineral in question might correspond to a species named chromite-hercynite or hercynite-chromite.

An analysis of the specks seen, *e. g.*, in Fig. 2, Pl. VII was not possible while the specks were not firmly detectable under the built-in microscope of the micro-analyzer. Furthermore, the size of the specks is at the extreme limit of the resolving power of the microanalyzer. Fortunately, in the specimens showing exsolution specks in abundance there are also larger flecks, which may show distinct anisotropy under the crossed nicols and which reveal variagation of color typical for the small exsolution specks (Fig. 1, Pl. VII). The analysis of these flecks gave as a result a content of about 20 % titanium, assuming that the flecks most probably are composed of ilmenite. As the exsolution specks are of a character very similar to the flecks analyzed, it may be assumed that the specks are likewise titaniferous and possibly composed of ilmenite. It may be pointed out that the specimen under consideration (investigated by means of a micro-analyzer) corresponds to analysis 11 in Table 1. This analysis also shows a high content of TiO_2, compared to the contents of TiO_2 in most of the analyses in the same table.

SOME GENETIC CONSIDERATIONS

The results as presented in the preceding pages are aimed primarily to offer preliminary data on the Kemi chromite as well as to augment the information previously published on the properties of the chromites found in chromium ores in various parts of the world (in addition to the investigations already cited, studies by van der Valt, 1942; Thayer, 1946; Du Rietz, 1956). On the other hand, however, the study carried out has revealed phenomena which stimulate further interest in regard to the concepts concerning the genesis of the chromium-bearing deposits. *(cf.* Fisher, 1929; Sampson, 1929 and 1942; Dunham *et al.*, 1958; Cameron and Emerson, 1959). In especial, the observations on the order of crystallization, on the paragenic succession of the ore minerals, on the diadochy of the main components or on the alteration and exsolution products require some additional consideration.

In the Kemi deposits, the olivine seems to have crystallized prior to the chromite and oxide ore material. This order of crystallization is duly indicated by textures in which the inclusions of serpentinized olivine in the chromite grains are shown (Fig. 2, Pl. VIII). Analogical inclusions in the chromites have been thoroughly desribed by Krause (1958).

The varying degree of corrosion visible as more or less rounded forms of the individual chromite crystals suggest that during the crystallization of the ore gravitative agencies had been in operation; the chromite crystals which were the last to be crystallized and subsequently were trapped in the outermost portions of the molten phase show, as expected, less corroded forms compared with the forms of chromites crystallized at an early stage. The latter had obviously been attacked for a longer time by corrosive factors, especially if the crystals have been transferred, *e. g.*, by gravitative sinking, to the areas of higher temperatures (see Krause, *op. cit.*).

An estimate of the temperatures at which the ore started to crystallize is a further subject of interest. When approaching this question, it must be emphasized that the chromium ores generally have been considered to be representatives of ores formed in conditions corresponding to those of an early magmatic stage and that a similar concept in most cases has been applied in regard to the formation of the titaniferous iron ores. Indicating this obviously close genetical association, the chromium ores contain typical, though small amounts of titanium, and, on the other hand, the titaniferous iron ores, especially their ilmenite component, regularly reveal small but characteristic amounts of chromium. This circumstance actually offers orientative means for estimating the primary conditions and mutual relationships prevailing in the crystallization of chromium ores and titaniferous iron ores from a common source. In this respect, the following observations relating to the present study are particularly noteworthy:

— The occurrence of ilmenite as separate grains outside the chromite or in association with the magnetite, partly surrounding the chromites.

— The occurrence of exsoluted titaniferous component in the chromite.

On the basis of the first-mentioned observation, it is probable that the main part of the phase containing titanium reacted independently in regard to the crystallization of the chromite. The second observation shows, on the other hand, that a limited miscibility had existed between the chromium- and titanium-bearing phases during the crystallization of the chromite. At a high temperature, and as if, considered analogously, there had been a magnetite, the titanium was conceivably able to incorporate the chromite lattice in the form of the cubic ulvöspinel, *i. e.*, ferro-ortotitanite, which was first described by Mogensen (1946). In connection with the magnetites in the titaniferous iron ores, it has been observed that the titanium originally contained in the form of $TiFe_2O_4$ in the magnetite mixed crystal, will unmix under conditions of decreasing temperature as ulvöspinel and/or ilmenite, depending on the availability of the oxygenium (Ramdohr, 1953). The products of exsolution observed in the Kemi chromite most probably consist of ilmenite. Moreover, the presence of these formations, whether composed of ulvöspinel or ilmenite, indicate that the crystallization of the phase containing titanium had been adjusted to the time the unmixing took place. Subsequently, a marked interval of time between the chromite crystallized first and the ilmenite (+ magnetite) crystallized later may be assumed. This further implies that the crystallization of the chromite started in a considerably higher temperature than that of the ilmenite.

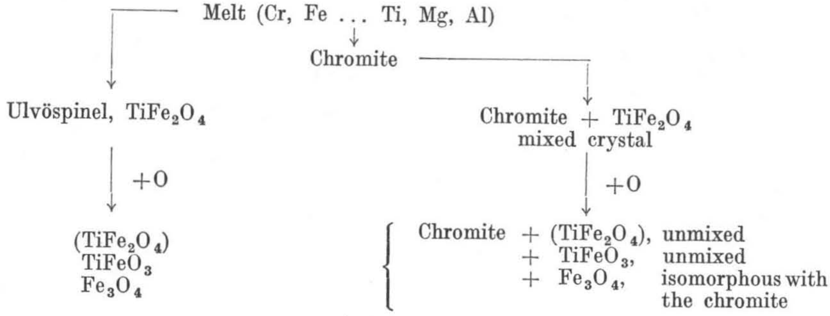


Fig. 9.

Summarizing the data and premises given in the foregoing, it seems that the crystallization of the material responsible for the formation of the Kemi deposits started in high temperatures denoting an early magmatic stage. Presumably there existed in these conditions a limited miscibility between the common source melt and the oxide material including, first of all, chromium, titanium, iron, magnesium and aluminium. In other words, the total process producing the material of the Kemi deposits may be described as a liquid-magmatic segregation of an oxide phase in the course of crystallization differentiation — in the way advocated by Schneiderhöhn, especially, in several connections *(e.g.*, 1949 and 1958). Within the melt segregated, the crystallization of oxide species may have occurred in a succession which, in accordance with the observations of the present study, would be presented as seen in Fig. 9.

It may be pointed out that, on the basis of the results obtained by homogenization experiments, the exsolution of ilmenite from magnetite in titaniferous iron ores takes place in temperatures between ca. 700—400° C depending on the amount of volatiles, mineralizers, etc. (Ramdohr, 1955, p.706). With respect to the crystallization of the chromium ores, these temperatures obviously must be considered too low. For example, the experimental results reported by R. Fisher (1950) show that melts made from mixtures of normal gabbro with chromite up to 10 percent produced a Cr-rich liquid and a Cr-poor liquid at 1 400° C and that the crystallization of the Cr-rich liquid yielded chromite and olivine. These results support well the previous concept of the present authors that a chromium-rich oxide melt might have separated at an early stage of the ctystallization differentiation and that the temperature required for the crystallization of the chromite probably greatly exceeds the temperature presupposed by the exsolution of ilmenite from magnetite. Looked at in a broader aspect the aforementioned conclusion implies that in the course of magmatic processes the ilmenite magnetite ores must crystallize considerably later than the chromium ores, although the materials for both of these ores have evolved from a magmatic oxide melt segregated at an early stage. The remarkable diadochy observed between Fe^{++} and Mg further testifies to a kind of differentiation within the chromium-bearing phase itself. In the cooling system the chromites rich in Mg probably have been the first to crystallize.

After the silicate and oxide phases of early crystallization the serpentinization by autohydratization obviously took place within the ultrabasic horizon. It was during this stage that the alteration bands, as observed in the Kemi chromite as well as the phenomena of corrosion as illustrated in Figs. 1 and 2, Pl. II, were produced. Presumably close to this phase, there originated the first generation of the sulphide minerals found as tiny spots in the chromites and in the matrix of the high-grade ore. The crystallization of the phase including the Ni- and Co-sulphides and -arsenides accounts, as anticipated, for still later stages during the genetical history of the Kemi deposits, *i. e.*, the effects of hydrothermal activity, whereby the serpentinization has become more intense and in the shear zones, especially, abundant chlorite, talc and iron sulphides have been formed.

CONCLUDING REMARKS

The following main conclusions may be drawn from the results presented in the foregoing:

— There appear to be ores of three different grain sizes in the Kemi deposits. The coarse grained ore is the dominating type. The middle grained ore, commonly showing a chain-texture of the chromite grains, obviously represents the latest crystallized portion of the chromite-rich melt. The fine grained ore was formed by a splitting up of the coarse grained ore along the zones of strong tectonic movements.

— No variations of significance were revealed by the X-ray study in regard to the lattice parameters of the chromites investigated.

— The composition of the Kemi chromite approaches upon analysis, that of alumoberezowskite.

— The alteration of chromite accompanied by magnetite segregations along the fractures and grain borders is a widely distributed phenomenon in the chromites studied. The alteration bands comprise a material containing more Fe but less Mg and Cr than the original chromite. This material may be tentatively considered as chromite-hercynite, according to Winchell's definitions.

— There occur in the chromite exsolution specks and lamellae which probably consist of ilmenite. It has been assumed that under conditions of

high temperature the titanium incorporated the chromite lattice in the form of ulvöspinel, giving rise to an exsolution of ilmenite from the chromite.
— A wide diadocic substitution between Fe^{++} and Mg has been established in the chromites investigated. It has been assumed that the chromites with a higher Mg-content probably belong to the portions of the chromite-rich melt that had crystallized earlier.
— Besides the chromite, the ore contains minute amounts of sulphide and arsenide minerals containing Cu, Ni and Co. The formation of these constituents is most probably due to the effects of hydrothermal activity, whereby abundant chlorite, talc and iron sulphides have been formed in the shear zones.
— It has been proposed that the chromite ore in the Kemi deposits originated as a liquid-magmatic segregation in conjunction with the gravitative crystallization differentiation of the ultrabasic rock suite previously described from the Kemi region.

Acknowledgements — The authors wish to express their deepest gratitude to Mr. Valto Veltheim, Phil. lic. with Mr. Erkki Lyytikäinen, M. Sc., and Mr. Erik Lindberg, who served as the field geologists during the diamond drilling operations in Kemi. They all offered generous help in choosing and locating the material used for this study. Further, it gives pleasure to extend sincere thanks to Mr. Arvo Löfgren, M.Sc., for the spectrographic determinations and to Mrs. Irja Huhta, M. Sc., for assistance in the analytical work. Thanks are also due to Mr. Tapio Alholinna, who carefully completed the tedious separation of the chromite fractions. The authors express their gratitude to Mr. Erkki Halme, Geological Survey of Finland, who is responsible for all the photographic work here included and has skillfully reproduced the phenomena observed under the microscope.

Having had the tentive results of the study at his disposal at the time of the XXI International Geological Congress in Copenhagen, the first author enjoyed the opportunity of engaging in a number of fruitful discussions with authors having earlier experience in research into chromite ores. Particular mention should be made of the discussions with Drs. T. P. Thayer, Paul Ramdohr and Albert Maucher, all of whom gave valuable information and counsel on the study here presented.

REFERENCES

CAESAR, F. and KONOPICKY, K. (1939) Die FeO-Bestimmung im Chromerz. Ber. deut. geram. Ges. 20.

CAMERON, E. W. and EMERSON, M. E. (1959) The Origin of Certain Chromite Deposits of the Eastern Part of the Bushveld Complex. Econ. Geol. 54.

DUNHAM, K. C., PHILLIPS, R., CHALMERS, R. A. and JONES, D. A. (1958) The Chromiferous Ultrabasic Rocks of Eastern Sierra Leone. Geol. Survey Dept., Sierra Leone, short paper n:o 2.

DU RIETZ., T. (1956) The Content of Chromium and Nickel in the Caledonian Ultrabasic Rocks of Sweden. Geol. Fören. i Stockholm Förh. 78.

ENKOVAARA, A., HÄRME, M. and VÄYRYNEN, H. (1953) Kivilajikartan selitys C5—B5, Oulu—Tornio. English summary. General geological map of Finland, 1: 400 000.

FISHER, LLOYD, W. (1929) Origin of Chromite Deposits. Econ. Geol. 24.

FISHER, REINHARD (1950) Entmischungen in Schmelzen aus Schwermetall-Oxyden, Silikaten und Phosphaten. N. Jahrb. Min. Abh. 81.

HORNINGER, GEORG (1941) Beobachtungen am Erzinhalt von Gesteinen und an Chromerz aus Tampadel in Schlesien. Zeitschr. f. Krist. Min. u. Petr. Abt. B, Bd. 52.

JENNESS, STUARD, E. (1959) Magnetic Chromite from Shaal Pond, Northeastern Newfoundland. Econ. Geol. 54.

KRAUSE, H. (1958) Erzmikroskopische Untersuchungen an türkischen Chromiten. N. Jahrb. Min., Abh. 90.

MOGENSEN, E. A. (1946) A Ferrotitanate Ore from Södra Ulvöen. Geol. Fören. i Stockholm Förh. 68.

PINSL, HANS (1944) Photometrische Eisenbestimmung in Eisenerzen und Schlacken mit lichtelektrischer Messung. Z. Ver. deut. Chem. Beih. 48.

RAMDOHR, PAUL (1953) Ulvöspinel and its Importance in Titanium-rich Magmatic Iron Deposits. Econ. Geol. 48.

—»— (1955) Die Erzmineralien und ihre Verwachsungen. Akad. Verlag, Berlin.

SAMPSON, EDUARD (1929) May Chromite Crystallize Later? Econ. Geol. 24.

—»— (1942) Chromite Deposits. *In*: Ore Deposits as related to Structural Features. Princeton.

SCHNEIDERHÖHN, HANS (1944) Erzlagerstätten. Jena.

—»— (1958) Die Erzlagerstätten der Erde, Bd. I. Stuttgart.

SPANGENBERG, K. (1943) Die Chromerzlagerstätten von Tampadel am Zopten. Z. prakt. Geol. 51.

STEVENS, ROLLIN, E. (1944) Composition of Some Chromites of the Western Hemisphere. Amer. Mineralogist 29.

THAYER, T. P. (1946) Preliminary Chemical Correlation of Chromite with the Containing Rocks. Econ. Geol. 41.

van der Valt, C. F. J. (1942) Chrome Ores of the Western Bushveld Complex Trans. Geol. Soc. of South Africa. Vol. 44.

de Vijkerslooth, P. (1943) Mikroskopische Beobachtungen an antolischen Chromerzen. Z. Inst. Lagerstättenforsch. der Türkei M. T. A. 2/30.

Watts, H. L. (1958) Volumetric Determination of Aluminium in Presence of Iron, Titanium, Calsium, Silican and other Impurities. Anal. Chem. 30.

Winchell, A. N. (1941) The Spinel Group. Amer. Mineralogist 26.

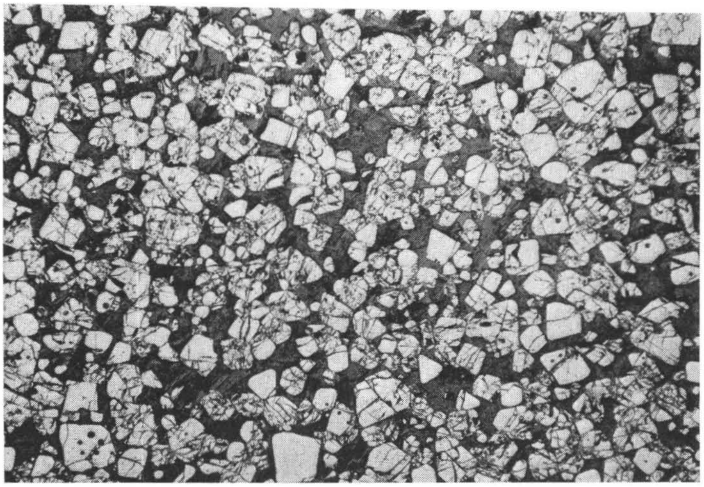


Fig. 1. Coarse grained ore. Typical cataclastic structure. Here and there inclusions of serpentinized olivine grains in the chromite are visible. x 10.

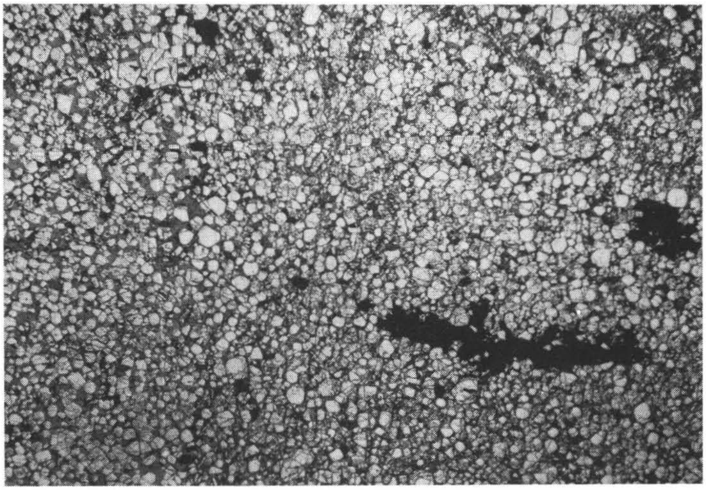


Fig. 2. Medium grained ore. In the upper right corner, two narrow zones of a later crushing are evident (see, Fig. 2, Pl. III). x 10.

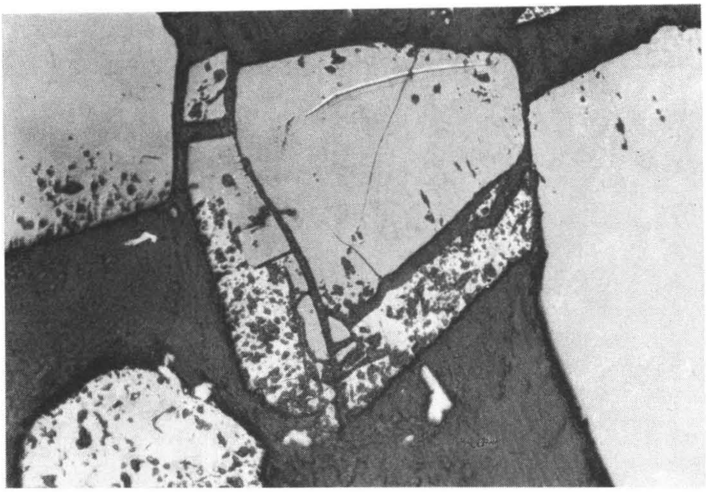


Fig. 1. Corrosion of the magnetite surrounding the chromite grain. The matrix antigorite serpentine. x 160.

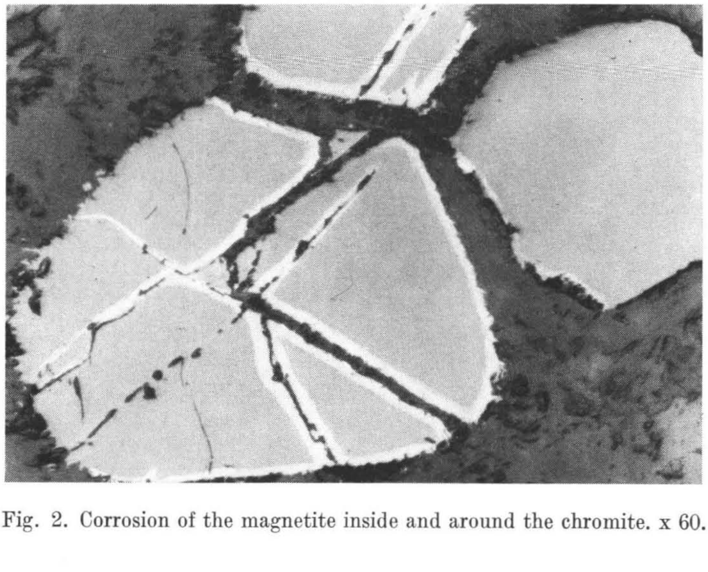


Fig. 2. Corrosion of the magnetite inside and around the chromite. x 60.

Fig. 1. Fine grained ore. x 10.

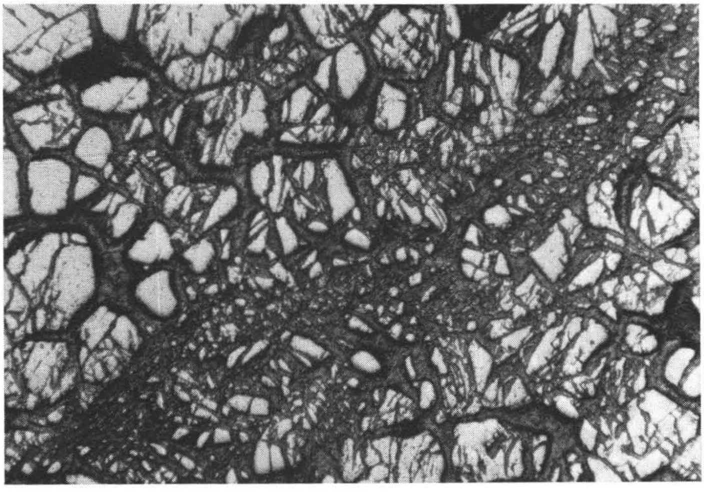


Fig. 2. A narrow crush zone along which a strong cataclastic breaking of chromite grains has taken place (see, Fig. 2, Pl. I). ×60.

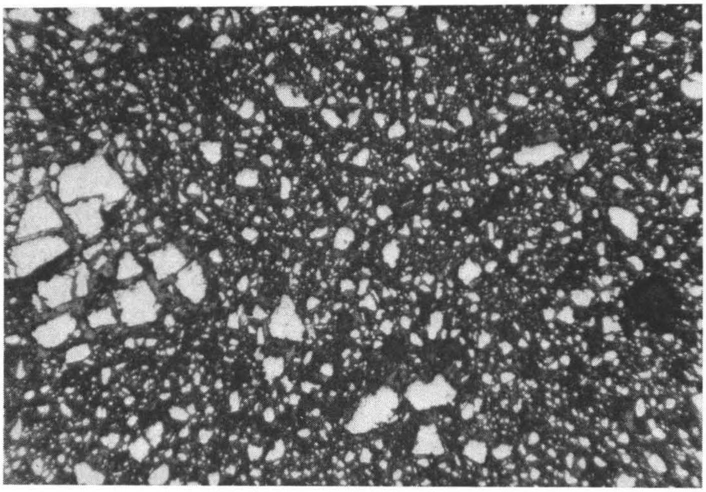


Fig. 1. Final stage of the cataclasis of the coarse grained ore amounts to the structure of the fine grained ore. The picture was taken from the fine grained ore by using a magnification equal to that used for Fig. 2, Pl. III. x 60.

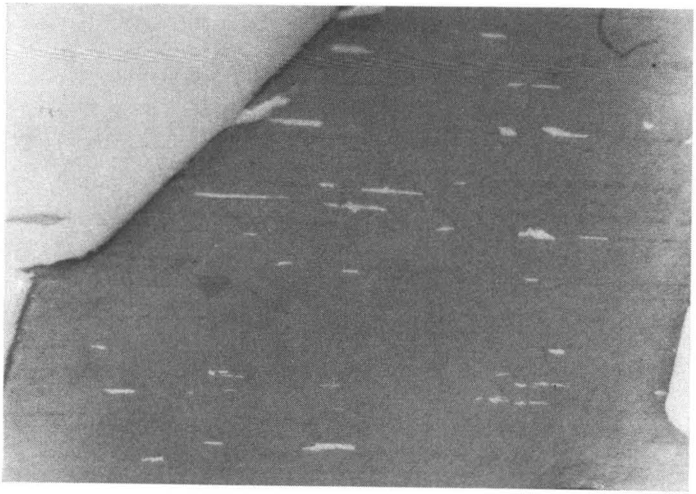


Fig. 2. Interstitial ilmenite orientated according to the parallel structures present in the silicatic matrix. x 160.

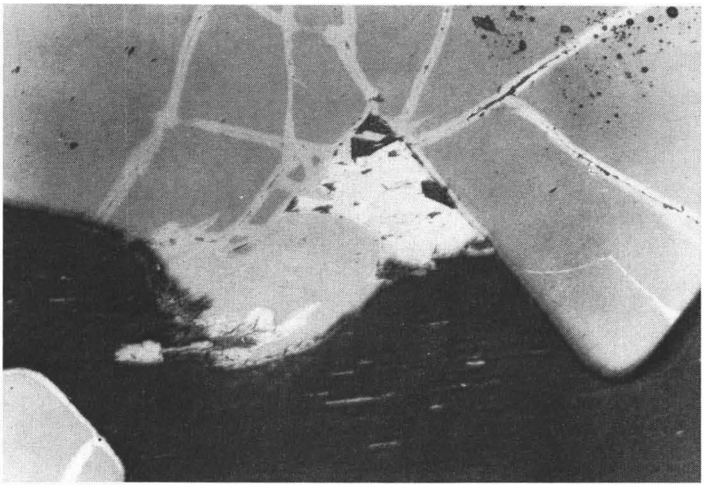


Fig. 1. Bands of secondary alteration in the chromite. An area of magnetite bordered by chromite in center of the figure. x 160.

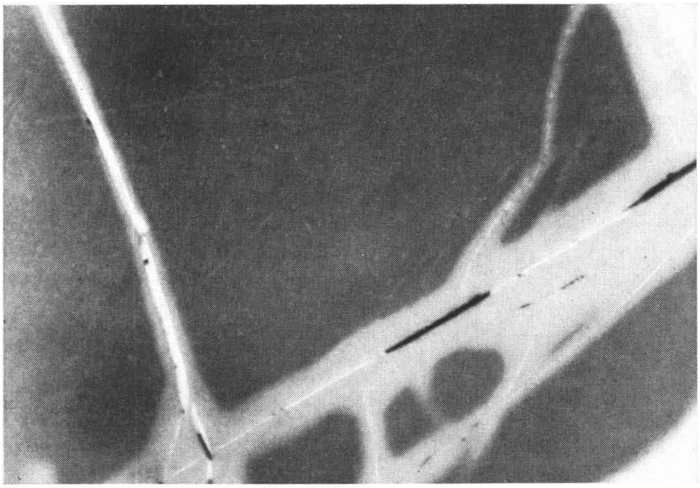


Fig. 2. Bands of secondary alteration in the chromite. The bands are dominated by »grey magnetite». The narrow stripes showing the highest reflectivity are composed of the magnetite. x 650, oil.

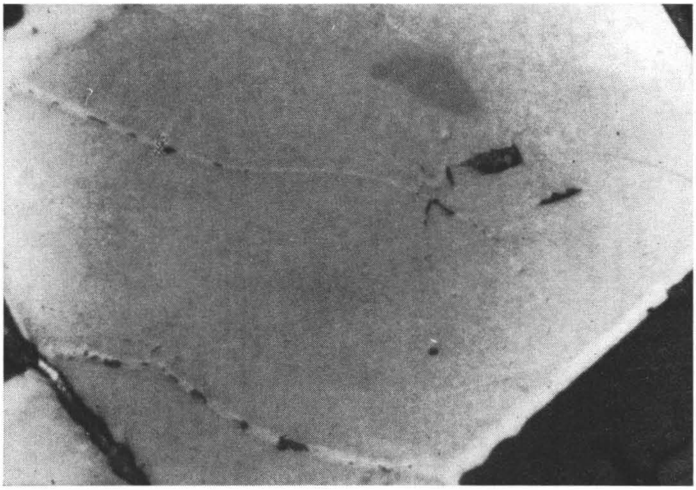


Fig. 1. A grain of the chromite showing an intense alteration and surrounded by a magnetite rim. A small grain only of the original chromite has escaped the effect of alteration. x 650, oil.

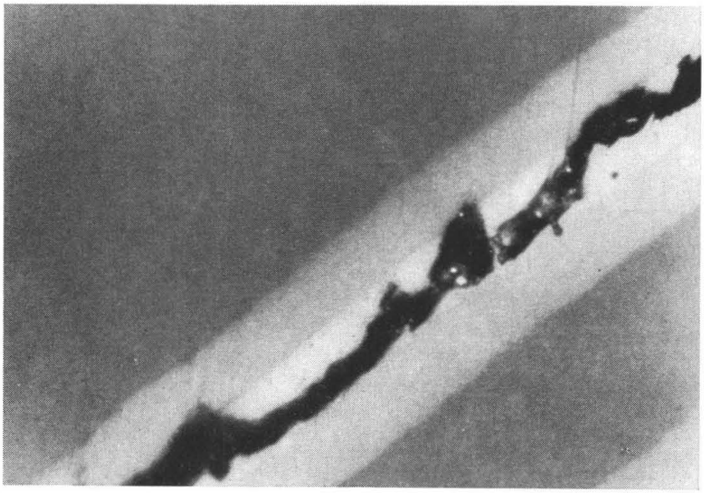


Fig. 2. A detail from an altered band in the chromite. Dark grey = chromite; pale grey = »grey magnetite»; white = magnetite; black = silicate. x 650, oil.

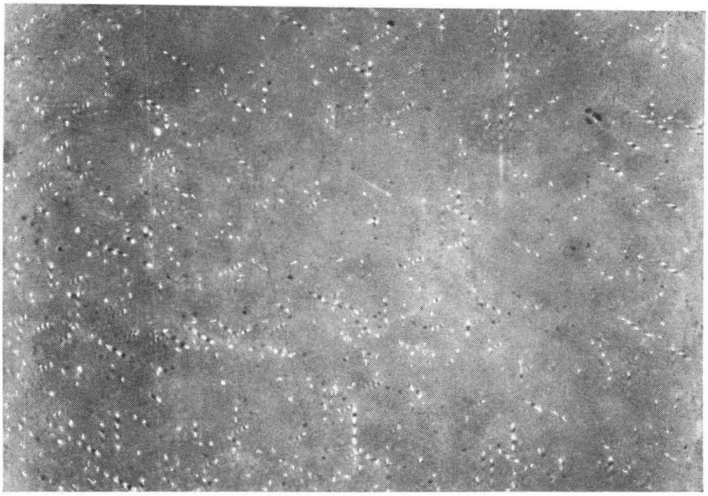


Fig. 1. Speack pattern in the chromite. x 650, oil.

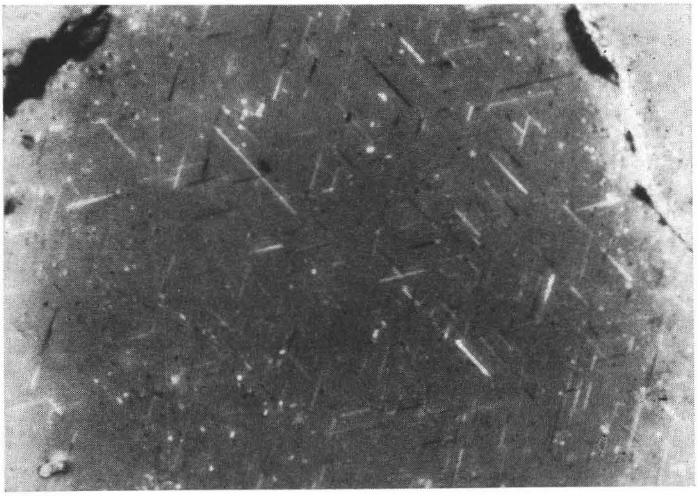


Fig. 2. Lamellae pattern in the chromite. The figure probably shows another section from the pattern seen in the former figure. x 650, oil.

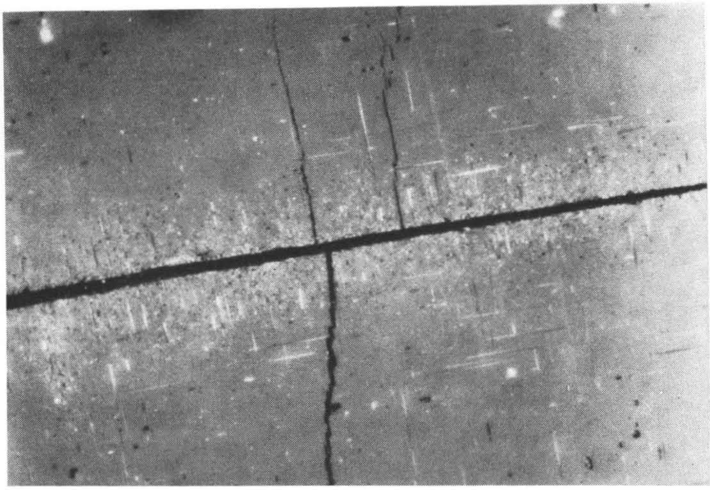


Fig. 1. Alteration spots and lamellae pattern along the crack borders in the chromite. x 650, oil.

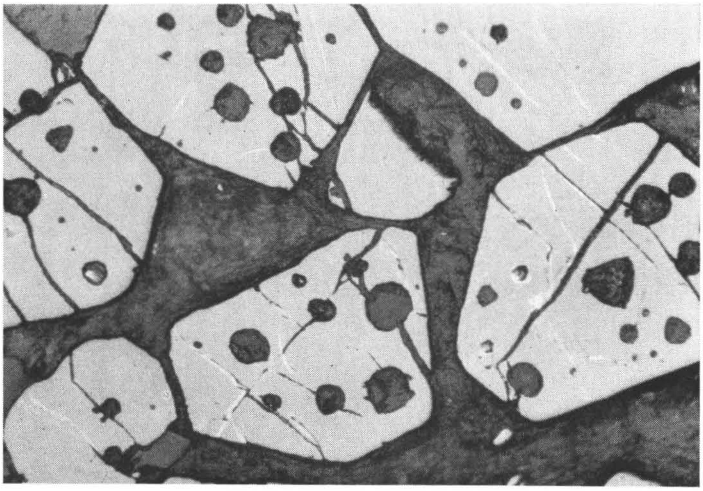


Fig. 2. Abundantly serpentinized inclusions of olivine in the chromite. x 60.