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ON THE GEOCHEMISTRY OF SWEDISH IRON ORES AND ASSOCIATED ROCKS

A STUDY ON IRON-ORE FORMATION

BY

STURE LANDERGREN

Pris 5 kronor

STOCKHOLM 1948
AB. KARTOGRAFISKA INSTITUTET. ESSELTE AB.
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AV

STURE LANDERGREN
FILOSOFIE LICENTIAT

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Preface.

In this paper are presented the results of an investigation of the geochemistry of iron ores and associated rocks. The author's primary intention was to study the distribution of some significant minor constituents in the Swedish pre-Cambrian iron ores. During the course of the investigation, however, it proved necessary to enlarge the research material to include ore types not represented in the Swedish pre-Cambrian iron-bearing formations.

In order to make possible a discussion of the problems connected with the iron-ore formation in the upper lithosphere from a geochemical point of view, a statistical study was necessary of the distribution of the most important major constituents of iron ores and of the principal igneous rocks.

The spectrochemical investigation of the minor constituents was started as early as 1937 while the author was studying spectrochemical research methods at the well-known geochemical laboratory of Professor V. M. Goldschmidt at the University of Oslo.

In the year 1940 a geochemical laboratory was founded at the Geological Survey of Sweden, so the investigations mentioned could continue there. In 1943 the author published a geochemical study on the apatite iron ores of the Grängesberg mines. That paper forms part of the present more extensive work.

During the war other problems craved attention in the geochemical laboratory, so that at times my studies on iron ores were interrupted. Other difficulties arose during the war. Owing to the lack of communications with foreign research institutions the research material could not be made as comprehensive as desired.

Stockholm, February 1948.

Sture Landergren.

Abstract.

This volume deals with the geochemistry of iron ores. By means of spectrochemical analyses some significant minor constituents have been determined in samples mainly from the pre-Cambrian iron-ore regions of Sweden. For the sake of comparison some samples of iron ores of different age from non-Swedish regions have been analysed.

On the basis of the analytical data available some significant statistical quantities have been computed in iron ores as well as in the main igneous rock series. Special regard has been paid to the relationship between the distribution principles governing some major constituents in the iron ores, on the one hand, and in the igneous rocks on the other. A method is proposed for geochemical investigations of igneous rocks by means of statistical data.

With the aid of geochemical premises the endogene relationship between iron ores and their associated igneous rocks has been discussed.

A theory on the principles governing the formation of iron ores has been advanced and employed with special regard to the origin of the pre-Cambrian iron ores of Sweden.

Introduction.

In an earlier investigation by the author on the geochemistry of the apatite iron ores of the Grängesberg mines in Central Sweden the opinion was advanced, with the aid of geochemical premises, that the ores in question must be regarded as magmatic — on account of their geological occurrence — but of secondary magmatic formation. The primary enrichment of iron took place in a cycle in the upper lithosphere and occurred mainly in the exogene phase of the cycle.

Apart from the accuracy of the working hypothesis advanced in the paper mentioned, it would seem convenient to divide the ore-forming processes into two moments, especially when dealing with problems connected with the origin of metamorphic ores. The primary moment is the enrichment of the ore-forming elements and the secondary moment includes the geological processes that give the enrichment product the geological features that are distinctive of an ore. It is evident, however, that secondary processes of some kind may also frequently involve an enrichment moment, but the primary enrichment is nevertheless the principal cause of the ore formation.

This way of looking upon the problems connected with the origin of ores — axiomatic in itself — is of importance with regard to the research methods to be used. Thus, when studying the primary moment of an ore-forming process we should deal with the principles governing the distribution of the elements

— an essential geochemical matter — since in such a research geochemistry would have one of its most important applications.

We are fairly well informed regarding the distribution of the elements in different geological milieus and we have, too, a fair idea of the average contents of most elements in the upper lithosphere, thanks to the fundamental investigations of F. W. Clarke, H. S. Washington, R. A. Daly, V. M. Goldschmidt, G. Hevesy, and many others. However, when turning to the principles regulating the distribution and, especially, the enrichment of elements during the geological evolution in the upper lithosphere our knowledge is somewhat limited. Indeed, many hypotheses have been advanced but few of them are founded on facts, for there are a number of difficulties to overcome. Some elements can become enriched due to either exogene or endogene processes, some of them — probably the major part — only in connection with exogene agents. The author is inclined to consider that the effects of endogene activity in connection with the enrichment of elements in the upper lithosphere have hitherto been overrated.

In this investigation the problems connected with the enrichment of iron and the ore formation will be dealt with. The distribution of some elements significant to different stages of the development of the upper lithosphere have been estimated and discussed. The distribution of some of the major constituents of igneous rocks and iron ores has been compared and discussed on the basis of their correlation coefficients and other statistical characteristics. Finally, the author advances his opinion — based on geochemical premises — on the principles governing iron-ore formation in the upper lithosphere.

The book is divided into two parts. The first part contains the data of the research material, an account of the methods used and the analytical results. In part two the problems are discussed from a geochemical point of view.

Part One.

Chapter I.

Research Material.

Average samples of ores and rocks are, of course, the most suitable research material when studying the distribution of elements. When such material has been available it has, therefore, been preferred, and several average samples of ores have been placed at the author's disposal from the various mining fields included in this investigation. Most of the samples, however, emanate from rock or ore specimens in the collections of the Geological Survey of Sweden, the Mineralogical Department of the Museum of Natural History and the University of Stockholm. A very valuable collection of samples of titaniferous iron ores was kindly placed at the author's disposal by the United States Geological Survey and the National Museum in Washington. A number of samples of ores and rocks from Central Sweden have been collected by Professor Nils H. Magnusson, Stockholm, and by the author. A collection of samples of Finnish bog iron ores has been available to the author thanks to the courtesy of Professor E. Kranck of Helsingfors.

In some cases spectrochemical analyses on minor constituents have been made on material which had previously been chemically analysed. A few data regarding the distribution of some minor constituents emanate from the literature.

The ore samples from Central Sweden have generally been magnetically separated and the magnetic and non-magnetic fractions have been spectrochemically analysed separately in order to get an idea of the distribution of some minor constituents of magnetite and gangue respectively. All the samples of apatite ores from Northern Sweden have undergone magnetic separation.

The analytical data necessary for the statistical calculations have been obtained from the various literature at my disposal. The following works have been mainly employed: H. S. Washington, Chemical Analyses of Igneous Rocks (120); F. W. Clarke and H. S. Washington, The Composition of the Earth's Crust (15); F. W. Clarke, The Data of Geochemistry (14); V. M. Goldschmidt, Geochemische Verteilungsgesetze der Elemente IX (46); Walter Larsson, Chemical Analyses of Swedish Rocks (72); S. Palmqvist, Geochemical

Studies on the Iron-bearing Liassic Series in Southern Sweden (96); Jernkontorets analyser å svenska järn- och manganmalmer II (63); W. Cross, Lavas of Hawaii and their Relations (16); Th. G. Sahama, On the Geochemistry of the East Fennoscandian Rapakivi Granites (103); and H. Hougen, E. Klüver, O. A. Lökke, Undersökelser over Norske Lerer V (62).

Elements Investigated.

The Ferrides. This collective term is proposed for the following elements: titanium, vanadium, chromium, manganese, iron, cobalt, and nickel. As regards the atomic structure the ferrides form a group of transition elements where the construction of the incomplete M-shell continues while the outer shell of the core remains unchanged. Accordingly, the chemical differentiation is comparatively feeble, as mentioned by F. W. Aston (3) and V. M. Goldschmidt (46). This finds an expression in a certain coordination of the distribution of the ferrides in Nature. Thus, when studying the geochemistry of iron, especially the enrichment of iron, the contents of the other ferrides in different cases of enrichment should be regarded as significant.

Lithium. This member of the alkali metals is univalent with an ionic radius = 0.78 Å and enters a crystal structure in six-coordination quite similar to the divalent magnesium, a major constituent of igneous rocks and skarn rocks associated with iron ores.

From a geochemical point of view Li may substitute Mg in crystals formed in a later stage of an endogene development. Thus, the content of Li and the ratio Li/Mg may be regarded as significant, especially for the magnesium-bearing skarn rocks.

In the exogene development of the earth's crust Li can become enriched in aluminous marine sediments. It should be emphasized, too, that the ratio Li/Mg in the upper lithosphere is much higher than the corresponding value of sea-water.

Rubidium. The ionic radius of this univalent alkali metal is large (= 1.43 Å) and in minerals Rb is seldom found in lower coordination than nine to ten. It occurs to a large extent in potassium minerals of the later stages of endogene development. The ionic radius of potassium is 1.33 Å. Thus, the ratio Rb/K will increase towards the latest fraction of a crystallizing magma.

In the marine clay sediments Rb can be enriched (through adsorbtion) and the ratio Rb/K tends to values above the average of the upper lithosphere. The average content of the ratio mentioned is, therefore, higher than that of sea-water.

In this investigation the contents of Rb and the ratio Rb/K are studied in the salic rocks associated with iron ores and in the gangues of iron ores.

Beryllium. According to investigations on the geochemistry of beryllium it is enriched in the residual liquid during magmatic differentiation. The ionic radius is small (0.34 Å) and it generally occurs in four-coordination. In the sedimentary development beryllium may become enriched in aluminous marine sediments. In the present investigation the content of beryllium is noted in the gangues of the iron ores and in the rocks of Central Sweden associated with the iron ores.

Boron. This element was earlier looked upon as an element exclusively significant to and enriched in magmatic residual solutions. Later geochemical investigations have shown that the chief milieu of enrichment of boron is the marine clay sediments. In marine iron ores, too, it can become enriched. The content of boron has been estimated in all iron ores and their associated rocks investigated.

The Lanthanides. Some few examples of the distribution of this group of elements in apatite iron ores are involved in this investigation. The results mainly emanate from an earlier investigation by the author (67).

Molybdenum and Tungsten. The distribution of these two metals is of minor importance for the genetic problems to be discussed. Nevertheless, the distribution of Mo and W in iron ores may be of interest from an economic point of view.

The Quartz Ratio (qv). This quantity is the molecular proportion in per cent of SiO_2 and the divalent oxides of calcium, magnesium, iron and manganese. In calculations of qv in iron ores, however, one equivalent FeO necessary for the magnetite molecule, and, in apatite iron ores, also one equivalent CaO for the apatite molecule, are excluded.

The ratio qv was introduced by H. E. Johansson (64), whose fundamental investigations on the chemistry of the iron ores of Central Sweden made possible a classification of the iron ores in question from a chemical point of view. Even if one may have suspicions as to a quotient including so many components, it has nevertheless proved useful in giving an idea of the content of quartz entering the gangues of iron ores and the quartz content of rocks.

Degree of Oxidation (og). The importance of the ratio Fe_2O_3/FeO is, of course, plain to any reader. The quantity og is calculated according to a formula advanced by I. Sahlin (105) and is the content of oxygen bound to iron in per cent of the oxygen present if calculated to be bound as Fe_2O_3.

The Ratio MgO/CaO (mc). The ratio in question is the molecular proportion in per cent of MgO and CaO. In a pure endogene development of a magma mc decreases as the content of SiO_2 increases, partly on account of the difference in ionic radii of magnesium and calcium respectively ($Mg^{2+} = 0.78$ Å and $Ca^{2+} = 0.96$ Å) and partly due to the difference in coordination number, magnesium being six-coordinated and calcium higher than six-coordinated. Thus, the correlation between qv and mc is essential when dealing with the problem of the origin of rocks associated with iron ores and of igneous rocks on the whole.

The Ratio MgO/FeO (mgf). This quotient is calculated in the same manner as the mc just mentioned. The ratio mgf is of interest in connection with the distribution of some ferrides in rocks and iron ores.

The Ratio K_2O/Na_2O *(kn).* This molecular proportion in per cent of the two main alkalies corresponds to the k-value of Niggli's system. Thus, kn=100 k. The ratio kn is of major importance when discussing the iron ores of central Sweden and their associated rocks.

The Ratio Mn/Fe (mf). The quantity in question is, of course, essential for various kinds of enrichment processes of iron in the upper lithosphere. Especially in the case of the ores of Central Sweden is the correlation between mf and the other ratios mentioned above of great importance.

Research Methods.

Most of the major constituents have been determined by means of chemical analyses made in the chemical laboratory of the Geological Survey of Sweden. Some control analyses of minor constituents have also been made in the chemical laboratory mentioned.

Spectrochemical Methods. The minor and some of the major constituents have been determined by means of optical spectral analyses. The methods used are familiar to any geochemist or spectral analyst. There is no reason, therefore, to repeat the spectrochemical technique in all details; it is available in the literature cited below. Thus, only a short survey is given of the instruments and methods used in this investigation.

For analyses in the ultra-violet spectral range a medium-sized quartz spectrograph of Zeiss's construction ("Q 24") has been mainly used. Lately, also a large quartz spectrograph of Littrow type (Adam Hilger, London, type E:292) has been used in some cases.

For the visual spectral region a three-prism glass spectrograph of Zeiss's construction (Zeiss' Dreiprismenspektrograph) with the cameras f: 85 cm and f: 130 cm (the latter with autocollimation) has been used. Especially in cases when a large dispersion and dissolving power was necessary the latter camera proved very convenient. Further optical data regarding the spectrographs mentioned are available in the catalogues of spectrographs from the manufacturers in question.

The electric arc has been used as a source of light in all cases. The interrupted arc method has been used in cases when metal electrodes were used. In such cases copper rods with a length of 20 mm and of a diameter of 3 mm were used. The powdered samples to be analysed were packed into a half-spherical bore in the electrode used as cathode. In a few cases also carbon rods with a length of 25 mm and a diameter of 5 mm were used.

The interrupted arc method was elaborated by K. Pfeilsticker (97). The special technique used in the geochemical laboratory of the Geological Survey has earlier been described by the author (69).

The technique of the permanent carbon arc method was worked out by R. Mannkoppf and Cl. Peters (85), collaborators of V. M. Goldschmidt. The method in question still vindicates its position as the most useful one when determining minor constituents in rocks and minerals. It has been described in its geochemical applications by several investigators of the Goldschmidt school, *i.a.* L. W. Strock (112), C. Preuss (98), W. Noll (94), W. von Engelhardt (19), and others. The method most generally applied for the purification of carbon for spectrochemical use has been described by A. Gatterer (28).

In quantitative work it is preferable to project the light source, or the cathode layer respectively, enlarged on the collimator lens or the prism of the spectrograph. By means of three condenser lenses and a diaphragm (cf. H. Kaiser (65) the slit becomes uniformly and diffusely illuminated with a maximum intensity. The focal length of the condenser lenses used is adapted to the aperture of the spectrograph. This optical arrangement has proved very useful in quantitative work and has been applied in the present investigation.

However, in cases when the whole aperture of the spectrograph is needed, a sharp image of the arc has been focussed on the spectrograph slit by means of a spherical condenser lens. As Wa. and We. Gerlach (39) have emphasized, maximum intensity will be reached when the magnification is 1: 1 and the aperture of the condenser lens is equal to that of the collimator lens of the spectrograph.

In front of the spectrographic slit was placed a three or six step light filter. The filters have three or six adjacent areas of density, respectively, bearing a known relation to each other and producing three or six spectra of different density with a single exposure. On the filter, or in front of it, a quartz condenser lens (f=200 mm) was placed in order to produce the uniform illumination at the slit as mentioned above. In working with the permanent carbon arc method a rotating seven-step sector replaced the light filter. The time of exposure for each step decreased with the factor two.

The results obtainable with the step sector or the light filter method have proved to be of sufficient quantitative accuracy for the present purpose, even when the photometric measurements are replaced by visual inspection of the spectra. This very useful method of estimation has been described by L. W. Strock (112) and has *i.a.* been applied in a spectrochemical investigation of Swedish sphalerites by O. Gabrielson (27).

In the photometric measurements of the spectral line intensities two types of photometers have been used: a non-recording spectral line photometer of Zeiss's construction ("Spektrallinienphotometer") and a non-recording photometer originally constructed by the late Dr. G. Phragmén and co-workers of Metallografiska Institutet, Stockholm, and now manufactured by the instrument makers Stålex of Stockholm. In fig. 1 the optical arrangement of the Stålex photometer is schematically illustrated.

The reproducibility of results obtained by means of spectrochemical methods depends to an appreciable extent on the composition of the standard mixtures used. Thus, in the present investigation, a series of standard mixtures was prepared to approximate as closely as possible to the nature and composition of the actual samples to be analysed. In determining the content of ferrides in iron ores, for instance, an iron ore, whose contents of the ferrides to be determined were below the limits for spectrochemical estimation, was chosen as the basic component of the standard mixture series. When using an internal standard (*e.g.* chromium) it was added as a mixture of Cr_2O_3 in quartz, ferride-free felspar or calcite, equivalent to 10 per cent Cr_2O_3. One part of this mixture was carefully mixed with one part of all standard mixtures and the samples to be analysed. The samples and mixtures thus contained 5 per cent of Cr_2O_3.

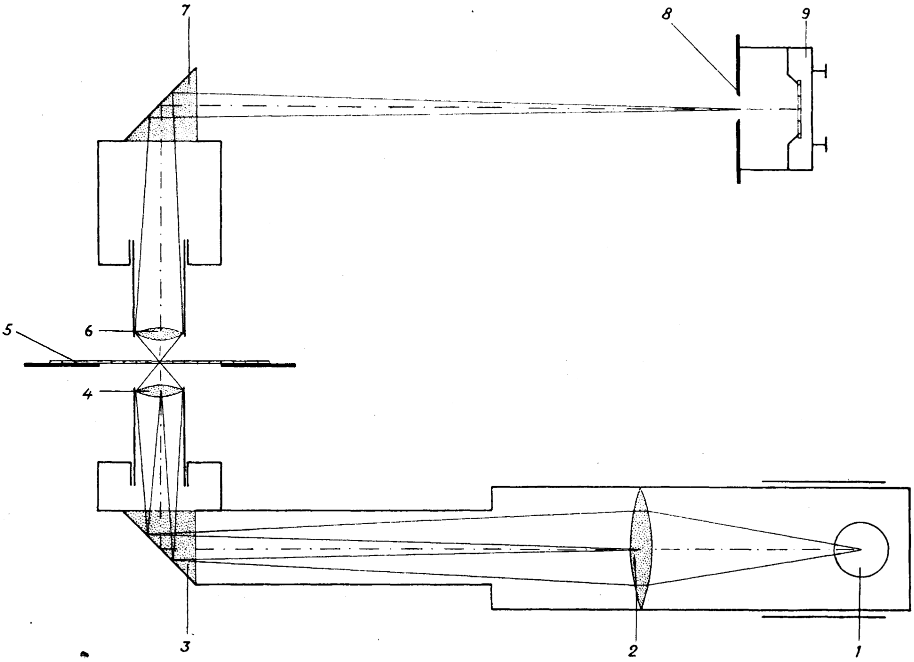

Fig. 1. The optic arrangement in the Stålex spectrophotometer. 1 light source, 2, 4 and 6 condenser lenses, 3 and 7 glass-prisms and mirrors, 5 table with the spectral plate, 8 slit, and 9 photoelectric cell.

The accuracy of the spectrochemical methods used is shown in the survey below. The standard deviation from the mean is approximately 10 to 30 per cent. This degree of accuracy is quite sufficient in the present investigation, if we bear in mind that the distribution of the minor constituents can vary much beyond the limits of analytical errors.

A survey of the analytical data of the elements spectrochemically determined is given below.

Titanium. Spectrum obtained with the carbon arc cathode layer method. Spectral lines 3349.4 and 3349.0. In determining Ti in magnetites the Fe line 3347.9 was used as internal standard. In other cases, when the content of Ti was low, it was estimated by comparing a standard spectrum with the spectrum of the samples analysed. The accuracy of the lower titanium contents is comparatively low. The error is approximately ± 40 per cent. The higher contents of Ti are all chemically determined.

Vanadium. Spectrum obtained with the carbon arc cathode layer method. Spectral line: 3184.0. Internal standard Cr 3163.1 or Fe 3184.9 (in cases when Fe was chemically determined). The lower contents estimated by means of the step sector method. Error ± 25 per cent. The higher contents were determined by means of photometric measurement of the line intensities. Error: ± 10 per cent.

Chromium. Spectrum obtained as above. Spectral line: 4254.3. The contents estimated by visual inspection and comparison with a standard spectrum of chromium. Error: approximately ± 30 per cent.

Manganese. Spectrum obtained as above. Spectral line: 2576.1. Internal standard: Cr 2571.7 or Fe 2575.8. The contents estimated by means of the step sector method (error ± 25 per cent) or by means of photometric measurement of the line intensities (error < ± 10 per cent).

Iron. In most cases iron was chemically determined. In some cases iron was spectrochemically estimated (up to 20 per cent of Fe) and then with Cr as internal standard. Method: see above. Fe line: 2999.5, Cr line: 2998.8. Error approximately ± 15—20 per cent.

Cobalt. Spectrum obtained as above. In cases when chromium was used as internal standard, the following pair of lines was used: Co 3405.1 and Cr 3403.3. When iron served as internal standard, the lines Co 3453.5 and Fe 3450.3 were used. In both cases the contents were estimated by means of the step sector method. Error approximately ± 25 per cent.

Nickel. Spectrum obtained by means of the carbon arc cathode layer method. Spectral line 3414.8. Internal standard Cr 3421.2 or Fe 3415.5. In most cases the line intensities were measured with the aid of the photometer. Error ± 10 per cent.

Lithium. Spectrum obtained either by means of the carbon arc method, cf Strock (111), or the interrupted arc with copper electrodes. In the carbon arc method strontium served as internal standard. Spectral lines used: Li 6707.9 and Sr 6408.5. In cases when the interrupted arc was used the intensity ratio spectral line/background was measured. The latter method was used only with low contents of Li. Errors: the carbon arc method with internal standard ± 10 per cent or lower; the interrupted arc method ± 15—20 per cent. In the preparation of the standard mixture series of Li a synthetic glass, containing 1 per cent Li, was used as basic substance.

Beryllium. Spectrum obtained with the carbon arc method. Spectral line 2348.6. The contents estimated by means of the step sector method. Error approximately ± 25 per cent.

Boron. Spectrum obtained by means of the interrupted arc method with copper electrodes. Spectral line B 2497.7. Internal standard Sb 2598.1 or 2478.3 depending on the content of iron present in the sample to be analysed. The line intensities were measured with the aid of a photometer. (Cf. Landergren (69).

Magnesium. Spectrum obtained with the carbon arc method. Spectral line Mg 2781.4. Internal standard Cr 2780.7. Line intensities measured by means of a photometer. Error ± 10—15 per cent.

Potassium. Spectrum obtained by means of the interrupted arc method with copper electrodes. Spectral line K 7664.9. The intensity ratio line/background was measured. Error approximately ± 20 per cent.

Rubidium. Spectrum obtained by means of the carbon arc method. Internal standard was barium. Spectral lines used were Rb 7800.3 and Ba 7780.5. Line intensities measured by means of a photometer. Error ± 15 per cent. The basic substance for the preparation of the standard mixture series was a synthetic glass containing 1 per cent Rb. See further Goldschmidt, Bauer and Witte (53).

Molybdenum. Spectrum obtained by means of the carbon arc method. Spectral line used: Mo 3170.3 and 3864.1. The intensity ratio line/background was measured. Error approximately ± 20 per cent.

Tungsten. The carbon arc cathode layer method was applied. Spectral lines: W 2947.0 and 4008.8. The intensity ratio line/background was measured by means of a photometer. Error approximately ± 20 per cent.

Arcing Procedure. a): The carbon arc cathode layer method: Time of exposure 2 minutes. Rotating step sector or light filter in front of the spectrographic slit. A 220 volt direct current was employed, regulated with a variable resistance to 2.5 amps during the first 30 seconds of exposure, and then 8 to 9 amps for 90 seconds.

b): The interrupted arc method: Total time of exposure 2 minutes. Light filter in front of the spectrograph slit. The rotating switch was so regulated that the effective exposure was 30 sec, which makes 120 discharges a minute and each discharge $^1/_8$ sec. A 220 volt direct current was regulated with a variable resistance to approximately 9 amps, except for the boron analyses, where it was regulated to 4 amps.

Photographic Procedure. The opening of the spectrographic slit was 0.01 mm in the ultra-violet range and 0.02—0.05 mm in the visible range.

The following spectral plates have been used: a): in the ultra-violet range: Perutz' Graphische Platte B, Agfa Phototechnische Platte A and Agfa Ultraviolett Platte. b): In the visible range: Agfa Spektral "blau", "gelb" and "rot". Ilford long range spectral plate and (in the infra-red region) Agfa Infrarot 800 rapid and Ilford infra-red plate.

The plates were developed in 3 to 4 minutes at 18° C in a metholhydrochinone developer.

Statistical Calculations.

The quantities, terms and methods of calculation were as follows:

$$qv = \frac{100\,SiO_2}{SiO_2 + CaO + MgO + FeO + MnO};$$

$$og = \frac{100\,(0.300 + 0.222\,p)}{(0.700 + 0.778\,p)\,\frac{0.3}{0.7}};\ p = \text{the ratio } FeO/Fe_2O_3 \text{ in per cent of weight.}$$

$$mc = \frac{100\,MgO}{MgO + CaO};$$ The ratios mgf, kn and mf were calculated as for mc.

All ratios are molecular.

N is the number of analyses included in the calculation, except for the iron ores of Central Sweden, where *N* represents the average for each mining field included in the calculations. Thus, 1,600 analyses of average samples of iron ores are distributed between 214 mining fields.

M is the arithmetic mean. Thus $M = \frac{\Sigma\,x}{N}$. M has generally been calculated from the frequency tables and with the aid of the provisional mean M′. Thus

$$M = \frac{\Sigma(x - M')}{N} + M'.$$

T is called the mode and was calculated in the iron ores of Sweden.

σ is the standard deviation and calculated according to the formula

$$\sigma^2 = \frac{\Sigma(x - M')^2}{N} - (M - M')^2.$$ $100\,\sigma/M$ is the relative distribution or the coefficient of dispersion.

x and y are the variable quantities, *viz.* the ratios mentioned above.

$x_{max} - x_{min}$ gives the maximum dispersion.

r is called the product-moment coefficient of correlation of x and y in the frequency distribution. r is calculated according to the formula

$$r = \frac{\Sigma\,(x - M_x)\cdot(y - M_y)}{\sqrt{\Sigma\,(x - M_x)^2}\cdot\sqrt{\Sigma\,(y - M_y)^2}}.$$

M_x and M_y are the means of the variables x and y respectively. $r_{qv,mc}$ represents the product-moment coefficient of correlation between the ratios qv and mc, and so forth. The limits of the r-values are $+1$ and -1.

The standard deviation of the sampling distribution of r ("standard error of r") is approximately $(1 - r^2)/\sqrt{N}$, but this is only so when N is large (cf. A. C. Aitken (1); G. Yule, M. G. Kendall (126); and F. Wigforss (124).

Chapter II. Distribution of the Major Constituents.

In this chapter are presented the statistical data of the distribution of the major constituents in the igneous rocks and the iron ores of Sweden.

As mentioned earlier the purpose of the statistical investigation is to gain a conception of the principles of distribution. Thus, the r-values are of major importance.

The research material is the chemical analyses, available in the literature, of the most important igneous rocks and of Swedish iron ores, the latter having been the subject of the most thorough study. Chemical analyses of glacial clay from Norway have also been statistically calculated in order to demonstrate the geochemical features as regards the distribution of the major constituents significant to a type of sediment formed mainly due to the mechanical and chemical work of ice and fresh water. Unfortunately, the content of alkalies is generally not determined in Swedish iron ores. The computation of kn was impossible for that reason.

The results are presented in tables and histograms. The statistical data of the ratios are found to the left and the r-values to the right side in the tables. In the histograms the abscissa represents the ratios in question and the ordinate the frequency in per cent. The class-intervals in the rectangles are 5 or 10 units.

The Igneous Rocks.

The Quartz Ratio (qv). The igneous rocks are classified on the basis of their content of SiO_2. While the quartz ratio, qv, is a function of the content of SiO_2, this ratio should be regarded as the basis to which other ratios calculated should be related. Table 1 contains the statistical data of qv and its correlation coefficients. As to the left side of the table, no comments are necessary for reasons mentioned above. The right side, however, is of importance, showing the r-values which will be discussed in various connections.

The r-values of Table 1 illustrate, from a geochemical point of view, features of the distribution of the major constituents which will be familiar to any petrologist. Thus, $r_{qv,mc}$ is negative — with the exception of the Rapakivi granites of Finland and the glacial clays of Norway. This means that minerals

Table 1. **The Quartz Ratio (qv).**

	N	qv		M	σ	$\frac{100\sigma}{M}$	r-values				
		min	max				qv,mc	qv,og	qv,mgf	qv,kn	qv,mf
Igneous rocks											
Average:											
Peridotites.........	40	34.0	54.0	42.4	5.7	13.4	— 0.76	— 0.08	— 0.50	— 0.04	+ 0.09
Gabbros...........	237	41.0	91.0	64.3	7.2	11.1	— 0.32	+ 0.13	— 0.45	+ 0.11	— 0.11
Diorites...........	263	58.0	95.0	77.5	8.0	10.3	— 0.23	+ 0.31	— 0.17	+ 0.22	+ 0.24
Granites...........	170	83.0	99.0	93.9	3.8	4.1	— 0.06	+ 0.27	— 0.21	+ 0.24	+ 0.21
Basalts............	63	54.0	85.0	73.1	6.5	9.1	— 0.58	+ 0.70	— 0.39	+ 0.62	+ 0.24
Andesites..........	181	62.0	95.0	81.0	6.4	7.9	— 0.37	+ 0.42	+ 0.01	+ 0.23	+ 0.15
Rhyolites..........	64	90.0	99.8	97.8	3.5	3.6	— 0.02	+ 0.38	— 0.12	+ 0.16	— 0.22
Sweden:											
Gabbros...........	25	50.0	82.0	62.2	7.8	12.7	— 0.63	+ 0.26	—	+ 0.15	— 0.16
Diorites...........	32	56.0	83.0	70.7	8.3	11.7	— 0.18	+ 0.45	—	+ 0.01	+ 0.21
Granites...........	120	79.0	99.0	93.1	4.0	4.3	— 0.10	+ 0.12	—	+ 0.30	+ 0.07
Leptites...........	158	53.0	99.7	96.3	3.3	3.4	— 0.03	+ 0.23	— 0.20	+ 0.06	— 0.24
Other Regions:											
Rapakivi granites (Finland)	33	88.2	98.9	94.3	2.9	3.1	+ 0.28	+ 0.55	+ 0.38	+ 0.60	— 0.21
Volcanic series (Hawaii)..........	43	47.9	97.8	66.5	11.2	16.9	— 0.79	+ 0.54	— 0.35	+ 0.36	+ 0.49
Sediment											
Glacial clay, (Norway)..........	80	79.2	93.7	86.4	3.5	4.0	+ 0.05	+ 0.75	— 0.04	+ 0.03	+ 0.17

rich in magnesium in relation to calcium are significant for the basic members of rocks.

There are, however, other aspects of the quantity of $r_{qv,mc}$ to which preliminary attention should be paid. The numerical value of $r_{qv,mc}$ decreases as qv increases and approaches zero in the most salic members. Now, if the negative sign of $r_{qv,mc}$ represents a distribution principle, the same applies to the decreasing numerical value of it as qv increases. The latter principle is equally important, especially with regard to the origin of the upper lithosphere, which is mainly built up of salic rocks. The two principles mentioned will, therefore, be discussed in detail in the next part of this paper.

Turning to $r_{qv,og}$, we find that it is positive and that there are no exceptions. This is in agreement with the well-known fact that the content of minerals containing trivalent iron increases as the content of SiO_2 in the rocks increases. V. M. Goldschmidt has mentioned this feature with reference to the rock series of the Oslo field (47), but, as far as the author knows, this very important relationship between qv and og has hitherto been overlooked by petrologists. The importance of $r_{qv,og}$ in the igneous rocks should be plain to anyone, bearing in mind the fact that this quantity is an expression of the distribution principle of oxygen, the most abundant element in the upper lithosphere.

The numerical value of $r_{qv,og}$ varies between 0.12 (in the Swedish granites) and 0.70 (in the basalts of the world). No regularity could be discovered in the relation of $r_{qv,og}$ to the means of qv.

The correlation between qv and kn is also positive in all the cases observed. This is, too, in full agreement with petrological experience, while the minerals rich in potassium increase towards the most salic rocks. The numerical values of $r_{qv,kn}$ are lower than those of $r_{qv,og}$ on the whole, and some of them approach zero.

Finally, $r_{qv,mf}$ is irregular. The numerical values are comparatively low, in some cases positive, in others negative. The existence of a relationship between qv and mf in the igneous rocks may be questionable. Some geologists are of opinion that the ratio Mn/Fe increases towards the salic residual magmas, *e.g.* G. Berg and F. Friedensburg (9). Such a relationship may exist in some exceptional cases, but it is certainly no rule, as seen from Tables 1 and 6.

The histograms in fig. 2 illustrate the frequency distribution of qv in the igneous rocks investigated.

Degree of Oxidation (og). As already mentioned above, the degree of oxidation is of great importance, especially when dealing with problems connected with iron-ore formation in the upper lithosphere. One can readily share the opinion of B. Mason (86, p. 119) that "The system FeO-Fe_2O_3 is probably the most important metal oxide system known to Man".

However, the determining of FeO in rocks and ores raises difficulties due to the preparation of the samples to be chemically analysed. Oxidation can easily take place, *e.g.* in the grinding, and then the content of FeO will become too low. When sulphur is present, on the other hand, there may be a reduction of Fe_2O_3, which makes the values of FeO too high.

In Table 2 the statistical data of og are given. As seen from the left side of the table, the means of og increase as qv increases (cf. Table 1) in the rocks. They are in fact all but proportional. The means of og in the basic rocks (basalts and gabbros) are 77.5—79.1. The highest value is reached by the rhyolites (87.4). For comparison it should be mentioned that the og-value of magnetite is 88.9.

The right side of Table 2 contains the r-values. The figures of $r_{qv,og}$ have been discussed above. The correlation coefficients of og and mc are negative with the exception of the Rapakivi granite. The numerical values are low and some of them approach zero. Also the two other r-values, $r_{og,kn}$ and $r_{og,mf}$, show undecided tendencies and several values approach zero. Apart from the significant $r_{og,qv}$, the other r-values illustrating the relationship between og and mc,kn and mf respectively, are of minor importance on the whole.

Fig. 3 shows the frequency distribution of og in the igneous rocks and the glacial clays.

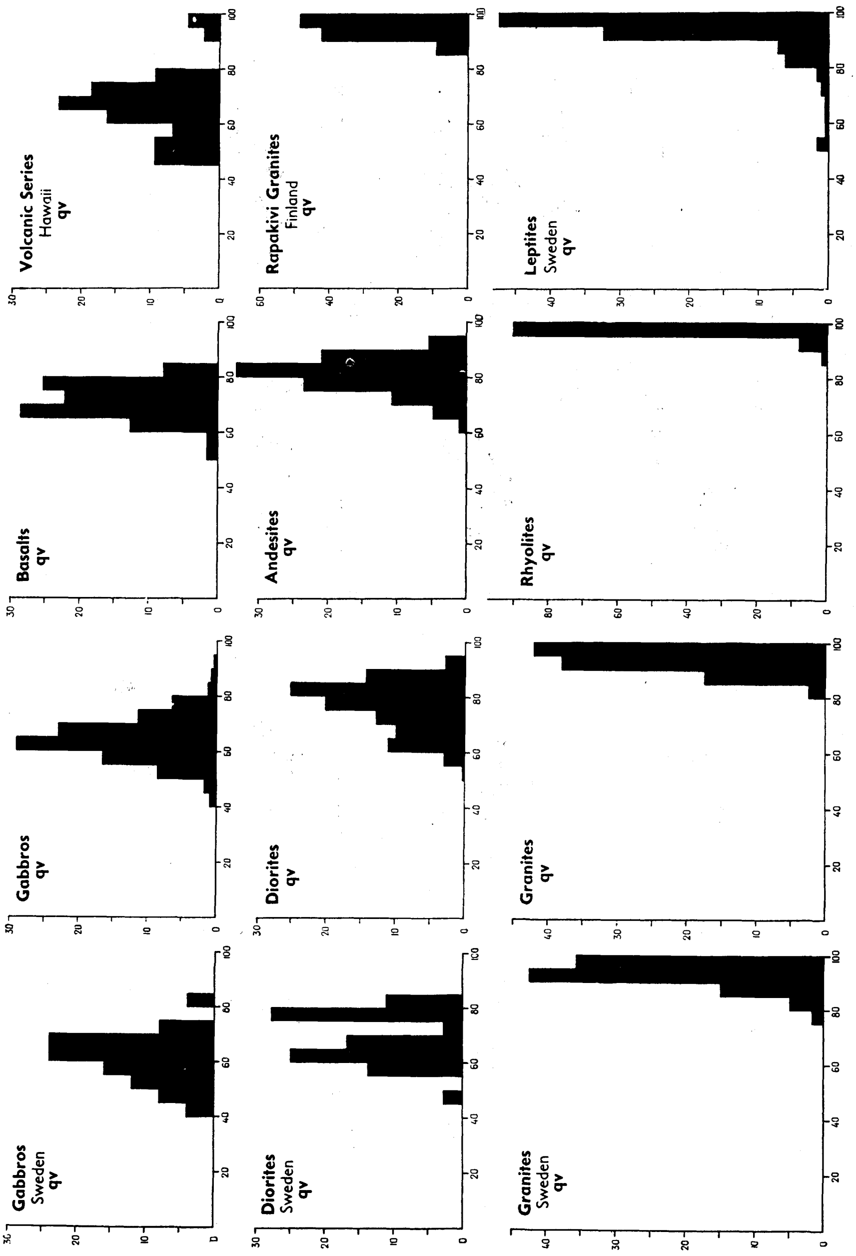

Fig. 2. Histograms of the percentage frequency distribution (ordinate) of the quartz ratio qv (abscissa) in the igneous rocks.

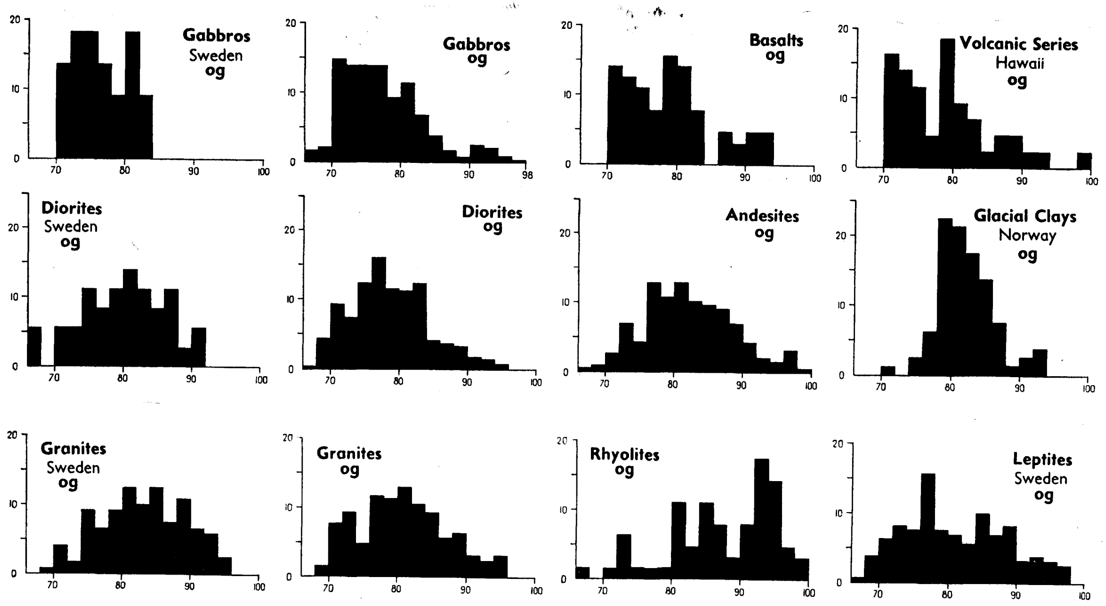

Fig. 3. Histograms of the percentage frequency distribution (ordinate) of the degree of oxidation og (abscissa) in the igneous rocks and glacial clay.

Table 2. **Degree of Oxidation (og).**

	N	og		M	σ	$\frac{100\sigma}{M}$	r-values			
		min	max				og,mc	og,mgf	og,kn	og,mf
Igneous rocks										
Average:										
Peridotites	40	67.5	85.2	76.2	5.6	7.4	—0.05	+0.46	+0.06	+0.03
Gabbros	237	68.0	96.0	77.5	5.9	7.6	—0.23	+0.29	—0.03	+0.26
Diorites	237	68.0	96.0	78.9	5.6	7.1	—0.15	+0.39	+0.02	+0.17
Granites	172	68.0	96.0	80.9	6.6	8.2	—0.02	+0.41	+0.12	+0.14
Basalts	64	70.7	97.7	79.1	6.2	7.9	—0.54	+0.30	+0.43	+0.10
Andesites	181	67.4	99.1	85.1	6.3	7.4	—0.09	+0.57	+0.01	+0.01
Rhyolites	62	67.7	98.7	87.4	8.4	9.6	—0.15	+0.40	+0.15	—0.39
Sweden:										
Gabbros	22	70.0	84.0	76.6	3.9	5.0	—0.02	—	—0.33	—0.07
Diorites	36	68.0	90.4	80.1	5.9	7.4	—0.27	—	+0.25	+0.80
Granites	120	68.0	96.0	83.1	6.2	7.4	—0.12	—	—0.13	+0.16
Leptites	159	67.7	98.0	81.2	7.3	9.0	—0.12	+0.14	+0.13	—0.13
Other regions:										
Rapakivi granites (Finland)	33	69.1	90.1	75.6	4.3	5.7	+0.64	+0.28	—0.16	+0.18
Volcanic series (Hawaii)	43	70.4	99.4	78.8	6.6	8.4	—0.36	+0.17	—0.03	+0.51
Sediment										
Glacial clay (Norway)	80	71.7	92.9	82.2	4.0	4.9	+0.01	+0.39	+0.05	+0.19

Table 3. **The Ratio MgO/CaO (mc).**

	N	mc		M	σ	$\frac{100\sigma}{M}$	r-values		
		min	max				mc,mgf	mc,kn	mc,mf
Igneous rocks									
Average:									
Peridotites	40	63.4	100	89.1	10.3	11.5	+0.14	+0.31	—0.44
Gabbros	224	10.0	90.0	46.0	13.3	28.9	+0.31	+0.08	+0.06
Diorites	237	4.8	73.1	42.6	10.3	24.2	+0.49	—0.02	—0.16
Granites	219	10.0	85.0	36.3	13.0	35.8	+0.45	+0.13	—0.01
Basalts	64	19.0	72.0	44.7	10.5	23.5	+0.57	+0.19	—0.17
Andesites	181	15.2	66.0	38.1	9.3	24.4	+0.42	—0.14	—0.16
Rhyolites	63	0	100	30.4	20.2	66.4	+0.40	+0.15	+0.10
Sweden:									
Gabbros	25	15.0	80.0	50.1	15.7	31.4	—	—0.14	+0.51
Diorites	36	21.6	76.4	45.8	11.9	25.8	—	—0.06	—0.38
Granites	120	10.0	85.0	36.4	12.9	35.4	—	—0.14	—0.32
Leptites	159	2.0	100	54.4	25.5	47.0	+0.46	+0.33	—0.01
Other regions:									
Rapakivi granites (Finland)	29	4.6	46.2	19.8	10.9	55.0	+0.94	—0.07	+0.22
Volcanic series (Hawaii)	43	17.4	77.9	47.0	12.1	25.8	+0.68	—0.45	—0.44
Sediment									
Glacial clay (Norway)	80	42.6	78.0	60.6	8.3	13.6	+0.15	+0.42	—0.13

Table 4. **The Ratio MgO/FeO (mgf).**

	N	mgf		M	σ	$\frac{100\,\sigma}{M}$	r-values	
		min	max				mgf,kn	mgf,mf
Igneous rocks								
Average:								
Peridotites	40	62.0	94.3	81.8	9.9	12.1	—0.32	+0.61
Gabbros	236	14.0	96.5	65.2	14.8	22.7	—0.19	+0.37
Diorites	276	23.8	90.8	59.8	10.6	17.8	—0.02	+0.04
Granites	245	1.1	90.5	45.5	17.0	37.4	—0.09	+0.04
Basalts	107	32.0	86.5	66.7	11.6	17.4	+0.19	—0.01
Andesites	166	17.7	97.0	60.9	13.8	21.7	—0.02	—0.01
Rhyolites	57	4.0	92.8	43.2	21.0	47.5	+0.06	—0.10
Leptites (Sweden)	159	9.1	98.0	56.5	20.0	35.4	—0.01	—0.03
Other regions:								
Rapakivi granites (Finland)	33	3.6	46.1	16.7	11.0	65.9	—0.09	+0.16
Volcanic series (Hawaii)	43	23.0	84.6	58.0	15.5	26.7	—0.43	—0.37
Sediment								
Glacial clay (Norway)	80	51.0	75.0	62.6	4.9	7.8	+0.01	+0.25

The Ratio MgO/CaO (mc). As mentioned earlier there is reason to presume that mc decreases as qv increases during the endogene development of a crystallizing magma. As discussed above mc is antibatic to qv and og respectively.

As seen from the right side of Table 3, $r_{mc,kn}$ and $r_{mc,mf}$ show undecided tendencies and several of the r-values approach zero. In fact, there seems to be but little relationship between the quantities in question.

Turning to the left side of the table, we find that the coefficient of dispersion, *viz.* $100\,\sigma/M$, has become considerable, showing an increasing tendency as qv increases in the igneous rocks.

In the histograms of the frequency distribution of mc (fig. 4) the tendency mentioned is illustrated. Special attention should be paid to the histograms of the leptites of Sweden and the rhyolites of the world.

The Ratio MgO/FeO (mgf). In petrology it is well known that the magnesium-bearing minerals are among the first to crystallize in a cooling magma. Thus magnesium-bearing olivine forsterite is formed earlier than iron-olivine fayalite. According to V. M. Goldschmidt this is due to the difference in ionic radius of Mg^{2+} (0.78 Å) and of Fe^{2+} (0.83 Å). He writes (45): "If there is some small difference of ionic radius, the bond is weakened for the larger ion; therefore the melting point of iron olivine is lower than that of magnesium olivine, and the larger ion is concentrated in the mother-liquor as compared with the smaller ion according to the fusion diagram found by Bowen and Schairer."

Table 4 contains some statistical data of mgf. As seen in the left side of the table, the means of mgf decrease as qv increases, in agreement with what was mentioned above and similar to the trends of mc. It is to be noted that the dispersion of mgf is greater than that of mc (cf. Table 3).

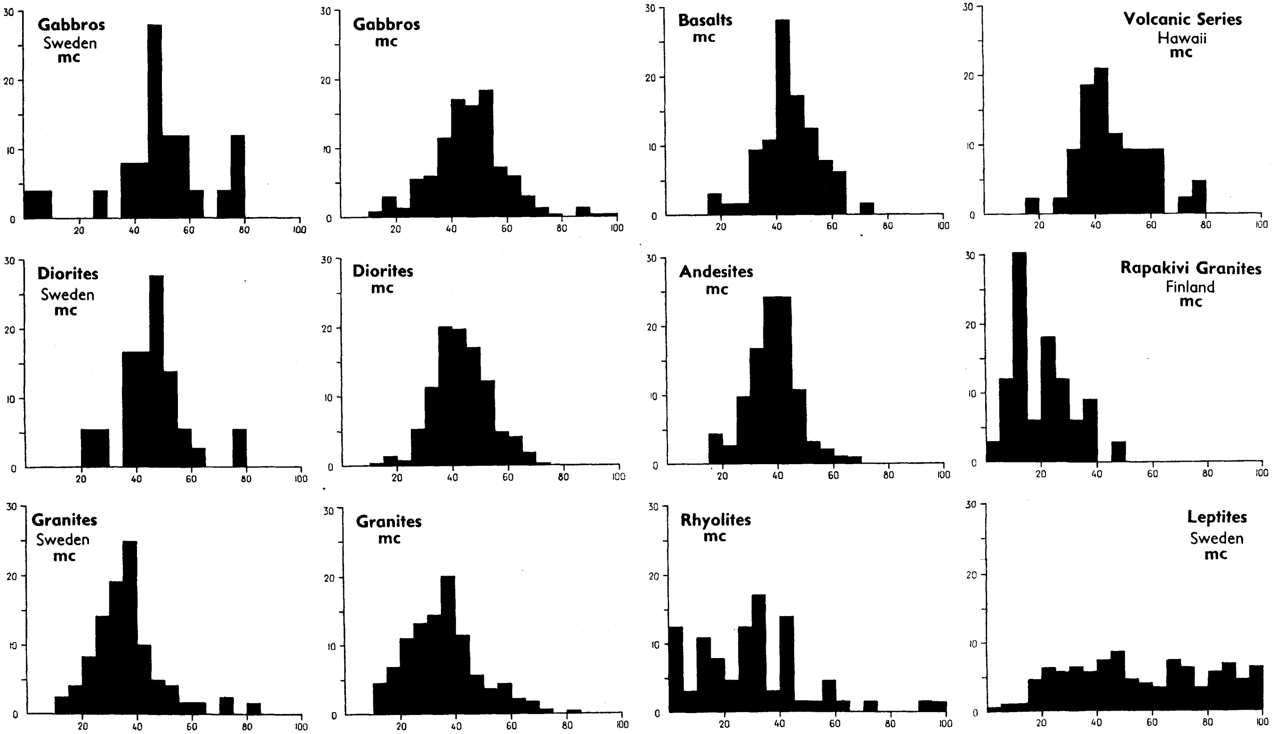

Fig. 4. Histograms of the percentage frequency distribution (ordinate) of the ratio MgO/CaO mc (abscissa) in the igneous rocks.

Table 5. **The Ratio K_2O/Na_2O (kn).**

	N	kn		M	σ	$\frac{100\,\sigma}{M}$	$r_{kn, mf}$
		min	max				
Igneous rocks							
Average:							
Peridotites	27	0	100	33.2	23.2	70.1	—0.14
Gabbros	224	1.0	90.0	19.4	12.1	62.5	—0.11
Diorites	269	3.8	78.6	27.8	14.3	51.5	+0.19
Granites	219	10.0	90.0	46.0	13.2	28.8	+0.10
Basalts	64	7.0	55.0	26.0	11.2	43.0	+0.11
Andesites	174	11.0	72.6	28.2	11.1	39.3	+0.03
Rhyolites	64	4.0	96.0	48.9	18.1	37.0	+0.04
Sweden:							
Gabbros	25	1.0	40.0	16.5	10.2	61.8	+0.08
Diorites	32	0.4	91.0	29.7	17.3	58.3	+0.40
Granites	120	0	90.0	49.6	15.2	30.6	+0.14
Leptites	158	1.0	96.0	44.8	28.9	64.5	+0.04
Other regions:							
Rapakivi granites (Finland)	29	38.0	69.0	55.3	5.4	9.8	—0.40
Volcanic series (Hawaii)	43	3.6	34.9	17.4	6.0	34.5	+0.30
Sediment							
Glacial clay (Norway)	80	37.0	68.0	56.0	6.1	10.9	+0.17

The r-values calculated (the right side of the table) show, on the whole, trends similar to those found for mc, but it should be noticed that the correlations in question are feebler than the corresponding ones of mc. Further, the tendency noted for $r_{qv,mc}$, that the numerical values decrease as qv increases, is not so decided in the case of mgf.

The correlation between mgf and some of the ferrides is of great importance and will be mentioned later (see pp. 126—127).

Fig. 5 below contains the histograms showing the frequency distribution of mgf.

The Ratio K_2O/Na_2O (kn). Table 5 above shows the statistical data of kn. Turning first to the left side of the table, we find that the means for kn in the igneous rocks increase comparatively rapidly as qv increases, in agreement with petrological experience. The dispersion is rather high. The lowest value is shown by the Rapakivi granites of Finland (9.8). The glacial clay of Norway is low too (= 10.9). In the other rocks, however, the coefficient of dispersion, 100 σ/M, is 28.8—64.5. Here one notes the tendency towards decreasing values of the coefficient in question as qv increases. This does not correspond to the tendency of the numerical values of $r_{qv,kn}$. Thus, there seem to be factors other than the dispersion influencing the r-values.

The undecided tendency of the r-values of kn, mc and kn, og has already been mentioned. The correlation kn,mf will be discussed in connection with the ratio below.

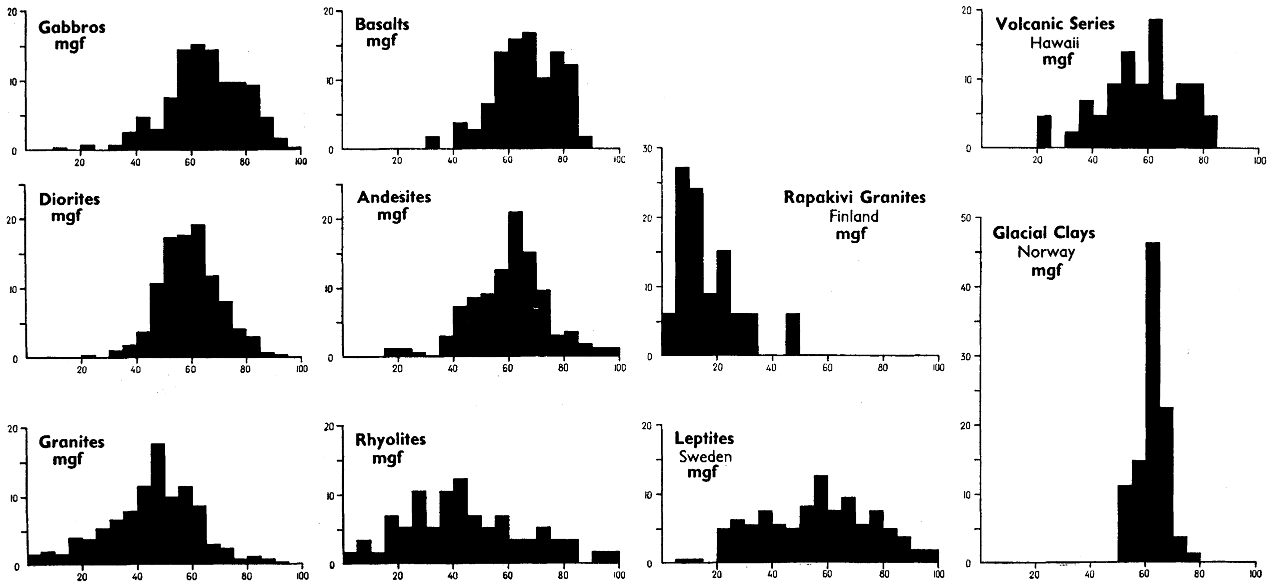

Fig. 5. Histograms of the percentage frequency distribution (ordinate) of the ratio MgO/FeO mgf (abscissa) in the igneous rocks and glacial clay.

Table 6. **The Ratio Mn/Fe (mf).**

	N	mf		M	σ	$\frac{100\,\sigma}{M}$
Igneous rocks		min	max			
Average:						
Peridotites	21	0	9.25	2.5	2.4	97.0
Gabbros	82	0.13	17.40	3.2	3.0	93.5
Diorites	147	0.43	13.75	1.8	2.3	128.0
Granites	158	0.16	31.81	7.0	6.2	89.0
Basalts	63	0	7.53	1.8	1.0	15.5
Andesites	174	0.22	29.5	2.2	1.0	45.3
Rhyolites	52	0	30.0	6.4	7.2	113.0
Sweden:						
Gabbros	15	0.88	27.6	4.4	6.6	150.0
Diorites	15	0	7.2	2.4	2.3	95.0
Granites	118	0	34.7	5.6	4.5	80.0
Leptites	120	0	31.0	3.5	4.6	131
Other regions:						
Rapakivi granites (Finland)	29	0.42	2.58	1.3	0.6	41.9
Volcanic series (Hawaii)	43	0	9.15	2.8	2.1	75
Sediment						
Glacial clay (Norway)	80	0.68	2.95	1.6	0.5	31.2

In fig. 6 the histograms illustrate the distribution of the ratio kn in the igneous rocks. It should be noted that the kn-distribution in granites is more regular (approaching a normal frequency distribution) than in the basic members of the igneous rocks. Further, the distribution of kn in the ore-bearing leptites of Central Sweden shows a considerable dispersion towards the extreme kn-values.

The Ratio Mn/Fe (mf). Unfortunately our knowledge of the distribution of manganese in minerals, rocks and sediments is very scanty, and difficulty is experienced when dealing with the ratio mf. However, some statistical data of the ratio mf are presented on the basis of the analyses available, but the results should be treated with discernment.

The left side of Table 6 again contains the figures of the means and the dispersion of mf. As regards the means we find that they vary in a very peculiar manner in relation to the corresponding means of qv (cf. Table 1). Thus, the gabbros show higher means than the diorites, and the means of the granites increase quite considerably. A similar trend is found in the effusive rock series. Thus, the basalts and the andesites have approximately the same means, but in the rhyolites it has increased to a value about three times that of the aforementioned rocks. Now, if this be a common tendency in the upper lithosphere, the ratio mf can reach considerable values only in the most salic rocks. The basic rocks have an average ratio of mf approximately equal to the average of the upper lithosphere, about 2.0.

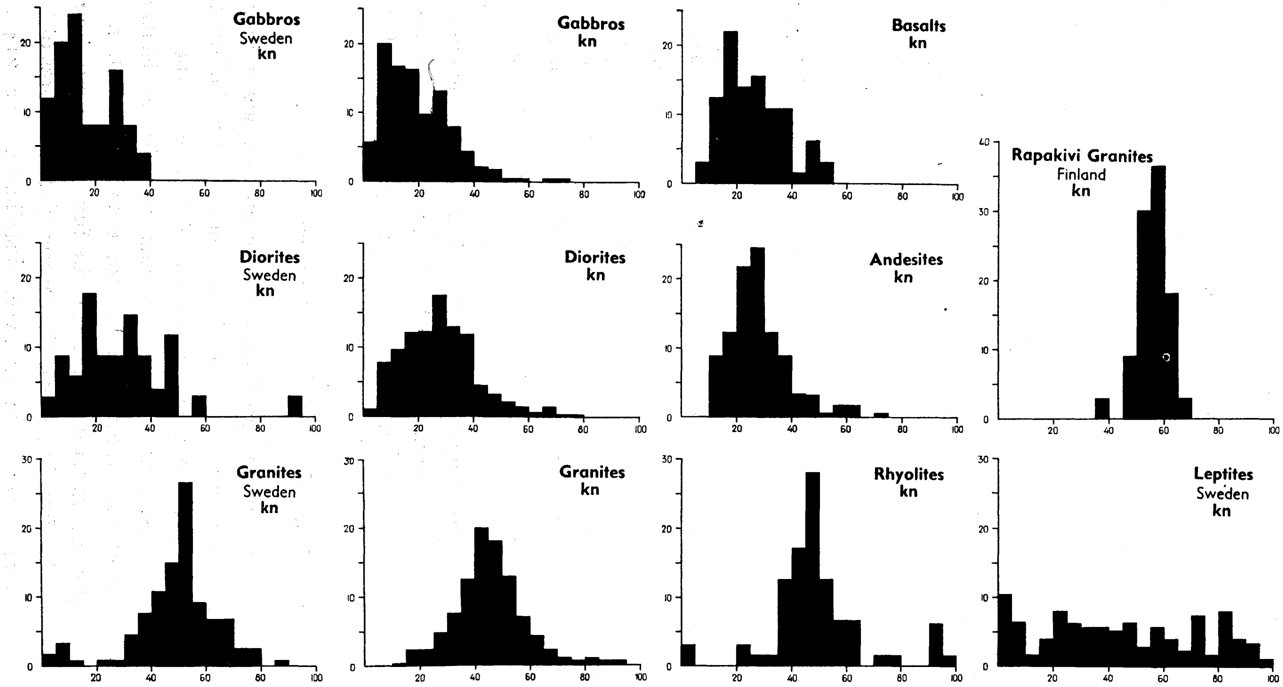

Fig. 6. Histograms of the percentage frequency distribution (ordinate) of the ratio K_2O/Na_2O kn (abscissa) in the igneous rocks.

Let us now turn to the pre-Cambrian rocks of Fennoscandia. The average contents of iron and manganese respectively have been estimated by Clarke and Washington (15). They are 4.98 per cent Fe and 0.108 per cent Mn, and the ratio mf thus 2.2. However, the authors mentioned make the following comments on the average composition of the igneous rocks of Fennoscandia: "This average is no doubt fairly representative of the Fennoscandian area, although the abundant granitic rocks are possibly too little represented."

If the analyses available of the igneous rocks of Sweden (72) are representative, and if we bear in mind the abundance of granites in this part of Fennoscandia, we arrive at a probable value of the ratio mf approximately = 5, which is in very poor agreement with the corresponding average value of Fennoscandia as estimated by Clarke and Washington in their paper quoted above. Again, it is advisable to be very careful with the analytical data of manganese.

The difficulties in estimating the means of mf will be plain when taking into account the coefficients of dispersion. They are considerable and may influence the estimations in question.

On the right side of Tables 1—5 are found the correlation coefficients. The tendency is undecided. In this connection only one coefficient should be mentioned, $r_{\mathrm{mf,kn}}$. In most cases it is positive, but the numerical values approach zero. On the whole there seems to be no indisputable correlation between the two ratios in question. The author would like to draw attention to the feeble or non-existent correlation between kn and mf in the leptites of Central Sweden, a geochemical feature which should be taken into account when dealing with the relation between the manganiferous iron ores of the region in question, on the one hand, and the potassium-bearing leptites in the same region, on the other.

In fig. 7 is shown the frequency distribution of mf in the igneous rocks. The histograms illustrate the tendency of mf to "spread" in the salic rocks. The histograms illustrate, too, the extremely asymmetric form of the distribution.

The Iron Ores of Central and Northern Sweden.

The statistical data on the Swedish pre-Cambrian iron ores will now be presented. The ratios calculated are the same as those of the igneous rocks. Unfortunately there are no data available concerning the content of alkalies in the iron ores of Sweden, so that a discussion on the ratio kn must be deferred. Neither can the ratio mgf be discussed for evident reasons. Some comments will be made on the tables containing the statistical data. In the first column are found the ore types investigated. The first line shows the means of the iron ores of Central Sweden. The calculations cover 1,600 analyses distributed over 214 mining fields. Thus N = 214, for it would be incorrect from a statistical point of view to make the calculations on the basis of N = 1,600 as the number of analyses

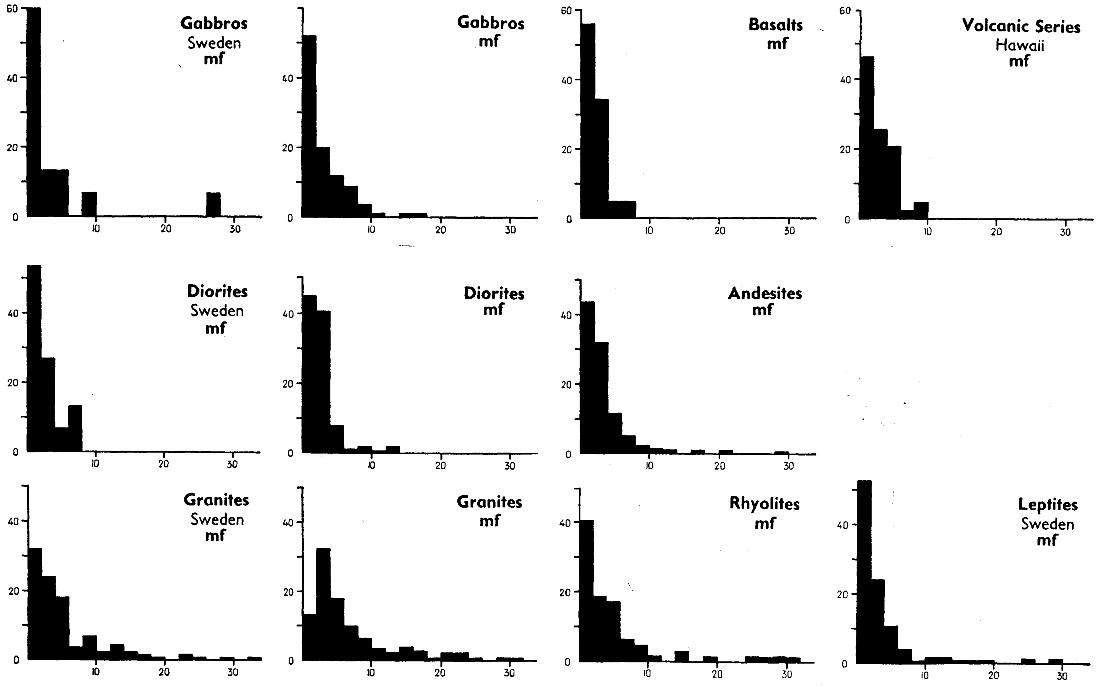

Fig. 7. Histograms of the percentage frequency distribution (ordinate) of the ratio Mn/Fe mf (abscissa) in the igneous rocks.

Table 7. **The Quarts Ratio (qv).**

	N	qv		M	T	σ	$\frac{100\sigma}{M}$	r-values		
		min	max					qv,mc	qv,og	qv,mf
Iron Ores of Central Sweden:										
Average of the Region......	214	0	100	56.5	55.0	6.7	11.9	+ 0.02	+ 0.52	— 0.62
Quartz ores (not banded), avg.	38	50	96	74.2	92.5	14.8	20.0	— 0.38	+ 0.53	— 0.35
Quartz ores (banded), avg. ...	51	47	94	81.9	83.5	9.6	11.7	— 0.06	— 0.25	— 0.05
Skarn and lime ores, (mf $<$ 2) avg.	52	17	74	51.2	47.5	11.0	21.5	+ 0.08	+ 0.20	— 0.15
Skarn and lime ores (mf $>$ 2) avg.	29	6	74	36.8	42.5	19.7	53.5	— 0.15	+ 0.35	— 0.78
Apatite ores (Grängesberg)...	34	37	79	54.1	52.5	9.2	17.0	+ 0.16	— 0.09	— 0.29
Swedish Ore Fields:										
Bispberg (quartz ore)	78	56	98	79.8	92.5	13.1	16.8	— 0.48	+ 0.21	— 0.17
Striberg (quartzbanded ore)..	55	54	97	82.3	92.5	14.2	17.3	— 0.57	+ 0.48	— 0.23
Persberg (skarn ore mf $<$ 2)...	32	16	59	44.6	52.5	11.0	24.6	+ 0.31	0	— 0.64
Björnberget (skarn ore mf $<$ 2)	25	12	66	29.6	17.5	18.3	61.8	+ 0.94	— 0.07	— 0.57
Dannemora (skarn-dolomite ore mf $>$ 2)...............	92	5	60	34.8	37.5	11.8	34.0	+ 0.28	— 0.04	— 0.58
Klackberg (skarn-dolomite ore mf $>$ 2)....................	37	0	21	11.4	7.5	4.4	39.0	+ 0.22	+ 0.51	— 0.38
Kiirunavaara (apatite ore)...	24	38	75	52.4	47.5	8.6	16.5	+ 0.08	+ 0.27	— 0.18
Gällivare (apatite ore).......	58	26	76	54.1	62.5	13.4	24.5	— 0.03	+ 0.37	— 0.28

from the various mining fields varies. In order to avoid the overemphasizing of some ore fields and ore types, the mean of each mining field is taken as the unit. The other N-values of the tables represent the number of single analyses involved in the calculations, but it should be mentioned that each single analysis represents an average sample.

In the upper part of the tables, the figures for the various ore types are presented. The lower part shows the figures from some ore fields representative for the region. In the iron ores of Sweden the quantity T is calculated, *viz.* the arithmetic mean of the class-interval representing the maximum frequency. The quantity is called 'the mode'.

The Quartz Ratio (qv). It is plain that the quartz ratio will vary in iron ores from regions representing so many chemically different iron-ore types. As seen from Table 7 the variance of M is 11.4—82.3 and of T 7.5—92.5. The dispersion varies, too, and is quite high in some cases ($100\,\sigma/M = 11.7—61.8$).

It should be observed that the contents of SiO_2 and CO_3 are antibatic. Thus, increasing qv corresponds to the decreasing content of carbonate, especially within the qv-values 0 to 50. This fact is of importance with reference to the distribution of certain minor constituents, and especially influences the ratio mf, which will be discussed later.

The ore types investigated represent the most predominant pre-Cambrian iron-ore types in Sweden and the mean of qv varies approximately between 0 and 100. Thus, the ratio qv in the iron ores is the basis to which the other ratios

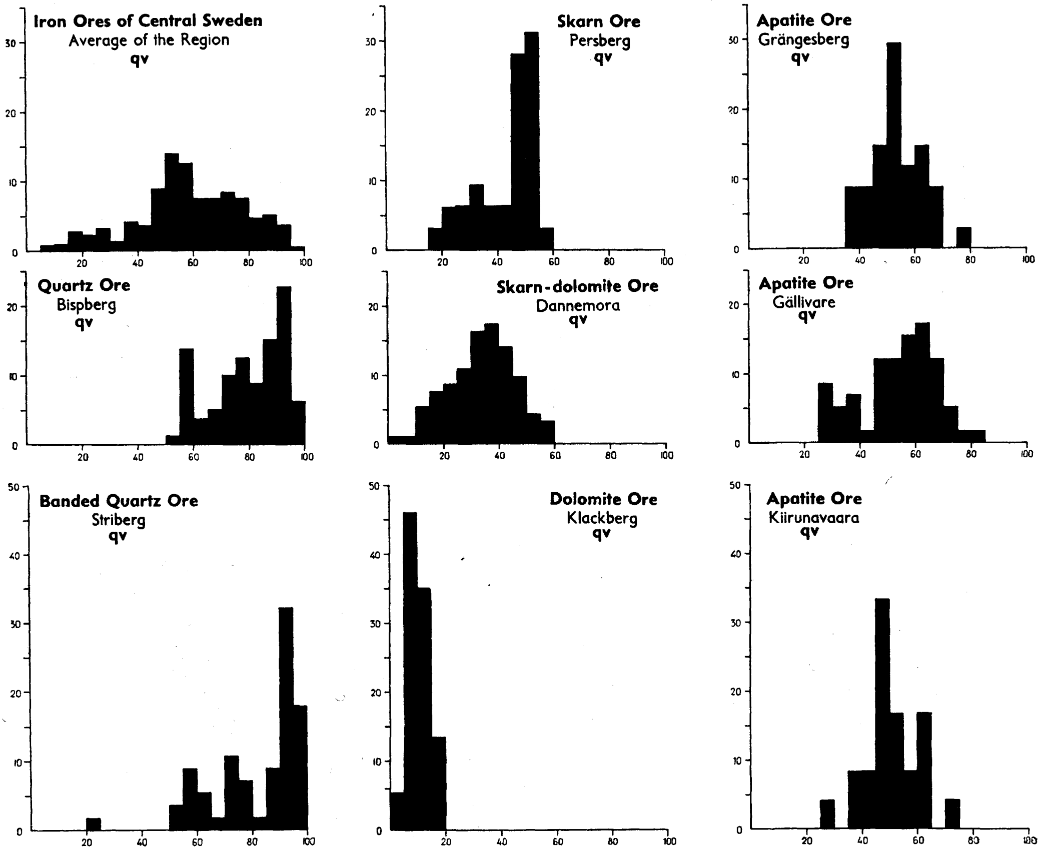

Fig. 8. Histograms of the percentage frequency distribution (ordinate) of the quartz ratio qv (abscissa) in some Swedish iron ore types.

should be referred, as in the case of the igneous rocks as mentioned before. From this point of view the distribution of the major constituents in the iron ores, on the one hand, and in the igneous rocks, on the other, will be discussed and compared.

As regards the r-values of qv, some features should be emphasized. Taking the iron-ore bearing region of Central Sweden as a unit, where the iron ores certainly are chemically differentiated but — at any rate primarily — syngenetic to the leptite formation, the figures representing the averages of the region may be of interest. Thus, $r_{qv,mc}$ for the region approaches zero. This lack of correlation between qv and mc will be plain upon observing the tendency of $r_{qv,mc}$ in the various iron-ore types and ore fields investigated. The correlation coefficient in question varies between -0.57 and $+0.94$. Further, we find that the ore types with the highest qv-values have negative $r_{qv,mc}$. The skarn and lime ores show an undecided tendency on the whole, but all the ore

Table 8. **Degree of Oxidation (og).**

	N	og		M	T	σ	$\frac{100\sigma}{M}$	r-values	
		min	max					og,mc	og,mf
Iron Ores of Central Sweden:									
Average of the Region	213	75	100	89.8	88.9	3.5	3.9	0	— 0.53
Quartz ores (not banded) avg.	37	81	99	92.8	99.0 (88.9)	4.5	4.8	— 0.19	— 0.42
Quartz ores (banded) avg.	51	89	99	96.2	96.2	2.5	2.7	— 0.23	+ 0.14
Skarn and lime ores (mf $<$ 2) avg.	58	87	99	89.1	88.9	1.5	1.7	+ 0.15	+ 0.29
Skarn and lime ores (mf $>$ 2) avg.	30	67	96	87.0	88.9	5.0	5.7	+ 0.09	— 0.49
Apatite ores (Grängesberg)	34	84	97	91.7	91.5	2.9	3.2	— 0.25	— 0.08
Swedish Ore Fields:									
Bispberg (quartz ore, not banded)	78	85	96	91.0	88.9	2.1	2.3	+ 0.05	+ 0.11
Striberg (quartz ore, banded)	55	87	100	95.0	97.5	4.1	4.3	— 0.57	— 0.44
Persberg (skarn ore, mf $<$ 2)	32	88	89	88.7	88.9	0.3	0.4	+ 0.02	— 0.23
Björnberget (skarn ore mf $<$ 2)	25	88	90	88.9	88.9	0.4	0.5	— 0.04	— 0.06
Dannemora (skarn-dolomite ore mf $>$ 2)	92	86	90	88.3	88.9	0.8	0.9	— 0.32	+ 0.22
Klackberg (skarn-dolomite ore mf $>$ 2)	37	83	88.	86.3	86.5	0.9	1.1	+ 0.15	— 0.67
Kiirunavaara (apatite ore)	24	89	93	90.1	90.1	9.5	10.6	— 0.37	+ 0.15
Gällivare (apatite ore)	58	87	98	90.1	88.9	2.5	2.8	— 0.15	— 0.24

fields in which this ore type dominates have a positive $r_{qv,mc}$. The apatite iron ores (including the ore fields in Northern Sweden) show r-values approaching zero.

The correlation qv,og will be examined in connection with a discussion on the ratio og below.

Turning to $r_{qv,mf}$, we find a decisive tendency: the r-values are all negative. This tendency holds good for the whole region of Central Sweden as well as for the various ore types examined.

In fig. 8, histograms show the frequency distribution of qv in some of the iron ores, and in Central Sweden as a whole.

Degree of Oxidation (og). The degree of oxidation is a function of the ratio Fe_2O_3/FeO. Consequently the og-values depend on the frequency of the two ore-forming minerals, magnetite and hematite respectively.

In Table 8, M and T indicate which of the two minerals mentioned dominates in the various ore types (og of pure magnetite is 88.9 and of pure hematite 100). The dispersion is low for reasons easily understood. In this connection, it should be observed that the og-values of iron ores are higher than those of igneous rocks with corresponding qv-values.

The most significant trend is the correlation between the means of qv and og in the pre-Cambrian iron ores of Sweden. They are all but proportional ($r_{qv(M),og(M)} = +0.99$). This geochemical feature agrees with that of the igneous rocks.

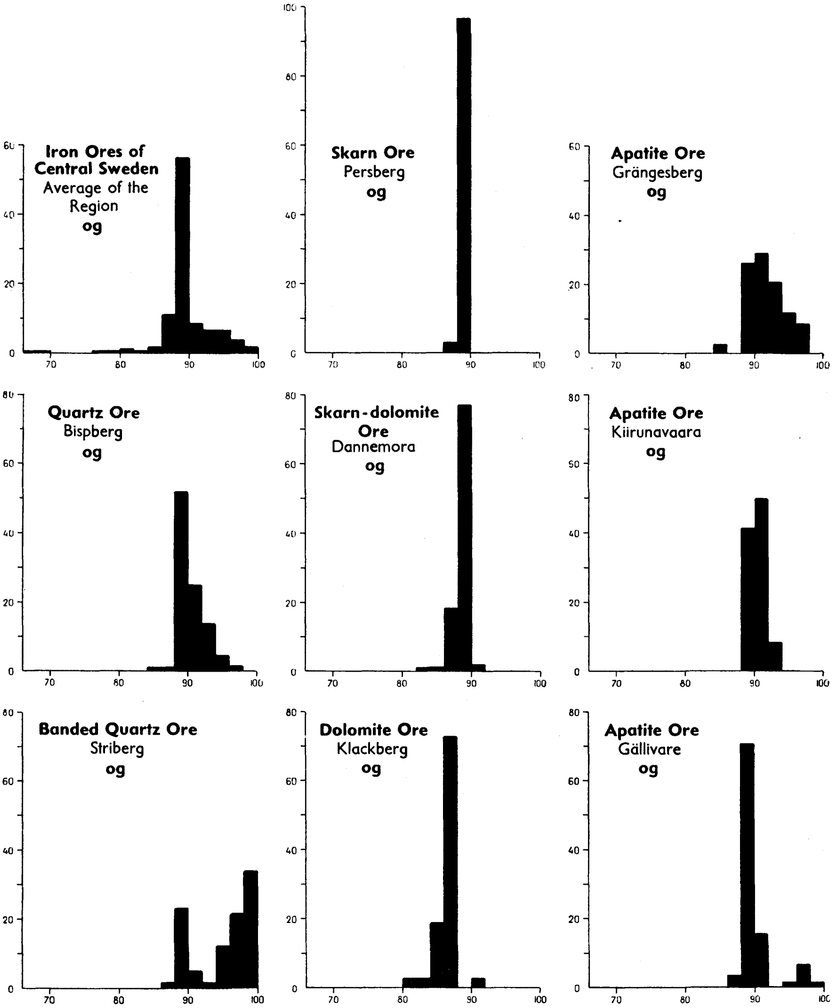

Fig. 9. Histograms of the percentage frequency distribution (ordinate) of the degree of oxidation og (abscissa) in some Swedish iron ore types.

The correlation between og, on the one hand, and the other ratios, on the other, is rather irregular. Thus, $r_{qv,og}$ is positive in some cases but negative or zero in others. This may be due to the metamorphic processes — including reduction or oxidation — which the iron ores have undergone. As regards $r_{og,mc}$ and $r_{og,mf}$ the tendency is undecided, as seen from Table 8.

The histograms showing the frequency distribution of og are characterized mainly by the frequency of the predominant ore mineral, as illustrated in fig. 9 above.

The Ratio MgO/CaO (mc). The statistical data of this ratio can be summa-

Table 9. **The Ratio MgO/CaO (mc).**

	M	mc		M	T	σ	$\frac{100\,\sigma}{M}$	$r_{mc,\,mf}$
		min	max					
Iron Ores of Central Sweden:								
Average of the region..........	214	0	100	54.5	55.0	9.5	17.4	−0.15
Quartz ores (not banded) avg. ..	38	12	79	49.4	47.5	16.2	32.8	+0.20
Quartz ores (banded) avg.	51	0	66	39.9	37.0	15.4	38.7	−0.15
Skarn and lime ores (mf < 2) avg.	52	17	91	52.7	67.0	20.2	38.3	−0.14
Skarn and lime ores (mf > 2) avg.	29	0	93	55.6	47.5	17.5	31.4	+0.13
Apatite ores (Grängesberg)......	34	49	91	68.1	67.5	9.4	13.9	+0.36
Swedish Ore Fields:								
Bispberg (quartz ore, not banded)	78	20	97	59.5	62.5 (47.5)	17.1	28.8	+0.13
Striberg (quartz ore, banded) ...	55	0	100	46.0	37.5 (32.5)	23.1	50.0	+0.19
Persberg (skarn ore mf < 2)....	32	42	96	68.9	72.5	16.9	24.6	−0.33
Björnberget (skarn ore mf < 2)..	25	17	59	31.4	25.0	12.3	39.0	−0.50
Dannemora (skarn-dolomite ore mf > 2).....................	92	35	78	58.0	67.5	11.4	19.6	−0.06
Klackberg (skarn-dolomite ore mf > 2).....................	37	41	84	60.3	57.5 (67.5)	10.1	16.6	+0.03
Kiirunavaara (apatite ore)......	24	38	80	63.7	72.5	11.3	17.7	−0.57
Gällivare (apatite ore)..........	58	50	94	70.3	72.5	8.7	12.4	−0.01

rized briefly. The means of mc show no correlation to the corresponding qv-values. The correlation between mc and the other ratios is undecided. As mentioned before, the skarn and lime ores of Persberg, Björnberget, Dannemora, and Klackberg have positive values of $r_{mc,qv}$. The Björnberget ore is all but proportional as regards qv and mc ($r_{qv,mc} = +0.94$).

The histograms of the frequency distribution of mc show some peculiar features which should be mentioned (fig. 10).

Thus, the histograms of some ore types (*e.g.* Persberg, Striberg) show a very irregular or asymmetric distribution. The histogram of Persberg shows a two-humped distribution and the banded quartz ore of Striberg a four-humped one. It is obvious that the types of distribution mentioned are of a very complex nature, indicating the influence of several secondary factors in the distribution of calcium and magnesium.

The Ratio Mn/Fe (mf). As already mentioned $r_{qv,mf}$ is negative in all the cases investigated, indicating that we have to deal with a distribution principle in this respect. H. E. Johansson has paid attention to this feature in the chemistry of the iron ores of Central Sweden (64), and in diagrams he has shown that the content of carbonates in the iron ores and their content of manganese are symbatic on the whole. Thus, the ratio mf is of a certain importance when dealing with the origin of iron ores.

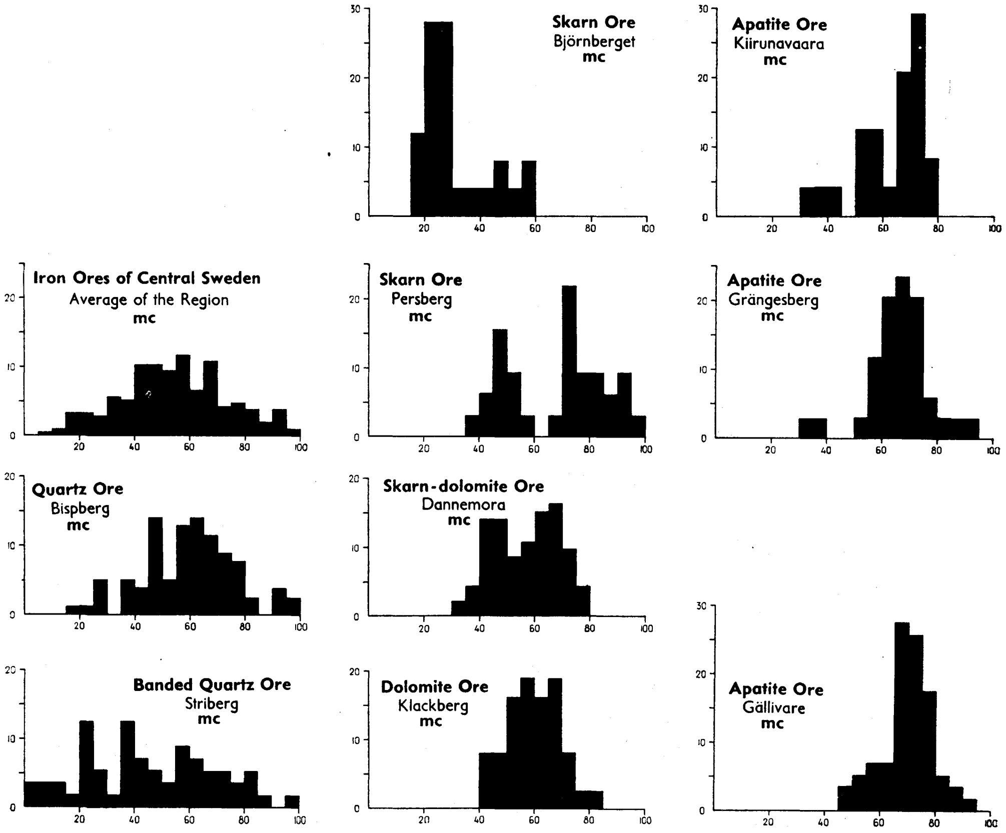

Fig. 10. Histograms of the percentage frequency distribution (ordinate) of the ratio MgO/CaO mc in some Swedish iron ore types.

Table 10 shows the statistical data of mf. The M-values vary and on the whole depend on the corresponding qv-values (cf. Table 7). The average for mf in Central Sweden is approximately the same as that of the upper lithosphere, *viz.* 2. The mode (T), however, is only 0.3, showing that most of the iron ores of Central Sweden are extremely poor in manganese, 80 per cent of the ores having values of mf < 2. The dispersion is considerable. The correlation coefficients have been examined earlier.

The histograms showing the frequency distribution of mf are found in fig. 11 below.

The frequency distribution of mf in the iron ores of Central Sweden, illustrated in the left histogram, is characterized by the maximum frequency of iron ores poor in manganese. Thus, the distribution shows an extremely asymmetrical J-shaped form, approximately of the same type as that of the salic igneous rocks (cf. fig. 7). Upon classifying the iron ores of Central Sweden into two

Table 10. **The Ratio Mn/Fe (mf).**

	N	mf		M	T	σ	$\frac{100\,\sigma}{M}$
		min	max				
Iron Ores of Central Sweden:							
Average of the region	212	0	12.0	2.0	0.3	2.8	145.0
Quartz ores (not banded) avg.	37	0.1	0.8	0.3	0.2	0.2	60.6
Quartz ores (banded) avg.	51	0	0.6	0.2	0.1	0.1	56.5
Skarn and lime ores (mf < 2) avg.	52	0.1	1.2	0.5	0.3	0.3	54.0
Skarn and lime ores (mf > 2) avg.	30	2.1	12.0	5.7	2.5	2.9	51.0
Apatite ores (Grängesberg)	34	0.1	1.1	0.3	0.15	0.2	69.4
Swedish Ore Fields:							
Bispberg (quartz ore, not banded)	72	0	0.7	0.2	0.05	0.1	74.0
Striberg (quartz ore, banded)	55	0	0.6	0.2	0.15	0.1	63.0
Persberg (skarn ore, mf < 2)	32	0.1	0.7	0.4	0.35	0.2	37.3
Björnberget (skarn ore, mf < 2)	25	0.2	1.1	0.5	0.3	0.2	46.7
Dannemora (skarn-dolomite ore, mf > 2)	92	0.6	12.0	3.5	3.0	1.9	55.3
Klackberg (skarn-dolomite ore, mf > 2)	37	6.3	11.0	8.7	9.0	1.2	13.9
Kiirunavaara (apatite ore)	24	0.1	0.3	0.1	0.15	0.05	36.7
Gällivare (apatite ore)	58	0.1	0.3	0.1	0.15	0.06	40.0

groups, one with mf < 2 and the other with mf > 2, and making histograms of the frequency distribution of mf < 2 and mf > 2 respectively, we find that the histogram of the former shows a rather complex distribution and the latter a very asymmetric form of distribution. This indicates that the quantity of mf in the iron ores of Central Sweden is regulated by many factors, the presence of carbonate ions being one of them. The other histograms in fig. 11 show J-shaped or extremely assymetrical forms.

The Liassic Iron-bearing Series of Southern Sweden.

Thanks to important pioneer work on the geochemistry of the above formation by Sven Palmqvist (96), our knowledge of the geochemistry of sedimentary iron ores has been enriched considerably. On the basis of a great number of chemical analyses by Palmqvist, the present author has made statistical computations with the aid of the same methods as used before. The statistical data of the iron ores of Southern Sweden are presented in Table 11 below. The upper part of the table contains the data on the whole region and the lower part the data from a sampling of pure sideritic ores.

The Quartz Ratios qv and qvs. According to Palmqvist (96, p. 16) silicic acid occurs in the iron ores in the form of SiO_2 (sand), Al-silicates as clay and in the form of some iron-aluminium silicates. As it may be important to know the statistical data, both for the bulk of SiO_2 and for the SiO_2 found only in silicates, the author has calculated two qv-quantities, qv and qvs. Thus, qv

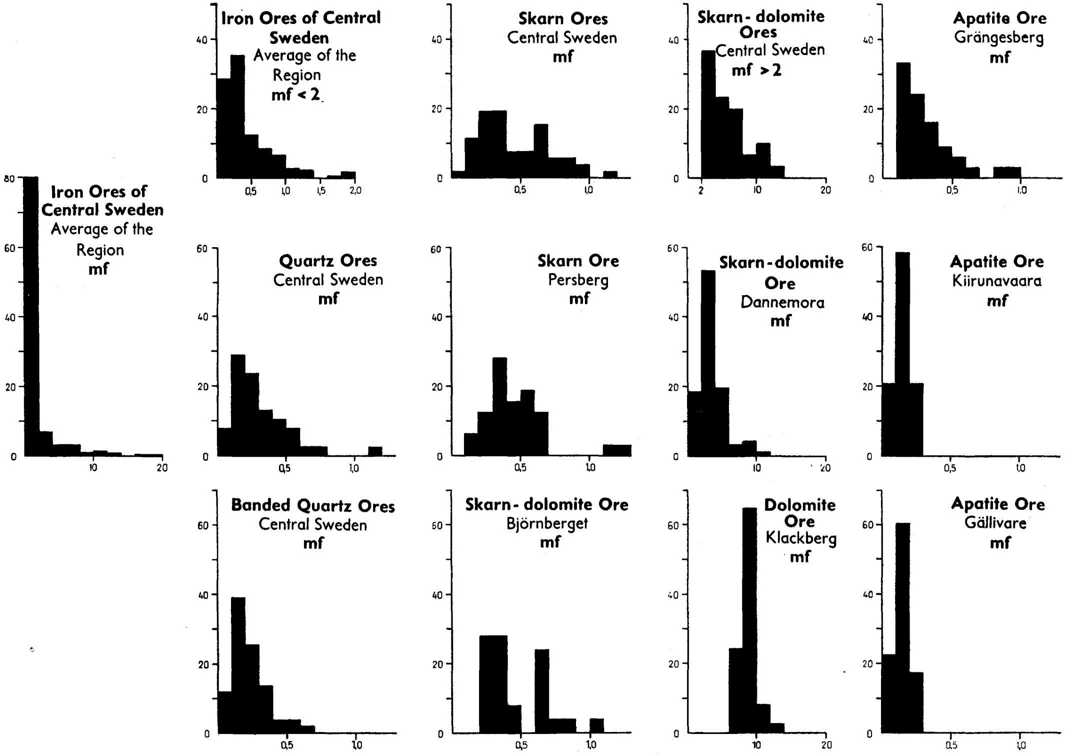

Fig. 11. Histograms of the percentage frequency distribution (ordinate) of the ratio Mn/Fe mf (abscissa) in some Swedish iron ore types.

Table 11. **The Liassic Iron-bearing Series in Southern Sweden.**

A. The Whole Region.

Ratio	N	x_{max}	x_{min}	M	σ	$\frac{100\,\sigma}{M}$	r - values					
							qv	qvs	mc	og	kn	mf
qv	60	83	7	27.6	21.3	77.2	—	+ 0.70	+ 0.43	+ 0.78	— 0.20	— 0.45
qvs	60	97	12	52.2	29.2	56.0	+ 0.70	—	+ 0.24	+ 0.54	— 0.21	— 0.30
mc	60	88	0.7	29.2	16.3	55.9	+ 0.43	+ 0.24	—	+ 0.34	— 0.06	— 0.27
og	60	96.7	67.2	73.4	6.3	8.6	+ 0.78	+ 0.54	+ 0.34	—	— 0.11	— 0.34
kn	59	100	71	84.8	4.5	5.3	— 0.20	— 0.21	— 0.06	— 0.11	—	+ 0.04
mf	60	1.8	0	0.7	0.4	54.0	— 0.45	— 0.30	— 0.27	— 0.34	+ 0.04	—

B. Pure Sideritic Ores.

Ratio	N	x_{max}	x_{min}	M	σ	$\frac{100\,\sigma}{M}$	r - values					
							qv	qvs	mc	og	kn	mf
qv	22	83	8	21.4	21.5	100.5	—	+ 0.96	+ 0.68	+ 0.99	— 0.19	— 0.20
qvs	22	84	12	28.2	20.9	74.1	+ 0.96	—	+ 0.32	+ 0.96	— 0.03	— 0.28
mc	22	55	8	27.0	12.4	45.8	+ 0.68	+ 0.32	—	+ 0.63	— 0.25	— 0.41
og	22	96.7	67.8	73.3	8.2	11.2	+ 0.99	+ 0.96	+ 0.63	—	— 0.11	— 0.38
kn	22	100	75	83.1	5.7	6.8	— 0.19	— 0.03	— 0.25	— 0.11	—	+ 0.08
mf	22	1.8	0.3	0.9	0.4	48.5	— 0.20	— 0.28	— 0.41	— 0.38	+ 0.08	—

represents the ratio where sand is excluded, and qvs where sand is included in the calculation of the quartz ratio.

As seen from Table 11, the two means for qv are relatively low and only a little higher in the region than in the sideritic ores. The mean for qvs in the whole region, on the other hand, is much higher than qvs of the sideritic ores, where qv and qvs are approximately equal. The dispersion of both qv and qvs is fairly high: 56.0—100.5 per cent.

It is of interest to study the correlation coefficients of qv and qvs. $r_{qv,qvs}$ is high. In the region $r_{qv,qvs}$ is + 0.70 and in the siderites the coefficient is + 0.96. In general the numerical values of r_{qv} are greater than those of r_{qvs}. There are two exceptions. The correlation coefficients $r_{qv,kn}$ and $r_{qvs,kn}$ are approximately equal for the whole region. Further, the numerical value of $r_{qvs,mf}$ (— 0.28) is slightly higher than of $r_{qv,mf}$ (— 0.20). In some cases the differences between the r-values of qv and qvs are considerable. Thus, *e.g.* $r_{qv,mc}$ in the sideritic ores is + 0.68 but $r_{qvs,mc}$ is only + 0.32 in the same ore type.

As regards the correlations qv,mc and qvs,mc, we find that they are all positive. This trend is similar to that found in the skarn and lime ores of Central Sweden, *i.e.* at Persberg, Björnberget, Dannemora, and Klackberg (cf. Table 7). On the other hand it is contrary to the tendency found in the igneous rocks, where $r_{qv,mc}$ is almost always negative.

The correlations qv,og and qvs,og are positive, too, and the r-values can reach appreciable amounts and approach proportionality (*e.g.* $r_{qv,og}$ in the sideritic ores, which is + 0.99).

In the sedimentary iron ores of Southern Sweden $r_{qv,kn}$ and $r_{qvs,kn}$ are low with a negative sign. The correlation in question may be regarded as doubtful.

Finally, $r_{qv,mf}$ and $r_{qvs,mf}$ are negative and the numerical values can be regarded as medium for the region and medium to feeble in the sideritic ores. This is in full agreement with the trends of the pre-Cambrian iron ores of Central Sweden.

The Ratio MgO/CaO (mc). The mean value for mc is 29.2 for the whole region and 27.0 for the sideritic ores. Compared with the means of mc in the iron ores of Central Sweden, the figures are lower, the lowest value for the latter region being 31.4 (Björnberget). The dispersion is approximately the same for the two regions in question.

The correlation coefficients of mc are higher in the sideritic ores than in the region. Thus, $r_{mc,og}$ in the sideritic ores is + 0.63, and in the whole region + 0.34. The values for $r_{mc,kn}$ are — 0.25 and — 0.06, respectively, and for $r_{mc,mf}$ — 0.41 and — 0.27, respectively.

Degree of Oxidation (og). Due to an excess of FeO the degree of oxidation is comparatively low. The mean is about 73 and much lower than the means of the igneous rocks and the pre-Cambrian iron ores of Sweden. The dispersion is not remarkable. The correlation coefficients — not discussed before — are unimportant.

The Ratio K_2O/Na_2O (kn). This ratio is of a certain importance, giving an idea of the distribution of the two principal alkalies in marine sedimentary iron ores. The mean of kn — in the whole region as well as in the siderites — is high, 84.8 and 83.1 respectively. This is a good illustration of the well-known fact that potassium becomes adsorbed in marine clay (and iron-bearing) sediments. The dispersion of kn is low.

The correlation coefficients in which kn is one of the variables, have relatively low numerical values and some of them are almost zero. The non-correlation between kn and mf (+ 0.04 and + 0.08 respectively) should be emphasized in this connection. Thus, we are dealing with an iron-bearing sedimentary formation where an iron ore poor in manganese has been formed in a milieu containing an excess of potassium (kn $>$ 83).

The Ratio Mn/Fe (mf). The mean of the ratio mf is far below the mean for the upper lithosphere, which is approximately 2. Thus the mean for the whole region is 0.7 and for the sideritic ores 0.9.

As mentioned above, the iron ores of Southern Sweden are mainly carbonate ores poor in manganese, but nevertheless the correlation between mf and qv is negative, as in the case of the pre-Cambrian iron ores of Central Sweden. It should be observed, however, that there are carbonate ores poor in manganese

Table 12. **Titaniferous Iron Ores.**

	N	x_{min}	x_{max}	M	σ	$\frac{100\,\sigma}{M}$	Correlation coefficients			
Ratio:										
qv	33	4	82	47.2	16.2	34.3	$r_{qv,mc}$ + 0.13			
og	33	69.2	89.4	83.2	29.4	35.3	$r_{qv,og}$ + 0.17			
mc	33	12	100	61.4	22.0	35.8	$r_{qv,mgf}$ — 0.15			
mgf	33	0.4	66	17.5	16.3	93.5	$r_{qv,kn}$ + 0.05			
kn	21	0	83	24.1	20.5	85.0	$r_{qv,mf}$ + 0.35			
mf	33	0	5	1.3	1.36	104.0				
Oxide:							MgO	FeO	Fe_2O_3	TiO_2
MgO	33	0.1	18	4.3	4.12	96.0	—	— 0.3	— 0.6	+ 0.25
FeO	33	10.5	34.6	25.3	6.6	26.1	— 0.3	—	+ 0.4	0
Fe_2O_3	33	1.4	65.3	31.6	15.8	50.0	— 0.6	+ 0.4	—	— 0.35
TiO_2	33	1.0	18.5	7.5	5.7	76.0	+ 0.25	0	— 0.35	—

in Central Sweden, too. The ratio mf certainly increases as qv decreases (*viz.* as the content of carbonate increases), but it should be kept in mind that the magnitude of mf is also dependent on the magnitude of mf in the primary source of the sediment in question and on the physico-chemical conditions during the transport and during the precipitation.

Titaniferous Iron Ores.

Table 12 presents some statistical data on the titaniferous iron ores. The calculations are based on analyses of titaniferous iron ores in Washington's work (120) and in that of J. Singewald Jr (108). Thus, most of the analyses are from deposits in the United States.

The Quartz Ratio (qv). The quantity qv varies considerably, as seen from the standard deviation. The mean of qv corresponds to the basic members of the skarn ores and the apatite iron ores in Sweden.

The value for $r_{qv,mc}$ is positive and the correlation is feeble between the two quantities. It should be observed that the corresponding r-value for the igneous rocks is negative and rather high.

The Ratio MgO/CaO (mc). There is an evident excess of MgO in these ores and the mean is > 50, but the amplitude is fairly great.

Degree of Oxidation (og). The og-value is comparatively low due to the excess of divalent iron significant for this ore type. The correlation qv,og is positive but quite feeble.

If the og-value is plotted in the diagram in fig. 16 the titaniferous iron ores are found to fall between the igneous rock series and the Swedish iron-ore series represented in the upper curve.

The Ratio MgO/FeO (mgf). The mean for this ratio shows a strong excess of bivalent iron, which is quite natural since the formation of the titaniferous iron ores occurs in a stage of development in the endogene phase where most of the magnesium content has already crystallized. In this connection it should be observed that iron becomes enriched in a *later* stage of development than magnesium, but the enrichment does not take place in the residual magma. It is evidently quite incorrect in this connection to use the term "residual enrichment of iron", sometimes unfortunately met with in the literature.

The Ratio K_2O/Na_2O (kn). The excess of sodium in this ore type is of interest. There exists no relationship between the quantities qv and kn.

The Ratio Mn/Fe (mf) is of minor interest in this connection. The lower part of Table 12 contains some statistical data on some oxides of the ores. These data are of special interest when considering the origin of this ore type and will be discussed later.

Summary.

The rocks and ores examined are classified on the basis of the quantity of qv. Therefore this quantity, and its relationship to the other ratios, is of primary importance. The correlation coefficients where qv is included (one of the variables) are consequently significant.

Although the r-values not including qv are of little importance at this stage, some of them will be discussed later. So far we have only dealt with the correlation between a single pair of variables, but in the next part of this book, the correlation between three variables will be mentioned too (partial correlation). It is, as a matter of fact, essential for the discussion of a possible hypothesis to know whether a correlation observed between, say, kn and mf can or cannot be accounted for solely by a correlation observed between kn and qv, mf and qv.

Table 13 below is a survey of the mean values of the ratios statistically computed in the igneous rocks and iron ores investigated.

Fig. 12 shows the relation between the means of qv (abscissa) and og (ordinate) in the igneous rocks and the glacial clays of Norway. As seen from the diagram, the positive correlation, approaching proportionality, between the two means in question is well illustrated.

The Rapakivi granites (point 11) show a slight deficiency of og. Further, the andesites (point 5) and the rhyolites (point 6) show higher og-values than the corresponding plutonic equivalents (the diorites and granites, respectively). The dotted horizontal line marks the og-value for magnetite (= 88.9).

Fig. 13 illustrates the relation qv-mc. It shows the decreasing tendency of the mc-means as the qv-values increase. However, there are three exceptions: the leptites of Sweden (point 10) and the glacial clays of Norway (point 13) show an excess of mc, and the Rapakivi granites of Finland (point 11) show a deficiency of mc, as compared with the other means, which are all but inversely proportional.

Table 13. **Survey of the M-values of qv, og, mc, mf, mgf and kn.**

Rocks and ores	qv	og	mc	mf	mgf	kn
Gabbros (World)	64	78	46	3.2	65	19
Gabbros (Sweden)	62	77	50	4.4	—	17
Diorites (World)	78	79	43	1.8	60	28
Diorites (Sweden)	71	80	46	2.4	—	30
Granites (World)	94	81	36	7.0	46	46
Granites (Sweden)	93	83	36	5.6	—	50
Basalts (World)	73	79	45	1.8	67	26
Andesites (World)	81	85	38	2.2	61	28
Rhyolites (World)	98	87	30	6.4	43	49
Leptites (Sweden)	96	81	54	3.5	57	45
Rapakivi granites (Finland)	94	76	20	1.3	17	55
Volcanic rock series (Hawaii)	67	79	47	2.8	58	17
Glacial clay (Norway)	86	82	61	1.6	63	56
qvs	52					
Iron sediments (S. Sweden)	28	73	29	0.7	—	85
qvs	28					
Sideritic ore (S. Sweden)	21	73	27	0.9	—	83
Iron ores, avg (Central Sweden)	58	89.8	55	2.0	—	—
Quartz ores, avg (Central Sweden)	74	92.8	49	0.3	—	—
Quartz ores, banded, avg (Central Sweden)	82	96.2	40	0.2	—	—
Skarn and lime ores, mf < 2, avg »	51	89.1	53	0.5	—	—
Skarn and lime ores, mf > 2, avg »	37	87.0	56	5.7	—	—
Swedish ore fields:						
Bispberg (quartz ore)	80	91.0	60	0.2	—	—
Striberg (quartz ore, banded)	82	95.0	46	0.2	—	—
Persberg (skarn ore, mf < 2)	45	88.7	69	0.4	—	—
Björnberget (skarn ore, mf < 2)	30	88.9	31	0.5	—	—
Dannemora (skarn-dolomite ore)	35	88.3	58	3.5	—	—
Klackberg (skarn-dolomite ore)	11	86.3	60	8.7	—	—
Grängesberg (apatite ore)	54	91.7	68	0.3	—	—
Kiirunavaara (apatite ore)	52	90.1	64	0.1	—	—
Gällivare (apatite ore)	54	90.1	70	0.1	—	—
Tuollavaara (apatite ore)	49	89.7	80	0.1	—	—

The relation between qv and mf in the igneous rocks is seen from the diagram in fig. 14. As mentioned earlier the mean values of mf should be regarded as uncertain, and some of the irregularly distributed dots of the means may be accounted for by analytical errors. However, it would seem to be impossible to draw the general conclusion that mf increases as qv increases. In fact, in the region of qv between 60 and 90 the tendency of mf is a decreasing one. In the region of qv > 90, on the contrary, the distribution of mf is irregular.

Fig. 15 demonstrates the relation between qv-means and kn-means in the igneous rocks. The means of kn tend to increase as the qv-values increase. It should be mentioned that the glacial clay shows an excess of kn in comparison with the other mean values.

Turning to the iron ores, the relation qv-og is illustrated in fig. 16. Here we find trends in the relation in question similar to those found in the igneous

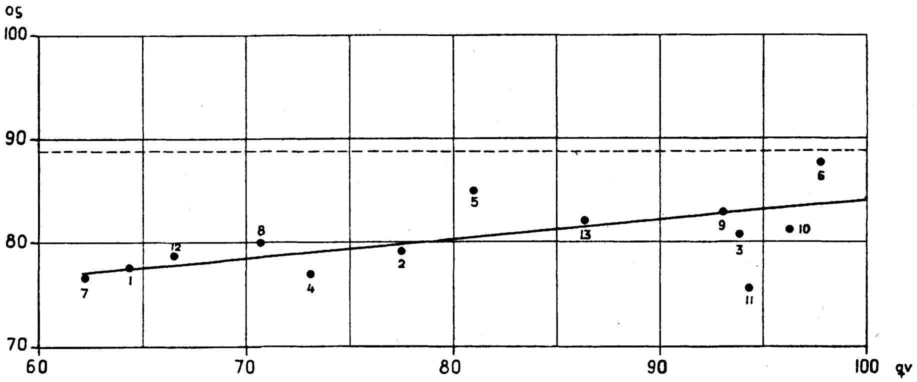

Fig. 12. Diagram of the relationship between the quartz ratio qv (abscissa) and the degree of oxidation og (ordinate) in the igneous rocks and glacial clay.
1 gabbros (avg), 2 diorites (avg), 3 granites (avg), 4 basalts (avg), 5 andesites (avg), 6 rhyolites (avg), 7 gabbros (Sweden), 8 diorites (Sweden), 9 granites (Sweden), 10 leptites (Sweden), 11 rapakivi granites (Finland), 12 volcanic series (Hawaii), and 13 glacial clay (Norway). The dotted line is the og-value for magnetite.

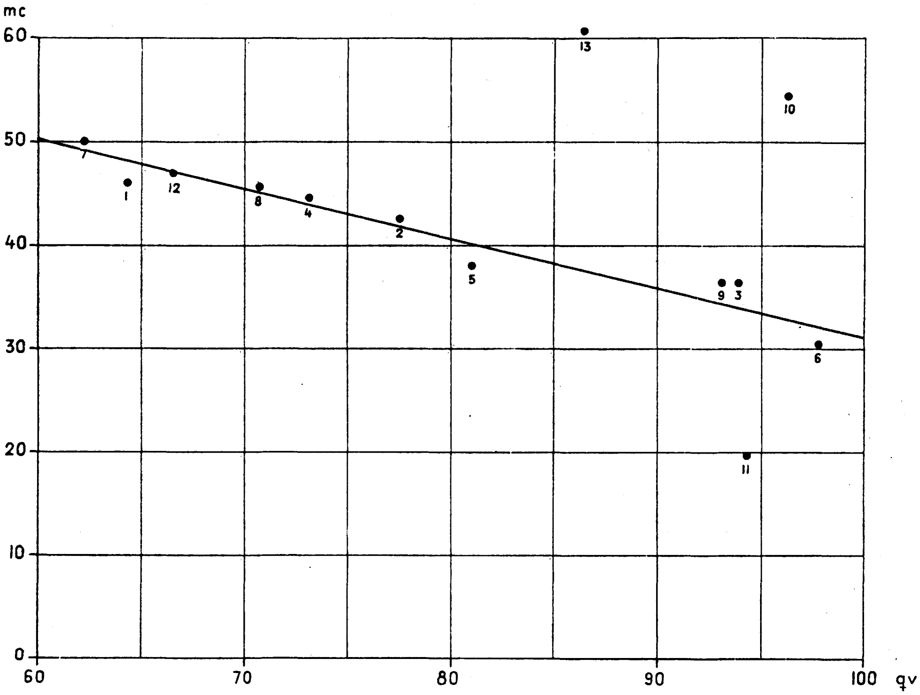

Fig. 13. Diagram of the relationship between the quartz ratio qv (abscissa) and the ratio MgO/CaO mc (ordinate) in the igneous rocks and glacial clay.
1 gabbros (avg), 2 diorites (avg), 3 granites (avg), 4 basalts (avg), 5 andesites (avg), 6 rhyolites (avg), 7 gabbros (Sweden), 8 diorites (Sweden), 9 granites (Sweden), 10 leptites (Sweden), 11 rapakivi granites (Finland), 12 volcanic series (Hawaii), and 13 glacial clay (Norway).

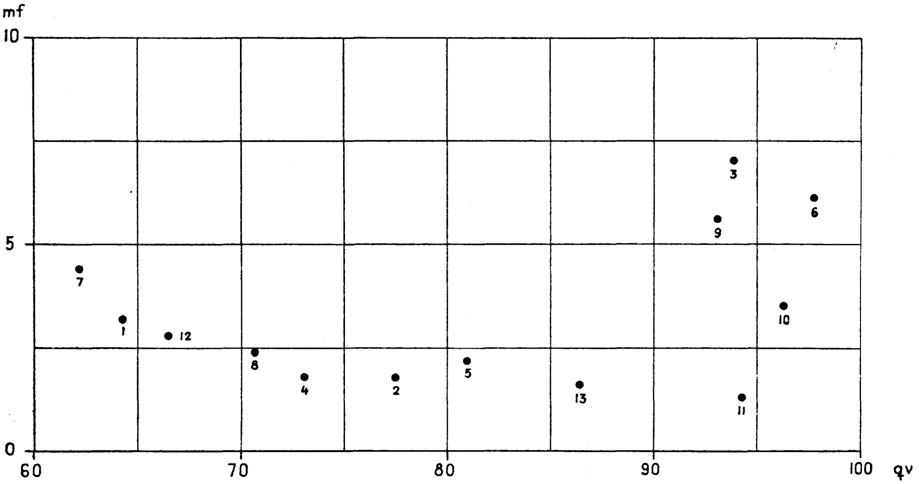

Fig. 14. Diagram of the relationship between the quartz ratio qv (abscissa) and the ratio Mn/Fe mf (ordinate) in the igneous rocks and glacial clay.
1 gabbros (avg), 2 diorites (avg), 3 granites (avg), 4 basalts (avg), 5 andesites (avg), 6 rhyolites (avg), 7 gabbros (Sweden), 8 diorites (Sweden), 9 granites (Sweden), 10 leptites (Sweden), 11 rapakivi granites (Finland), 12 volcanic series (Hawaii), and 13 glacial clay (Norway).

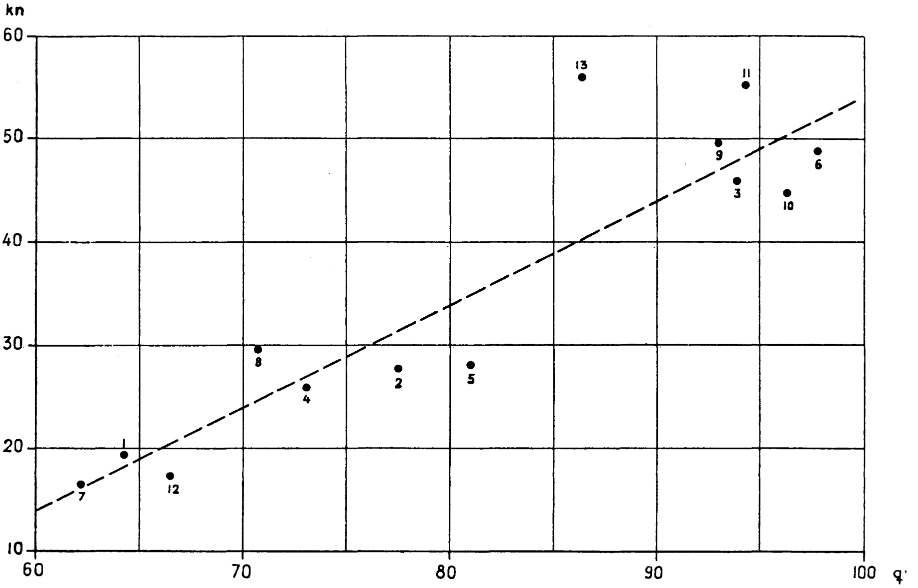

Fig. 15. Diagram of the relationship between the quartz ratio qv (abscissa) and the ratio K_2O/Na_2O kn (ordinate) in the igneous rocks and glacial clay.
1 gabbros (avg), 2 diorites (avg), 3 granites (avg), 4 basalts (avg), 5 andesites (avg), 6 rhyolites (avg), 7 gabbros (Sweden), 8 diorites (Sweden), 9 granites (Sweden), 10 leptites (Sweden), 11 rapakivi granites (Finland), 12 volcanic series (Hawaii), and 13 glacial clay (Norway).

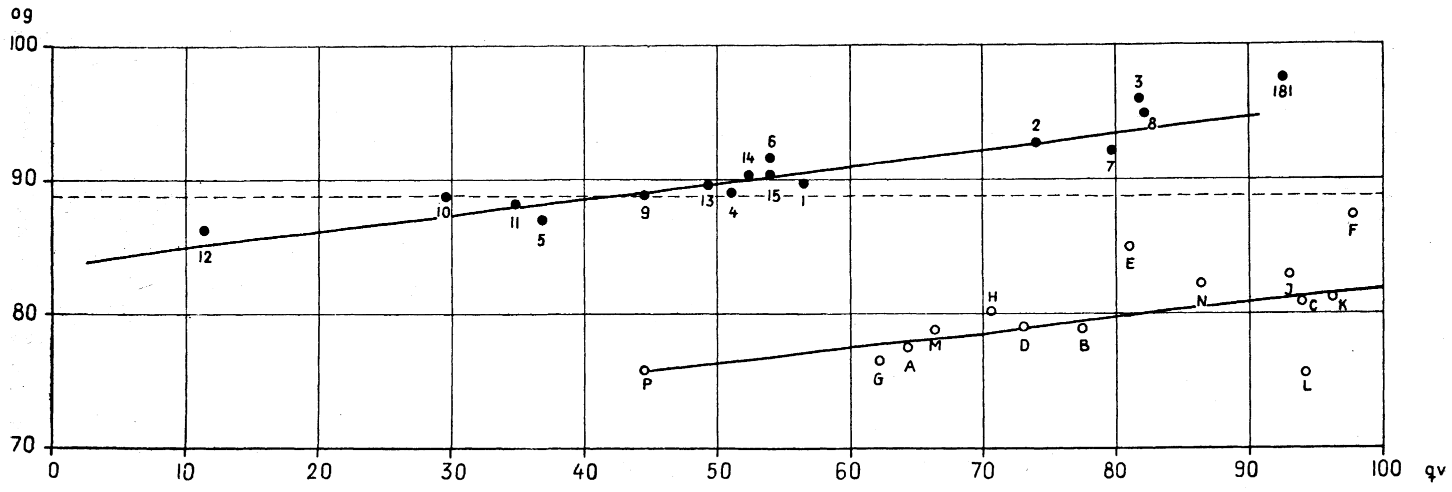

Fig. 16. Diagram of the relationship between the quartz ratio qv (abscissa) and the degree of oxidation og (ordinate). The upper curve: pre-Cambrian iron ores of Sweden. The lower curve: the igneous rocks and glacial clay.

1 iron ores of central Sweden (avg), 2 quartz ores, not banded (avg), 3 quartz ores, banded (avg), 4 skarn and lime ores with mf < 2 (avg), 5 skarn and lime ores with mf > 2 (avg), 6 apatite ore, Grängesberg, 7 quartz ores, Bispberg, 8 banded quartz ores, Striberg, (8) banded quartz ores of Striberg (with high qv-value), 9 skarn ores, Persberg, 10 skarn ores, Björnberget, 11 skarn-dolomite ores, Dannemora, 12 skarn-dolomite ores, Klackberg, 13 apatite ores, Tuollavaara, 14 apatite ores, Kiruna, and 15 apatite ores, Gällivare.

P peridotites (avg), A gabbros (avg), B diorites (avg), C granites (avg), D basalts (avg), E andesites (avg), F rhyolites (avg), G gabbros (Sweden), H diorites (Sweden), J granites (Sweden), K leptites (Sweden), L rapakivi granites (Finland), M volcanic series (Hawaii), and N glacial clay (Norway).

The dotted line is the og-value for magnetite.

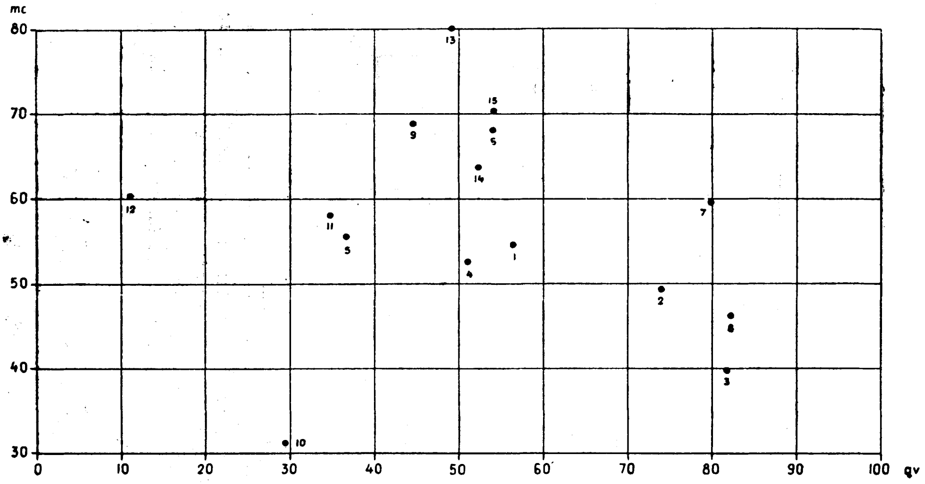

Fig. 17. Diagram of the relationship between the quartz ratio qv (abscissa) and the ratio MgO/CaO mc (ordinate) in pre-Cambrian iron ores of Sweden.
1 iron ores of central Sweden (avg), 2 quartz ores, not banded (avg), 3 quartz ores, banded (avg), 4 skarn and lime ores with mf < 2 (avg), 5 skarn and lime ores with mf > 2 (avg), 6 apatite ore, Grängesberg, 7 quartz ore, Bispberg, 8 banded quartz ore, Striberg, 9 skarn ore, Persberg, 10 skarn ore, Björnberget, 11 skarn-dolomite ore, Dannemora, 12 skarn-dolomite ore, Klackberg, 13 apatite ore, Tuollavaara, 14 apatite ore, Kiruna, 15 apatite ore, Gällivare.

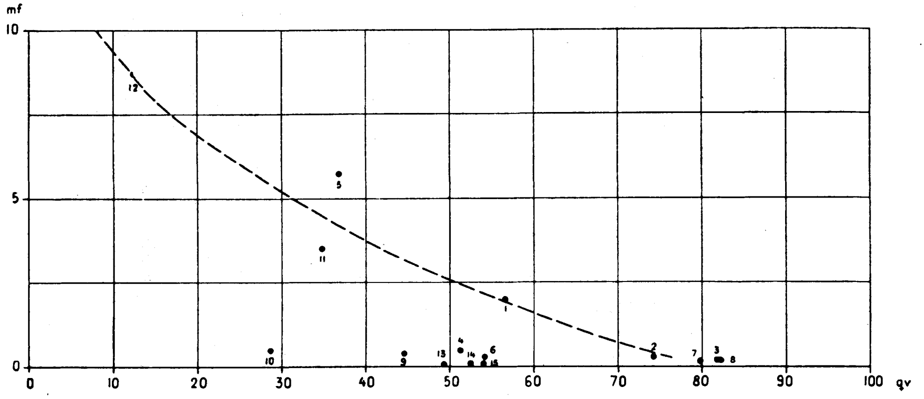

Fig. 18. Diagram of the relationship between the quartz ratio qv (abscissa) and the ratio Mn/Fe mf (ordinate) in pre-Cambrian iron ores of Sweden.
1 iron ores of central Sweden (avg), 2 quartz ores, not banded (avg), 3 quartz ores, banded (avg.), 4 skarn and lime ores with mf < 2 (avg.), 5 skarn and lime ores with mf > 2 (avg), 6 apatite ore, Grängesberg, 7 quartz ore, Bispberg, 8 banded quartz ore, Striberg, 9 skarn ore, Passberg, 10 skarn ore, Björnberget, 11 skarn-dolomite ore, Dannemora, 12 skarn-dolomite ore, Klackberg, 13 apatite ore, Tuollavaara, 14 apatite ore, Kiruna, 15 apatite ore, Gällivare.

rocks, *i.e.* a positive correlation between the means of qv and og approaching proportionality. However, the og-values are higher in the iron ores than in the igneous rocks, as seen from the diagram, where the figures of the igneous rocks are plotted for comparison.

Table 14. **A Survey of the r-values of qv and mc, og, mf and kn.**

Rocks and ores	$r_{qv,mc}$	$r_{qv,og}$	$r_{qv,mf}$	$r_{qv,kn}$
Gabbros (World)	—0.32	+0.13	—0.11	+0.11
Gabbros (Sweden)	—0.63	+0.26	—0.16	+0.15
Diorites (World)	—0.23	+0.31	+0.24	+0.22
Diorites (Sweden)	—0.18	+0.45	+0.21	+0.01
Granites (World)	—0.06	+0.27	+0.21	+0.24
Granites (Sweden)	—0.10	+0.12	+0.07	+0.30
Rapakivi granites (Finland)	+0.28	+0.55	—0.21	+0.60
Volcanic rock series (Hawaii)	—0.79	+0.54	+0.49	+0.36
Basalts (World)	—0.58	+0.70	+0.24	+0.62
Andesites (World)	—0.37	+0.42	+0.15	+0.23
Rhyolites (World)	—0.02	+0.38	—0.22	+0.16
Leptites (Sweden)	—0.03	+0.23	—0.24	+0.06
Glacial clay (Norway)	+0.05	+0.75	+0.17	+0.03
Iron ores of Sweden:				
Iron-bearing Liassic series, avg, S. Sweden with qvs	+0.24	+0.54	—0.30	—0.21
	+0.43	+0.78	—0.45	—0.20
Sideritic ores, S. Sweden with qvs	+0.32	+0.96	—0.28	—0.03
	+0.68	+0.99	—0.20	—0.19
Central Sweden, average of the region	+0.02	+0.52	—0.62	
Quartz ores, not banded, avg	—0.38	+0.53	—0.62	
Quartz ores, banded, avg	—0.06	—0.25	—0.05	
Skarn and lime ores, mf < 2, avg	+0.08	+0.20	—0.15	
Skarn and lime ores, mf > 2, avg	—0.15	+0.35	—0.78	
Apatite ore (Grängesberg)	+0.16	—0.09	—0.29	
Apatite ore (Kiirunavaara)	+0.08	+0.27	—0.18	
Apatite ore (Gällivare)	—0.03	+0.37	—0.28	
Quartz ore, not banded (Bispberg)	—0.48	+0.21	—0.17	
Quartz ore, banded (Striberg)	—0.57	+0.48	—0.23	
Skarn ore, mf < 2 (Persberg)	+0.31	0	—0.64	
Skarn ore, mf < 2 (Björnberget)	+0.94	—0.07	—0.57	
Skarn-dolomite ore, mf > 2 (Dannemora)	+0.28	—0.04	—0.58	
Skarn-dolomite ore, mf > 2 (Klackberg)	+0.22	+0.51	—0.38	

Fig. 17 illustrates the lack of relationship between the mean quantities of qv and mc in the iron ores.

Finally, fig. 18 illustrates the relation between the qv-means and the mf-means in the iron ores. As seen from the diagram, some of the ores show decreasing mf-values as qv increases. Most of the iron ores, however, have extremely low mf-values, quite independent of their qv-values, but it should be emphasized that the correlation coefficients of qv,mf always have a negative sign.

Table 14 is a survey of the correlation coefficients between qv, on the one hand, and mc,og,mf and kn, respectively, on the other. To sum up we find that on the whole $r_{qv,mc}$ is negative in the igneous rocks. It is positive in the Liassic iron-bearing series of Southern Sweden and undecided in the pre-Cambrian iron ores of Sweden.

The correlation between qv and og is positive in the igneous rocks, in the Liassic iron-bearing series of Southern Sweden and in some of the pre-Cambrian iron ores of Sweden. Some of the latter ores have a negative sign for $r_{qv,og}$, probably due to reducing metamorphic processes.

The correlation qv,mf is undecided in the igneous rocks but always negative in the iron ores.

Finally, $r_{qv,kn}$ is positive in the igneous rocks but negative in the Liassic iron ores of Southern Sweden.

Chapter III. The Distribution of the Minor Constituents.

In this chapter, the contents of the minor constituents in the iron ores and — for Central Sweden — their associated rocks, are discussed. The analytical data are distributed over several tables and grouped according to regions, groups of elements and kinds of samples. Each sample analysed has its specific number in all the tables belonging to the same region. All contents are given in per cent of weight.

The Iron-Ore bearing Region of Central Sweden (Bergslagen).

Tables 15—28 show the contents of minor constituents in the iron ores and their associated rocks. The grouping of the samples into regions and ore fields agrees with that made by Per Geijer and Nils H. Magnusson in their work on the geology of the iron ores of Central Sweden (38), this in order to facilitate comparisons between the geological and geochemical features of the region.

The ferrides. Table 15 shows the distribution of the ferrides in the iron ores of Central Sweden. The figures in the third column, marked "m" and "g" respectively, give the contents of the magnetic and the non-magnetic fractions for each sample in per cent. Thus, the figures for each sample in the upper line represent the contents of ferrides in the magnetic fraction, and the figures below show the contents of ferrides in the gangue or in the hematite ores excluding magnetite. In the cases where no figures are shown in the third column, the sample in question has not been magnetically separated, and the content of ferrides refers to the iron ore.

The contents of ferrides are given in per cent of weight. The figures for the iron require an explanation. The content of iron in the gangues is only spectrochemically estimated up to approximately 20 per cent. In cases when definite figures and not only "> 20" are given, the iron content was determined chemically.

Table 16 presents the content of ferrides in the rocks associated with the iron ores of Central Sweden. The research material emanates mainly from the Mineralogical Department of the Museum of Natural History in Stockholm, and from samples chemically analysed by Dr. Naima Sahlbom of Stockholm.

Table 15. **The Distribution of Ferrides in Iron Ores of Central Sweden.**

No.	Ore Type and Locality		Ti	V	Cr	Mn	Fe	Co	Ni
	The Persberg Region:								
1	Skarn-magnetite ore, Storgruvan, the Persberg Field	m: 84.7	0.04	< 0.001		0.1		< 0.001	< 0.001
		g: 15.4	0.02	0.003	0.01	0.4	7.8	< 0.003	< 0.001
2	Skarn-magnetite ore, "the kernel", Alabama, the Persberg Field	m: 89.5	< 0.01	< 0.001		0.03		< 0.001	< 0.001
		g: 10.5	< 0.01	0.002	0.02	0.3	7.6	< 0.003	< 0.001
3	Skarn-magnetite ore, "the shell", Alabama, the Persberg Field	m: 78.1	0.06	< 0.001		0.02		< 0.001	< 0.001
		g: 21.9	0.06	< 0.001	0.002	0.15	7.8	< 0.003	< 0.001
4	Serpentine-skarn-magnetite ore, Skärstöten, the Persberg Field	m: 77.8	0.02	< 0.001		0.2		< 0.001	< 0.001
		g: 22.2	0.03	< 0.001	< 0.001	0.3	4.0	< 0.003	0.002
5	Lime-magnetite ore, Skärstöten, the Persberg Field	m: 58.8	0.02	< 0.001		0.1		< 0.001	< 0.001
		g: 41.2	0.01	0.003	0.001	0.3	5.2	< 0.003	< 0.001
	The Nordmark Region:								
6	Skarn-magnetite ore, the Nordmark Mine	m: 80.4	0.02	< 0.001		0.2		< 0.001	< 0.001
		g: 19.6	0.01	< 0.001	0.01	> 1.0	7.8	< 0.003	< 0.001
7	Skarn-magnetite ore, the Taberg Mine	m: 92.0	< 0.01	< 0.001		1.0		< 0.001	< 0.001
		g: 8.0	0.01	< 0.001	0.03	1.0	7.8	< 0.003	< 0.001
8	Soft ore, the Taberg Mine	m: 32.2	0.04	< 0.001		1.0		< 0.001	< 0.001
		g: 67.8	0.09	< 0.001	0.05	0.3	> 20.0	< 0.003	< 0.003
9	Skarn-magnetite ore, the Finnmosse Mine	m: 92.2	0.07	< 0.001		0.2		< 0.001	< 0.001
		g: 7.8	< 0.01	0.001	0.05	0.9	> 20.0	< 0.003	0.01
10	Lime-magnetite ore, the Finnmosse Mine	m: 72.2	0.07	< 0.001		0.2		< 0.001	< 0.001
		g: 27.8	0.02	< 0.001	< 0.001	> 1.0	5.6	< 0.003	< 0.001
	The Grythyttan Region:								
11	Skarn-magnetite ore, the Högborn Ore Field	m: 37.9	0.03	< 0.001		0.03		< 0.001	< 0.001
		g: 62.1	0.03	< 0.001	0.001	0.3	9.8	< 0.003	0.002
12	Skarn-magnetite ore, the Finnberget Mine	m: 68.9	0.06	< 0.001		0.02		< 0.001	< 0.001
		g: 31.1	0.04	< 0.001	0.005	0.45	12.5	0.003	< 0.001
13	Skarn-lime-magnetite ore, the Finnberget Mine	m: 67.8	0.04	< 0.001		0.02		< 0.001	< 0.001
		g: 32.2	0.03	< 0.001	0.005	0.3	10.2	< 0.003	< 0.001
14	Lime-magnetite ore, the Finnberget Mine	m: 47.3	0.1	< 0.001		0.06		< 0.001	< 0.001
		g: 52.7	0.05	0.009	0.008	0.4	7.1	< 0.003	< 0.001
	The Nora-Viker Region:								
15	Quartz-magnetite ore, the Pershyttan Mines		0.04	0.002	0.001	0.06	56.9	0.003	0.003
16	Quartz-hematite ore, the Pershyttan Mines		0.4	0.004	0.002	0.05	53.8	0.003	0.003
17	Quartz-magnetite ore, the Klacka-Lerberg Mine	m: 80.3	0.05	< 0.001		0.6		< 0.001	< 0.001
		g: 19.7		< 0.001	< 0.001	0.3	13.5	< 0.003	< 0.001
18	Quartz-magnetite ore, the Nyberget Mine	m: 96.2	0.03	< 0.001		0.06		< 0.001	< 0.001
		g: 3.8	0.03	< 0.001	0.003	0.25	12.5	< 0.003	< 0.001
19	Quartz-magnetite-hematite ore, Grundgruvan, the Dalkarlsberg Mine	m: 70.6	0.04	< 0.001		0.06		< 0.001	< 0.001
		g: 29.4	0.02	0.003	< 0.001	> 1.0	> 20.0	0.004	< 0.001
20	Quartz-magnetite-hematite ore, banded, Kärrgruvan, the Striberg Mines		0.02	0.03	0.003	0.04	64.5	0.006	0.006
21	Quartz-garnet-hematite ore, banded, the Striberg Mines		< 0.01	0.02	0.003	0.01	52.5	0.01	0.008
22	Quartz-hematite ore, banded, the Striberg Mines	m: 6.6	< 0.01	0.001		0.3		< 0.001	0.003
		g: 93.4	< 0.01	0.001	< 0.001	0.03	> 20.0	< 0.003	< 0.001
23	Micaceous hematite ore, the Åsboberg Mine	m: 1.1	0.07	< 0.001		0.2		0.001	0.01
		g: 98.9	< 0.01	0.002	< 0.001	0.02	> 20.0	< 0.003	< 0.001

No.	Ore Type and Locality	Ti	V	Cr	Mn	Fe	Co	Ni
	The Region Linde-Guldsmedshyttan-Ramsberg:							
24	Quartz-hematite ore, banded, the Stripa Mine	0.02	0.02	0.008	0.09	52.0	0.005	0.001
25	Quartz-hematite ore, banded, from the footwall, Stripa	0.03	0.01	0.003	0.10	50.0	< 0.003	0.001
26	Quartz-hematite ore (avg), the Stråssa Mine	0.04	0.001	0.009	0.13	36.5	< 0.003	< 0.001
27	Quartz-magnetite ore, the Stråssa Mine	0.08	0.002	0.005	0.08	46.6	< 0.003	< 0.001
28	Quartz-hematite ore, the Blanka Mine m: 1.0	0.02	0.001		0.04		0.001	0.01
	g: 99.0	0.02	0.002	< 0.001	0.1	> 20.0	< 0.003	0.005
29	Lime-magnetite ore, Skött-gruvan m: 79.4	0.02	< 0.001		0.9		< 0.001	< 0.001
	g: 20.6	0.02	0.006	< 0.001	> 1.0	5.5	< 0.003	< 0.001
	The Ljusnarsberg Region:							
	Manganiferous iron ores from the Bastkärn field (No. 30—38):							
30	Knebelite ore, Backgruvan	< 0.01	0.005	0.003	4.50	37.4	0.001	0.001
31	Knebelite ore, rich in Pb, Backgruvan	0.01	0.007	0.002	3.82	38.4	0.004	< 0.001
32	Lime ore, Backgruvan	0.02	0.007	< 0.001	3.77	49.0	0.006	0.002
33	Knebelite ore with amphibole, garnet and mica	0.04	0.008	0.003	6.02	41.4	< 0.003	0.003
34	Knebelite ore with amphibole and mica	0.02	0.003	0.002	5.22	41.2	0.005	0.002
35	Knebelite ore rich in mica	0.03	0.007	0.001	5.10	40.5	0.003	0.001
36	Rich ore, mainly knebeliteskarn	0.03	0.008	< 0.001	3.90	57.4	0.003	0.003
37	Rich ore, calcareous	0.02	0.007	< 0.001	4.92	59.9	0.003	0.002
38	Rich ore with pyrite	0.01	0.010	0.002	3.42	57.4	0.003	0.001
39	Lime-magnetite ore, the Ställberg Mines m: 71.4	0.03	< 0.001		1.0		< 0.001	< 0.001
	g: 28.6	0.02	0.001	< 0.001	> 1.0	12.7	< 0.003	< 0.001
40	Lime-magnetite ore, the Ställberg Mines m: 76.4	0.01	0.001		1.0		0.001	0.001
	g: 23.6		0.01	0.001	0.62	7.1	0.003	0.004
41	Quartz-magnetite ore, the Lomberg Mines	0.05	< 0.001	< 0.001	0.08	65.3	< 0.001	< 0.001
42	Quartz-magnetite-hematite ore, the Lomberg Mines	< 0.11	0.001	< 0.001	1.0	39.9	< 0.001	< 0.001
43	Micaceous hematite ore, the Lomberg mines	< 0.10	0.001	< 0.001	0.05	57.7	< 0.001	< 0.001
44	Hematite-banded leptite, the Lomberg Mines	0.86	< 0.001	< 0.001	0.02	43.6	< 0.001	< 0.001
45	Skarn-lime-magnetite ore, the Pullero Mines	0.03	< 0.001	< 0.001	0.11	57.5	< 0.001	< 0.001
46	Skarn-lime-magnetite ore, the Pullero Mines	0.02	< 0.001	< 0.001	0.19	53.2	< 0.001	< 0.001
47	Skarn-lime-magnetite ore, the Pullero Mines	0.10	< 0.001	< 0.001	0.23	18.3	< 0.001	< 0.001
48	Skarn-lime-magnetite ore, the Pullero Mines	0.04	< 0.001	< 0.001	0.25		< 0.001	< 0.001
	The Grangärde-Ludvika Region:							
	The Grängesberg Ore Field (Nos. 49—55):							
49	Apatite-magnetite ore, the Export Field (avg)	0.09	0.18	< 0.001	0.16	63.2	0.002	0.006
50	Apatite-magnetite ore, the Lönnfallet Mine (avg)	0.11	0.16	< 0.001	0.12	51.9	0.005	0.006
51	Magnetite ore (poor in P), the Risberg Field (avg)	0.06	0.01	< 0.001	0.07	66.0	0.002	0.006

No.	Ore Type and Locality		Ti	V	Cr	Mn	Fe	Co	Ni
52	Magnetite-hematite ore (poor in P) the Risberg Field		0.15	0.001	< 0.001	0.02	58.0	0.001	0.001
53	Hematite ore (poor in P) the Risberg Field		3.10	0.05	< 0.001	0.10		0.001	0.001
54	Magnetite ore, Gudmundberget		0.19	0.001	< 0.001	0.55		0.001	0.001
55	Magnetite-hematite ore, the Granlund Mine		0.04	< 0.001	< 0.001	0.01		< 0.001	< 0.001
56	Apatite-magnetite ore, the Blötberget Mine	m: 88.4	0.1	0.1		0.03		0.001	0.005
		g: 11.6	0.02	0.02	0.001	0.60	10.0	0.003	0.004
57	Apatite-hematite ore, the Blötberget Mine	m: 1.2	0.06	0.03		0.2		0.003	0.01
		g: 98.8	0.2	0.1	< 0.001	0.03	> 20.0	< 0.003	0.001
58	Apatite-magnetite ore, the Fredmundberget Mine	m: 82.1	0.3	0.2		0.10		0.003	0.006
		g: 17.9	0.01	0.001	0.008	0.15	12.5	< 0.003	< 0.001
59	Apatite-hematite ore, the Fredmundberget Mine	m: 30.4	0.01	< 0.001		0.06		0.001	< 0.001
		g: 69.6	0.02	0.01	< 0.001	0.03	> 20.0	< 0.003	< 0.001
60	Epidote-hematite ore, the Fredmundberget Mine	m: 18.4	0.01	0.001		0.04		< 0.001	< 0.001
		g: 81.6	0.08	0.005	0.05	0.08	> 20.0	< 0.003	< 0.001
61	Apatite-magnetite ore, the Lekomberget Mine	m: 81.9	0.05	0.02		0.07		0.003	0.005
		g: 18.1		< 0.001	< 0.001	0.22	15.0	0.006	0.02
62	Quartz-magnetite ore, Våghalsen, the Finnäs Field	m: 78.2	0.06	< 0.001		0.02		< 0.001	< 0.001
		g: 21.8		0.003	0.04	0.15	10.2	< 0.003	< 0.001
63	Quartz-hematite ore, Våghalsen, the Finnäs Field........	m: 23.7	0.02	< 0.001		0.03		< 0.001	< 0.001
		g: 76.3	0.06	0.002	< 0.001	0.05	> 20.0	< 0.003	< 0.001
64	Quartz-magnetite ore, the Iviken Field	m: 75.3	< 0.01	< 0.001		0.07		< 0.001	< 0.001
		g: 24.7	0.02	< 0.001	< 0.001	0.15	4.5	< 0.003	< 0.001
65	Quartz-hematite ore, the Iviken Field	m: 9.2	< 0.01	< 0.001		0.2		0.002	< 0.001
		g: 90.8	0.02	0.003	< 0.001	0.15	> 20.0	< 0.003	0.005
66	Quartz-magnetite ore, the Ickorrbotten Field	m: 80.5	< 0.01	< 0.001		0.07		0.002	< 0.001
		g: 19.5	0.03	< 0.001	< 0.001	0.3	7.6	< 0.003	< 0.001
67	Quartz-hematite ore, the Ickorrbotten Field	m: 20.0	< 0.01	< 0.001		0.03		< 0.001	< 0.001
		g: 80.0	0.03	0.003	< 0.001	0.04	> 20.0	< 0.003	0.002
68	Quarts-magnetite-hematite ore, the Håksberg Field	m: 38.6	< 0.01	< 0.001		0.03		0.001	0.001
		g: 61.4	0.02	0.01	< 0.001	0.03	> 20.0	< 0.003	< 0.001
69	Quartz-magnetite-hematite ore, the Gräsberg Field	m: 21.1	0.02	< 0.001		0.1		< 0.001	< 0.001
		g: 78.9	< 0.01	0.002	< 0.001	0.4	> 20.0	< 0.003	0.006
70	Skarn-magnetite ore, the Mårtens Mine, Saxberget	m: 68.0	0.02	< 0.001		0.10		< 0.001	0.002
		g: 32.0	0.02	0.001	0.002	0.55	12.5	0.006	0.01
71	Lime-skarn-magnetite ore, the Björnberget Field		0.06	< 0.001	< 0.001	0.19	46.9	< 0.001	< 0.001
72	Lime-skarn-magnetite ore, the Björnberget Field		0.05	< 0.001	< 0.001	0.16	57.3	< 0.001	< 0.001
73	Lime-skarn-magnetite ore, the Björnberget Field		0.48	< 0.001	< 0.001	0.20	15.7	< 0.001	< 0.001
	The Norrbärke Region:								
74	Quartz-skarn-magnetite ore, the Kärrgruvan Field	m: 74.6	0.07	< 0.001		0.1		0.002	< 0.001
		g: 25.4	0.2	< 0.001	< 0.001	0.6	7.8	< 0.003	< 0.001
75	Quartz-magnetite-hematite ore, the Kärrgruvan Field	m: 47.8	< 0.01	< 0.001	< 0.001	0.04		< 0.001	< 0.001
		g: 52.2	0.08	0.002	< 0.001	0.03	> 20.0	< 0.003	0.002
76	Skarn-magnetite ore, the Kärrgruvan Field	m: 62.4	< 0.01	< 0.001		0.06		< 0.001	< 0.001
		g: 37.6	0.02	< 0.001	< 0.001	0.22	5.6	< 0.003	< 0.001
	The Skinnskatteberg Region:								
	The Riddarhytte Ore Fields (Nos. 77—88):								
77	Skarn-magnetite ore, the Källfallet Mine ("Anton")	m: 88.1	0.02	< 0.001		< 0.03		< 0.001	< 0.001
		g: 11.9	0.03	< 0.001	0.001	0.05	7.1	< 0.003	< 0.001

No.	Ore Type and Locality		Ti	V	Cr	Mn	Fe	Co	Ni
78	Skarn-magnetite ore, the Källfallet Mine ("Waldemar")	m: 90.4	0.02	< 0.001		0.03		< 0.001	< 0.001
		g: 9.6	0.02	< 0.001	0.002	0.09	7.6	< 0.003	< 0.001
79	Quartz-magnetite ore, poor in sulphides, the Myrbacks Field	m: 79.7		< 0.001		0.1		< 0.001	< 0.001
		g: 20.3	0.07	< 0.001	0.001	0.6	6.3	0.003	< 0.001
80	Quartz-magnetite ore, rich in sulphides, the Myrbacks Field	m: 57.8	0.02	< 0.001		0.1		0.001	< 0.001
		g: 42.2	0.05	< 0.001	0.004	0.6	7.8	0.03	0.004
81	Quartz-magnetite ore, poor in sulphides, Pellegruvan, the Hans Urbasson Field	m: 84.0	< 0.01	< 0.001		0.06		0.003	< 0.001
		g: 16.0	0.03	< 0.001	< 0.001	1.0	12.5	0.01	< 0.001
82	Quartz-magnetite ore, rich in sulphides, Pellegruvan, the Hans Urbasson Field	m: 94.8	< 0.01	< 0.001		0.06		0.006	< 0.001
		g: 5.2	0.5	0.02	0.01	1.0	7.0	< 0.003	0.003
83	Sulphide ore, rich in cobaltite, Pellegruvan, the Hans Urbasson Field	m: 59.4	< 0.01	< 0.001		0.06		> 1.0	< 0.001
		g: 40.6	0.03	< 0.001	< 0.001	0.62	22.0	> 1.0	0.03
84	Skarn-magnetite ore. the Höjdgruve Field	m: 58.7	0.01	< 0.001		0.2		< 0.001	< 0.001
		g: 41.3	0.01	< 0.001	0.08	> 1.0	15.0	< 0.003	< 0.001
85	Quartz-hematite ore, banded, type: Blåkulla, the Bastnäs Field	m: 2.0	0.02	0.003		0.1		0.001	0.003
		g: 98.0	0.03	< 0.001	0.001	0.03	5.6	0.003	< 0.001
86	Quartz-hematite ore, banded, type: Blåkulla, the Bastnäs Field	m: 5.3	< 0.01	< 0.001		0.1		0.001	0.001
		g: 94.7	0.01	0.002	0.02	0.05	> 20.0	< 0.003	< 0.001
87	Quartz-skarn-hematite ore, banded, type: Blåkulla, the Bastnäs Field	m: 63.0	< 0.01	< 0.001		0.07		< 0.001	< 0.001
		g: 37.0	< 0.01	0.001	< 0.001	0.25	11.1	0.007	0.008
88	Skarn-magnetite ore, the Persgruvan Mine	m: 91.1	0.01	0.001		0.03		0.001	0.001
		g: 8.9	0.01	0.001	0.003	1.0	10.2	0.003	0.002
	The Norberg Region:								
89	Skarn-magnetite ore, the Malmkärra Mine	m: 84.6	< 0.01	< 0.001		0.1		< 0.001	< 0.001
		g: 15.4	0.02	< 0.001	0.001	0.32	6.3	< 0.003	0.002
90	Skarn-magnetite ore, the Malmkärra Mine	m: 83.1	< 0.01	< 0.001		0.1		< 0.001	< 0.001
		g: 16.9	0.01	< 0.001	0.03	0.6	6.3	< 0.003	< 0.001
91	Quartz-hematite ore, banded, the Norrberg Field (avg 1940)		0.02	0.005	0.001	0.05	47.1	< 0.003	0.001
92	Quartz-hematite ore, banded, close to a diabase, the Norrberg Field	m: 1.7	0.04	< 0.001		0.2		< 0.001	0.003
		g: 98.3	< 0.01	0.002	< 0.001	0.25	> 20.0	< 0.003	0.002
93	Lime-magnetite ore, Åsgruvan, the Getbacken Field	m: 75.5	< 0.01	< 0.001		0.2		< 0.001	< 0.001
		g: 24.5	0.01	0.002	0.001	0.6	5.6	< 0.001	0.003
94	Diopside-skarn-magnetite ore, Åsgruvan, the Getbacken Field	m: 21.1	0.06	0.003		0.06		< 0.001	< 0.001
		g: 78.9	0.03	< 0.001	< 0.001	0.32	7.8	< 0.003	0.001
95	Actinolite-skarn-magnetite ore, Åsgruvan, the Getbacken Field	m: 41.4	0.01	< 0.001		0.06		< 0.001	< 0.001
		g: 58.6	0.03	< 0.001	0.01	0.25	7.1	< 0.003	0.001
96	Quartz-hematite ore, banded, Örlinggr., the Norberg Field	m: 12.6	< 0.01	< 0.001		0.2		< 0.001	< 0.001
		g: 87.4	0.01	0.002	0.003	0.05	> 20.0	0.003	0.002
97	Skarn-hematite ore, banded, Örlinggr., the Norberg Field	m: 21.1	< 0.01	< 0.001		0.2		< 0.001	< 0.001
		g: 78.9	0.01	0.001	0.001	0.07	> 20.0	0.003	0.003
98	Skarn-hematite ore, banded and rich in garnet, Örlinggruvan, the Norberg Field	m: 9.1	0.01	0.001		0.2		0.001	0.001
		g: 90.9	0.01	0.002	0.002	0.25	20.0	0.003	0.001
99	Quartz-hematite ores from the Norberg Field (avg 1940)		0.03	0.005	< 0.001	0.04	47.2	< 0.003	0.001
100	Quartz-hematite ores from the Norberg Mining District (avg 1940)		0.04	0.003	0.005	0.07	47.7	< 0.003	0.002
101	Lime-magnetite ore, Gröndal, the Klackberg Field	m: 84.9	< 0.01	< 0.001		> 1.0		< 0.001	< 0.001
		g: 15.1	< 0.01	< 0.001	< 0.001	1.0	12.5	< 0.003	< 0.001

No.	Ore Type and Locality		Ti	V	Cr	Mn	Fe	Co	Ni
102	Lime-magnetite ore, Storgruvan, the Klackberg Field	m: 62.3	< 0.01	< 0.001		> 1.0		< 0.001	< 0.001
		g: 37.7	< 0.01	< 0.001	< 0.001	> 1.0	13.7	< 0.003	< 0.001
103	Lime-magnetite ore (avg 1933), the G:la Kolningberg Field		0.01	0.01	< 0.003	5.14	48.6	0.002	0.003
104	Lime-magnetite ore, (avg 1933) the Nya Kolningsberg Field		0.02	0.01	< 0.003	4.23	44.4	0.004	0.002
	The Garpenberg Region:								
105	Diopside-skarn-magnetite ore, the Ryllshytte Mines	m: 74.6	< 0.01	< 0.001		0.2		0.001	< 0.001
		g: 25.4	< 0.01	< 0.001	< 0.001	0.6	7.8	< 0.003	< 0.001
106	Skarn-magnetite ore, the Holmgruvan Field	m: 34.1	< 0.01	< 0.001		> 1.0		< 0.001	< 0.001
		g: 65.9	0.01	< 0.001	< 0.001	> 1.0	12.0	< 0.003	< 0.001
107	Skarn-magnetite ore, rich in sulphides, Holmgruvan	m: 58.5	< 0.01	0.001		1.0		0.001	0.001
		g: 41.5	< 0.01	0.001	0.003	1.0	7.6	0.01	0.001
108	Actinoliteskarn-magnetite ore, the Intrånget Mines	m: 72.8	< 0.01	0.001		0.1		0.001	0.001
		g: 27.2	0.01	0.001	0.05	0.62	9.0	0.003	0.001
109	Cummingtonite-skarn-magnetite ore, the Intrånget Mines	m: 50.3	0.06	< 0.001		0.02		< 0.001	< 0.001
		g: 49.7	0.03	< 0.001	< 0.001	0.45	12.5	< 0.003	< 0.001
110	Skarn-magnetite ore, the Vik type, the Intrånget Mines	m: 49.1	< 0.01	< 0.001		0.1		0.001	< 0.001
		g: 50.9	< 0.01	< 0.001	< 0.001	1.0	12.6	0.003	< 0.001
111	Skarn-magnetite ore, the Karl type, the Intrånget Mines	m: 84.4	< 0.01	< 0.001		0.06		0.03	< 0.001
		g: 15.6	< 0.01	< 0.001	< 0.001	0.3	9.0	< 0.001	< 0.001
112	Skarn-magnetite ore, the Kron type, the Intrånget Mines	m: 88.3	0.04	< 0.001		0.03		< 0.001	< 0.001
		g: 11.7	0.02	< 0.001	0.001	0.62	15.0	< 0.003	< 0.001
113	Magnetite concentrate from skarn-magnetite ore of the Stjärn ore type	m: 94.5	< 0.01	< 0.001		0.1		< 0.001	< 0.001
		g: 5.5							
114	Pyroxene-garnet-skarn ore the Netzel ore type, the Intrånget Mines	m: 61.7	< 0.01	< 0.001		0.1		0.002	< 0.001
		g: 38.3	< 0.01	< 0.001	0.001	0.6	7.8	0.02	< 0.001
115	Skarn-magnetite ore, G:la Stjälkgruvan, the Intrånget Mines	m: 51.0	0.04	< 0.001		0.1		< 0.001	< 0.001
		g: 49.0	0.02	< 0.001	< 0.001	1.0	10.2	< 0.003	< 0.001
	The Silvberg-Säter Region:								
116	Quartz-magnetite ore, the Bispberg Field	m: 94.0	< 0.01	< 0.001		0.2		< 0.001	< 0.001
		g: 6.0	0.01	< 0.001	< 0.001	0.65	12.5	< 0.003	< 0.001
117	Quartz-magnetite ore, coarse grained, the Bispberg Field	m: 97.6	< 0.01	< 0.001		0.2		< 0.001	< 0.001
		g: 2.4	0.01	0.003	0.002	0.9	> 20.0	< 0.003	< 0.001
118	Quartz-magnetite ore, banded and coarse grained, the Bispberg Field	m: 78.1	< 0.01	< 0.001		0.2		< 0.001	< 0.001
		g: 21.9	< 0.01	0.001	< 0.001	0.03	6.5	< 0.003	< 0.001
119	Quartz-hematite ore, banded, the Bispberg Field	m: 4.0	< 0.01	< 0.001		0.07		< 0.001	< 0.001
		g: 96.0	< 0.01	0.001	0.03	0.03	> 20.0	< 0.003	< 0.001
120	Skarn-hematite ore, banded, the Bispberg Field	m: 0.7	< 0.01	< 0.001		0.1		0.04	0.003
		g: 99.3	< 0.01	0.003	< 0.001	0.2	> 20.0	< 0.003	0.01
121	Talcous skarn-hematite ore, the Bispberg Field	m: 1.5	0.02	0.001		0.1		< 0.001	< 0.001
		g: 98.5	0.03	0.008	< 0.001	0.06	> 20.0	< 0.003	< 0.001
	The Southern part of the St. Tuna Region:								
122	Knebelite-skarn-magnetite ore, the Tuna-Hästberg Field	m: 13.7	0.04	< 0.001		> 1.0		0.004	< 0.001
		g: 86.3	0.01	0.002	0.001	> 1.0	19.0	0.006	0.004
123	Apatite-magnetite ore, Bäckgruvan, the Idkerberget Field		0.01	0.02	0.002	0.07	64.5	< 0.003	0.001
124	Apatite-magnetite ore from the hanging wall, Väggruvan, the Idkerberget Field		0.90	0.10	0.05	0.05	56.3	0.005	0.01

No.	Ore Type and Locality		Ti	V	Cr	Mn	Fe	Co	Ni
125	Apatite-magnetite ore, Bergmästargruvan, the Idkerberget Field		0.05	0.08	0.01	0.06	60	0.004	0.008
126	Apatite-magnetite ore, Centralgruvan, the Idkerberget Field		0.01	0.10	0.005	0.07	60	0.005	0.009
	The Uppland Region:								
127	Lime-magnetite ore, banded, the Ramhäll Field		0.01	< 0.001	0.003	> 1.0	40.5	< 0.003	0.01
128	Lime-skarn-magnetite ore, Sveagruvan, the Dannemora Field (avg)	m: 75.2	0.01	< 0.001				< 0.001	< 0.001
		g: 24.8	0.02	< 0.001	0.001	2.62	47.2		
129	Lime-skarn-magnetite ore, Sveagruvan, the Dannemora Field (avg)	m: 78.5	< 0.01	< 0.001				< 0.001	< 0.001
		g: 21.5	< 0.01	< 0.001	0.001	2.11	51.9	0.01	< 0.001
130	Lime-skarn-magnetite ore, Mellanfälten, the Dannemora Field (avg)	m: 78.3	< 0.01	< 0.001				< 0.001	< 0.001
		g: 21.7	0.01	0.001	0.005	1.69	52.0	< 0.003	< 0.001
131	Lime-skarn-magnetite ore, Mellanfälten, the Dannemora Field (avg)	m: 78.6	< 0.01	< 0.001				< 0.001	< 0.001
		g: 21.4	< 0.01	0.002	0.005	1.72	51.4	< 0.003	< 0.001
132	Lime-skarn-magnetite ore, Diamantgruvan, the Dannemora Field (avg)	m: 78.3	< 0.01	< 0.001				< 0.001	< 0.001
		g: 21.7	< 0.01	< 0.001	0.004	2.71	50.4	< 0.003	< 0.001
133	Lime-skarn-magnetite ore, Diamantgruvan, the Dannemora Field (avg)	m: 79.3	< 0.01	< 0.001				< 0.001	< 0.001
		g: 20.7	0.02	0.005	0.001	2.56	50.4	0.01	0.003
134	Skarn-magnetite ore, Eknäs, the Herräng Field		< 0.01	0.008	< 0.001	0.38	45.9	0.02	0.002
135	Skarn-magnetite ore, Viking, the Herräng Field		0.02	0.004	< 0.001	0.60	42.2	0.01	0.003
136	Quartz-skarn-magnetite ore, Spatgruvan, the Herräng Field		0.05	0.006	0.001	0.09	47.1	0.006	0.002
137	Skarn-magnetite ore, Fabiangruvan, the Herräng Field		0.03	0.004	0.01	0.12	35.8	0.003	0.004
138	Skarn-magnetite ore, Sjö- och Dammgruvan, the Herräng Field		0.04	0.002	0.003	0.13	30.2	0.004	0.001
	The Södermanland Region:								
139	Quartz-magnetite ore, the Kantorp Mine	m: 48.5	0.07	< 0.001		0.02		< 0.001	< 0.001
		g: 51.5	0.2	< 0.001	0.004	0.1	7.8	< 0.003	< 0.001
140	Quartz-hematite ore, the Kantorp Mine	m: 6.0	< 0.01	< 0.001		0.06		< 0.001	0.005
		g: 94.0	0.1	< 0.001	0.03	0.01	15.0	< 0.003	< 0.001
141	Skarn-magnetite ore, homogenous, the Utö Mines		0.1	0.005		1.0	45	0.003	0.007
142	Quartz-hematite ore, banded, the Utö Mines		0.03	0.009	0.005	0.05	42.5	0.01	0.005

The samples were collected by the late Dr. H. E. Johansson and the late Professor Hj. Sjögren of Stockholm and were destined for inclusion in an investigation on the chemistry of the iron-ore bearing rocks of Central Sweden. Unfortunately, only part of this investigation was published (109). The material in question was kindly placed at the author's disposal by the Director of the Mineralogical Department of the Museum, the late Professor G. Aminoff.

Table 16. **The Distribution of Ferrides in Rocks from the Iron Ore Region of Central Sweden.**

No	Rock and Locality	Ti	V	Cr	Mn	Fe	Co	Ni
	Leptites:							
1	Leptite, Finnarmossgruvan	0.10	0.004	0.004	0.05	1.20	< 0.003	0.002
2	Potassic leptite, Backgruvan	0.14	0.010	0.002	0.085	2.35	< 0.003	< 0.001
3	Skarn-banded microline-plagioclase leptite, the Taberg Mine	0.22	0.005	0.004	0.015	0.75	< 0.003	< 0.001
4	Albite leptite, the Nordmark Mine	0.09	0.02	0.01	0.03	0.89	0.003	0.002
12	White albite leptite, the Rösberg Mine, Järnboås	< 0.01	< 0.001	0.003	tr.	0.13	< 0.003	< 0.001
13	Brown-grey helleflinta, Nora socken	0.07	0.002	0.003	0.008	0.91	< 0.003	0.005
14	Grey helleflinta, the Knapptorp Mine, Nora	0.07	< 0.001	0.004	0.015	1.18	< 0.003	< 0.001
15	Dark helleflinta-leptite, the Viker Mine	0.22	0.03	0.01	0.03	1.57	0.003	0.002
16	Grey helleflinta, the Nya Viker Field	0.05	0.01	0.002	0.04	1.62	< 0.003	0.001
17	Plagioclase leptite with needles of amphibole, the Bergäng Mines	0.11	0.02	0.002	0.015	1.11	< 0.003	0.01
18	Red leptite, the Skofttorp Field	0.50	0.05	0.007	0.085	2.76	< 0.003	0.001
19	Gneissose biotite-muscovite leptite, the Pershytte Field	0.49	0.07	0.006	0.05	5.50	< 0.003	0.001
20	Dark-grey biotite-leptite, the Nedre Pershytte Field	0.59	0.005	0.003	0.07	4.60	< 0.003	< 0.001
21	Leptite, Dalberget, the Klacka-Lerberg Field	0.07	0.004	0.004	0.015	0.79	< 0.003	< 0.001
22	Pink porphyric plagioclase-leptite, the Timansberg Field	0.02	< 0.001	0.002	0.008	1.10	< 0.003	0.002
23	Grey leptite, the Dalkarlsberg Mine	0.12	< 0.001	0.01	0.015	2.05	< 0.003	0.002
24	Plagioclase leptite, Kärrgruvan, the Striberg Field	0.006	< 0.001	0.003	0.008	0.08	< 0.003	< 0.001
25	Red potassic leptite, Kominstergruvan, the Striberg Field	0.07	0.002	0.005	0.008	1.72	< 0.003	0.001
26	Red leptite, Grindgruvan, the Striberg Field	< 0.01	0.002	0.003	0.05	1.65	< 0.003	0.003
27	Leptite, the Stråssa Field	0.36	0.03	0.01	0.008	3.05	< 0.003	0.002
29	Grey leptite, the S. Ställberg Field, Ljusnarsberg	0.16	0.001	0.03	0.09	1.87	0.003	0.003
30	Grey leptite, the Svartvik Field	0.05	0.004	0.004	0.03	1.47	< 0.003	0.01
33	Red leptite, the Iviken Mine	0.31	0.02	0.004	0.04	2.83	< 0.003	0.001
34	Grey plagioclase leptite, the Ickorrbotten Mine	0.12	0.003	0.004	0.015	3.19	< 0.003	< 0.001
35	Grey potassic leptite, the Hilläng Mine	0.12	0.007	0.003	0.008	2.36	< 0.001	< 0.001
36	Dark leptite, E. Stortäktsgruvan, Västanfors	0.31	0.02	0.004	0.04	2.83	< 0.003	0.001
37	White microline leptite, Östanmossa, the Norberg Field	0.06	0.005	0.002	< 0.01	0.32	< 0.003	0.001
38	Red leptite, Stålgruvan, the Norberg Field	0.08	< 0.001	0.001	0.008	0.36	< 0.003	0.003
40	Grey schistose leptite, the Norberg Field	0.05	0.003	0.003	< 0.01	1.33	< 0.003	< 0.001
41	Red leptite, the Norberg Field	0.01	0.001	0.001	0.008	0.65	< 0.003	< 0.001
44	Red plagioclase leptite, the Bispberg Field	0.09	0.004	0.009	tr.	1.58	< 0.003	< 0.001
45	Red leptite, the Säter Mines	0.06	0.02	0.2	0.02	5.66	0.003	0.002

No	Rock and Locality	Ti	V	Cr	Mn	Fe	Co	Ni
	Metamorphic Rocks:							
51	Yellowish quartz-muscovite schist, the Rösberg Field	0.03	0.008	0.005	0.008	1.51	< 0.003	0.001
52	Quartz-cordierite rock, the Dalkarlsberg Mine	0.08	< 0.001	0.008	0.015	2.24	< 0.003	0.001
53	Quartz-biotite schist, Stripa-Glifsa, the Striberg Field	0.05	0.009	0.005	0.015	8.50	< 0.003	0.001
54	Quartz-muscovite schist, the Åsboberg Mine, Nora	0.07	< 0.001	0.002	< 0.01	0.58	< 0.003	< 0.001
55	Andalusite quartzite, Garpenberg	0.06	0.002	0.002	0.05	3.19	0.003	0.001
56	Cordierite-gedrite rock, the Getå Silver Mine	0.09	0.001	0.004	0.03	7.58	< 0.003	< 0.001
	Skarn Rocks:							
57	Cummingtonite skarn, the Persberg Mines	0.01	0.01	0.005	0.14	17.54	0.003	0.001
58	Amphibole skarn, Stripa-Glifsa, the Striberg Field	0.02	0.01	< 0.001	0.05	7.28	0.003	0.001
59	Quartz-amphibole skarn, Stripa-Glifsa, the Striberg Field	0.06	0.009	0.003	0.05	4.71	< 0.003	0.001
60	Cummingtonite skarn, Hagalund Mine, the Striberg Field	< 0.01	0.006	0.001	0.18	12.14	< 0.003	< 0.001
61	Mn-garnet amphibole skarn, the Kråknäs Mine, the Norberg Field	0.67	0.10	0.008	5.98	13.90	0.003	0.006
	Granites and Gneisses:							
62	Albite-mica gneiss, Kvarnstensberget, the Striberg Field	0.06	0.02	0.007	0.008	0.73	< 0.003	0.04
63	Red gneiss, the Striberg Field	0.06	< 0.001	0.002	0.015	2.95	< 0.003	0.001
64	Plagioclase gneiss, the Lekomberg Mine	0.06	0.006	0.007	< 0.01	0.36	0.003	< 0.001
65	Plagioclase gneiss from the footwall, the Idkerberget Mines	0.55	0.01	0.002	0.02	1.98	< 0.003	< 0.001
66	Plagioclase gneiss, the Intränget Mines	0.09	0.009	0.005	0.015	1.57	< 0.003	< 0.001
67	Red mottled gneiss-granite, the Penning Mine, Torsåker	0.32	0.003	0.007	0.42	5.96	0.003	0.001
68	Grey plagioclase gneiss, the Malmberget Mine, Torsåker	0.06	0.003	0.003	0.015	1.29	< 0.003	0.002
	Amphibolites:							
69	Quartz-magnetite amphibolite, the Striberg Field	1.08	0.15	0.005	0.09	11.20	0.004	0.002
70	Amphibolite, the Idkerberget Mines	1.04	0.02	0.001	0.14	13.10	< 0.003	0.001

The author would also like to acknowledge the kindness of Dr. B. Asklund, who made available the late Dr. Johanssons annotations containing the figures of the chemical analyses.

The figures for Ti, Mn and Fe in Table 16 emanate from the chemical analyses by Dr. Sahlbom. The other ferrides were spectrochemically determined in the geochemical laboratory of the Geological Survey.

For the preliminary discussion on the distribution of the ferrides in the iron-ore region of Central Sweden, we may be guided by Tables 17—22 below, containing statistical data on the distribution of the ferrides.

Table 17. **The Distribution of Titanium in Iron Ores and Rocks from Central Sweden.**

Class	< 0.01	0.01—0.05	0.05—0.10	0.10—0.50	> 0.50
Magnetite ore:					
Magnetite....	47.5	35.5	15.5	1.5	0
Gangue......	23.5	61.0	8.5	5.0	2.0
Hematite ore ..	21.5	60.5	6.0	6.0	6.0
Leptite	8.0	10.0	46.0	28.0	8.0

Titanium (Table 17). The average content of Ti in the upper lithosphere is, according to V. M. Goldschmidt, 0.5 per cent (46). Compared with this mean value, it is evident that the iron ores of Central Sweden are poor in Ti. So are the rocks associated with the ores. The content of Ti in the magnetites tends to be lower than that of the ores. In the rocks, on the other hand, the figures for Ti are a little higher.

Vanadium (Table 18). The mean for V in the upper lithosphere is 0.015 per cent (V. M. Goldschmidt) (46). According to Table 18 the magnetites of the ores are poor in vanadium, except those of the apatite iron ores. The gangue rocks are also poor in vanadium, but the tendency is towards increasing values. This tendency is still more accentuated in the hematite ores. The apatite ores have an excess of vanadium compared with the mean. The distribution of vanadium in magnetite and gangue respectively will be discussed in detail in connection with the apatite iron ores of Northern Sweden.

In the rocks associated with the ores, the distribution of V is almost uniform and on the whole similar to that in the hematite ores.

Table 18. **The Distribution of Vanadium in Iron Ores and Rocks from Central Sweden.**

Class	< 0.001	0.001—0.005	0.005—0.01	0.01—0.05	0.05—0.1	> 0.1
Magnetite ore:						
Magnetite....	95.5	1.5	0	3.0	0	0
Gangue......	65.0	27.5	3.0	4.5	0	0
Hematite ore...	23.5	47.0	14.5	12.0	3.0	0
Apatite ore.....	0	0	9.0	18.0	27.5	45.5
Leptite.........	18.0	30.0	20.0	26.0	4.0	2.0

Chromium. The distribution of this element is shown in Table 19. Compared with the mean for Cr in the upper lithosphere — 0.02 per cent according to V. M. Goldschmidt (46) — there is a deficiency of Cr in the iron-ore region of Central Sweden. There seems to be no difference between the distribution in the gangues of the magnetite ores and that in the hematite ores. The ore-

Table 19. **The Distribution of Chromium in Iron Ores and Rocks from Central Sweden.**

Class	< 0.001	0.001—0.005	0.005—0.01	0.01—0.05	0.05—0.1	> 0.1
Magnetite ore:						
Gangue......	51.0	26.0	7.0	11.0	5.0	0
Hematite ore...	50.0	34.0	4.5	9.0	2.5	0
Leptite.........	2.0	60.0	26.0	10.0	0	2.0

bearing rocks show an increasing tendency, the mode being 0.001—0.005 per cent Cr.

Manganese (Table 20). The ratio Mn/Fe has already been discussed in the preceding chapter. In Table 20 some figures are given showing the principal distribution of manganese in the iron ores and the rocks of Central Sweden.

Table 20. **The Distribution of Manganese in Iron Ores and Rocks from Central Sweden.**

Class	< 0.01	0.01—0.05	0.05—0.10	0.10—0.50	0.50—1.0	> 1.0
Magnetite ore:						
Magnetite....	1.5	23.0	23.0	37.0	11.0	4.5
Gangue......	1.5	6.0	6.0	38.0	33.5	15.0
Hematite ore...	6.0	33.0	30.0	28.0	3.0	0
Leptite.........	32.0	40.0	20.0	6.0	0	2.0

Cobalt (Table 21). Unfortunately, from a spectrochemical point of view the content of cobalt is rather low in this region, so that the figures presented are estimated and thus approximate. As seen from Table 21, the magnetites of the ores as well as of the ore-bearing rocks are poor in Co and the contents are mainly below the average for the upper lithosphere, which is estimated at 0.004 per cent Co by V. M. Goldschmidt (46). In those cases where the contents of cobalt show relatively high values, *i.e.* in the gangues of the magnetite ores and in the hematite ores, the content of Co probably emanates from sulphide minerals — mainly pyrite — often present in the iron ores.

Table 21. **The Distribution of Cobalt in Iron Ores and Rocks from Central Sweden.**

Class	< 0.001	0.001—0.003	0.003—0.006	0.006—0.01	0.01—0.03
Magnetite ore:					
Magnetite....	83.0	11.0	3.0	1.5	1.5
Gangue......	0	79.5	8.0	3.0	9.5
Hematite ore...	0	79.0	10.5	3.5	7.0
Leptite.........	0	80.0	20.0	0	0

Table 22. **The Distribution of Nickel in Iron Ores and Rocks from Central Sweden.**

Class	< 0.001	0.001—0.003	0.003—0.006	0.006—0.01	0.01—0.03	> 0.03
Magnetite ore:						
Magnetite....	98.0	2.0	0	0	0	0
Gangue......	72.5	11.5	11.5	1.5	3.0	0
Hematite ore...	39.5	35.5	14.5	10.5	0	0
Leptite.........	38.0	46.0	8.0	2.0	4.0	2.0

Nickel (Table 22). The average content of nickel in the upper lithosphere was estimated at 0.01 per cent by V. M. Goldschmidt (46). In general there is a deficiency of Ni in the ores and rocks investigated, the majority of the analyses showing values < 0.01 per cent Ni. A comparison between the distribution of cobalt and nickel discloses the tendencies to be very similar.

The ratio Co/Ni has been much discussed in geochemical literature. According to V. M. Goldschmidt (46) this ratio is 0.4 for the upper lithosphere. If that is right, the ratio in question for the iron ores and rocks in Central Sweden is higher and approaches 1.

Lithium, Rubidium, and the Ratios Li/Mg and Rb/K. Tables 23 and 24 show the distribution of the two alkalies lithium and rubidium and the ratios Li/Mg and Rb/K. Magnesium and potassium were partly chemically, and partly spectrochemically determined. In the latter method the accuracy is lower, but sufficient to give an idea of the magnitude of the ratios in question.

Tables 25 and 26 contain some statistical data regarding the distribution of Li and Rb respectively.

In the first column of Table 23 "(o)" represents the content of Li and Rb, respectively, in the ore, and "(g)" stands for the content in question in the gangue (*viz.* ore excluding magnetite).

Lithium. Table 23 contains the analytical data on lithium in the iron ores. We find that the content of Li is very low both in the ores and in their gangues, quite independent of the ore types represented. Only in some skarn ores is the content of Li higher, but it never reaches any appreciable amount.

Turning to the leptites and other rocks associated with the iron ores, we find similar trends, *i.e.* the content of Li is low. Among the rocks showing a relatively high content of Li, the slates of the Grythytte series, some helleflintas, and leptites rich in mica should be mentioned.

Table 25 is a survey of the distribution of lithium in the gangues of the iron ores and in the ore-bearing rocks.

According to an investigation on the geochemistry of lithium by L. W. Strock (111) the average value of Li in the upper lithosphere is 0.0065 per cent. As seen in Table 25, only about 9 per cent of the ores (gangues) and 12 per cent of the rocks contain Li in quantities equal to or higher than the mean. The

Table 23. **The Distribution of Lithium, Magnesium, Potassium, and Rubidium in Iron Ores and their Gangues from the Iron-Ore Region of Central Sweden.**

No.	Ore (o), Gangue (g) and Locality	Li	Mg	$\frac{100\,Li}{Mg}$	K	Rb	$\frac{100\,Rb}{K}$
	The Persberg Region:						
1	Skarn-magnetite ore (g), Storgruvan, the Persberg Field	0.002	5.0	0.14	0.22	< 0.001	< 0.21
2	Skarn-magnetite ore (g), "the kernel", Alabama, the Persberg Field	0.001	7.1	0.05	0.14	< 0.001	< 0.33
3	Skarn-magnetite ore (g), "the shell", Alabama, the Persberg Field	< 0.0005	7.1	< 0.025	0.07	< 0.001	< 0.65
4	Serpentine-skarn-magnetite ore, (g) Skärstöten, the Persberg Field	0.001	15.0	0.02	0.10	< 0.001	< 0.46
5	Lime-magnetite ore, (g) Skärstöten, the Persberg Field	< 0.0005	6.2	< 0.03	< 0.07	< 0.001	—
	The Nordmark Region:						
6	Skarn-magnetite ore, (g) the Nordmark Mine	0.001	10.5	0.03	0.30	0.001	0.15
7	Skarn-magnetite ore, (g) the Taberg Mine..	0.0005	7.1	0.02	0.25	0.001	0.18
8	Soft ore, (g) the Taberg Mine	0.003	< 0.1	> 10.5	0.30	0.004	0.61
9	Skarn-magnetite ore, (g) the Finnmosse Mine	0.001	> 15.0	< 0.02	0.25	< 0.001	< 0.18
10	Lime-magnetite ore, (g) the Finnmosse Mine	0.0005	3.5	0.05	0.14	0.003	0.98
	The Grythyttan Region:						
11	Skarn-magnetite ore, (g) the Högborn Field	0.001	6.2	0.06	0.22	< 0.001	< 0.21
12	Skarn-magnetite ore, (g) the Finnberget Mine	0.001	3.5	0.10	0.30	0.008	1.22
13	Skarn-lime-magnetite ore, (g) the Finnberget Mine	0.002	1.6	0.44	0.25	0.007	1.28
14	Lime-magnetite ore, (g) the Finnberget Mine	< 0.0005	0.70	< 0.25	0.35	0.006	0.78
	The Nora-Viker Region:						
15	Quartz-magnetite ore, (o) the Pershyttan Mines	0.0007	0.4	0.60		< 0.001	—
16	Quartz-hematite ore, (o) the Pershyttan Mines	0.001	0.6	0.58	1.1	0.004	0.17
17	Quartz-magnetite ore, (g) the Klacka-Lerberg Mine	0.001	7.1	0.05		< 0.001	
18	Quartz-magnetite ore, (g) the Nyberget Mine	0.002	6.2	0.11	> 1.0	0.18	< 8.2
19	Quartz-magnetite-hematite ore, (g) Grundgruvan, the Dalkarlsberg Mine	0.001	0.60	0.58	0.20	0.0006	0.14
20	Quartz-magnetite-hematite ore, banded, (o) Kärrgruvan, the Striberg Field	< 0.0005	0.39	< 0.45		< 0.001	—
21	Quartz-garnet-hematite ore, banded, the Striberg Field (o)	0.007	0.21	1.17		< 0.001	
22	Quartz-hematite ore, banded, (g) the Striberg Field	< 0.0005	0.1			< 0.0005	
23	Micaceous hematite ore, (g) the Åsboberg Mine	< 0.0005	< 0.1			< 0.0005	
	The Region Linde-Guldsmedshyttan-Ramsberg:						
24	Quartz-hematite ore, banded, (o) the Stripa Mine	0.001	4.8	0.07	0.2	0.001	0.23
25	Quartz-hematite ore, banded, (o) from the foot-wall, the Stripa Mine	0.0005	3.1	0.06		< 0.001	
26	Quartz-hematite ore, (avg (o), the Stråssa Mine	0.001	0.28	1.24	0.47	0.004	0.39
27	Quartz-magnetite ore, (o) the Stråssa Mine	0.002	1.48	0.48	0.32	0.01	1.43

No.	Ore (o), Gangue (g) and Locality	Li	Mg	100 Li/Mg	K	Rb	100 Rb/K
28	Quartz-hematite ore, (g) the Blanka Mine	< 0.0005	0.50	< 3.5		< 0.0005	
29	Lime-magnetite ore, (g) Sköttgruvan	0.0005	5.5	0.032		< 0.001	
	The Ljusnarsberg Region:						
	Manganiferous Iron Ores from the Bastkärn Field (Nos. 30—38):						
30	Knebelite ore, (o) Backgruvan, 265 m level	< 0.0005	0.8	< 0.21		< 0.0005	
31	Knebelite ore, rich in Pb, (o) Backgruvan, 265 m level	< 0.0005	0.60	< 0.29		< 0.0005	
32	Lime ore, (o) Backgruvan, 265 m level	< 0.0005	2.22	< 0.08		< 0.0005	
33	Knebelite ore, containing amphibole, garnet, and mica (o)	0.0005	0.99	0.18	1.0	0.004	0.18
34	Knebelite ore, containing amphibole and mica (o)	0.0005	0.92	0.19	1.1	0.0007	0.03
35	Knebelite ore, containing mica (o)	0.002	1.03	0.68	0.9	0.008	0.41
36	Rich ore, mainly knebelite-skarn (o)	< 0.0005	0.90	< 0.19		< 0.0005	
37	Rich ore, calcareous (o)	< 0.0005	0.79	< 0.22		< 0.0005	
38	Rich ore, pyrite-bearing (o)	< 0.0005	1.70	< 0.10		< 0.0005	
39	Lime-magnetite ore (g), the Ställberg Mines	0.001	5.1	0.07	0.07	0.006	3.9
40	Lime-magnetite ore (g), the Ställberg Mines	0.001	1.6	0.22	0.22	< 0.001	< 0.21
41	Quartz-magnetite ore (o), the Lomberg Mines	0.002	9.2	0.08	0.6	< 0.0003	< 0.02
42	Quartz-magnetite-hematite ore (o), the Lomberg Mines	0.0003	1.3	0.08		0.005	
43	Micaceous hematite ore (o), the Lomberg Mines	0.0008	0.2	1.4		< 0.0003	
44	Hematite-banded leptite (o), the Lomberg Mines	0.0006	0.4	0.5			
45	Skarn-lime-magnetite ore (o), the Pullero Mines	0.0008	4.8	0.06	0.4	0.0009	0.1
46	Skarn-lime-magnetite ore (o), the Pullero Mines	0.001	6.6	0 05	0.3	< 0.0003	< 0.05
47	Skarn-lime-magnetite ore (o), the Pullero Mines	0.0006	1.6	0.13	0.3	< 0.0003	< 0.05
48	Skarn-lime-magnetite ore (o), the Pullero Mines	0.0006	3.7	0.06	0.2	< 0.0003	< 0.07
	The Grangärde-Ludvika Region:						
	The Grängesberg Ore Field (Nos. 49—55):						
49	Apatite-magnetite ore (g), the Export Field (avg)	0.017	8.2	0.77	1.1	0.1	4.16
50	Apatite-magnetite ore (g), the Lönnfallet Mine (avg)	0.0004	8.9	0.02	0.74	0.017	1.05
51 53	Magnetite ore (poor in P), (g), the Risberg Field (avg)	0.003	4.9	0.21	2.1	0.055	1.2
56	Apatite-magnetite ore (g), the Blötberget Mine	0.003	2.5	0.42	0.45	0.01	1.02
57	Apatite-hematite ore (o), the Blötberget Mine	< 0.0005	0.5	< 0.35	0.15	< 0.001	< 0.31
58	Apatite-magnetite ore (g), the Fredmundberget Mine	0.005	6.2	0.28	< 0.07	< 0.001	—
59	Apatite-hematite ore (g), the Fredmundberget Mine	0.003	0.25	4.2	0.07	0.0007	0.46
60	Epidote-hematite ore (o), the Fredmundberget Mine	0.0008	0.10	2.8	0.07	0.0006	0.39
61	Apatite-magnetite ore (g), the Lekomberget Mine	0.003	3.5	0.31	0.15	0.01	3.05
62	Quartz-magnetite ore (g), Våghalsen, the Finnäs Field	< 0.0005	0.35	< 0.5	0.50	0.007	0.64

No.	Ore (o), Gangue (g) and Locality	Li	Mg	$\frac{100\,\mathrm{Li}}{\mathrm{Mg}}$	K	Rb	$\frac{100\,\mathrm{Rb}}{\mathrm{K}}$
63	Quartz-hematite ore (g), Våghalsen, the Finnäs Field	0.0008	0.5	0.56	0.22	0.001	0.21
64	Quartz-magnetite ore (g), the Iviken Field	0.001	0.5	0.7	0.07	< 0.001	< 0.65
65	Quartz-hematite ore (o), the Iviken Field	< 0.0005	< 0.1	—	0.09	< 0.0003	< 0.15
66	Quartz-magnetite ore (g), the Ickorrbotten Field	0.008	1.6	1.75	0.3	0.03	4.6
67	Quartz-hematite ore (g), the Ickorrbotten Field	0.001	0.6	0.6	0.18	< 0.001	< 0.25
68	Quartz-magnetite-hematite ore (g), the Håksberg Field	0.003	0.2	5.25		< 0.0005	
69	Quartz-magnetite-hematite ore (g), the Gräsberg Field	< 0.0005	0.1	< 1.75		< 0.0005	
70	Skarn-magnetite ore (g), the Mårten Mine	0.004	2.8	0.5		< 0.001	
71	Lime-skarn-magnetite ore (g), the Björnberget Field	0.0003	2.4	0.04		0.006	
72	Lime-skarn-magnetite ore (g), the Björnberget Field	0.0005	9.8	0.02		< 0.0003	
73	Lima-skarn-magnetite ore (g), the Björnberget Field	0.0003	1.5	0.07	0.4	0.14	16.0
	The Norrbärke Region:						
74	Quartz-skarn-magnetite ore (g), the Kärrgruvan Field	< 0.0005	2.8	< 0.06	0.27	0.005	0.85
75	Quartz-magnetite-hematite ore (g), the Kärrgruvan Field	< 0.0005	0.75	< 0.23	0.22	< 0.001	< 0.21
76	Skarn-magnetite ore (g), the Kärrgruvan Field	0.003	9.2	0.11	0.12	0.003	1.2
	The Skinnskatteberg Region:						
	The Riddarhytte Ore Fields (Nos. 77—88):						
77	Skarn-magnetite ore (g), the Källfallet Mine ("Anton")	0.0005	7.1	0.03	0.14	0.007	2.3
78	Skarn-magnetite ore (g), the Källfallet Mine ("Waldemar")	0.002	7.1	0.1	< 0.07	< 0.001	—
79	Quartz-magnetite ore, poor in sulphides (g), the Myrbacks Field	0.02	2.4	2.9	> 1.0	0.02	< 0.9
80	Quartz-magnetite ore, rich in sulphides (g), the Myrbacks Field	0.007	1.1	2.2	0.20	0.02	4.6
81	Quartz-magnetite ore, poor in sulphides (g), Pellegruvan, the Hans Urbasson Field	0.01	2.8	1.25	> 1.0	0.05	< 2.3
82	Quartz-magnetite ore, rich in sulphides (g), Pellegruvan, the Hans Urbasson Field	0.02	5.0	1.40	0.12	< 0.001	< 0.4
83	Sulphide ore, rich in cobaltite (o), Pellegruvan, the Hans Urbasson Field	0.01	1.1	3.0	0.22	0.01	2.1
84	Skarn-magnetite ore (g), the Höjdgruve Field	0.003	9.2	0.11	0.30	0.007	1.1
85	Quartz-hematite ore, banded, of the Blåkulla type (o), the Bastnäs Field	< 0.0005	1.6	< 0.11	0.18	< 0.001	< 0.25
86	Quartz-hematite ore, banded, of the Blåkulla type (o), the Bastnäs Field	0.0005	0.5	0.35	0.20	< 0.001	< 0.25
87	Quartz-skarn-hematite ore, banded, of the Blåkulla type (g), the Bastnäs Field	0.001	10.0	0.04	0.10	0.0003	0.14
88	Skarn-magnetite ore (g), the Persgruvan Field	0.0005	10.5	0.02	0.16	< 0.001	< 0.29
	The Norberg Region:						
	The Norberg Ore Fields (Nos. 89—104):						
89	Skarn-magnetite ore (g), the Malmkärra Mine	0.02	10.5	0.67	0.10	0.001	0.46
90	Skarn-magnetite ore (g), the Malmkärra Mine	0.001	7.1	0.05	0.07	0.01	6.54

No.	Ore (o), Gangue (g) and Locality	Li	Mg	$\frac{100\,\mathrm{Li}}{\mathrm{Mg}}$	K	Rb	$\frac{100\,\mathrm{Rb}}{\mathrm{K}}$
91	Quartz-hematite ore, banded (o), the Norrberg Field (avg 1940)	< 0.0005	0.7	< 0.25	0.1	0.001	0.46
92	Quartz-hematite ore, banded, close to a diabase (o), the Norrberg Field	< 0.0005	0.3	< 0.6	0.09	< 0.001	< 0.5
93	Lime-magnetite ore (g), Åsgruvan, the Getbacken Field	0.003	3.5	0.3	0.11	< 0.001	< 0.4
94	Diopside-skarn-magnetite ore (g), Åsgruvan, the Getbacken Field	< 0.0005	5.0	< 0.04	0.10	< 0.001	< 0.46
95	Actinolite-skarn-magnetite ore (g), Åsgruvan, the Getbacken Field	0.001	7.1	0.05	0.08	< 0.001	< 0.57
96	Quartz-hematite ore, banded (g), Örlinggruvan, the Norberg Field	< 0.0005	0.5	< 0.35		< 0.001	
97	Skarn-hematite ore, banded (g), Örlinggruvan, the Norberg Field	0.0006	2.5	0.08		< 0.001	
98	Skarn-hematite ore, banded, and rich in garnet (g), Örlinggruvan, the Norberg Field	< 0.0005	0.7	< 0.25	0.09	< 0.001	< 0.51
99	Quartz-hematite ores from the Norberg Field (avg 1940) (o)	< 0.0005	0.9	< 0.19		< 0.001	
100	Quartz-hematite ores from the Norberg Mining Fields (avg 1940) (o)	< 0.0005	0.3	< 0.58		< 0.001	
101	Lime-magnetite ore (g), Gröndal, the Klackberg Field	0.0005	6.1	0.03		< 0.001	
102	Lime-magnetite ore (g), Storgruvan, the Klackberg Field	0.0005	2.8	0.06		< 0.001	
103	Lime-magnetite ore (o), (avg 1933), the G:la Kolningberg Field	< 0.0005	1.8	< 0.1		< 0.001	
104	Lime-magnetite ore (o), (avg 1933), the Nya Kolningberg Field	< 0.0005	2.2	< 0.08		< 0.001	
	The Garpenberg Region:						
105	Diopside-skarn-magnetite ore (g), the Ryllshytte Mines	0.001	12.5	0.03	< 0.07	< 0.001	—
106	Skarn-magnetite ore (g), the Holmgruvan Field	0.0008	1.6	0.18	0.30	0.01	1.52
107	Skarn-magnetite ore, rich in sulphides (g), the Holmgruvan Field	< 0.0005	1.6	< 0.11	0.23	0.004	0.80
108	Actinolite-skarn-magnetite ore (g), the Intrånget Mines	0.0005	7.1	0.02	0.14	< 0.001	< 0.33
109	Cummingtonite-skarn-magnetite ore (g), the Intrånget Mines	0.0005	8.5	0.02	0.13	< 0.001	< 0.36
110	Skarn-magnetite ore (g), (the Vik ore), the Intrånget Mines	< 0.0005	3.5	< 0.05	0.14	0.03	9.8
111	Skarn-magnetite ore (g), (the Karl ore), the Intrånget Mines	< 0.0005	5.0	< 0.04	0.17	< 0.001	< 0.27
112	Skarn-magnetite ore (g), (the Kron ore), the Intrånget Mines	0.003	7.1	0.15	0.10	< 0.001	< 0.46
114	Pyroxene-garnet-skarn ore ,(the Netzel ore), the Intrånget Mines (o)	< 0.0005	3.5	< 0.05	0.12	0.004	1.52
115	Skarn-magnetite ore, G:la Stjälkgruvan, the Intrånget Mines (o)	0.0006	5.0	0.04	0.14	< 0.001	< 0.33
	The Silvberg-Säter Region:						
116	Quartz-magnetite ore (g), the Bispberg Field	0.001	4.0	0.09	< 0.07	< 0.001	—
117	Quartz-magnetite ore, coarse grained (g), the Bispberg Field	0.0008	3.2	0.09	0.08	< 0.001	< 0.57
118	Quartz-magnetite ore, banded and coarse grained (o), the Bispberg Field	< 0.0005	0.7	< 0.25	0.14	< 0.001	< 0.33

No.	Ore (o), Gangue (g) and Locality	Li	Mg	$\frac{100\,\text{Li}}{\text{Mg}}$	K	Rb	$\frac{100\,\text{Rb}}{\text{K}}$
119	Quartz-hematite ore, banded (o), the Bispberg Field	< 0.0005	0.3	< 0.58	0.11	0.0003	0.12
120	Skarn-hematite ore, banded (o), the Bispberg Field	0.0005	6.0	0.03	< 0.07	< 0.0003	—
121	Talcous Skarn-hematite ore (o), the Bispberg Field	< 0.0005	5.0	< 0.035	0.10	< 0.001	< 0.46
	The southern Part of the St. Tuna Region:						
122	Knebelite-skarn-magnetite ore (g), the Tuna-Hästberg Field	< 0.0005	1.0	< 0.18		< 0.0005	
123	Apatite-magnetite ore (g), Bäckgruvan, the Idkerberget Field	< 0.0005	0.2	< 0.88		< 0.0005	
124	Apatite-magnetite ore from the hanging wall (g), Väggruvan, the Idkerberget Field	< 0.0005	< 0.1	—		< 0.001	
125	Apatite-magnetite ore (g), Bergmästargruvan, the Idkerberget Field	< 0.0005	0.25	< 0.7		< 0.0005	
126	Apatite-magnetite ore (g), Centralgruvan, the Idkerberget Field	< 0.0005	0.90	< 0.19		< 0.0005	
	The Uppland Region:						
127	Lime-magnetite ore, banded (o), the Ramhäll Field	0.001	1.4	0.25	0.7	0.02	1.3
128	Lime-skarn-magnetite ore (g), (avg), Sveagruvan, the Dannemora Field	< 0.0005	7.1	< 0.02	0.12	0.003	1.14
129	Lime-skarn-magnetite ore (g), (avg), Sveagruvan, the Dannemora Field	< 0.0005	5.5	< 0.03	0.20	< 0.001	< 0.23
130	Lime-skarn-magnetite ore (g), (avg), Mellanfälten, the Dannemora Field	< 0.0005	7.1	< 0.02	0.30	0.006	0.92
131	Lime-skarn-magnetite ore (g), (avg), Mellanfälten, the Dannemora Field	< 0.0005	5.5	< 0.03	0.20	< 0.001	< 0.23
132	Lime-skarn-magnetite ore (g), (avg), Diamantgruvan, the Dannemora Field	0.004	7.1	0.20	0.15	< 0.001	< 0.31
133	Lime-skarn-magnetite ore (g), (avg), Diamantgruvan, the Dannemora Field	< 0.0005	4.5	< 0.04	0.08	< 0.001	< 0.57
134	Skarn-magnetite ore (o), Eknäs, the Herräng Field	0.0006	1.21	0.17	0.02	< 0.001	< 2.3
135	Skarn-magnetite ore (o), Viking, the Herräng Field	0.0005	1.72	0.10	0.12	< 0.001	< 0.38
136	Quartz-skarn-magnetite ore (o), Spatgruvan, the Herräng Field	0.001	1.19	0.29	0.32	0.003	0.43
137	Skarn-magnetite ore (o), Fabiangruvan, the Herräng Field	0.001	3.82	0.09	0.12	< 0.001	< 0.38
138	Skarn-magnetite ore (o), Sjö- och Dammgruvan, the Herräng Field	0.0006	3.00	0.07	0.09	< 0.001	< 0.51
	The Södermanland Region:						
139	Quartz-magnetite ore (g), the Kantorp Mine	0.01	3.5	1.0	0.18	< 0.001	< 0.25
140	Quartz-hematite ore (g), the Kantorp Mine	0.004	0.25	5.6	0.40	< 0.001	< 0.12
141	Skarn-magnetite ore, homogenous (o), the Utö Mines	0.02	1.2	5.8	> 2	0.06	< 1.4
142	Quartz-hematite ore, banded (o), the Utö Mines	0.007	0.55	4.5		< 0.003	

Table 24. **The Distribution of Lithium, Magnesium, Potassium, and Rubidium in Rocks from the Ore-bearing Regions of Central Sweden.**

No.	Rock and Locality	Li	Mg	$\frac{100\ \text{Li}}{\text{Mg}}$	K	Rb	$\frac{100\ \text{Rb}}{\text{K}}$
	Leptites:						
1	Leptite, Finnarmossgruvan	0.0005	1.18	0.15	1.59	0.004	0.12
2	Potassic leptite, Backgruvan	0.0005	1.01	0.18	7.30	0.03	0.19
3	Skarn-banded microcline-plagioclase leptite, the Taberg Mine	0.003	1.03	1.03	4.36	0.02	0.21
4	Albite-leptite, the Nordmark Mines	< 0.0005	0.85	< 0.21	0.008	0.004	50
5	Black helleflinta, Grythyttan	< 0.0005	0.20	< 0.88	2.63	0.007	0.12
6	Black helleflinta, Grythyttan	0.003	1.12	0.94	5.80	0.02	0.16
7	Helleflinta, Hällefors	< 0.0005	0.07	< 2.5	0.16	0.004	1.14
8	Helleflinta, Brevik, Grythyttan	< 0.0005	0.13	< 1.3	0.23	< 0.0003	0.10
9	Dark slate, Grythyttan	0.02	1.61	4.36	3.44	0.01	0.13
10	Black slate, Grythyttan	0.01	2.52	1.39	1.61	0.007	0.20
11	Light slate, Grythyttan	0.02	1.64	4.27	3.94	0.01	0.12
12	White albite-leptite, Rösberg	< 0.0005	0.17	< 1.05	0.32	0.0003	0.04
13	Brown-grey helleflinta, Nora socken	0.002	1.29	0.55	4.12	0.02	0.22
14	Grey helleflinta, Knapptorpgr, Nora	0.0005	0.21	0.83	1.84	0.008	0.20
15	Dark helleflinta-leptite, Viker	0.001	1.31	0.27	3.08	0.01	0.15
16	Grey helleflinta, Nya Viker Mine	0.02	1.62	4.4	4.07	0.01	0.11
17	Plagioclase-leptite with needles of amphibole, the Bergsäng Mines	< 0.0005	2.09	< 0.084	0.51	0.002	0.18
18	Red leptite, the Skofttorp Field	0.003	1.18	0.89	8.01	0.02	0.09
19	Biotite-muscovite-leptite, the Pershytte Field	0.02	1.04	6.8	4.97	0.03	0.28
20	Dark-grey biotite-leptite, the Nedre Pershytte Field	0.01	1.80	1.95	6.60	0.025	0.17
21	Leptite, Klacka-Lerberg	0.0006	0.43	0.48	4.18	0.01	0.11
22	Pink porphyric plagioclase-leptite, Timansberg	< 0.0005	0.24	< 0.74	0.22	0.002	0.42
23	Grey leptite, Dalkarlsberg	0.0005	0.90	0.20	2.67	0.01	0.17
24	Plagioclase-leptite, Kärrgruvan, the Striberg Field	0.0008	0.12	2.34	0.19	0.004	0.12
25	Red potassic leptite, Komministergruvan, the Striberg Field	0.0005	0.37	0.47	5.85	0.02	0.16
26	Red leptite, Grindgruvan, the Striberg Field	0.0005	0.70	0.25	7.18	0.015	0.10
27	Leptite, Stråssa	0.001	2.11	0.08	3.10	0.01	0.15
28	Leptite, the Bastkärn Field	0.0008	0.49	0.57	8.25	0.01	0.06
29	Grey leptite, the S. Ställberg Field, Ljusnarsberg	< 0.0005	0.42	0.42	10.98	0.05	0.21
30	Grey leptite, the Svartvik Field, Ljusnarsberg	0.0007	0.89	0.27	5.39	0.025	0.20
31	Red potassic leptite, Grängesberg		0.82		5.83	0.03	0.20
32	Grey sodic leptite, Grängesberg		0.76		1.36	0.009	0.30
33	Red leptite, the Iviken Mine	< 0.0005	0.19	< 0.92	6.85	0.03	0.20
34	Grey plagioclase-leptite, the Ickorrbotten Mine	0.002	1.13	0.62	0.97	0.003	0.14
35	Grey potassic leptite, the Hilläng Mine	0.0008	0.60	0.47	6.18	0.03	0.21
36	Dark leptite, Västanfors	0.003	0.99	1.06	6.38	0.03	0.22
37	White microcline-leptite, Östanmossa, Norberg	< 0.0005	0.46	< 0.38	7.65	0.006	0.04
38	Red leptite, Stålgruvan, Norberg	< 0.0005	0.10	< 1.75	7.29	0.02	0.13
39	Sodic leptite, Kallmorberg, Norberg	< 0.0005	0.29	< 0.61	0.32	0.001	0.14
40	Grey schistose leptite, Norberg	0.002	0.36	1.95	3.39	0.008	0.11

No.	Rock and Locality	Li	Mg	$\frac{100\ \mathrm{Li}}{\mathrm{Mg}}$	K	Rb	$\frac{100\ \mathrm{Rb}}{\mathrm{K}}$
41	Red leptite, Norberg	< 0.0005	0.012	< 14.6	3.49	0.08	1.03
42	Leptite, Norberg	< 0.0005	0.066	< 2.06	7.40	0.01	0.06
43	Sodic leptite, Norberg	< 0.0005	0.64	< 0.27	1.34	0.006	0.20
44	Red plagioclase-leptite, the Bispberg Field	< 0.0005	0.08	< 2.19	0.19	0.0003	0.07
45	Red leptite, the Säter Mines	< 0.0005	0.25	< 0.70	5.13	0.02	0.21
46	Sodic leptite, Markdalsgruvan, Grisslehamn	< 0.0005	0.57	< 0.31	0.34	0.0006	0.08
47	Potassic leptite, Vånga (avg)	0.0006	0.31	0.67	9.78	0.009	0.04
48	Potassic leptite, Norsholm, Vånga	0.0008	0.48	0.59	10.08	0.02	0.08
49	Potassic leptite, Nävekvarn, Tunaberg	< 0.0005	0.055	< 3.2	7.88	0.02	0.12
	Metamorphic Rocks:						
50	Quartz-chlorite-sericite schist, Grythyttan	0.001	4.18	0.08	1.68	0.004	0.11
51	Yellowish quartz-muscovite schist, the Rösberg Field	0.002	2.46	0.28	3.52	0.01	0.13
52	Quartz-cordierite rock, the Dalkarlsberg Mine	0.0007	3.23	0.08	1.91	0.008	0.19
53	Quartz-biotite schist, Stripa-Glifsa, the Striberg Field	0.003	4.84	0.22	3.24	0.02	0.28
54	Quartz-muscovite schist, the Åsboberg Mine	0.0005	1.36	0.14	2.48	0.02	0.37
55	Andalusite quartzite, Garpenberg	0.0005	1.58	0.11	0.63	0.001	0.07
56	Cordierite-gedrite rock, the Getå Silver Mine	< 0.0005	5.41	< 0.03	0.11	< 0.0005	< 0.21
	Skarn Rocks:						
57	Cummingtonite Rock, the Persberg Mines	0.0008	10.95	0.03	0.26	0.001	0.18
58	Amphibole skarn, Stripa-Glifsa, the Striberg Field	0.0005	11.65	0.015	0.12	< 0.0005	< 0.19
59	Quartz-amphibole skarn, Stripa-Glifsa, the Striberg Field	< 0.0005	3.72	< 0.05	0.34	0.001	0.13
60	Cummingtonite skarn, Hagalund Mine, the Striberg Field	0.0005	12.33	0.015	0.17	0.005	0.13
61	Mn-garnet-amphibole skarn, the Kråknäs Mine, Norberg	< 0.0005	3.92	< 0.05	2.50	0.002	0.36
	Granites and Gneisses:						
62	Albite-mica-gneiss, Kvarnstensberget, the Striberg Field	0.0005	0.58	0.31	1.48	0.003	0.09
63	Red gneiss, the Striberg Field	0.0008	0.31	0.91	2.60	0.006	0.11
64	Plagioclase gneiss, the Lekomberg Mine	0.001	0.28	1.24	0.63	0.001	0.07
65	Plagioclase gneiss from the foot-wall, the Idkerberget Mines	0.0005	2.04	0.09	0.37	< 0.0005	< 0.06
66	Plagioclase gneiss, the Intrånget Mines	< 0.0005	0.21	< 0.83	3.49	0.02	0.26
67	Red gneiss-granite, Penninggruvan, Torsåker	< 0.0005	1.74	< 0.10	3.82	0.01	0.12
68	Grey plagioclase gneiss, the Malmberg Mine, Torsåker	0.0005	1.71	0.10	1.38	0.008	0.27
	Amphibolites:						
69	Quartz-magnetite amphibolite, the Striberg Field	0.0006	3.16	0.07	0.82	0.003	0.17
70	Amphibolite, the Idkerberget Mines	< 0.0005	3.46	< 0.05	0.94	0.003	0.15

Table 25. **The Distribution of Lithium in the Pre-Cambrian Iron Ores and associated Rocks of Central Sweden.**

Class	Gangue	Leptite	Metam. rock	Gneiss
0.0001—0.0005.......	45.5	40.5	25.0	33.5
0.0005—0.001........	25.0	27.5	50.0	55.5
0.001 —0.005........	20.5	19.5	25.0	11.0
0.005 —0.01.........	4.5	0	0	0
0.01 —0.05.........	4.5	12.5	0	0
Average content..... (weight per cent)	0.0023	0.0058	0.0011	0.0011

fact that most iron ores and their associated rocks show a strong deficiency of lithium, is a very remarkable geochemical phenomenon.

The ratio Li/Mg is lower than might be expected in the light of the investigation by Strock quoted above. From a crystal-chemical point of view, the magnitude of the ratio Li/Mg is, as mentioned earlier, of great interest, and both Strock and Frans E. Wickman (125) have discussed the cause of the increasing value of the ratio in question as the acidity of the igneous rocks increases. The geochemistry of lithium and its geological importance will therefore be discussed in detail in the next part of this work.

Rubidium. The average value of Rb in the upper lithosphere is estimated at 0.031 per cent (V. M. Goldschmidt (46). In the iron ores there is generally a deficiency of Rb, as seen from Tables 23 and 26 below. Only 7.5 per cent of the ores contain Rb in quantities equal to or higher than the mean mentioned above. Thus, the deficiency of Rb is of approximately the same size as that of Li. In a few cases a high value of Rb corresponds to an increasing value of Li, but in most cases there seems to be little correlation between the contents of the two elements in question.

In the rocks associated with the iron ores we find that on the whole there is a deficiency of Rb, but this deficiency is less marked than in the case of the

Table 26. **The Distribution of Rubidium in the Pre-Cambrian Iron Ores and associated Rocks of Central Sweden.**

Class	Gangue	Leptite	Metamorphic rock	Gneiss
0.0001—0.0005.......	11.0	6.5	7.0	14.5
0.0005—0.001........	45.0	2.0	0	0
0.001 —0.005........	23.0	16.5	41.5	28.5
0.005 —0.01.........	10.0	16.5	16.5	28.5
0.01 —0.05.........	8.5	54.0	25.0	28.5
0.05 —0.1..........	2.5	4.5	0	0
Average content..... (weight per cent)	0.0057	0.018	0.0086	0.01

ores (see Table 23). About 25 per cent of the samples analysed have contents equal to or higher than the mean, as seen from Table 26 above.

A symbaty of considerable strength exists between the contents of Rb and K in the rocks, the correlation coefficient (r) being + 0.84. It should be mentioned here that the correlation between Rb and the ratio Rb/K shows a feeble antibatic tendency, the r-value being — 0.27.

Beryllium, Boron, Molybdenum, and Tungsten. Tables 27 and 28 show the contents of the above elements.

Beryllium. The content of Be in the upper lithosphere varies according to milieu:

Igneous rocks (I. and W. Noddack (91)	0.0005	% Be
Igneous rocks (V. M. Goldschmidt and Cl. Peters (49)	0.00018	” ”
Apatite iron ores of Grängesberg (S. Landergren (68)	0.0006	” ”
Clay slate (V. M. Goldschmidt, H. Hauptmann, and Cl. Peters (51)	0.00055	” ”
Marine bottom sediment from Tyrrhenian Sea, Mediterranean (S. Landergren (71)	0.0013	” ”

Table 27 below shows the contents of Be in the iron ores. In the spectra of the iron ores the spectral lines of Be were generally not visible. Thus, the content of Be is < 0.001 per cent. In some cases, however, the content increases, *e.g.* in the skarn ores of the Persberg region and in various ore types in the Riddarhyttan and Norberg regions. On the whole there seems to be little relation between the content of Be and the ore type.

The content of Be in the rocks associated with the iron ores is generally below the limit for spectrochemical estimation, as seen from Table 28.

Boron. In order to facilitate a comparison between the boron contents in the iron ores and their associated rocks, the following figures show the distribution of boron in various milieus:

Igneous rocks (V. M. Goldschmidt (46)	0.0003	% B
Marine sediments (V. M. Goldschmidt (50)	0.015	” ”
Liassic iron sediments from Southern Sweden (S. Palmqvist (96)	0.03—0.003	” ”
Bottom sediment from the west coast of Sweden (S. Landergren (70)	0.014	” ”
Alum shale (Cambrium), Southern Sweden (S. Landergren (70)	0.014	” ”
Bottom sediment from the Tyrrhenian Sea, Mediterranean (S. Landergren (71)	0.005	” ”

The distribution of boron in pre-Cambrian rocks in the southern part of Finnish Lapland has been investigated by Th. G. Sahama (102). He found,

Table 27. **The Distribution of Beryllium, Boron, Molybdenum, and Tungsten in Iron Ores of Central Sweden.**

No.	Ore (o), Gangue (g) and Locality	Be	B	Mo	W
	The Persberg Region:				
1	Skarn-magnetite ore (g), Storgruvan, Persberg	0.005	< 0.001	< 0.003	< 0.01
2	Skarn-magnetite ore (g), "the kernel", Alabama, Persberg	0.007	0.001	< 0.003	< 0.01
3	Skarn-magnetite ore (g), "the shell", Alabama, Persberg	< 0.001	< 0.001	0.005	0.01
4	Serpentine-skarn-magnetite ore (g), Skärstöten, Persberg	< 0.001	0.006	< 0.003	< 0.01
5	Lime-magnetite ore (g), Skärstöten, Persberg	< 0.001	0.005	< 0.003	< 0.01
	The Nordmark Region:				
6	Skarn-magnetite ore (g), the Nordmark Mine	0.003	0.002	< 0.003	< 0.01
7	Skarn-magnetite ore (g), the Taberg Mine	0.01	0.003	0.4	0.03
8	Soft ore (g), the Taberg Mine	< 0.001	0.001	0.005	< 0.01
9	Skarn-magnetite ore (g), the Finnmosse Mine	0.003	0.001	< 0.003	< 0.01
10	Lime-magnetite ore (g), the Finnmosse Mine	0.002	< 0.001	< 0.003	< 0.01
	The Grythyttan Region:				
11	Skarn-magnetite ore (g), the Högborn Field	< 0.001	< 0.001	< 0.003	< 0.01
12	Skarn-magnetite ore (g), the Finnberget Mine	< 0.001	< 0.001	< 0.003	< 0.01
13	Skarn-lime-magnetite ore (g), the Finnberget Mine	< 0.001	< 0.001	< 0.003	< 0.01
14	Lime-magnetite ore (g), the Finnberget Mine	< 0.001	< 0.001	< 0.003	< 0.01
	The Nora-Viker Region:				
15	Quartz-magnetite ore (o), the Pershyttan Mine	< 0.003	< 0.001	< 0.003	< 0.01
16	Quartz-hematite ore (o), the Pershyttan Mine	< 0.003	0.001	< 0.003	< 0.01
17	Quartz-magnetite ore (g), the Klacka-Lerberg Mine	< 0.001	< 0.001	< 0.003	< 0.01
18	Quartz-magnetite ore (g), the Nyberget Mine	0.001	< 0.001	< 0.003	< 0.01
19	Quartz-magnetite-hematite ore (g), Grundgruvan, the Dalkarlsberg Field	< 0.001	< 0.001	< 0.003	< 0.01
20	Quartzbanded magnetite-hematite ore (o), Kärrgruvan, the Striberg Field	< 0.001	< 0.001	0.003	0.03
21	Quartz-garnet-hematite ore, banded (o), the Striberg Field	< 0.001	< 0.001	0.003	0.03
22	Quartz-hematite ore, banded (g), the Striberg Field	< 0.001	< 0.001	< 0.003	< 0.01
23	Micaceous quartz-hematite ore (g), the Åsboberg Mine	< 0.001	< 0.001	< 0.003	< 0.01
	The Region Linde-Guldsmedshyttan-Ramsberg:				
24	Quartz-hematite ore, banded (o), the Stripa Field	0.007	< 0.001	< 0.003	< 0.03
25	Quartz-hematite ore, banded (o), (foot-wall), the Stripa Field	0.001	< 0.001	0.005	< 0.03
26	Quartz-hematite ore (o), the Stråssa Field (avg)	< 0.001	< 0.001	0.003	< 0.03
27	Quartz-magnetite ore (o), the Stråssa Field	< 0.001	< 0.001	< 0.003	< 0.01
28	Quartz-hematite ore (g), the Blanka Field	0.002	< 0.001	< 0.003	< 0.01
29	Lime-magnetite ore (g), the Sköttgruvan Field	< 0.001	< 0.001	< 0.003	< 0.01
	The Ljusnarsberg Region:				
	Manganiferous iron ores from the Bastkärn Field:				
30	Knebelite ore (o), Backgruvan, 265 m level	< 0.001	< 0.001	< 0.003	< 0.01
31	Knebelite ore rich in Pb (o), Backgruvan, 265 m level	< 0.001	< 0.001	< 0.003	< 0.01

No.	Ore (o), Gangue (g) and Locality	Be	B	Mo	W
32	Lime-magnetite ore (o), Backgruvan, 265 m level	< 0.001	< 0.001	< 0.003	< 0.01
33	Knebelite ore with amphibole, garnet, and mica (o)	< 0.001	< 0.001	< 0.003	< 0.01
34	Knebelite ore with mica, and amphibole (o)	< 0.001	< 0.001	< 0.003	< 0.01
35	Knebelite ore with mica (o)	< 0.001	< 0.001	< 0.003	< 0.01
36	Rich ore, mainly knebelite skarn (o)	< 0.001	< 0.001	< 0.003	< 0.01
37	Lime-magnetite ore (rich ore) (o)	< 0.001	< 0.001	< 0.003	< 0.01
38	Magnetite ore, pyrite-bearing (rich ore) (o)	< 0.001	< 0.001	< 0.003	< 0.01
	The Ställberg Mines:				
39	Lime-magnetite ore (g)	0.003	0.003	< 0.003	< 0.01
40	Lime-magnetite ore (g)	0.001	0.003	< 0.003	< 0.01
	The Grangärde-Ludvika Region (excl. The Grängesberg Field):				
56	Apatite-magnetite ore (g), the Blötberget Field	< 0.001	< 0.001	< 0.003	< 0.01
57	Apatite-hematite ore (g), the Blötberget Field	< 0.001	< 0.001	0.01	< 0.01
58	Apatite-magnetite ore (g), the Fredmundberget Mine	< 0.001	< 0.001	0.003	< 0.01
59	Apatite-hematite ore (g), the Fredmundberget Mine	< 0.001	< 0.001	< 0.003	0.01
60	Epidote-hematite ore (g), the Fredmundberget Mine	0.001	< 0.001	< 0.003	< 0.01
61	Apatite-magnetite ore (g), the Lekomberget Mine	< 0.001	< 0.001	< 0.003	< 0.01
62	Quartz-magnetite ore (g), Våghalsen, the Finnäs Field	0.002	< 0.001	0.003	< 0.01
63	Quartz-hematite ore (g), Våghalsen, the Finnäs Field	0.002	< 0.001	0.005	< 0.01
64	Quartz-magnetite ore (g), the Iviken Field	< 0.001	< 0.001	< 0.003	< 0.01
65	Quartz-hematite ore (o), the Iviken Field	< 0.001	< 0.001	< 0.003	< 0.01
66	Quartz-magnetite ore (g), the Ickorrbotten Field	< 0.001	0.002	0.005	< 0.01
67	Quartz-hematite ore(g), the Ickorrbotten Field	< 0.001	0.003	< 0.003	< 0.01
68	Quartz-magnetite-hematite ore (g), the Håksberg Field	< 0.001	< 0.001	0.003	0.01
69	Quartz-magnetite-hematite ore (g), the Gräsberg Field	< 0.001	< 0.001	< 0.003	< 0.01
70	Skarn-magnetite ore (g), the Mårten Mine	< 0.001	< 0.001	< 0.003	< 0.01
	The Norrbärke Region:				
74	Quartz-skarn-magnetite ore (g), the Kärrgruvan Field	< 0.001	< 0.001	0.003	< 0.01
75	Quartz-magnetite-hematite ore (g), the Kärrgruvan Field	< 0.001	< 0.001	< 0.003	< 0.01
76	Skarn-magnetite ore (g), the Kärrgruvan Field	< 0.001	< 0.001	< 0.003	< 0.01
	The Skinnskatteberg Region:				
	The Riddarhytte Ore Fields:				
77	Skarn-magnetite ore (g), the Källfallet Mine ("Anton")	0.008	0.002	0.3	0.06
78	Skarn-magnetite ore (g), the Källfallet Mine ("Waldemar")	< 0.001	< 0.001	0.5	0.01
79	Quartz-magnetite ore, poor in sulphides (g), the Myrbacks Field	0.001	0.003	0.005	0.01
80	Quartz-magnetite ore, rich in sulphides (g), the Myrbacks Field	0.001	0.002	0.003	0.01
81	Quartz-magnetite ore, poor in sulphides (g), Pellegruvan, the Hans Urbasson Field	< 0.001	0.006	< 0.003	0.01
82	Quartz-magnetite ore, rich in sulphides (g), Pellegruvan, the Hans Urbasson Field	0.001	0.002		0.01

No.	Ore (o), Gangue (g) and Locality	Be	B	Mo	W
83	Sulphide ore, rich in cobaltite (o), Pellegruvan, the Hans Urbasson Field	< 0.001	0.28	< 0.003	0.03
84	Skarn-magnetite ore (g), the Höjdgruvan Field	< 0.001	< 0.001	0.003	0.02
85	Quartz-hematite ore, banded (o), Blåkulla type, the Bastnäs Field	0.01	0.002	0.005	< 0.01
86	Quartz-hematite ore, banded (o), Blåkulla type, the Bastnäs Field	0.01	0.003	< 0.003	< 0.01
87	Quartz-skarn-hematite ore, banded (g), Blåkulla type, the Bastnäs Field	0.01	< 0.001	< 0.003	< 0.01
88	Skarn-magnetite ore (g), the Persgruvan Field	0.01	0.004	0.5	0.03
	The Norberg Region (The Norberg Ore Fields):				
89	Skarn-magnetite ore (g), the Malmkärra Mine	< 0.001	< 0.001	0.004	0.04
90	Skarn-magnetite ore (g), the Malmkärra Mine	< 0.001	< 0.001	0.02	0.01
91	Quartz-hematite ore, banded (o), the Norberg Field (avg 1940)	0.006	< 0.001	< 0.005	< 0.03
92	Quartz-hematite ore, banded, close to a diabase contact (o), the Norberg Field	< 0.001	< 0.001	0.02	0.05
93	Lime-magnetite ore (g), the Getbacken Field (Åsgruvan)	0.01	< 0.001	< 0.003	< 0.01
94	Diopside-skarn-magnetite ore (g), the Getbacken Field (Åsgruvan)	0.002	0.003	< 0.003	< 0.01
95	Actinolite-skarn-magnetite ore (g), the Getbacken Field (Åsgruvan)	0.005	< 0.001	< 0.003	< 0.01
96	Quartz-hematite ore, banded (g), the Norberg Field (Örlinggruvan)	0.001	< 0.001	< 0.003	< 0.01
97	Skarn-hematite ore, banded (g), the Norberg Field (Örlinggruvan)	0.003	< 0.001	< 0.003	< 0.01
98	Pyroxene-garnet-hematite ore, banded (g), the Norberg Field (Örlinggruvan)	< 0.001	< 0.001	< 0.003	< 0.01
99	Quartz-hematite ore (o), the Norberg Field (avg 1940)	0.007	< 0.001	< 0.005	< 0.03
100	Quartz-hematite ore (o), the Norberg Field (avg 1940)	0.008	< 0.001	< 0.005	< 0.03
101	Lime-magnetite ore (g), the Klackberg Field (Gröndal)	< 0.001	< 0.001	< 0.003	< 0.01
102	Lime-magnetite ore (g), the Klackberg Field (Storgruvan)	< 0.001	0.002	< 0.003	< 0.01
103	Lime-magnetite ore (o), the Kolningberg Field (G:la), avg 1933	< 0.001	< 0.001	< 0.005	< 0.03
104	Lime-magnetite ore (o), the Kolningberg Field (Nya), avg 1933	< 0.001	< 0.001	< 0.005	< 0.03
	The Garpenberg Region:				
105	Diopside-skarn-magnetite ore (g), the Ryllshyttan Mine	0.008	0.001	< 0.003	< 0.01
106	Skarn-magnetite ore (g), the Holmgruvan Field	< 0.001	0.001	< 0.003	< 0.01
107	Skarn-magnetite ore, rich in sulphides (g), the Holmgruvan Field	< 0.001	< 0.001	< 0.003	< 0.01
	The Intrånget Field:				
108	Actinolite-skarn-magnetite ore (g)	< 0.001	< 0.001	< 0.003	< 0.01
109	Cummingtonite-skarn-magnetite ore (g)	< 0.001	< 0.001	< 0.003	< 0.01
110	Skarn-magnetite ore (g), Vikgruvan	0.001	0.001	< 0.003	< 0.01
111	Skarn-magnetite ore (g), (the Karl ore)	< 0.001	< 0.001	< 0.003	< 0.01
112	Skarn-magnetite ore (g), (the Kron ore)	< 0.001	< 0.001	0.003	< 0.01
113	Skarn-magnetite ore (g), (the Stjärn ore)		< 0.001		
114	Pyroxene-garnet-magnetite ore (g), (the Netzel ore)	0.002	0.001	< 0.003	< 0.01
115	Skarn-magnetite ore (g), G:la Stjälkgruvan	0.002	< 0.001	< 0.003	< 0.01

No.	Ore (o), Gangue (g) and Locality	Be	B	Mo	W
	The Silvberg-Säter Region (The Bispberg Field):				
116	Quartz-magnetite ore (g)	0.003	< 0.001	0.003	0.1
117	Quartz-magnetite ore, coarse grained (g)	0.01	0.001	0.003	< 0.01
118	Quartz-magnetite ore, banded and coarse grained (g)	0.005	0.002	< 0.003	< 0.01
119	Quartz-hematite ore, banded (g)	< 0.001	< 0.001	< 0.003	< 0.01
120	Skarn-hematite ore, banded (o)	0.003	< 0.001	0.008	0.02
121	Skarn-hematite ore, talcous (o)	< 0.001	< 0.001	0.003	0.01
	The Stora Tuna Region (the Southern Part):				
122	Knebelite-skarn-magnetite ore (g), the Tuna-Hästberg Field	< 0.061	< 0.001	< 0.003	< 0.01
123	Apatite-magnetite ore (g), Bäckgruvan, the Idkerberget Field	< 0.001	0.001	< 0.003	< 0.03
124	Apatite-magnetite ore (the hanging wall) (g), Väggruvan, the Idkerberget Field	< 0.001	< 0.001	< 0.003	< 0.03
125	Apatite-magnetite ore (g), Bergmästargruvan, the Idkerberget Field	< 0.001	0.002	< 0.003	< 0.01
126	Apatite-magnetite ore (g), Centralgruvan, the Idkerberget Field	0.001	< 0.001	< 0.003	< 0.01
	The Uppland Region:				
127	Lime-magnetite ore, banded (o), the Ramhäll Field	0.001	0.001	0.005	< 0.01
	The Dannemora Field:				
128	Lime-skarn-magnetite ore (g), Sveagruvan (avg)	< 0.001	0.002	< 0.003	< 0.01
129	Lime-skarn-magnetite ore (g), Sveagruvan (avg)	< 0.003	0.001	< 0.003	< 0.03
130	Lime-skarn-magnetite ore (g), Mellanfälten (avg)	< 0.001	0.001	< 0.003	< 0.01
131	Lime-skarn-magnetite ore (g), Mellanfälten (avg)	< 0.003	0.002	< 0.003	< 0.01
132	Lime-skarn-magnetite ore (g), Diamantgruvan (avg)	< 0.001	< 0.001	< 0.003	< 0.01
133	Lime-skarn-magnetite ore (g), Diamantgruvan (avg)	< 0.003	< 0.001	< 0.003	< 0.03
	The Herräng Field:				
134	Skarn-magnetite ore (o), Eknäsgruvan	0.007	< 0.001	< 0.003	< 0.01
135	Skarn-magnetite ore (o), Vikinggruvan	0.003	< 0.001	< 0.003	< 0.01
136	Quartz-skarn-magnetite ore (o), Spatgruvan	0.001	< 0.001	< 0.003	< 0.01
137	Skarn-magnetite ore (o), Fabiangruvan	0.005	< 0.001	< 0.003	< 0.01
138	Skarn-magnetite ore (o), Sjö- och Dammgruvan	0.007	< 0.001	< 0.003	< 0.01
	The Södermanland Region:				
139	Quartz-magnetite ore (g), the Kantorp Mine	0.003	0.001	< 0.003	< 0.01
140	Quartz-hematite ore (g), the Kantorp Mine	< 0.001	< 0.001	< 0.003	< 0.01
141	Skarn-magnetite ore, homogenous (o), the Utö Mines	0.003	< 0.001	< 0.003	< 0.01
142	Quartz-hematite ore, banded (o), the Utö Mines	< 0.001	0.003	< 0.003	< 0.01

in full agreement with the results obtained by the present author and presented below (Table 28), that the content of boron in the salic rocks of pre-Cambrian age is, on the whole, fairly low.

B. Wasserstein (121) has shown that boron is a constant constituent of braunite, and that the common ore minerals of manganese, apart from braunite, carry virtually no boron. This is also in agreement with the author's investiga-

Table 28. **The Distribution of Beryllium and Boron in Rocks from the Ore-bearing Regions of Central Sweden.**

No.	Rock and Locality	Be	B
	Leptites:		
1	Leptite, Finnarmossgruvan	0.002	< 0.001
2	Potassium leptite, Backgruvan	< 0.001	< 0.001
3	Skarn-banded microcline-plagioclase leptite, Taberg	< 0.001	< 0.001
4	Albite leptite, the Nordmark Mines	0.002	< 0.001
5	Black helleflinta, Grythyttan	< 0.003	< 0.001
6	Black helleflinta, Grythyttan	< 0.003	0.001
7	Helleflinta, Hellefors	< 0.003	< 0.001
8	Helleflinta, Brevik, Grythyttan	< 0.003	0.001
9	Dark slate, Grythyttan	< 0.003	0.01
10	Black slate, Grythyttan	< 0.003	< 0.001
11	Light slate, Grythyttan	< 0.003	0.01
12	White albite-leptite, Rösberg	< 0.001	< 0.001
13	Brown-grey helleflinta, Nora	< 0.001	0.005
14	Grey helleflinta, Knapptorg Mine, Nora	< 0.001	0.002
15	Dark helleflinta-leptite, Viker	< 0.001	0.1
16	Grey helleflinta, Nya Vikers Mine	< 0.001	0.008
17	Plagioclase-leptite with needles of amphibole, the Bergsäng Mine	< 0.001	< 0.001
18	Red leptite, the Skofttorp Field	< 0.001	0.001
19	Biotite-muscovite leptite, the Pershytte Field	0.001	0.001
20	Dark-grey biotite leptite, the Nedre Pershytte Field	< 0.001	0.01
21	Leptite, Klacka-Lerberg	< 0.001	0.001
22	Pink plagioclase-leptite, porphyric, Timansberg	< 0.001	< 0.001
23	Grey leptite, Dalkarlsberg	< 0.001	< 0.001
24	Plagioclase-leptite, Kärrgruvan, the Striberg Field	< 0.001	0.001
25	Red potassium leptite, Komministergruvan, Striberg	< 0.001	< 0.001
26	Red leptite, Grindgruvan, the Striberg Field	0.004	< 0.001
27	Leptite, Stråssa	< 0.001	0.004
28	Leptite, the Bastkärn Field	< 0.003	< 0.001
29	Grey leptite, the S. Ställberg Field, Ljusnarsberg	< 0.001	0.004
30	Grey leptite, the Svartvik Field, Ljusnarsberg	0.001	< 0.001
33	Red leptite, the Iviken Mine	< 0.001	< 0.001
34	Grey plagioclase-leptite, the Ickorrbotten Mine	< 0.001	0.001
35	Grey potassium leptite, the Hilläng Mine	< 0.001	< 0.001
36	Dark leptite, Västanfors	< 0.001	0.001
37	White microcline-leptite, Östanmossa, Norberg	< 0.001	< 0.001
38	Red leptite, Stålgruvan, Norberg	< 0.001	< 0.001
39	Sodium leptite, Kallmorberg, Norberg	< 0.003	< 0.001
40	Grey schistose leptite, Norberg	< 0.001	< 0.001
41	Red leptite, Norberg	< 0.001	< 0.001
42	Leptite, Norberg	< 0.003	< 0.001
43	Sodium leptite, Norberg	< 0.003	< 0.001
44	Red plagioclase-leptite, the Bispberg Field	< 0.001	< 0.001
45	Red leptite, the Säter Mines	< 0.001	< 0.001
46	Sodium leptite, Markdalsgruvan, Grisslehamn	< 0.003	< 0.001
47	Potassium leptite, Vånga (avg)	< 0.003	< 0.001
48	Potassium leptite, Norsholm, Vånga	< 0.003	< 0.001
49	Potassium leptite, Nävekvarn, Tunaberg	< 0.003	< 0.001
	Metamorphic Rocks:		
50	Quartz-chlorite-sericite schist, Grythyttan	< 0.003	0.05
51	Yellowish quartz-muscovite schist, the Rösberg Mine	0.002	0.001
52	Quartz-cordierite rock, the Dalkarlsberg Mine	< 0.001	< 0.001
53	Quartz-biotite schist, Stripa-Glifsa, Striberg	0.004	< 0.001

No.	Rock and Locality	Be	B
54	Quartz-muscovite schist, the Åsboberg Mine	0.002	< 0.001
55	Andalusite quartzite, Garpenberg	< 0.001	< 0.001
56	Cordierite-gedrite rock, the Getå Silver Mine	0.001	< 0.001
	Skarn Rocks:		
57	Cummingtonite rock, the Persberg Mines	0.003	< 0.001
58	Amphibole skarn, Stripa-Glifsa, the Striberg Field	0.01	< 0.001
59	Quartz-amphibole skarn, Stripa-Glifsa, Striberg	0.003	0.002
60	Cummingtonite skarn, Hagalund Mine, Striberg	0.004	< 0.001
61	Mn-bearing garnet-amphibole skarn, Kråknäs, Norberg	< 0.001	0.002
	Granites and Gneisses:		
62	Albite-mica gneiss, Kvarnstensberget, Striberg	< 0.001	0.01
63	Red gneiss, Striberg	< 0.001	0.001
64	Plagioclase gneiss, the Lekomberg Mines	< 0.001	< 0.001
65	Plagioclase gneiss (the foot-wall), the Idkerberget Mines	0.001	< 0.001
66	Plagioclase gneiss, the Intrånget Mines	< 0.001	< 0.003
67	Red gneiss-granite, Penninggruvan, Torsåker	< 0.001	0.001
68	Grey plagioclase gneiss, the Malmberget Mine, Torsåker	< 0.001	< 0.001
	Amphibolites:		
69	Quartz-magnetite amphibolite, the Striberg Field	< 0.001	0.002
70	Amphibolite, the Idkerberget Mines	< 0.001	< 0.001

tion of the manganiferous iron ores of Central Sweden. An earlier investigation by the author (70) shows that the manganese-bearing iron ores, in particular, show a distinct displacement towards the higher concentration classes of B. Among the manganese ores, those containing braunite seem to be richest in boron. A typical example is found in the Långban ores, where the braunite ore is much richer in boron than the hausmannite ore:

Braunite ore of Långban	0.033 per cent B
Hausmannite ore of Långban	0.003 " " "

As seen from Table 27, the iron ores of Central Sweden seldom contain boron to any appreciable amount, nor do the rocks associated with the ores, as seen from Table 28.

Molybdenum and Tungsten. There is a discrepancy in the estimates of the average content of molybdenum and tungsten in the upper lithosphere. G. Hevesy and R. Hobbie (59) found the following average contents in igneous rocks:

0.0015 per cent Mo
0.0069 " " W.

E. B. Sandell (106) has recently studied the abundance of tungsten in igneous rocks. According to him, the maximum content of tungsten "is not likely to exceed greatly the value" 0.00015 per cent W. He adds "at any rate the relative amounts of tungsten and molybdenum in the upper lithosphere are not greatly different". The author's experience of the distribution of the two metals in question in the pre-Cambrian rocks of Sweden, seem to confirm the results found by Sandell.

Table 27 shows the contents of the two metals in the iron ores. The limits for spectrochemical estimation are in this case far above the averages for both Mo and W. In most cases investigated the contents of the two metals are below the limits for estimation, which is 0.003 per cent for Mo and 0.01 per cent for W. Tables 29 and 30 are statistical surveys of the distribution of Mo and W.

Table 29. **The Distribution of Molybdenum in Iron Ores from Central Sweden.**

Class	Not separated ore	Non-magnetic fraction
< 0.003	63	73.5
0.003—0.01	37	19
0.01 —0.03	0	2.5
0.03 —0.1	0	0
$\geqq 0.1$	0	5

Table 30. **The Distribution of Tungsten in Iron Ores from Central Sweden.**

Class	Not separated ore	Non-magnetic fraction
< 0.01	50	82
0.01—0.05	49.5	16
0.05—0.1	0.5	1
$\geqq 0.1$	0	1

The contents above the limits for estimation may be of some technical interest, but it should be mentioned that the distribution of the two metals in question in the iron ores of Central Sweden is rather irregular. The most noteworthy enrichment of Mo and W is noted in the Riddarhytte, Norberg and Bispberg ore fields, as seen from Table 27.

The distribution of *the lanthanides* in some Swedish iron ores will be discussed below in connection with the apatite iron ores.

The Apatite Iron Ores of Northern Sweden.

In an earlier investigation by the author on the geochemistry of the apatite iron ores of the Grängesberg mines in central Sweden (68), some data were given on the distribution of some minor constituents. However, it proved desirable from various points of view to extend the investigation of the apatite ores. For this reason, the apatite iron ores from Northern Sweden have been included in the present investigation.

In Tables 31—34 the analytical data on the distribution of some minor constituents are to be found. Table 35 is a survey of the distribution of the lanthanides in some Swedish iron ores, including apatite ores from Central and Northern Sweden.

The Ferrides. Table 31 shows the distribution of the ferrides. Samples 1—14 have been magnetically separated with great care in order to obtain an idea of the distribution coefficients of some ferrides of magnetite and gangue respectively (Table 32).

For vanadium, manganese, cobalt and nickel three values are given for samples 1—14. Thus, "o" (see column 3) represents the contents of the ferrides in question in the ore, "m" in the magnetite, and "g" in the non-magnetic fraction.

Titanium. The content of Ti has only been estimated in the magnetic fraction. As far as analyses of the ores in question are available (63), the apatite ores of Northern Sweden are poor in titanium, though the content seems to be higher than that of the apatite ores of Central Sweden.

Vanadium. This element is enriched in the ores and the main part of the vanadium content is bound in the magnetic fraction. The content of V in these ores is of the same magnitude as in the apatite ores of Central Sweden.

Chromium. The content of Cr is low and in the magnetic fraction in most cases < 0.001 per cent. This is in agreement with the conditions in the Grängesberg apatite ore (68).

Manganese. As seen from the table, manganese is generally enriched in the non-magnetic fraction. The contents of Mn are usually somewhat above the average for the upper lithosphere.

Cobalt. The content of this metal is comparatively high and higher than that of the apatite ores of Central Sweden. In the Grängesberg ores the average content of Co is 0.003 per cent.

Nickel. Compared with the apatite ores of Grängesberg the content of Ni is higher and generally slightly above the average for the upper lithosphere (0.01 per cent Ni).

The average ratio Co/Ni is < 1, as in the ores of Grängesberg (0.6).

An experimental study by W. Oelsen and H. Maetz (95) on the system $FeO\text{-}CaO\text{-}P_2O_5\text{-}CaF_2\text{-}SiO_2$ yielded very interesting results, *inter alia* regarding the distribution of FeO and MnO in the system oxide-phosphate-fluorite. It has been shown that the immiscibility of an oxide-phosphate-fluorite melt is all but complete (at about 1,400° C) when mol CaO/mol $P_2O_5 = 3$. Then FeO (and MnO) has become almost immiscible with the phosphate-fluorite compound. At values of mol CaO/mol $P_2O_5 \lesseqgtr 3$ the immiscibility is incomplete.

Now, it would be of interest to study the distribution of the ferrides V, Mn,

Table 31. **The Distribution of Ferrides in Iron Ores of the Kiruna Type in Northern Sweden.**

No.	Ore Type and Locality	Separated in	Ti	V	Cr	Mn	Fe	Co	Ni
1	Magnetite ore, type A, Kiirunavaara, avg 1942, P = 0.017 %	o:	0.1	0.130	< 0.001	0.05	69.44	0.013	0.02
		m: 97.0		0.13		0.045		0.013	0.02
		g: 3.0		0.02		0.23		0.04	0.03
2	Magnetite ore, type D, Kiirunavaara, avg 1942, P = 1.96 %	o:	0.2	0.16	< 0.001	0.08	60.60	0.011	0.015
		m: 86.2		0.18		0.08		0.013	0.017
		g: 13.8		0.02		0.09		0.001	0.003
3	Magnetite ore, type D, Kiirunavaara, avg 1942, P = 3.60 %	o:	0.1	0.18	< 0.001	0.07	54.47	0.01	0.018
		m: 78.7		0.23		0.08		0.013	0.023
		g: 21.3		0.01		0.06		0.001	0.001
4	Magnetite ore, type Cl, Kiirunavaara, avg 1942, P = 0.392 %	o:	0.06	0.13	< 0.001	0.07	66.35	0.013	0.020
		m: 91.2		0.14		0.06		0.013	0.020
		g: 8.8		0.03		0.37		0.015	0.014
5	Magnetite ore, type A, Luossavaara, avg 1942, P = 0.018 %	o:	> 0.3	0.16	< 0.001	0.07	64.94	0.01	0.016
		m: 91.1		0.17		0.04		0.01	0.017
		g: 8.9		0.02		0.37		0.015	0.014
6	Magnetite ore, type B, Luossavaara, avg 1942, P = 0.062 %	o:	> 0.3	0.12	< 0.001	0.07	63.87	0.01	0.016
		m: 90.0		0.13		0.04		0.01	0.017
		g: 10.0		0.02		0.37		0.015	0.014
7	Magnetite ore, type R, Luossavaara,avg 1942, P = 4.35 %	o:	> 0.3	0.10	< 0.001	0.08	32.04	0.005	0.009
		m: 39.8		0.18		0.04		0.011	0.023
		g: 60.2		0.04		0.21		0.001	0.004
8	Magnetite ore, type A, Gällivare (Malmberget), avg 1942, P = 0.017 %	o:	> 0.3	0.110	< 0.001	0.06	69.47	0.013	0.013
		m: 96.3		0.13		0.05		0.011	0.033
		g: 3.7		0.02		0.5		0.07	0.009
9	Magnetite ore, type C, Gällivare (Malmberget), avg 1942, P = 0.217 %	o:	0.1	0.12	< 0.001	0.05	69.33	0.013	0.013
		m: 96.6		0.13		0.05		0.013	0.013
		g: 3.4		0.01		0.09		0.003	0.009
10	Magnetite ore, type C, Gällivare (Malmberget), avg 1942, P = 0.125 %	o:	0.2	0.12	< 0.001	0.08	65.74	0.013	0.017
		m: 93.3		0.13		0.07		0.014	0.018
		g: 6.7		0.002		0.37		0.003	0.009
11	Magnetite ore, type D, Gällivare (Malmberget), avg 1942, P = 0.641 %	o:	0.2	0.22	< 0.001	0.04	67.06	0.012	0.017
		m: 94.3		0.23		0.04		0.013	0.017
		g: 5.7		0.006		0.09		0.003	0.009
12	Magnetite-hematite ore, type D, Gällivare (Malmberget), avg 1942, P = 1.23 %	o:	0.1	0.09	< 0.001	0.05	62.52	0.011	0.016
		m: 86.9		0.11		0.05		0.013	0.017
		g: 13.1		0.03		0.08		0.003	0.003
13	Hematite ore, type D, Gällivare (Malmberget), avg 1942, P = 1.48 %	o:	0.2	0.09	< 0.001	0.09	60.19	0.011	0.015
		m: 1.2		0.11		0.15		0.018	0.10
		g: 98.8		0.10		0.09		0.011	0.014
14	Magnetite-hematite ore, type D, Gällivare (Malmberget), avg 1942, P = 1.75 %	o:	0.2	0.11	< 0.001	0.07	60.02	0.011	0.015
		m: 85.0		0.13		0.07		0.013	0.017
		g: 15.0		0.02		0.09		0.001	0.001
15	Magnetite ore, Ekströmsberg		0.10	0.02		0.3		0.003	0.01
16	Magnetite-hematite ore, Ekströmsberg		0.09	0.02		0.1		0.003	0.01
17	Quartz-hematite ore, Ekströmsberg		0.10	0.006		0.1		< 0.003	0.01
18	Magnetite ore, Mertainen		0.06	0.05		0.15		0.006	0.04
19	Magnetite ore, Lime-banded, Svappavaara		0.01	0.03		0.3		0.01	0.05
20	Magnetite ore, Nakerivaara		0.03	0.05		0.15		0.006	0.05

Table 32. **The Ratio P_2O_5/SiO_2 and the Distribution Ratio Magnetic Fraction/non-magnetic Fraction of the Ferrides Vanadium, Manganese, Cobalt, and Nickel and the corresponding Correlation Coefficients in the Apatite Iron Ores of Northern Sweden.**

No.	Ore Type and Locality	P	P_2O_5/SiO_2	V_m/V_{n-m}	Mn_m/Mn_{n-m}	Co_m/Co_{n-m}	Ni_m/Ni_{n-m}
1	Magnetite ore, type A, Kiirunavaara.........	0.017	0.05	6.5	0.2	0.33	0.67
2	Magnetite ore, type D, Kiirunavaara.........	1.96	4.15	9.0	0.9	13.0	5.7
3	Magnetite ore, type D, Kiirunavaara.........	3.60	9.70	23.0	1.3	13.0	23.0
4	Magnetite ore, type Cl, Kiirunavaara.........	0.392	0.83	4.7	0.16	0.87	1.4
5	Magnetite ore, type A, Luossavaara..........	0.018	0.028	8.5	0.11	0.67	1.2
6	Magnetite ore, type B, Luossavaara..........	0.062	0.068	6.5	0.11	0.67	1.2
7	Magnetite ore, type R, Luossavaara..........	4.35	1.19	4.5	0.19	11.0	5.7
8	Magnetite ore, type A, Gällivare.............	0.017	0.069	6.5	0.10	1.6	1.4
9	Magnetite ore, type C, Gällivare.............	0.217	0.88	13.0	0.56	4.3	1.4
10	Magnetite ore, type C, Gällivare.............	0.125	0.255	65.0	0.19	4.7	2.0
11	Magnetite ore, type D, Gällivare.............	0.641	1.91	38.3	0.44	4.3	1.9
12	Magnetite-hematite ore, type D, Gällivare.....	1.23	2.01	3.7	0.63	4.3	5.7
13	Hematite ore, type D, Gällivare.............	1.48	3.41	1.1	1.67	1.6	7.1
14	Magnetite-hematite ore, type D, Gällivare.....	1.75	3.01	6.5	0.78	13.0	17.0
	Correlation Coefficients						
	P_2O_5/SiO_2 and the ratios			+ 0.04	+ 0.71	+ 0.80	+ 0.78
	P_2O_5 and the ratios...			— 0.04	+ 0.68	+ 0.84	+ 0.85

Co, and Ni in the natural system magnetite-apatite-silicate represented in the apatite iron ores of the Kiruna type. On the basis of the analyses in Table 32, the author has calculated the distribution coefficients of the ferrides mentioned above in the system magnetite-gangue, where the gangue approximately represents the system apatite-silicate. Thus, the correlation coefficients have been calculated between the distribution coefficients of the ferrides on magnetite/gangue, on the one hand, and the content of P and the ratio P_2O_5/SiO_2, on the other. The third column of Table 31 shows the P-values, and the fourth column the values of the ratio P_2O_5/SiO_2. Columns 5—8 contain the distribution coefficients. Thus, $V_m/V_{n\text{-}m}$ represents the ratio vanadium in magnetite/vanadium in gangue, and so forth. At the bottom of Table 32 the correlation coefficients in question will be found.

The results are interesting. They show that the quantity of Mn, Co and Ni entering the magnetic fraction and the non-magnetic fraction respectively is

Table 33. **The Distribution of Lithium, Magnesium, Potassium, and Rubidium in Iron Ores of the Kiruna Type in Northern Sweden.**

No.	Ore Type (gangue) and Locality	Li	Mg	$\frac{100\ \text{Li}}{\text{Mg}}$	K	Rb	$\frac{100\ \text{Rb}}{\text{K}}$
1	Magnetite ore, type A, Kiirunavaara, avg 1942, P = 0.017 %	0.01	19.3	0.18	0.6	0.18	13.7
2	Magnetite ore, type D, Kiirunavaara, avg 1942, P = 1.96 %	0.002	0.69	1.0	1	0.004	1.83
3	Magnetite ore, type D, Kiirunavaara, avg 1942, P = 3.60 %	0.001	3.1	0.11	0.2	0.002	0.46
4	Magnetite ore, type Cl, Kiirunavaara, avg 1942, P = 0.392 %	0.005	7.4	0.24	0.4	0.01	1.14
5	Magnetite ore, type A, Luossavaara, avg 1942, P = 0.018 %	0.02	6.9	1.0	1	0.009	0.41
6	Magnetite ore, type B, Luossavaara, avg 1942, P = 0.062 %	0.003	8.2	0.13	0.3	0.01	1.68
7	Magnetite ore, type R, Luossavaara, avg 1942, P = 4.35 %	0.005	1.4	1.25	0.6	0.006	0.46
8	Magnetite ore, type A, Gällivare (Malmberget), avg 1942, P = 0.017 %	0.002	0.36	1.94	3	0.009	1.37
9	Magnetite ore, type C, Gällivare (Malmberget), avg 1942, P = 0.217 %	0.001	0.48	0.73		< 0.001	
10	Magnetite ore, type C, Gällivare (Malmberget), avg 1942, P = 0.125 %	0.0005	10	0.02	0.08	< 0.001	< 0.57
11	Magnetite ore, type D, Gällivare (Malmberget), avg 1942, P = 0.641 %	0.0006	11	0.02		< 0.001	
12	Magnetite-hematite ore, type D, Gällivare (Malmberget), avg 1942, P = 1.75 %	0.005	3.9	0.45	0.2	< 0.001	< 0.23
13	Hematite ore, type D, Gällivare (Malmberget), avg 1942, P = 1.48 %	0.0009	0.5	0.54	0.07	0.002	1.3
14	Magnetite-hematite ore, type D, Gällivare (Malmberget), avg 1942, P = 1.23 %	0.001	4.1	0.09		< 0.001	

dependent on the composition of the gangue, *viz.* the content of P and the ratio P_2O_5/SiO_2. The correlation is strongly positive.

Vanadium is an exception to the rule mentioned. There is no correlation between the two quantities in question, the correlation coefficients being + 0.04 and — 0.04, respectively, *viz.* practically zero. This lack of correlation is astonishing. It is probably due to the conditions during the mineral-forming processes. Therefore, if for some reason the reduction-oxidation potential varied so that the ionic charge of vanadium changed from say 3+ to 5+, vanadium could only enter the magnetite structure in the former case (V^{3+}), not in the latter (V^{5+}). If this variation in the ionic charge of vanadium was independent of the quantity of P or the ratio P_2O_5/SiO_2, the lack of correlation in question can be easily understood.

Lithium and Rubidium. As shown in Table 33, the contents of lithium and rubidium are low in the ores. Only in a few exceptional cases do the values increase to any appreciable amount. Thus the content of Li in samples Nos. 1

Table 34. **The Distribution of Beryllium, Boron, Molybdenum, and Tungsten in Iron Ores of the Kiruna Type in Northern Sweden.**

No.	Ore Type (gangue) and Locality	Be	B	Mo	W
1	Magnetite ore, type A, Kiirunavaara, avg 1942, P = 0.017 %	0.002	< 0.001	< 0.003	< 0.01
2	Magnetite ore, type D, Kiirunavaara, avg 1942, P = 1.96 %	< 0.001	< 0.001	< 0.003	< 0.01
3	Magnetite ore, type D, Kiirunavaara, avg 1942, P = 3.60 %	< 0.001	0.001	< 0.003	< 0.01
4	Magnetite ore, type Cl, Kiirunavaara, avg 1942, P = 0.392 %	0.001	< 0.001	< 0.003	< 0.01
5	Magnetite ore, type A, Luossavaara, avg 1942, P = 0.018 %	0.002	< 0.001	< 0.003	< 0.01
6	Magnetite ore, type B, Luossavaara, avg 1942, P = 0.062 %	0.003	< 0.001	< 0.003	< 0.01
7	Magnetite ore, type R, Luossavaara, avg 1942, P = 4.35 %	0.002	0.002	< 0.003	< 0.01
8	Magnetite ore, type A, Gällivare (Malmberget), avg 1942, P = 0.017 %	0.001	< 0.001	< 0.003	< 0.01
9	Magnetite ore, type C, Gällivare (Malmberget), avg 1942, P = 0.217 %	0.002	< 0.001	< 0.003	< 0.01
10	Magnetite ore, type C, Gällivare (Malmberget), avg 1942, P = 0.125 %	0.003	< 0.001	< 0.003	< 0.01
11	Magnetite ore, type D, Gällivare (Malmberget), avg 1942, P = 0.641 %	< 0.001	< 0.001	< 0.003	< 0.01
12	Magnetite-hematite ore, type D, Gällivare, avg 1942, P = 1.75 %	0.002	0.001	< 0.003	< 0.01
13	Hematite ore, type D, Gällivare (Malmberget), avg 1942, P = 1.48 %	< 0.001	< 0.001	< 0.003	< 0.01
14	Magnetite-hematite ore, type D, Gällivare, avg 1942, P = 1.23 %	0.002	< 0.001	< 0.003	< 0.01
	1—6 and 8—14 (ore)	< 0.001			
	7 (ore)	0.001			

and 5 and of Rb in samples Nos. 1, 4 and 6 is relatively high. Such exceptional Li and Rb contents are also found in the Grängesberg apatite iron ores.

The ratios Li/Mg and Rb/K are low and far below the average values of the upper lithosphere. Only in sample No. 1 has the ratio Rb/K a value which is slightly higher than the mean value.

Beryllium, Boron, Molybdenum, and Tungsten. The contents of these elements are shown in Table 34. In most cases the contents of B, Mo, and W are below the limits of spectrographical estimation and therefore cannot be discussed.

Beryllium seems to be enriched compared with the mean of the upper lithosphere. The average value of Be is of approximately the same magnitude as that of the Grängesberg apatite ores (68).

Yttrium and the Lanthanides. In Table 35 are shown the contents of yttrium and the lanthanides in some Swedish iron ore types. For comparison, the figures for the upper lithosphere (V. M. Goldschmidt (46) and the stony meteorites (I. Noddack (92) are added. All figures are in parts per million.

The data of the iron ores emanate from an earlier investigation by the author

Table 35. **The Distribution of Yttrium and Lanthanides in some Swedish Iron Ores, in the Upper Lithosphere, and in stony Meteorites.**

	i	ii	iii	iv	v	vi	vii	viii
39 Y	28.1	6.13	400	340	100	900	560	2,000
57 La	18.3	2.05	150	210	tr	350	—	815
58 Ce	46.1	2.30	225	290	—	450	tr	1,360
59 Pr	5.53	0.97	60	100	—	200	tr	270
60 Nd	23.9	3.37	225	200	tr	550	—	540
62 Sm	6.47	1.23	50	80	—	150	—	270
63 Eu	1.06	0.30	—	—	—	—	—	—
64 Gd	6.36	1.84	40	80	—	300	tr	—
65 Tb	0.91	0.58	—	—	—	—	—	—
66 Dy	4.47	2.34	40	80	—	400	tr	—
67 Ho	1.15	0.66	10	—	—	—	—	—
68 Er	2.47	1.93	—	80	tr	200	—	—
69 Tu	0.20	0.34	—	—	—	—	—	—
70 Yb	2.66	1.85	10	60	tr	200	—	—
71 Lu	0.75	0.60	—	20	tr	50	—	—

The figures in p.p.m.
i: The upper lithosphere (V. M. Goldschmidt (46).
ii: Stony meteorites (I. Noddack (92).
iii: Apatite-magnetite ore, Kiirunavaara, type G.
iv: " " " , Gällivare, type D.
v: " " " , Grängesberg.
vi: Apatite-hematite ore, the Blötberget mines.
vii: Dolomite-magnetite ore, carboniferous, Kolningberg, the Norberg District.
viii: Skarn-magnetite ore, the N. Ställberg mines.

(67) and should be regarded as preliminary. The estimations were made by means of X-ray spectrography at the Institute for Physical Chemistry of Freiburg University in Germany. The X-ray spectrographs used were constructed by Professor G. Hevesy (60).

As seen from the table, the contents of yttrium and the lanthanides in the apatite iron ores (iii—vi), a dolomite-magnetite ore (vii) and a skarn-magnetite ore (viii) are far above the average value for the upper lithosphere. In the apatite ores yttrium and the lanthanides certainly occur in the apatites. In the dolomite and skarn ores the elements in question may occur in minerals belonging to the orthite or epidote groups.

The relative frequency of the lanthanides varies. Thus we find that in sample vi there is a frequency maximum at Nd and in sample iii Ce and Nd are equal. In the other samples Ce is more abundant than Nd. A secondary maximum of Dy is found in sample vi. A semi-quantitative investigation of the distribution of the lanthanides in the Grängesberg apatite iron ores indicates that the relative frequency of the lanthanides can vary a great deal within an ore (68).

When comparing the frequency of the lanthanides in sample vi with the frequency in the stony meteorites (sample ii), we find a striking similarity. Thus, in both cases Nd is the most abundant element; there is further a secondary maximum of dysprosium. This similarity between the distribution of the lanthanides in the meteorites and in a pre-Cambrian iron ore, led the author to conclude that the distribution of the lanthanides in the pre-Cambrian iron ore could be regarded as a primary one and undisturbed by later metamorphic processes. However, after studying several types of distribution of the lanthanides in different rocks and ores, the author is inclined to consider the similarity in question an accident.

The Liassic Iron-bearing Series of Southern Sweden.

In S. Palmqvist's "Geochemical Studies on the Iron-bearing Liassic Series in Southern Sweden" (96), referred to earlier, some very interesting data are given on the distribution of some minor constituents, which will be reviewed and discussed. All the figures and calculations given are based upon Palmqvist's work.

Iron, titanium, and manganese have been chemically determined in 60 samples. Vanadium, chromium, cobalt, nickel, and boron were determined by means of spectrographic methods used at the Mineralogical Institute of Göttingen, Germany. (See (96), p. 119).

The Ferrides. Titanium. The average content of Ti in the Liassic series is equal to or below the average of the upper lithosphere, as seen from Table 36 below:

Table 36.

Siderites (average content of 33 samples)........	0.21 per cent Ti
Oolites (average content of 10 samples)..........	0.50 " " "
Sandstones (average content of 15 samples)......	0.44 " " "

However, in some cases the content of Ti can increase to appreciable amounts (up to 2.52 per cent Ti). Titanium then emanates from mechanically transported ilmenite, a fact which indicates "that during the formation the water has had, in the course of certain periods of time, a powerful transporting capacity" (Palmqvist (96), p. 187).

Vanadium. The content of vanadium is seen from Table 37.

Table 37.

Oolite from Kurremölla......................	0.024 per cent V
Siderite from Rödingeberg...................	0.0095 " " "
Siderite, rich in iron silicate, from Kurremölla..	0.040 " " "

As shown by Palmqvist, the content of vanadium in pure siderite is considerably lower than in samples containing both siderite and silicate of iron.

Chromium, Nickel, and Cobalt. Table 38 is a survey of the contents of the elements mentioned.

Table 38.

	% Ni	% Co	% Cr
Cement from the Baldringe road	0.04	0.0008	0.0007
Oolites from the Baldringe road	0.04	0.0008	0.035
Glauconites from the Baldringe road	0.0008	—	0.068
Siderite from the Baldringe road	0.004	—	—

To quote Palmqvist (96), (p. 126): "... we can state here, too, that the siderite contains least of the rarer elements and that the proportion of Cr is strikingly low, which would not have been the case had the sediments derived from a gabbroidal magma type."

Manganese. The content of Mn in the series investigated is seen from Table 39 below.

Table 39.

Siderites (average content of 32 samples)	0.28 per cent Mn
Oolites (average content of 9 samples)	0.18 " " "
Sandstones (average content of 12 samples)	0.19 " " "

This shows that the content of manganese tends to increasing values in the carbonate ores. This conforms to the conditions in the iron ores of Central Sweden, which show a positive correlation between the ratio mf and the content of carbonate.

The ratio Mn/Fe (mf) has been discussed already in Chapter II.

Boron. This element has been determined in the samples listed in Table 40.

Table 40.

	% B
Glauconite from the Baldringe road	0.032
Brown cement in the oolite from the Baldringe road	0.016
Oolite (enriched ooids) from the Baldringe road	0.016
Siderite, Kurremölla	0.016—0.003
Oolitic ore with siderite and iron silicate, Kurremölla	0.016—0.003
Siderite, Kurremölla	0.016—0.003
Siderite, Rödingeberg	0.016—0.003
Oolite, arenaceous, Rödingeberg	0.016

Palmqvist rightly considers that the series of strata met with is of a purely marine character. Here, too, we find that the siderites tend to lower values than the oolitic and glauconitic samples. This is in agreement with what was found in the marine sediments of the Tyrrhenian Sea (Mediterranean), where the content of boron — in spite of the purely marine character of the sediments — is remarkably low, due to the relatively high content of carbonate in the sediments (71).

The Bog Iron Ores of Finland.

The preceding chapter was devoted to the distribution of the minor constituents in the Liassic iron-bearing sediments of purely marine character.

Table 41. **The Distribution of Ferrides in Finnish Bog Iron Ores.**

No.	Locality	Ti	V	Cr	Mn	Fe	Co	Ni
1	Koirusvesi No. 1387..	0.10	< 0.001	< 0.001	14.1	18.8	0.01	0.003
2	” ” 1405..	0.01	< 0.001	< 0.001	5.9	34.8	0.02	0.006
3	” ” 1492..	1.0	< 0.001	< 0.001	8.9	12.0	0.008	0.002
4	” ” 1517..	0.03	< 0.001	< 0.001	12.0	31.0	0.01	0.01
5	” ” 1547..	< 0.01	< 0.001	< 0.001	0.6	49.9	0.03	0.001
6	” ” 1656..	0.03	< 0.001	< 0.001	16.7	26.1	0.008	0.004
7	Liesjärvi ” 2868..	0.15	< 0.001	< 0.001	1.65	44.22	0.01	0.001
8	” ” 2872..	0.08	< 0.001	< 0.001	1.10	33.43	0.006	0.001
9	Nilakka ” 2869..	0.10	< 0.001	< 0.001	0.89	44.22	0.008	0.004
10	Punelia ” 2870..	< 0.01	< 0.001	< 0.001	2.92	26.35	0.008	< 0.001
11	Lopenjärvi ” 2871..	0.03	< 0.001	< 0.001	0.83	42.44	0.02	< 0.001
12	Kirmajärvi.........	0.20	< 0.001	< 0.001	23.3	25.4	0.007	0.008
13	Kendjärvi, E. Karelia	0.20	< 0.001	< 0.001	15.35	28.27	0.02	0.01
14	Kyrösjärvi..........	0.02	< 0.001	< 0.001	0.20	40.4	0.01	0.003

Now, the distribution of the same elements in iron-bearing sediments of lacustrine origin will be discussed. The very valuable collection of bog iron ores was kindly placed at the author's disposal by Professor E. H. Kranck of Helsingfors.

The Ferrides. In Table 41 the contents of ferrides are shown. Iron and manganese have been chemically determined in Helsingfors. The other ferrides have been chemically determined in the chemical laboratory (Ti) and spectrochemically determined in the geochemical laboratory of the Geological Survey of Sweden (V, Cr, Co, and Ni).

Titanium. The content of this element is far below the average of the upper lithosphere, and also compared with the other Swedish iron ores hitherto discussed, the Finnish bog iron ores can be regarded as extremely poor in titanium. The high content of sample No. 3, however, is an exception and may be regarded as an accident.

The contents of ***vanadium*** and ***chromium*** are low in all the samples and below the limits for spectrographical estimation, *viz.* < 0.001 per cent metal.

Manganese. Thanks to the courtesy of Professor Kranck, the collection of bog iron ores has been chosen so as to make the variance of manganese contents as great as possible. Thus the contents of Mn vary from 0.20 per cent (sample No. 14) to 23.3 per cent (sample No. 12). The ratio $100\,\mathrm{Mn}/\mathrm{Mn} + \mathrm{Fe}$ $(= \mathrm{mf})$ also varies from 0.5 to 47.7.

The content of *iron* varies between 12 per cent (sample No. 3) and 49.9 per cent (sample No. 5).

Cobalt. The average value for Co is 0.013 per cent. In all cases the contents of Co are above the average for the upper lithosphere, which is 0.004 per cent (V. M. Goldschmidt (46). Compared with other Fennoscandian iron-ore types the content of cobalt is relatively high.

Nickel. The average content of Ni in the bog iron ores is 0.004 per cent.

Table 42. **The Distribution of Lithium, Magnesium, Potassium, and Rubidium in Finnish Bog Iron Ores.**

No.	Locality	Li	Mg	$\frac{100\text{ Li}}{\text{Mg}}$	K	Rb	$\frac{100\text{ Rb}}{\text{K}}$
1	Koirusvesi No. 1387.....	0.004	0.1	14		< 0.001	
2	” ” 1405.....	0.0005	0.1	1.7		< 0.001	
3	” ” 1492.....	0.001	0.5	0.7	0.06	0.001	0.76
4	” ” 1517.....	0.0006	0.1	2.1	0.04	< 0.001	< 1.14
5	” ” 1547.....	< 0.0005	< 0.1		< 0.04	< 0.001	
6	” ” 1656.....	< 0.0005	0.1	< 1.7	0.05	0.001	0.92
7	Liesjärvi ” 2868.....	0.004	0.3	4.7			
8	” ” 2872.....	0.0005	0.2	0.9	0.07	0.001	0.65
9	Nilakka ” 2869.....	< 0.0005	< 0.1			< 0.001	
10	Punelia ” 2870.....	< 0.0005	< 0.1				
11	Lopenjärvi ” 2871.....	< 0.0005	< 0.1				
12	Kirmajärvi...........	0.0005	0.09	1.9	0.05	0.001	0.92
13	Kendjärvi, E. Karelia..	0.0007	0.6	0.4	0.04	0.001	1.14
14	Kyrösjärvi............	< 0.0005	< 0.1				

In comparison with the average value for the upper lithosphere — 0.01 per cent — there is a deficiency of Ni in most of the samples investigated. The variation is 0.01—$<$0.001 per cent Ni.

The mean of the ratio Co/Ni is 3.1 in the bog iron ores. The variance of the ratio is appreciable, 0.88—$>$20. The ratio Co/Ni is 0.4 in the upper lithosphere.

There is no correlation between the contents of manganese, on the one hand, and the contents of Co and Ni, on the other. Nor is there any correlation between Fe and Co or Ni.

To sum up, we find that, with regard to the distribution of the ferrides in the bog iron ores, there is an excess of Mn and Co and a deficiency of other ferrides. This is a very interesting feature in the geochemistry of the lacustrine iron-bearing sediments.

Lithium, Potassium, Rubidium, and Magnesium. Table 42 is a survey of the distribution of the alkalies Li, K, and Rb and of Mg. Further the ratios Li-Mg and Rb/K are calculated.

The elements in question are all below the average content of the upper lithosphere. Lithium can also be said to be below the average value for clay sediments.

The ratio Li/Mg has approximately the same value as that of sediments on the whole (cf. Strock (111). The high value of sample No. 1 may be an accident.

Upon comparing the ratio Rb/K in the bog ores with that of the iron ores of Central Sweden, we find that the former generally have higher values. It is of approximately the same magnitude as that found in the apatite iron ores of Northern Sweden.

Beryllium, Boron, Molybdenum, and Tungsten. The distribution of these elements can be stated briefly. A survey of the contents is found in Table 43.

Table 43. **The Distribution of Beryllium, Boron, Molybdenum, and Tungsten in Finnish Bog Iron Ores.**

No.	Locality	Be	B	Mo	W
1	Koirusvesi No. 1387	< 0.001	0.003	< 0.005	< 0.01
2	" " 1405	< 0.001	0.003	< 0.005	< 0.01
3	" " 1492	< 0.001	0.003	0.006	< 0.01
4	" " 1517	0.001	0.003	0.005	< 0.01
5	" " 1547	< 0.001	0.003	< 0.005	< 0.01
6	" " 1656	0.001	0.002	< 0.005	< 0.01
7	Liesjärvi " 2868	< 0.001	0.003	< 0.005	< 0.01
8	" " 2872	< 0.001	0.002	< 0.005	< 0.01
9	Nilakka " 2869	0.001	0.003	< 0.005	< 0.01
10	Punelia " 2870	< 0.001	0.003	< 0.005	< 0.01
11	Lopenjärvi " 2871	< 0.001	0.003	< 0.005	< 0.01
12	Kirmajärvi	0.001	0.004	< 0.005	< 0.01
13	Kendjärvi, E. Karelia	0.0008	0.003	< 0.005	< 0.01
14	Kyrösjärvi	< 0.001	0.002	< 0.005	< 0.01

The content of Be is, in most cases, below the limit for spectrographic determination, *viz.* < 0.001 per cent.

Boron. The content of this element is not so low as might be expected, taking into consideration the lacustrine character of the sediments in question. The source of boron in the bog iron ores is difficult to explain. It may be that boron is of organic origin (cf. V. M. Goldschmidt (50).

Molybdenum and tungsten are both below the limits for spectrochemical estimation and, therefore, cannot be discussed.

With regard to the distribution of the elements mentioned above, it can be stated that there is a deficiency in the contents of most of them — apart from manganese and cobalt — in the Finnish bog iron ores, both in comparison with other iron ores and with the upper lithosphere.

Bedded and Unbedded Iron Ores in Great Britain.

A collection of samples of iron-ore types from some well-known ore deposits in Great Britain have been investigated to determine their contents of some minor constituents. The samples represent both bedded and unbedded ores and belong to the Mineralogical Department of the University of Stockholm.

Samples Nos. 1—8 are bedded ores of the following ore types:

Samples Nos. 1—4: The Northampton ironstones, Northamptonshire. Inferior Oölite, Dogger. Unweathered and weathered chamositic oolites and sideritic mudstone.

Samples Nos. 5: a—5: h: A vertical profile through the marlstones of Banbury, Oxfordshire. Middle Lias.

Samples Nos. 6—8: Frodingham ironstones, Lincolnshire. Limonitic oolites. Lower Lias.

The geology of the bedded ores quoted above is described in "Special Reports on the Mineral Resources of Great Britain", Volume XII, by C. B. Wedd (122). The petrography and chemistry is described by A. F. Hallimond in the "Special Reports", Volume XXIX (55).

Samples from two localities of unbedded iron ores have been spectrochemically investigated, namely samples 9: a—9: f of micaceous hematite from Great Rock Mine, Hennock, Devonshire, and sample No. 10 of limonitic iron ore from Carricks Mine, Wearhead, County Durham.

The geology of the ores mentioned is described in the aforementioned "Special Reports", Volume IX by Henry Dewey (18).

The Ferrides. Table 44 is a survey of the contents of ferrides. The contents of iron and titanium were chemically determined in the chemical laboratory of the Geological Survey, and the other ferrides spectrochemically determined.

Titanium. The content of this metal is, in all the cases investigated, below the average value for the upper lithosphere. In the bedded ores (samples Nos. 1—8) the content of Ti is approximately of the same magnitude as that of the Liassic ores of Southern Sweden (cf. Table 36).

Vanadium. In the bedded marine sediments (samples 1—8) vanadium is enriched in comparison with the average value of the upper lithosphere. However, in samples Nos. 3, 4 and 8 we find lower values, as the samples are either sideritic (Nos. 3 and 4) or lime-bearing (No. 8). This conforms to the conditions of the Liassic iron ores of Southern Sweden, where the content of vanadium decreases as the content of siderite increases.

In the unbedded ores the content of V is lower and below the average value of the upper lithosphere.

Chromium. As seen from Table 44 the content of Cr is higher in the chamositic oolite ore than in the sideritic ore from the same locality (samples 1—4). This trend is similar to that found in the case of vanadium. The marlstones from Banbury (samples Nos. 5: a—5: h) show contents of Cr which are remarkably high for a marine iron-bearing sediment. The ironstones from Frodingham have much lower contents of Cr (samples 6—8).

In the unbedded iron ores (samples 9 and 10) the content of Cr is low and far below the average for the upper lithosphere.

Manganese. In the bedded iron ores the content of Mn is, with few exceptions, equal to or higher than the average of the upper lithosphere.

As regards the unbedded ores investigated, the micaceous hematite from Great Rock Mine (samples Nos. 9: a—9: f) shows a content of Mn lower than the average value for the upper lithosphere, but the limonitic ore from Carricks Mine (sample No. 10) shows a content higher than the average.

Cobalt. This element is enriched in the bedded iron ores in almost all the cases investigated and this enrichment can become considerable, *e.g.* in sample No. 8: d, where the content of Co is 0.1, *i.e.* an enrichment of factor 25 compared

Table 44. **The Distribution of Ferrides in some Iron Ores of Great Britain.**

No.	Sediment and Locality	Ti	V	Cr	Mn	Fe	Co	Ni
1	Unweathered chamositic oolite (oolites of chamosite and subordinate limonite in sideritic groundmass), Stanton Lane Ironstone Pit, Northamptonshire.....	0.3	0.05	0.01	0.05	35.3	0.02	0.01
2	Weathered chamositic oolite, Cowthick Ironstone Pit, Northamptonshire.....	0.3	0.05	0.02	0.1	40.1	0.03	0.02
3	Unweathered sideritic mudstone, Cowthick Ironstone Pit, Northamptonshire	0.2	0.01	0.001	0.2	38.9	0.04	0.01
4	Weathered sideritic mudstone, Stanton Lane Ironstone Pit, Northamptonshire	0.2	< 0.003	0.003	0.1	50.5	0.06	0.004
5	Frodingham Ironstone (brown oxidized oolitic ironstone, mainly found in the upper part of the bed), Ashby Ville Pit, Scunthorpe, Lincolnshire........	0.2	0.03	0.002	0.2	25.8	0.02	0.01
6	Frodingham ironstone (grey-green chamosite ore occurring mainly in the middle and lower part of the bed), Bell Hag Pit, Scunthorpe, Lincolnshire...	0.2	0.05	0.003	0.1	5.4	0.01	0.01
7	Frodingham ironstone (shelly limestone courses occurring throughout the ironstone bed), Wing Mine, Scunthorpe, Lincolnshire......................	0.08	0.02	0.002	0.3	8.1	0.02	0.005
8	Marlstone ironstone, Oxford ironstone Company, Banbury, Oxfordshire:							
	a) top— 3 ft....................	0.4	0.08	0.03	0.2	38.2	0.03	0.006
	b: 3— 5 ".....................	0.2	0.07	0.03	0.3	44.4	0.02	0.02
	c: 5— 8 ".....................	0.4	0.04	0.03	0.3	38.7	0.02	0.05
	d: 8—10 ".....................	0.4	0.07	0.03	0.1	31.9	0.1	0.02
	e: 10—13 ".....................	0.3	0.05	0.03	0.2	32.3	0.01	0.04
	f: 13—16 ".....................	0.3	0.05	0.02	0.1	27.4	< 0.005	0.02
	g: 16—20 ".....................	0.4	0.06	0.02	0.1	36.8	< 0.005	0.02
	h: 20—24 ".....................	0.2	0.02	0.01	0.05	10.3	0.01	0.01
9	Micaceous hematite. (Six specimens including hard and soft ore. Veins up to 18 ins or 2 ft wide occur in granite of the Dartmoor Mass. Alongside the veins the granite is chloritized and traversed by minute strings of ore.) Great Rock Mine, Hennock, Devonshire:							
	a:	0.08	0.04	< 0.001	0.04	54.8	0.03	0.003
	b:	0.08	< 0.003	0.001	0.04	46.4	0.006	< 0.003
	c:	0.08	< 0.003	0.001	0.03	48.2	0.008	< 0.003
	d:	0.08	< 0.003	< 0.001	0.03	55.3	< 0.005	< 0.003
	e:	0.2	< 0.003	< 0.001	0.1	49.8	< 0.005	< 0.003
	f: (hard ore)....................	0.2	< 0.003	< 0.001	0.03	56.5	< 0.005	< 0.003
10	Limonitic iron ore (from oxidation of siderite-ankerite protore), Carricks Mine, Wearhead, County Durham....	0.2	< 0.003	< 0.001	0.8	36.3	0.02	< 0.003

with the average content of the upper lithosphere. A deficiency of Co is observed in samples 8: f and 8: g.

In the unbedded ores the content of Co is approximately equal to or above the average content of the upper lithosphere, but generally lower than the content of Co in the bedded ores.

Nickel. In the bedded ores the content of Ni is approximately equal to or higher than the average content of the upper lithosphere. The marlstones from Banbury (samples Nos 8: a—8: h), especially, show a general enrichment, the average for this locality being 0.023 per cent Ni. It should be mentioned, too, that the Banbury marlstones show a ratio Co/Ni < 1, contrary to other marine iron-bearing sediments hitherto investigated.

In the unbedded ores investigated the content of Ni is low and the ratio Co/Ni is > 1.

The distribution of ferrides in the British iron ores investigated is of great interest, especially as regards samples Nos. 1—8 on account of their purely marine character. Thus, we find that the ferrides can become enriched to appreciable amounts in the sedimentary milieu favourable for enrichment of iron. Of specific interest is the enrichment of the two elements vanadium and chromium in comparison with the other iron-ore types hitherto discussed. Only in the apatite iron ores is there an enrichment of vanadium equal to or higher than that found in the marine iron-bearing sediments.

Lithium, Magnesium, Potassium, and Rubidium. Table 45 is a survey of the distribution of the alkalies Li, K and Rb and of Mg. Further the ratios Li/Mg and Rb/K are shown.

The content of *lithium* in marine iron ores has been investigated by L. W. Strock (111). The average value of four samples of "Marine Eisenerze" is found to be 0.0035 per cent Li. The average content of Li in samples Nos. 1—4 and 5—7 is 0.0036 per cent Li, conforming to the value found by Strock. However, the marlstones from Banbury show a considerably higher content of Li. The average value of eight samples (Nos. 8: a—8: h) is 0.022 per cent Li, which implies an enrichment of Li with the factor 6 compared with the average value for marine clay sediments (cf. Strock (111) p. 203). Strock, too, found that the content of Li can reach considerable amounts in some cases, *e.g.* in the glauconite from Köpinge, Öland, Sweden — 0.016 per cent Li —, but generally the iron-bearing sediments investigated by Strock show lower contents of Li than do the marlstones from Banbury.

The figures of the ratio Li/Mg in samples 1—4 and 5—7 are in good agreement with the values for sediments found by Strock. However, in this ratio, too, the marlstones from Banbury show exceptionally high values, as seen from Table 44.

Upon turning to the unbedded ores investigated, we find that the micaceous hematites from Great Rock Mine (samples 9: a—9: f) have contents of Li similar to those found in the marlstones. The average value is 0.022 per cent Li. The ratio Li/Mg has also become considerable and of the same magnitude as found in the case of the marlstones. The average value is 18.5. This value, on the other hand, is of the same magnitude as that found by Strock in the granites (probably Variscian) in Germany, giving a ratio Li/Mg = 16.2. It

Table 45. **The Distribution of Lithium, Magnesium, Potassium, and Rubidium in some Iron Ores of Great Britain.**

No.	Sediment and Locality	Li	Mg	$\frac{100\,\text{Li}}{\text{Mg}}$	K	Rb	$\frac{100\,\text{Rb}}{\text{K}}$
1	Unweathered chamositic oolite, Stanton Lane Ironstone Pit, Northamptonshire	0.003	1.2	0.9	0.06	< 0.001	< 0.76
2	Weathered chamositic oolite, Cowthick Ironstone Pit, Northamptonshire	0.003	0.4	2.6	0.1	0.001	0.46
3	Unweathered sideritic mudstone, Cowthick Ironstone Pit, Northamptonshire	0.01	0.4	8.8	0.4	0.001	0.11
4	Weathered sideritic mudstone, Stanton Lane Ironstone Pit, Northamptonshire	0.002	0.3	2.3	0.05	< 0.001	< 0.92
5	Frodingham Ironstone, Ashby Ville Pit, Scunthorpe, Lincolnshire	0.002	0.9	0.8	0.1	0.001	0.46
6	Frodingham Ironstone, Bell Hag Pit, Scunthorpe, Lincolnshire	0.004	0.9	1.6	0.2	0.002	0.46
7	Frodingham Ironstone, Wing Mine, Scunthorpe, Lincolnshire	0.001	0.2	1.8	0.4	< 0.001	< 0.11
8	Marlstone Ironstone, Oxford Ironstone Company, Banbury, Oxfordshire:						
	a: top— 3 ft	0.02	0.4	17.5	0.04	< 0.001	< 1.15
	b: 3— 5 ”	0.01	0.3	11.7	0.04	< 0.001	< 1.15
	c: 5— 8 ”	0.03	0.4	26.3	0.05	< 0.001	< 0.92
	d: 8—10 ”	0.03	0.3	35.0	0.06	< 0.001	< 0.76
	e: 10—13 ”	0.03	0.3	35.0	0.07	0.001	0.65
	f: 13—16 ”	0.03	0.5	21.0	0.4	< 0.001	< 0.11
	g: 16—20 ”	0.02	0.6	11.7	0.1	0.001	0.46
	h: 20—24 ”	0.002	0.2	3.5	0.3	0.001	0.15
9	Micaceous hematite, Great Rock Mine, Hennock, Devonshire:						
	a:	0.04	0.7	20.0	0.6	0.03	2.3
	b:	0.03	0.5	21.0	0.7	0.05	3.3
	c:	0.03	0.3	35.0	0.6	0.04	3.0
	d:	0.003	0.3	3.5	0.9	0.01	0.51
	e:	0.02	0.5	14.0	1.0	0.02	0.91
	f:	0.01	0.2	17.5	0.5	0.002	0.18
10	Limonitic Iron Ore, Carrick Mine, Wearhead, County Durham	0.003	0.4	2.6	0.4	0.001	0.11

should be mentioned that the micaceous hematites of Great Rock Mine are connected with the Dartmoor granite of post-Devonian age.

The content of Li in the limonitic iron ores from Carricks Mine (sample No. 10) and the ratio Li/Mg respectively, are of the same magnitudes as the corresponding figures for samples Nos. 1—7.

The content of *rubidium* is low in the bedded iron ores with no exception. The ratio Rb/K varies, but the figures are by no means remarkable.

In the micaceous hematites from Great Rock Mine the content of Rb is

Table 46. **The Distribution of Beryllium, Boron, Molybdenum, and Tungsten in some Iron Ores of Great Britain.**

No.	Sediment and Locality	Be	B	Mo	W
1	Unweathered chamositic oolite, Stanton Lane Ironstone Pit, Northamptonshire	< 0.001	0.01	< 0.001	< 0.03
2	Weathered chamositic oolite, Cowthick Ironstone Pit, Northamptonshire......	0.001	0.009	< 0.001	< 0.03
3	Unweathered sideritic mudstone, Cowthick Ironstone Pit, Northamptonshire	< 0.001	0.01	< 0.001	< 0.03
4	Weathered sideritic mudstone, Stanton Lane Ironstone Pit, Northamptonshire	0.002	0.006	< 0.001	< 0.03
5	Frodingham Ironstone, Ashby Ville Pit, Scunthorpe, Lincolnshire.............	< 0.001	0.007	< 0.001	< 0.03
6	Frodingham Ironstone, Bell Hag Pit, Scunthorpe, Lincolnshire.............	0.001	0.002	< 0.001	< 0.03
7	Frodingham Ironstone, Wing Mine, Scunthorpe, Lincolnshire.............	< 0.001	0.007	< 0.001	< 0.03
8	Marlstone Ironstone, Oxford Ironstone Company, Banbury, Oxfordshire:				
	a: top— 3 ft......................	< 0.001	0.004	< 0.001	< 0.03
	b: 3— 5 "......................	0.002	0.005	< 0.001	< 0.03
	c: 5— 8 "......................	< 0.001	0.004	< 0.001	< 0.03
	d: 8—10 "......................	0.002	0.004	< 0.001	< 0.03
	e: 10—13 "......................	< 0.001	0.007	< 0.001	< 0.03
	f: 13—16 "......................	< 0.001	0.007	< 0.001	< 0.03
	g: 16—20 "......................	< 0.001	0.007	< 0.001	< 0.03
	h: 20—24 "......................	< 0.001	0.001	< 0.001	< 0.03
9	Micaceous hematite (Six specimens including hard and soft ore), Great Rock Mine, Hennock, Devonshire:				
	a:	< 0.001	0.01	< 0.001	0.3—0.03
	b:	0.001	0.008	< 0.001	$\overset{=}{<} 0.15$
	c:	0.001	0.003	< 0.001	$\overset{=}{<} 0.2$
	d:	< 0.001	0.002	< 0.001	$\overset{=}{<} 0.4$
	e:	0.001	0.003	< 0.001	$\overset{=}{<} 0.15$
	f:	< 0.001	0.002	< 0.001	$\overset{=}{<} 0.3$
10	Limonitic Iron Ore, Carricks Mine, Wearhead, County Durham..........	< 0.001	0.01	< 0.001	< 0.03

considerable. Excluding sample No. 9: f (probably an accident), the average content is 0.03 per cent Rb. This value conforms to the average for the upper lithosphere — 0.031 per cent Rb — estimated by V. M. Goldschmidt (46). The relatively high value of Rb in the micaceous hematites may be due to the connection with the Dartmoor granite together with the increasing lithium content. The ratio Rb/K is also comparatively high in the hematite ores.

In the limonitic iron ores from Carricks mine the content of Rb is low, as in the sedimentary ores (samples Nos. 1—8). This is also true of the ratio Rb/K.

Beryllium, Boron, Molybdenum, and Tungsten. Table 46 above shows the contents of the elements in question.

The content of *beryllium* is generally low. In some cases the contents are above the average for the upper lithosphere, but they are not remarkable.

Boron is enriched both in the bedded and the unbedded iron ores. Thus, the content of B in the bedded ores is that typical of marine sediments (cf. S. Palmqvist (96) and S. Landergren (70).

In the unbedded ores there is also an enrichment of boron in comparison with the average of the upper lithosphere, estimated at 0.0003 per cent B (V. M. Goldschmidt (46). It is doubtful whether the high boron content of the micaceous hematites of Great Rock Mine should be connected with the Dartmoor granite — as in the case of Li and Rb —, for such a high content of boron in a granite must be regarded as very exceptional.

The contents of *molybdenum* need no comments.

On account of the abundance of *tungsten* in the ores, only the content in the micaceous hematites will be discussed. It should be emphasized that the contents of tungsten in the ores in question are to be regarded as preliminary and approximate, as the spectrochemical estimations have not yet been checked by chemical analyses.

The spectrochemical analyses have indicated that there is an enrichment of tungsten in the micaceous hematites. The contents vary between 0.4—0.03 per cent W. The enrichment of this element would seem to be due to pneumatolytic activity in connection with the Dartmoor granite, which in many respects has given rise to pneumatolytic reactions of various kinds (see: The Geology of Dartmoor (76), pp. 74—75 by D. A. Mac Alister).

The Laterite-Bauxite Sediments of County Antrim, N. Ireland.

The lateritic and bauxitic sediments from Antrim have been chosen to illustrate the distribution of the minor constituents in allitic weathering products. Even though the lateritic weathering products probably play an unimportant part in the iron-ore formation in the upper lithosphere from a quantitative point of view, as far as we know at present, it may be of interest nevertheless to study the distribution of some significant minor constituents in this kind of iron enrichment products in Nature.

The samples investigated are from the collection of iron ores of the Mineralogical Department of the University of Stockholm and have been placed at the author's disposal through the courtesy of Professor P. Quensel.

The Ferrides. The contents of iron and titanium have been chemically determined in the chemical laboratory of the Geological Survey. The figures for Ti should be regarded as approximate. Table 47 shows the contents of ferrides.

Titanium. The enrichment of Ti in the laterites is a well-known feature of their chemistry. As seen from Table 47, the content of Ti is higher than the average of both the igneous rocks and iron ores hitherto discussed. In this connection it is only necessary to mention that there is no correlation between the contents of iron and those of titanium. On the contrary, the variation of the ratio Ti/Fe is considerable.

Table 47. **The Distribution of Ferrides in lateritic Iron Ores of County Antrim, N. Ireland.**

No.	Sediment and Locality	Ti	V	Cr	Mn	Fe	Co	Ni
1	Lateritic black magnetic iron ore, Glenariff.	7	0.1	0.04	0.3	46.5	< 0.005	< 0.003
2	Hematitic lateritic iron ore (soft, red, pebbly), Salmon's Drift Mine	2	0.08	0.04	0.01	54.3	< 0.005	< 0.003
3	Banded grey siliceous bauxite (derived probably from sediment composed of debris of acid igneous rocks), Salmon's Drift Mine.	0.8	< 0.003	0.04	0.06	1.8	0.10	0.06
4	Ferrugineous laterite (low grade aluminous iron ore), top of laterite section, Ballylig.	3	0.05	0.03	0.03	28.0	0.03	< 0.003
5	Red ferrugineous bauxite, derived from basalt, Bore 12, Ballylig. . .	3	0.02	0.02	0.15	26.1	0.02	0.01
6	Ferrugineous bauxite, formed from purple lithomarge of basaltic origin. (Traces of residual unaltered lithomarge can be seen). At 67 ft in bore 1, Ballylig.	2	0.04	0.03	0.02	20.6	0.02	0.06
7	Amorphous gibbsite, segregated in bauxite, Ballylig.	5	0.03	0.10	0.08	3.3	0.06	0.01
8	Ferrugineous bauxite. Streaky red, Skerry Mine (?).	3	0.03	0.03	0.01	22.7	0.03	< 0.003
9	Purple lithomarge, derived from basalt and underlying ferrugineous and aluminous laterite, Elginny, near Broughshane.	2	0.03	0.03	0.01	17.4	0.01	0.01
10	Mottled red and grey bauxite, Evishacrow Mine.	3	0.04	0.02	0.10	14.0	0.01	< 0.003
11	Grey siliceous bauxite, derived largely from debris of acid igneous rocks, Essathohan Mine.	5	0.01	0.03	0.09	2.4	0.02	0.006

The content of *vanadium* is generally higher than that of the upper lithosphere. Exceptions are the siliceous bauxite from Salmon's Drift Mine (sample No. 3) and Essathohan Mine (sample No. 11), where the content is below the average value of the upper lithosphere. The bauxites showing a deficiency of V are both from debris of acid igneous rocks, in which the content of vanadium is generally low. The weathering products deriving from basalt, on the other hand, have contents of V which are a little higher than the content of V in basalts in general.

Chromium is enriched in all the cases investigated in comparison with the average value of the upper lithosphere. Attention should be drawn to the fact that the content of Cr seems to be independent of the origin of the weathering products.

The tendency of *manganese* is undecided. In some cases the content is higher than the average value of the upper lithosphere, in others there is a deficiency. There seems to be no relation between the contents of Mn and those of the other ferrides.

Table 48. **The Distribution of Lithium, Magnesium, Potassium, and Rubidium in lateritic Iron Ores of County Antrim, N. Ireland.**

No.	Sediment and Locality	Li	Mg	$\frac{100\ Li}{Mg}$	K	Rb	$\frac{100\ Rb}{K}$
1	Lateritic black magnetic iron ore, Glenariff........	< 0.0005	—	—	< 0.03	< 0.001	—
2	Hematitic lateritic iron ore (soft, red, pebbly), Salmon's Drift Mine..............	< 0.0005	—	—	< 0.03	< 0.001	—
3	Banded grey siliceous bauxite (derived probably from sediment composed of debris of acid igneous rocks), Salmon's Drift Mine......	< 0.0005	—	—	< 0.03	< 0.001	—
4	Ferrugineous laterite, low grade aluminous iron ore, top of laterite section, bore no 14, Ballylig...........	< 0.0005	0.3	< 0.6	< 0.03	< 0.001	—
5	Red ferrugineous bauxite, derived from basalt (bore 12), Ballylig.............	< 0.0005	—	—	< 0.03	< 0.001	—
6	Ferrugineous bauxite formed from purple lithomarge of basaltic origin. Traces of residual unaltered lithomarge can be seen. At 67 ft, bore 1, Ballylig..........	< 0.0005	—	—	< 0.03	< 0.001	—
7	Amorphous gibbsite, segregated in bauxite, Ballylig	< 0.0005	—	—	< 0.03	< 0.001	—
8	Ferrugineous bauxite, Streaky red, Skerry Mine (?)	< 0.0005	—	—	< 0.03	< 0.001	—
9	Purple lithomarge, derived from basalt and underlying ferrugineous and aluminous laterite, Elginny, near Broughshane.............	< 0.0005	—	—	< 0.03	< 0.001	—
10	Mottled red and grey bauxite, Evishacrow Mine.....	< 0.0005	—	—	< 0.03	< 0.001	—
11	Grey siliceous bauxite, derived largely from debris of acid igneous rocks, Essathohan Mine............	0.0005	0.09	1.9	< 0.03	< 0.001	—

Cobalt. The content of Co in the laterites is a little higher than that of basalts in general, according to V. M. Goldschmidt (45), and also higher than that of the upper lithosphere on the whole. Two exceptions should be mentioned, namely the magnetic iron ore from Glenariff (sample No. 1) and the hematitic iron ore from Salmon's Drift Mine (sample No. 2), where the contents of Co are surprisingly low. In the grey siliceous bauxite, which is probably derived from sediments composed of debris of acid igneous rocks (sample No. 3), the content is surprisingly high, on the other hand, and far above the average value for the upper lithosphere. In the bauxite from Essathohan (sample No. 11) the content is also higher than the average value, in spite of the fact that

Table 49. **The Distribution of Beryllium, Boron, Molybdenum, and Tungsten in lateritic Iron Ores of County Antrim, N. Ireland.**

No.	Sediment and Locality	Be	B	Mo	W
1	Lateritic black magnetic iron ore, Glenariff	< 0.001	0.001	< 0.001	0.03
2	Hematitic lateritic iron ore (soft, red, pebbly), Salmon's Drift Mine	< 0.001	0.001	< 0.001	< 0.03
3	Banded grey siliceous bauxite (derived probably from sediment composed of debris of acid igneous rocks), Salmon's Drift Mine	< 0.001	< 0.001	< 0.001	< 0.03
4	Ferruginous laterite (low grade aluminous iron ore), top of laterite section, Ballylig	< 0.001	0.001	< 0.001	< 0.03
5	Red ferruginous bauxite, derived from basalt, Bore 12, Ballylig	< 0.001	0.001	< 0.001	< 0.03
6	Ferruginous bauxite formed from purple lithomarge of basaltic origin. Traces of residual unaltered lithomarge can be seen. At 67 ft, Bore 1, Ballylig	< 0.001	< 0.001	< 0.001	< 0.03
7	Amorphous gibbsite, segregated in bauxite, Ballylig	< 0.001	0.006	≦ 0.001	< 0.03
8	Ferruginous bauxite. Streaky red, Skerry Mine (?)	0.001	0.003	< 0.001	< 0.03
9	Purple lithomarge, derived from basalt and underlying ferruginous and aluminous laterite, Elginny, near Broughshane	< 0.001	0.004	< 0.001	< 0.03
10	Mottled red and grey bauxite, Evishacrow Mine	< 0.001	0.007	< 0.001	< 0.03
11	Grey siliceous bauxite, derived largely from debris of acid igneous rocks, Essathohan Mine	< 0.001	< 0.001	< 0.001	< 0.03

the material emanates from acid igneous rocks. Thus, the distribution of Co in the lateritic sediments can be very irregular.

Nickel is irregularly distributed, too, and there seems to be little correlation between the contents of Co and those of Ni. The ratio Co/Ni is generally > 1.

Lithium, Potassium, Rubidium, and Magnesium. Table 48 contains some figures showing the distribution of the elements in question.

As seen from the table, the contents of these elements are extremely low, which might be expected in lateritic sediments, in which the absence of the alkali metals, in particular, is significant.

Beryllium, Boron, Molybdenum, and Tungsten. Few comments will be necessary on the distribution of these elements. The contents, as seen from Table 49, are generally low.

Only in the case of *boron* can the content increase to values above the average value of the upper lithosphere. This is remarkable when taking into account the fact that the material emanates mainly from basalts or granites, which, in general, show very low contents of B, according to V. M. Goldschmidt and Cl. Peters (50).

Titaniferous Iron Ores.

The samples of this iron-ore type are from the Fennoscandian region (samples Nos. 1—12), from the United States (samples Nos. 14—24), and one sample from a Russian ore deposit (sample No. 13).

Most of the samples from ore deposits in the United States were placed at the author's disposal through the courtesy of the Director of the United States Geological Survey. The samples in question emanate partly from the collections of the Geological Survey and partly from the United States National Museum in Washington. The sample from Otanmäki, Finland, was kindly proffered by Dr. Kalervo Rankama of Helsingfors, and the sample from Ulfön, Sweden (No. 3) by Dr. F. Mogensen of Ludvika, Sweden. The other samples are from the Mineralogical Department of the University of Stockholm.

The Ferrides. The distribution of ferrides in the titaniferous iron ores is of especial importance, as the origin of this ore type is regarded as primarily magmatic and connected with rocks derived from the sima, *viz.* the inferior lithosphere.

Much care has been devoted to the determinations of the ferrides in the titaniferous iron ores, and several have been made both chemically and spectrochemically. The agreement has proved very good throughout.

Table 50 is a survey of the contents of ferrides.

Titanium. According to J. Singewald Jr., (108) the term "titaniferous" is used to designate those magnetic ores of iron that carry more than 2 or 3 per cent of titanium. As seen from Table 50, all the samples come within this category. The contents vary from 3.18 to 23.5 per cent Ti.

Vanadium. The abundance of vanadium in titaniferous iron ores is well-known. It should be mentioned that N. G. Sefström, the Swedish chemist, discovered the metal in iron emanating from the titaniferous iron ores of Smålands Taberg, Sweden (1830).

The content of V varies considerably — 0.03—0.4 per cent — in the ores. However, in the magnetic concentrate of the ores from Lake Sanford (samples Nos. 18—23) the average value is 0.41 per cent and the mean deviation only about ± 17 per cent. The content of the non-magnetic fraction of the same ore (sample No. 24) is comparatively low, indicating that the greater part of the vanadium enters the magnetite structure.

The ratio Ti/V in the magnetic concentrate mentioned is comparatively constant, too. The mean is 18 ± 40 per cent. In the ores, on the other hand, the ratio Ti/V varies considerably, and the deviation from the mean is about ± 130 per cent.

Chromium. In comparison with the average value of the upper lithosphere — 0.02 per cent — the content of chromium has increased considerably. The relatively high content of Cr can be regarded as significant for titaniferous

Table 50. **The Distribution of Ferrides in Titaniferous Iron Ores.**

No.	Locality	Ti	V	Cr	Mn	Fe	Co	Ni
1	Routivare, Kvikkjokk, Sweden	9.05	0.05	0.3	> 1.0	54.2	0.03	0.03
2	Vallatj, Kvikkjokk, Sweden	8.16	0.03	0.2	0.65	56.7	0.02	0.02
3	Ulfön, Nordingrå (avg), Sweden	5.08	0.24	0.14	0.23	29.04	0.01	0.01
4	S. Ulfön, Grunna, Nordingrå, Sweden	3.97	0.30	0.55	0.60	37.85	0.01	0.02
5	Kramsta, type A (avg), Järvsö, Sweden	3.18	0.12	0.2	1.0	23.6	0.01	0.009
6	Kramsta, type B (avg), Järvsö, Sweden	5.52	0.23	0.2	0.5	31.6	0.02	0.02
7	Taberg, Småland, Sweden	3.35	0.06	0.2	0.3	31.4	0.02	0.03
8	Inglamåla, Småland, Sweden	4.39	0.08	0.1	1.10	33.3	0.01	0.001
9	Egersund-Soggendal, Norway	23.5	0.06	0.3	0.9	42.3	0.02	0.06
10	Egersund-Soggendal, Norway	high	0.07	0.3	0.7		0.04	0.10
11	Egersund-Soggendal, Norway	high	0.09	0.1	1.0		0.04	0.08
12	Otanmäki, Finland	9.8	0.40	0.3	0.32	51.4	0.03	0.02
13	Kusa, U.S.S.R.	8.56	0.09	0.1	0.95	50.2	0.01	0.01
14	Iron Mountain, Wyoming, U.S.A.	9.17	0.21	0.03	0.2	50.6	0.03	0.02
15	Laramie Mountains, Wyoming, U.S.A.	11.5	0.1	0.3	0.9	50.0	0.03	0.04
16	Iron Hill Mine, Cumberland, Rhode Island, U.S.A.	6.5	0.08	0.003	0.5	30.9	0.02	0.02
17	Champlain Mine, Essex County, N.Y., U.S.A.	12.0	0.2	0.4	0.6	44.1	0.03	0.03
18	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	7.25	0.36	0.13	0.2	59.1	0.03	0.02
19	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	4.20	0.45	0.21	0.06	58.2	0.02	0.01
20	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	7.52	0.38	0.17	0.1	58.8	0.02	0.02
21	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	8.65	0.37	0.19	0.4	57.1	0.03	0.02
22	Lake Sanford, Essex County, N.Y. U.S.A., (magnetic concentrate)	9.67	0.36	0.17	0.2	56.2	0,03	0.02
23	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	5.56	0.53	0.03	0.07	55.7	0.01	0.01
24	Lake Sanford, Essex County, N.Y., U.S.A., (non-magnetic fraction)	8.16	0.07	0.003	0.1	18.8	0.007	0.006

iron ores connected with basic igneous rocks. However, the contents vary from 0.003 to 0.55 per cent.

In the ores from Lake Sanford, the ratio of the content of Cr in the magnetic concentrate and in the non-magnetic fraction respectively is $\gg 1$, showing that Cr preferably enters the magnetite structure, a trend corresponding to that of vanadium.

Manganese. The content of this ferride is, too, above the average content of the upper lithosphere in almost all the cases investigated.

The ratio Mn/Fe (mf) is of some interest. The mean value of the ratio is 1.8, *i.e.* approximately equal to the average value calculated for the upper lithosphere. As seen from Table 6 on p. 30, the average value of the ratio is 1.8 for the basalts and 3.2 for the gabbros. Thus, the ratio has decreased slightly in the titaniferous iron ores in comparison with the rocks mentioned. In the iron ores connected with salic rocks hitherto investigated, the ratio in question is much lower than that of the titaniferous iron ores, as seen from Table 10 on

Table 51. **The Distribution of Lithium, Magnesium, Potassium, and Rubidium in Titaniferous Iron Ores.**

No.	Locality	Li	Mg	$\frac{100\ \mathrm{Li}}{\mathrm{Mg}}$	K	Rb	$\frac{100\ \mathrm{Rb}}{\mathrm{K}}$
1	Routivare, Kvikkjokk, Sweden	< 0.0005	3.5	< 0.05		< 0.001	
2	Vallatj, Kvikkjokk, Sweden	< 0.0005	1.6	< 0.11		< 0.001	
3	Ulfön, Nordingrå, (avg) Sweden	0.0005	6.2	0.03	0.4	0.0008	0.09
4	S. Ulfön, Grunna, Nordingrå, Sweden	0.0007	4.7	0.05		< 0.001	
5	Kramsta, type A (avg), Järvsö, Sweden	0.0008	7.1	0.04	0.4	0.002	0.28
6	Kramsta, type B (avg), Järvsö, Sweden	0.001	4.5	0.08	0.08	0.0008	0.46
7	Taberg, Småland, Sweden	0.0005	9.2	0.02		< 0.001	
8	Inglamåla, Småland, Sweden	0.001	6.2	0.06	0.2	0.0007	0.16
9	Egersund-Soggendal, Norway	< 0.0005	3.0	< 0.06	< 0.05	< 0.001	
12	Otanmäki, Finland	< 0.0005	2.8	< 0.06		< 0.001	
13	Kusa, U.S.S.R.	< 0.0005	3.5	< 0.05		< 0.001	
14	Iron Mountain, Wyoming, U.S.A.	0.0005	1.5	0.12	< 0.03	< 0.001	
15	Laramie Mountains, Wyoming, U.S.A.	< 0.0005				< 0.003	
16	Iron Hill Mine, Cumberland, R.I., U.S.A.	0.001	> 3.0	< 0.12		< 0.003	
17	Champlain Mine, Essex County, N.Y., U.S.A.	< 0.0005				< 0.003	
18	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	< 0.0005	1.2	< 0.15	< 0.03	< 0.001	
19	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	0.0005	1.3	0.13	0.04	0.001	1.14
20	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	< 0.0005	0.9	< 0.19	0.2	0.001	0.28
21	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	0.0005	1.5	< 0.12	< 0.03	< 0.001	
22	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	0.0005	1.2	0.15	< 0.03	< 0.001	
23	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	0.0005	0.9	0.19	< 0.03	< 0.001	
24	Lake Sanford, Essex County, N.Y., U.S.A., (non-magnetic fraction)	0.003	> 3.0	< 0.35	0.1	0.001	0.46

p. 40, in spite of the fact that the quantity mf is considerably higher in the salic rocks on the whole than in the basic rocks mentioned before, as seen from Table 6.

Cobalt has become enriched in this ore type. In all cases the contents exceed the average of the upper lithosphere. According to V. M. Goldschmidt (45) the content of Co in gabbros is approximately 0.008 per cent. Thus we find that the content has increased in the ores in relation to the gabbros.

Nickel. In the work by J. Singewald Jr. on the titaniferous iron ores of the United States (108), some data are given on the content of Ni in the ores in question. These data disagree with the author's spectrochemical determinations of the nickel contents of titaniferous iron ores from the Fennoscandian region (samples 1—12). Most of the contents of Ni available in Singewald's work exceeded the contents of the latter region by approximately one order of magnitude. Thus, the author was in doubt as to whether the data presented by Singewald were significant for the titaniferous iron ores in the

Table 52. **The Distribution of Beryllium, Boron, Molybdenum, and Tungsten in Titaniferous Iron Ores.**

No.	Locality	Be	B	Mo	W
1	Routivare, Kvikkjokk, Sweden	< 0.001	< 0.001	< 0.005	< 0.01
2	Vallatj, Kvikkjokk, Sweden	< 0.001	< 0.001	< 0.005	< 0.01
3	Ulfön, Nordingrå, Sweden	< 0.001		< 0.005	< 0.01
4	S. Ulfön, Grunna, Nordingrå, Sweden	< 0.001		< 0.005	< 0.01
5	Kramsta, Järvsö, type A (avg), Sweden	< 0.001		< 0.005	< 0.01
6	Kramsta, Järvsö, type B (avg), Sweden	< 0.001		< 0.005	< 0.01
7	Taberg, Småland, Sweden	< 0.001	0.002	< 0.005	< 0.01
8	Inglamåla, Småland, Sweden	< 0.001		< 0.005	< 0.01
9	Egersund-Soggendal, Norway	< 0.001		< 0.005	< 0.01
10	Egersund-Soggendal, Norway	< 0.001		< 0.005	< 0.01
11	Egersund-Soggendal, Norway	< 0.001		< 0.005	< 0.01
12	Otanmäki, Finland	< 0.001		< 0.005	< 0.01
13	Kusa, U.S.S.R.	< 0.001		< 0.005	< 0.01
14	Iron Mountain, Wyoming, U.S.A.	< 0.001		< 0.005	< 0.01
15	Laramie Mountains, Wyoming, U.S.A.	< 0.001	< 0.001		
16	Iron Hill Mine, Cumberland, R.I., U.S.A.	0.001	< 0.001		
17	Champlain Mine, Essex County, N.Y., U.S.A.	< 0.001	< 0.001		
18—23	Lake Sanford, Essex County, N.Y., U.S.A., (magnetic concentrate)	< 0.001		< 0.005	< 0.01
24	Lake Sanford, Essex County, N.Y., U.S.A., (non-magnetic fraction)	< 0.001	< 0.001	< 0.005	< 0.01

United States. The new spectrochemical analyses of the samples of ores that the author received from the United States Geological Survey agree, at any rate, with those of the Fennoscandian ores, also regarding the content of Ni. Thus, it seems to the author that the new analyses of Ni presented in Table 50 are more significant for the titaniferous iron ores on the whole.

According to V. M. Goldschmidt (45) the content of Ni in gabbros is 0.016 per cent. As seen from the table, the content in the ores is generally higher.

On the basis of the figures given by Goldschmidt the ratio Co/Ni in gabbros is 0.5 and in the upper lithosphere 0.4. In the titaniferous iron ores the mean value has increased to 1.4. This displacement of the magnitude of the ratio in question agrees with that reported in iron ores on the whole, independent of their origin and geological character and independent, too, of the ratio MgO/FeO (mgf). This interesting geochemical feature will be discussed in the next part of this work.

As seen from the table both Ni and Co are enriched in the magnetic concentrate in comparison with the non-magnetic fraction (samples Nos. 18—24).

Lithium, Potassium, Rubidium, and Magnesium. Table 51 is a survey of the contents of the alkalies and magnesium and of the ratios Li/Mg and Rb/K respectively.

The content of alkalies is low and no comments are necessary. The content of magnesium is, as expected, relatively high.

The ratio Li/Mg is low and this is in agreement with the conclusions drawn by Strock (111) and — from a different point of view — by F. E. Wickman (125).

The ratio Rb/K is of little importance in this connection.

Beryllium, Boron, Molybdenum, and Tungsten. Table 52 shows the contents of the elements in question. The contents are low and of no real interest.

Sundry Non-Titaniferous Iron Ores From Various Localities.

Tables 53—55 contain a survey of the distribution of the minor constituents in sundry iron ores in the World. Most of the samples are from the collection of iron ores of the Mineralogical Department of the University of Stockholm. Samples 26—29 emanate from the United States National Museum in Washington.

Table 53 is a survey of the contents of the ferrides.

Table 54 shows the contents of the alkali metals and magnesium. The ratios Li/Mg and Rb/K are calculated and shown in the table.

The contents of beryllium, boron, molybdenum, and tungsten are given in Table 55.

As seen from the tables mentioned, the distribution of the minor constituents in the various ore types investigated varies in a manner similar to that of the ore types discussed before. The contents of the various elements in the ore types represented in Tables 53—55 agree well with the corresponding figures of the ore types hitherto discussed. No comment is, therefore, necessary in this connection. However, in the summary and in the second part some of the figures given in the tables mentioned will be discussed in different connections.

Summary.

The distribution of the minor constituents — as seen from the analytical data presented — first gives an impression of irregularity. It is obvious that many factors have influenced their distribution, especially with regard to the metamorphic ores. Several of them have undergone various processes, each of these bringing about a change in the contents of elements.

Tables 56—58 below contain surveys on the distribution of the minor constituents. The figures are the calculated average values of the various ore and rock types represented in this investigation. The calculations are as thorough as possible as is the distribution of the analytical data over the different ore types.

Table 56 is a survey of the distribution of the ferrides in the iron ores. A short summary will be given in conjunction with the table.

Table 53. **The Distribution of Ferrides in various Iron Ores from non-Swedish Regions.**

No.	Ore Type and Locality	Ti	V	Cr	Mn	Fe	Co	Ni
1	Quartz-banded magnetite ore, South Varanger, Norway	0.02	0.004	0.001	0.25		< 0.003	0.01
2	Siderite ore, Eisenfeld, Siegen, Germany	0.06	0.002	< 0.001	~ 1		0.005	0.002
3	Hematite ore, the Fortuna Mine, Germany	0.03	0.02	0.003	0.3		< 0.003	0.01
4	Minette ore, Heinzenberg, Lorraine, France	0.08	0.02	0.01	0.3		0.03	0.01
5	Minette ore, the grey bed, Luxembourg	0.09	0.05	0.01	0.1	53.4	0.008	0.01
6	Minette ore, the brown bed, Luxembourg	0.10	0.03	0.03	0.5		0.005	0.02
7	Minette ore, the black bed, Luxembourg	0.08	0.05	0.03	1.1	47.5	0.02	0.02
8	Minette ore, the green bed, Luxembourg	0.05	0.05	0.02	1.2		0.03	0.04
9	Hematite ore, irisated, Cap Calamita, Elba, Italy	0.05	0.001	0.004	0.1	68.1	< 0.003	0.001
10	Hematite-pyroxene-ilvaite rock, Cap Calamita, Elba, Italy	0.02	0.002	< 0.001	1.1	15.1	0.005	< 0.001
11	Hematite with kaolin, Rio Marina, Elba, Italy	0.06	0.006	< 0.001	0.02	68.1	< 0.003	0.002
12	Hematite ore, Bilbao, Spain	0.01	0.004	0.001	0.1	61.4	0.003	0.02
13	Hematite ore, Bilbao, Spain	0.3	0.002	0.003	1.3		< 0.003	< 0.001
14	Hematite ore, (campanil), the Pacifica Mine, Bilbao, Spain	0.02	< 0.001	< 0.001	2.0	55.9	0.01	< 0.001
15	Hematite ore, Oviedo, Spain	0.08	0.03	0.03	0.75	29.6	0.003	0.01
16	Limonitic ore, the S:ta Rosa Mine, Cartagena, Spain	0.02	0.004	< 0.001	0.1		0.003	0.005
17	Magnetite ore, martitized, Gora Magnitnaja, Ural Mts, U.S.S.R.	0.02	0.007	0.001	0.25	65.5	0.03	0.01
18	Magnetite ore, martitized, Gora Magnitnaja, Ural Mts, U.S.S.R.	0.01	0.004	0.002	0.15		0.003	0.004
19	Magnetite ore, martitized, Wyssokaya Gora, Ural Mts, U.S.S.R.	< 0.01	0.04	0.001	0.30	61.3	0.02	0.005
20	Magnetite ore, Goroblagodat, Ural Mts, U.S.S.R.	< 0.01	0.10	0.003	0.75	69.8	0.01	0.003
21	Magnetite ore, martitized, Goroblagodat, Ural Mts, U.S.S.R.	0.10	0.10	0.003	1.1		< 0.003	0.003
22	Apatite-magnetite ore, Mineville District, N.Y., U.S.A.	0.2	0.01	0.003	0.1		< 0.003	0.005
23	Magnetite ore, Barton Hill, Mineville District, N.Y., U.S.A.	0.1	0.001	< 0.001	0.09		< 0.003	0.01
24	Magnetite ore (rich ore), Palmer Hill, Adirondacks, N.Y., U.S.A.	0.2	0.003	0.007	0.45		0.002	0.01
25	Magnetite ore, Nigger Hel'r Mine, Warren Co., N.Y., U.S.A.	0.3	0.004	< 0.001	0.06	65.2	0.003	0.003
26	Magnetite ore, Bevitt Lot Mine, Elizabeth, Essex County, N.Y., U.S.A.	0.5	0.005	< 0.001	0.08	48.7	0.005	0.006
27	Magnetite ore, Crown Point Mine, Crown Point, Essex County, N.Y., U.S.A.	0.1	0.01	0.001	0.05	67.9	0.005	0.003
28	Magnetite ore, Scofield Mine, Essex County, N.Y., U.S.A.	0.3	0.009	0.001	0.06	67.5	0.004	0.005
29	Magnetite ore, Hibernia, Morris County, N. Jersey, U.S.A.	0.5	0.06	0.002	0.07	51.4	0.009	0.01
30	Hematite ore ("specular ore"), Ishpening, Marquette District, U.S.A.	0.01	0.003	0.05	0.09		< 0.003	0.01
31	Jaspilite ore, Ishpening, Marquette District, U.S.A.	0.01	0.003	< 0.001	0.05		< 0.003	0.005
32	Jaspilite ore, Marquette District, U.S.A.	0.02	0.003	0.001	0.3	52.2	< 0.003	0.003
33	Hematite ore, Soudan, Vermilion, U.S.A.	0.06	0.004	0.03	0.04		0.003	0.02

Table 54. **The Distribution of Lithium, Magnesium, Potassium, and Rubidium in various Iron Ores from non-Swedish Regions.**

No.	Ore Type and Locality	Li	Mg	$\frac{100\,\text{Li}}{\text{Mg}}$	K	Rb	$\frac{100\,\text{Rb}}{\text{K}}$
1	Quartz-banded magnetite ore, South Varanger, Norway	< 0.0005	0.4	0.44		< 0.001	
2	Siderite ore, Eisenfeld, Siegen, Germany	< 0.0005	1.0	< 0.18		< 0.001	
3	Hematite ore, Fortuna Mine, Lahn-Dill, Germany	0.008	> 7	< 0.40		< 0.001	
4	Minette ore, Heinzenberg, Lorraine, France	0.009	0.9	3.5		< 0.001	
5	Minette ore, the grey bed, Luxembourg	0.004	0.7	2.0		< 0.001	
6	Minette ore, the brown bed, Luxembourg	0.01	2.1	1.67	0.07	0.001	0.65
7	Minette ore, the black bed, Luxembourg	0.003	1.4	0.75		< 0.001	
8	Minette ore, the green bed, Luxembourg	0.003	1.0	1.05		< 0.001	
9	Hematite ore, irisated, Cap Calamita, Elba, Italy	0.001	0.1	3.5		< 0.001	
10	Hematite-pyroxene-ilvaite rock, Cap Calamita, Elba, Italy	< 0.0005	> 7			< 0.001	
11	Hematite with kaolin, Rio Marina, Elba, Italy	0.0005	0.5	0.35		< 0.001	
12	Hematite ore, Bilbao, Spain	< 0.0005	0.1	< 1.75		< 0.001	
13	Hematite ore, Bilbao, Spain	0.02	5.5	1.40		< 0.001	
14	Hematite ore, campanil, the Pacific Mine, Bilbao, Spain	< 0.0005	4.5	< 0.04		< 0.001	
15	Hematite ore, Oviedo, Spain	0.02	1.1	6.37	0.08	0.001	0.57
16	Limonitic ore, S:ta Rosa Mine, Cartagena, Spain	0.0005	0.1	1.75		< 0.001	
17	Magnetite ore, martitized, Gora Magnitnaja, Ural Mts, U.S.S.R.	0.002	0.4	1.75		< 0.001	
18	Magnetite ore, martitized, Gora Magnitnaja, Ural Mts, U.S.S.R.	< 0.0005	0.6	< 0.29		< 0.001	
19	Magnetite ore, martitized, Wyssokaya Gora, Ural Mts, U.S.S.R.	0.02	2.5	2.8		< 0.001	
20	Magnetite ore, Goroblagodat, Ural Mts, U.S.S.R.	< 0.0005	0.5	< 0.35		< 0.001	
21	Magnetite ore, martitized, Goroblagodat, Ural Mts, U.S.S.R.	0.0008	0.9	0.31		< 0.001	
22	Apatite ore, Mineville District, N.Y., U.S.A.	0.002	0.7	1.0		< 0.001	
23	Magnetite ore, Barton Hill, Mineville District, N.Y., U.S.A.	0.001	0.6	0.58		< 0.001	
24	Magnetite ore (rich ore), Palmer Hill, Adirondacks, N.Y., U.S.A.	< 0.0005	0.5	< 0.35	0.1	0.001	0.46
25	Magnetite ore, Nigger Hel'r Mine, Warren Co., N.Y., U.S.A.	< 0.0005				< 0.003	
26	Magnetite ore, Bevitt Lot Mine, Elizabeth, Essex County, N.Y., U.S.A.	0.0008	0.8	0.35		< 0.003	
27	Magnetite ore, Crown Point Mine, Crown Point, Essex County, N.Y., U.S.A.	< 0.0005				< 0.003	
28	Magnetite ore, Scofield Mine, Essex County, N.Y., U.S.A.	0.0005	0.3	0.58		< 0.003	
29	Magnetite ore, Hibernia, Morris County, New Jersey, U.S.A.	0.002	1.3	0.54			
30	Hematite ore, ("specular ore"), Ishpening, Marquette District, U.S.A.	0.003	0.2	5.26	0.05	0.001	0.92
31	Jaspilite ore Ishpening, Marquette District, U.S.A.	< 0.0005	1.6	< 0.11		< 0.001	
32	Jaspilite ore, Marquette District, U.S.A.	< 0.0005	0.8	< 0.22		< 0.001	
33	Hematite ore, Soudan, Vermilion, U.S.A.	< 0.0005	0.2	< 0.87		< 0.001	

Table 55. **The Distribution of Beryllium, Boron, Molybdenum, and Tungsten in various Iron Ores from non-Swedish Regions.**

No.	Ore Type and Locality	Be	B	Mo	W
1	Quartz-banded magnetite ore, South Varanger, Norway	< 0.001	< 0.001	< 0.001	< 0.03
2	Siderite ore, Eisenfeld, Siegen, Germany	< 0.001	< 0.001	< 0.003	< 0.03
3	Hematite ore, Fortuna Mine, Lahn-Dill, Germany	0.001	0.002	< 0.001	< 0.03
4	Minette ore, Heinzenberg, Lorraine, France	0.003	0.002	< 0.001	< 0.03
5	Minette ore, the grey bed, Luxembourg	0.002	0.001	< 0.003	0.03
6	Minette ore, the brown bed, Luxembourg	< 0.001	0.01	< 0.001	< 0.03
7	Minette ore, the black bed, Luxembourg	< 0.001	0.001	< 0.001	< 0.03
8	Minette ore, the green bed, Luxembourg	< 0.001	0.001	< 0.001	< 0.03
9	Hematite ore, irisated, Cap Calamita, Elba, Italy	< 0.001	< 0.001	< 0.001	0.1
10	Hematite-pyroxene-ilvaite rock, Cap Calamita, Elba, Italy	0.005	< 0.001	< 0.001	< 0.03
11	Hematite with kaolin, Rio Marina, Elba, Italy	< 0.001	< 0.001	< 0.001	0.03
12	Hematite ore, Bilbao, Spain	< 0.001	0.002	< 0.001	< 0.03
13	Hematite ore, Bilbao, Spain	< 0.001	< 0.001	< 0.001	< 0.03
14	Hematite ore, campanil, the Pacific Mine, Bilbao, Spain	< 0.001	< 0.001	< 0.001	< 0.03
15	Hematite ore, Oviedo, Spain	0.009	0.002	< 0.001	< 0.03
16	Limonitic ore, S:ta Rosa Mine, Cartagena, Spain	< 0.001	< 0.001	< 0.001	< 0.03
17	Magnetite ore, martitized, Gora Magnitnaja, Ural Mts, U.S.S.R.	< 0.001	< 0.001	< 0.001	< 0.03
18	Magnetite ore, martitized, Gora Magnitnaja, Ural Mts, U.S.S.R.	< 0.001	< 0.001	< 0.001	< 0.03
19	Magnetite ore, martitized, Wyssokaya Gora, Ural Mts, U.S.S.R.	< 0.001	< 0.001	< 0.001	< 0.03
20	Magnetite ore, Goroblagodat, Ural Mts, U.S.S.R.	< 0.001	< 0.001	< 0.001	< 0.03
21	Magnetite ore, martitized, Goroblagodat, Ural Mts, U.S.S.R.	< 0.001	< 0.001	< 0.001	< 0.03
22	Apatite-magnetite ore, Mineville District, N.Y., U.S.A.	0.002	< 0.001	< 0.001	< 0.03
23	Magnetite ore, Barton Hill, Mineville N.Y., U.S.A.	< 0.001	< 0.001	< 0.001	< 0.03
24	Magnetite ore (rich ore), Palmer Hill, Adirondacks, N.Y., U.S.A.	< 0.001	< 0.001	< 0.001	< 0.03
25	Magnetite ore, Nigger Hel'r Mine, Warren County, N.Y., U.S.A.	0.001	0.001		
26	Magnetite ore, Bevitt Lot Mine, Elizabeth, Essex County, N.Y., U.S.A.	0.002	< 0.001		
27	Magnetite ore, Crown Point Mine, Crown Point, Essex Co., N.Y., U.S.A.	0.002	< 0.001		
28	Magnetite ore, Scofield Mine, Essex County, N.Y., U.S.A.	0.001	< 0.001		
29	Magnetite ore, Hibernia, Morris County, New Jersey, U.S.A.	0.001	< 0.001		
30	Hematite ore ("specular ore"), Ishpening, Marquette District, U.S.A.	< 0.001	< 0.001	< 0.001	< 0.03
31	Jaspilite ore, Ishpening, Marquette District, U.S.A.	< 0.001	0.002	< 0.001	< 0.03
32	Jaspilite ore, Marquette District, U.S.A.	< 0.001	0.001	< 0.001	< 0.03
33	Hematite ore, Soudan, Vermilion, U.S.A.	< 0.001	0.001	< 0.001	< 0.03

Table 56. **A Survey of the Distribution of the Ferrides in the Iron Ores investigated.**

Ore type	Ti	V	Cr	Mn	Fe	Co	Ni
Pre-Cambrian ores of Central Sweden:							
Quartz ore, not banded ..	0.075	0.0024	0.004	0.17	55	0.0016	0.0013
Quartz ore, banded......	0.01	0.0085	0.005	0.12	52	0.0027	0.0020
Skarn ore...............	0.025	0.0013	0.011	0.34	53	0.0023	0.0013
Lime and dolomite ore...	0.02	0.002	0.0015	3.0	48	0.0015	0.0012
Apatite ore.............	0.17	0.14	0.007	0.13	60	0.0026	0.0056
Northern Sweden:							
Apatite ore.............	0.19	0.13	< 0.001	0.07	62	0.0093	0.020
Titaniferous ore	10.67	0.14	0.22	0.65	41.3	0.02	0.03
Sedimentary ores:							
Marine sediments:							
Oolitic-siliceous ore.......	0.39	0.05	0.024	0.16	31	0.02	0.02
Sideritic ore............	0.20	0.007	0.002	0.26	38	0.03	0.005
Lacustrine sediment:							
Bog ore.................	0.15	< 0.001	< 0.001	7.45	32.7	0.013	0.004
Lateritic sediments:							
Laterite-bauxite ore......	3.25	0.04	0.04	0.08	29	0.03	0.018

Titanium. Apart from the titaniferous iron ores, the content of the element in question is low. Thus, the abundance of Ti in the pre-Cambrian ores of Sweden is 0.01—0.19. The marine sediments show increasing values, but in all the cases investigated the average values are below the average of the upper lithosphere. Only the laterites show a relatively high content of titanium.

Vanadium. In the quartz, skarn, and lime ores of Central Sweden the average content of vanadium is low. This is also the case with the sideritic and the bog ores. Among the sediments only the oolitic ores and the laterites show contents above the average value of the upper lithosphere. The highest content is found in the titaniferous ores and the apatite ores.

Chromium. The titaniferous, the oolitic and the lateritic ores show contents of chromium with a considerable enrichment factor in comparison with the upper lithosphere. The other ores investigated show a deficiency of chromium.

Manganese. In most cases manganese is enriched in the ores investigated. The apatite ores of Northern Sweden and the lateritic sediments are exceptions.

Cobalt. The pre-Cambrian iron ores of Central Sweden show a deficiency of this element. In the other cases investigated cobalt has become enriched when compared with the upper lithosphere.

Nickel. In the apatite ores of Northern Sweden, in the titaniferous iron ores and — among the sediments — in the oolitic and lateritic ores nickel has become enriched. In the other ores there is a deficiency in the content compared with the upper lithosphere.

Table 57. **The Distribution of the Ferrides in the Leptites, Skarn Rocks, and Gneisses.**

	Leptites	Skarn rocks	Gneisses	Igneous rocks
Ti	0.15	0.05	0.07	0.44
V	0.011	0.006	0.007	0.015
Cr	0.005	0.004	0.005	0.02
Mn	0.03	0.05	0.01	0.1
Fe	1.86	7.20	2.12	5.0
Co[1]	0.0016	0.0020	0.0019	0.0023
Ni[1]	0.0019	0.0013	0.0009	0.008

[1] The figures for Co and Ni in the igneous rocks after Sandell and Goldich (107).

As seen from the table, the pre-Cambrian iron ores of Central Sweden show, on the whole, a remarkable deficiency in the content of ferrides, not only in comparison with other ore types represented in this investigation, but also in comparison with the contents of the upper lithosphere in general, and especially the leptites and other rocks associated with the iron ores in question, when bearing in mind the enrichment of iron with more than one degree of magnitude.

For comparison, the data on the distribution of the ferrides in leptites, skarn rocks, gneisses, and the upper lithosphere are given in Table 57 above.

The figures in Table 57 show that the content of ferrides in the rocks of Central Sweden is far below the average content in the upper lithosphere, with the exception of the content of iron in the skarn rocks. Further, in the latter rocks the ferride contents are in general a little below the corresponding contents of leptites. The gneisses investigated show contents of approximately the same size as those of the leptites.

The distribution of lithium, rubidium, beryllium, and boron is shown in Table 58. As regards the average contents of the elements mentioned in the ores of Central Sweden as well as in the apatite ores of Northern Sweden, values are calculated both for the ores and for the corresponding gangues in order to facilitate comparisons with other iron ores, on the one hand, and with the ore-bearing rocks of Central Sweden, on the other.

Lithium. As seen from the table there is a deficiency of lithium in the pre-Cambrian iron ores of Sweden both in comparison with the leptites and compared with the upper lithosphere. The quartz ores of Central Sweden and the apatite ores of Northern Sweden show the highest values.

As regards the sedimentary ores, only those of marine character show figures above the average of the sediments in the upper lithosphere (cf. Strock (111).

Rubidium. Also in the case of rubidium there is a deficiency in all the ores and rocks investigated, if compared with the average value for the upper lithosphere, as estimated by V. M. Goldschmidt (46). The abundance of Rb is

Table 58. **A Survey of the Distribution of Lithium, Rubidium, Beryllium, and Boron in the Iron Ores and Rocks investigated.**

No.		Li	Rb	Be	B
1	The ore-bearing region of Central Sweden:				
	Quartz ore, not banded.........	o: 0.0012	0.005	0.0012	0.0007
		g: 0.0035	0.014	0.0033	0.0019
	Quartz ore, banded............	o: 0.0006	0.0006	0.0029	0.0006
		g: 0.0017	0.0017	0.0084	0.0016
	Skarn ore.....................	o: 0.0007	0.0029	0.0016	0.0005
		g: 0.0019	0.0083	0.0046	0.0015
	Lime and dolomite ore.........	o: 0.0004	0.001	0.0005	0.0007
		g: 0.0011	0.003	0.0014	0.0019
	Leptite........................	0.0058	0.018	0.0014	0.003
	Ore-bearing rocks, metamorphosed	0.0011	0.0086	0.004	0.0015
	Gneiss........................	0.0011	0.010	0.001	0.002
2	Northern Sweden:				
	Apatite ore....................	o: 0.0008	0.0009	0.0003	0.00001
		g: 0.004	0.0046	0.0017	0.0007
3	Titaniferous ore................	0.0005	0.0009	$<$ 0.001	0.0007
4	Sedimentary ores:				
	Marine sediments:				
	Oolitic-siliceous ore.............	0.012	0.0007	0.001	0.0073
	Sideritic ore...................	0.01	0.0005	0.001	0.0028
5	Lacustrine sediments:				
	Bog ore......................	0.001	0.0008	0.0007	0.0029
6	Lateritic sediments:				
	Laterite-bauxite ore............	$<$ 0.0005	0.0005	0.0005	0.002

highest in the leptites, but also in the quartz ores of Central Sweden the average content is considerable, a trend corresponding to that found in lithium. In the skarn rocks, too, the abundance is relatively high and approaches that of the quartz ores. On the whole, the amount of rubidium in the iron ores of Central Sweden seems to be higher than that of the other ore types investigated. This feature, however, is contrary to that found in lithium.

Beryllium. First it should be emphasized that the figures indicating the abundance of beryllium should be regarded as uncertain, due to the fact that the contents of Be in general are too low to permit of accurate determinations by means of spectrochemical methods.

There seems to be an enrichment of beryllium in connection with iron enrichment in general, presuming that the average content in the upper lithosphere — estimated by V. M. Goldschmidt (46) — be right. In comparison with the content of Be in the leptites, however, the iron ores show a slight deficiency.

Boron. V. M. Goldschmidt has estimated the abundance of boron in the igneous rocks (0.0003 per cent) and in the marine clay sediments (0.015 per cent) (46). However, the figures mentioned will be of little value for comparisons. In this connection it can be stated only that in all the cases investigated the boron contents are below those of marine sediments but far above the average of the igneous rocks. This geochemical feature has been discussed in detail in other connections.

It has proved impossible to estimate average values for the two elements *molybdenum* and *tungsten,* as most of the contents are below the limit for spectrochemical determinations. In those cases where the metals in question show contents above the limits mentioned — 0.001 per cent Mo and 0.03 per cent W — the figures are to be found in the tables for the various regions.

This summary concludes the first part of this book. In the next part, the problems connected with the geochemistry of the elements investigated and the iron-ore formation in the upper lithosphere will be discussed on the basis of the data presented in this part.

Part Two.

Chapter IV. On the Geochemistry of the Ferrides.

Introduction.

Geochemists, geologists, and geophysicists have advanced several hypotheses on the constitution and history of the interior of the Earth. A valuable survey of the 20th century concepts on this matter is given by A. F. Buddington (12).

When dealing with the problems of the distribution of the elements in the Earth's crust, it would naturally be desirous to know as much as possible regarding the relative abundance of elements in the primary stage of evolution, *i.e.* in an undifferentiated matter. The greatest difficulty encountered in our endeavours to obtain numerical values of the relative abundance in this case is that of defining a fair sample. The Earth as a whole may be considered such a sample, but since the main part of the interior is inaccessible, we have got to find other methods to arrive at a reasonable conception of what may be regarded as a primary distribution of elements.

If we desire a distribution principle of elements of sufficient universality, the rule suggested by William D. Harkins is the first to be considered. Harkins pointed out that the elements with even atomic numbers are more abundant than those with odd numbers. Further, he arrived at the conclusion that the even-numbered members are always more abundant than the adjacent odd-numbered elements (56, p. 862).

In a series of important laboratory studies on the relative abundance of the lanthanides in the Earth's crust, V. M. Goldschmidt and L. Thomassen (48) found that Harkins' rule is strictly applicable in this coherent group of elements. Other investigations by Ida Noddack (92), E. Minami (88), Th. G. Sahama and V. Vähätalo (104), and the author (67) (cf also Table 35), have shown that, even in vastly different milieus, no deviations from Harkins' rule have so far been found as regards the relative abundance of the lanthanides.

Thus, the chemical differentiation is too feeble in the lanthanides to permit of any deviation from Harkins' rule, and the reasons are plain enough when considering the atomic structure of the lanthanides. The electrons (neglecting the inner ones) are grouped as follows:

$4s^2 4p^6 4d^{10} 4f^{0-14} 5s^2 5p^6$. The construction of the 4f-group continues while the outer electrons remain constant.

Now, when dealing with the alterations in the distribution of elements under different conditions, it would be more profitable to study alterations in the relative abundance of a coherent group of elements where the chemical differentiation is less feeble than that of the lanthanides, so that alterations in the relative abundance might be put in relation to differences in the milieus investigated.

The ferrides will be such a coherent group. Here the electrons are arranged as follows: $3s^2 3p^6 3d^{2-8}$. Thus, the completion of the 3d-group continues, but in this case the electrons belong to an outer "shell" (the M-shell). The next shell (the N-shell) is the seat of the valency electrons. This arrangement of the electrons finds an expression in a certain coordination of the ferrides in Nature, but the chemical differentiation is strong enough to effect alterations in the relative abundance of the ferride members in different milieus.

When dealing with problems connected with the enrichment of iron, the most abundant member, it is evidently of importance to study the distribution of all ferrides in different milieus. The geochemistry of the ferrides will consequently be closely discussed.

The "even-odd" rule for the distribution of elements, advanced by William D. Harkins (56), holds good also for the relative abundance of isotopes, as shown by F. W. Aston (3) and V. M. Goldschmidt (46). Since the abundance of elements discussed by Goldschmidt in his work quoted above refers to the mass-number (M), the author considers it suitable to choose the same x-axis, *viz.* the mass-numbers 46—62, to illustrate the relative abundance of the ferrides in different milieus. In the calculations are included the two calcium-isotopes $M = 46$ and $M = 48$, and the unimportant nickel isotope $M = 64$ is excluded.

The Abundance of the Ferride Isotopes in different Milieus.

Cosmos. On the basis of the data available on the distribution of elements, V. M. Goldschmidt has calculated the average abundance of elements in Cosmos, supposing that the relative abundance of isotopes for each element is similar to that found in material emanating from the Earth's crust (46), p. 120). The relative abundance of the ferride isotopes has been recalculated from Goldschmidt's tables and is shown in the diagram, fig. 19.

As seen from the diagram the even-odd rule for the abundance of isotopes is very well illustrated.

The abundance in Meteorites. The distribution of the ferrides in meteorites is well known to us thanks to investigations by O. C. Farrington (25), G. P. Merrill (87), G. Hevesy (58), I. and W. Noddack (90), V. M. Goldschmidt (44), and others. To ascertain the average contents of the various elements in mete-

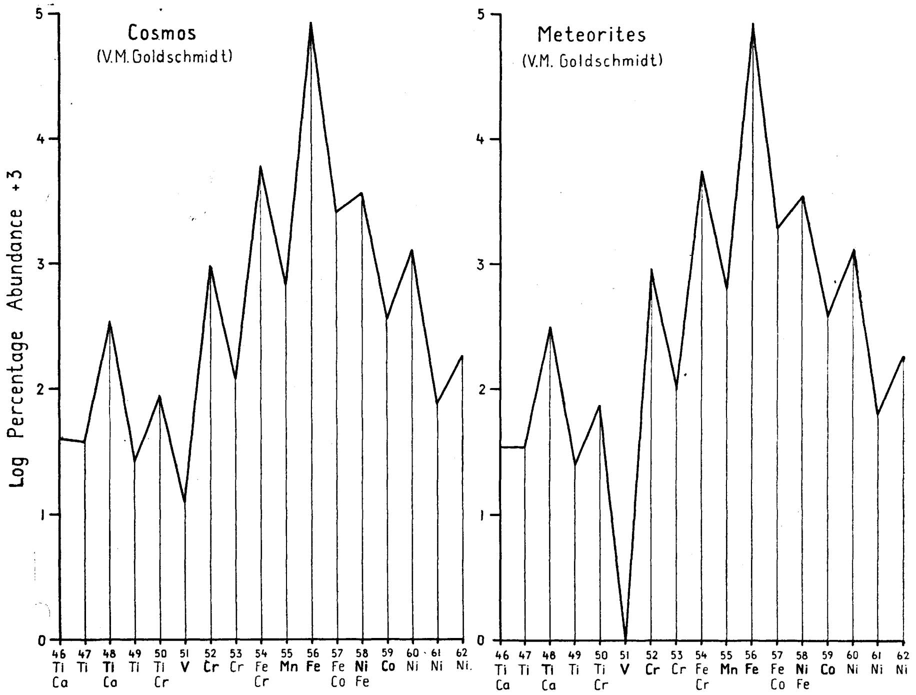

Fig. 19. Diagram of the percentage abundance of the ferride isotopes with mass-numbers 46—62 in Cosmos and Meteorites (mean).

orites V. M. Goldschmidt has made an estimate, assuming that the average composition of the meteorites is as follows: ten parts of stony meteorites, two parts of iron meteorites and one part of troilites. He arrives at the relative abundance — recalculated for the mass-numbers 46—62 — illustrated in fig. 19.

The correctness of Goldschmidt's assumption regarding the proportion of the three meteoritic phases may be discussed, but the estimate of the relative abundance seems to be reasonable. Thus, the similarity between the relative abundance of the ferride isotopes in Cosmos, on the one hand (fig. 19), and in the average of the meteorites, on the other (fig. 19), is obvious. In both cases the even-odd rule is strictly valid.

Now the question may be asked: What is the relative abundance of the ferride isotopes in the three phases (the iron, stone, and sulphide phase, respectively) after the primary endogene differentiation? It is well known that the lithophile tendency of the ferrides increases as the atomic number decreases, *viz.* from 28 Ni to 22 Ti. On the other hand, the chalcophile and siderophile tendency is greatest for the triade Fe-Co-Ni. These elements also show the greatest similarity in their atomic structure. The features mentioned find an expression in their relative abundance in the three meteoritic phases.

On the basis of investigations by Goldschmidt and I. and W. Noddack on

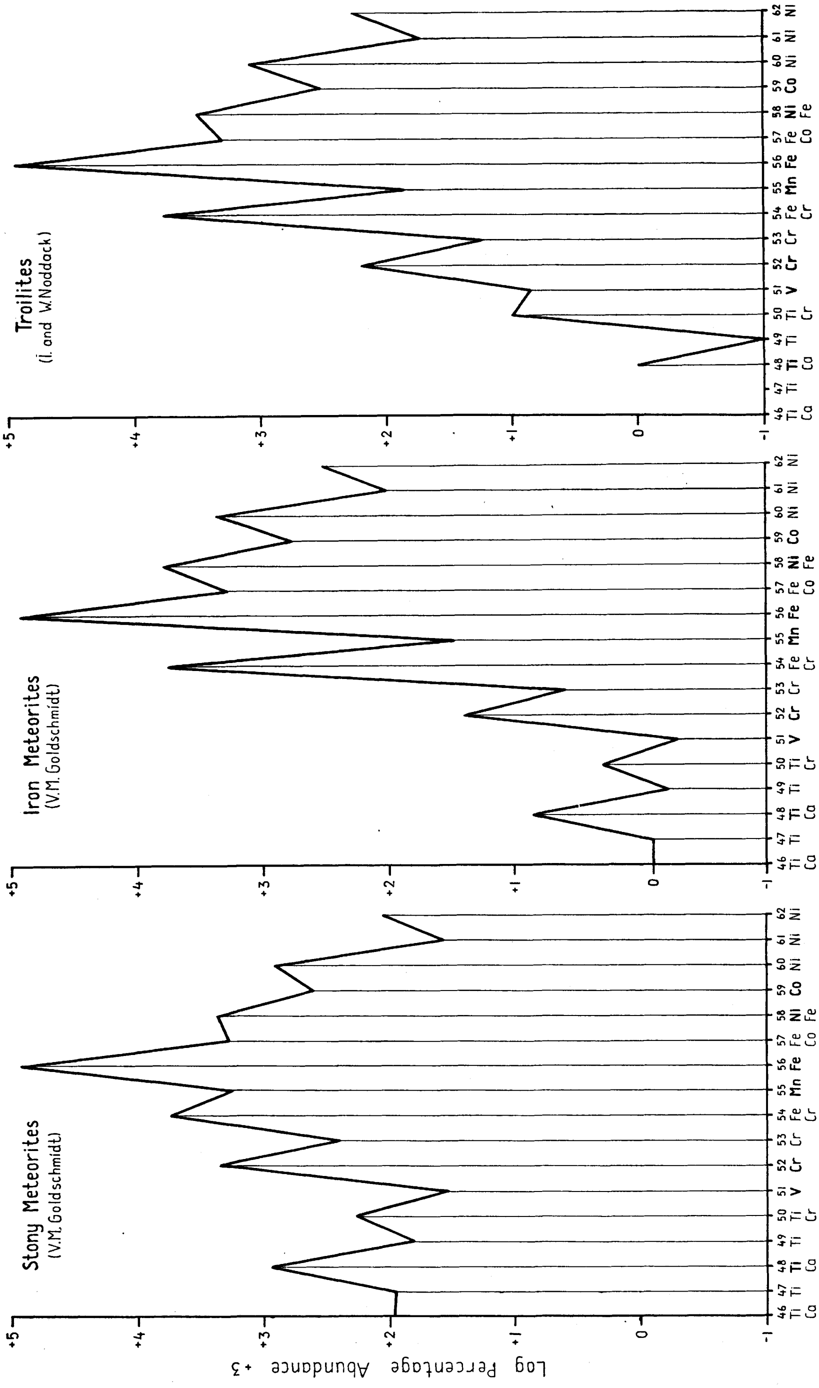

Fig. 20. Diagram of the percentage abundance of the ferrides isotopes with mass-numbers 46—62 in the three meteoritic phases.

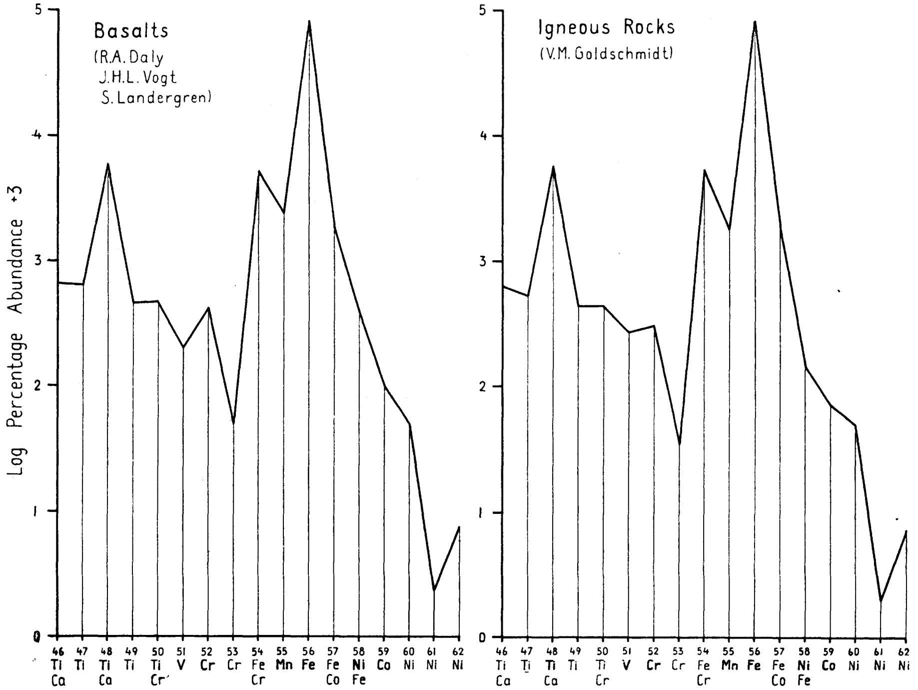

Fig. 21. Diagram of the percentage abundance of the ferride isotopes with mass-numbers 46—62 in basalts and in the igneous rocks (mean).

the distribution of elements in meteorites, the author has calculated the relative abundance of the ferride isotopes in the three meteoritic phases, using Aston's figures for the percentage abundance of isotopes in his work quoted above (3). This is shown in fig. 20.

It is evident that the data available must be regarded as approximations, and their validity as average values may be discussed. However, they show the tendency in the distribution of the ferrides, and the main geochemical features of the various members of the ferrides appear in the diagrams in fig. 20. Thus, the isotopes of the members with a lithophile tendency (M: 46—55) are most abundant in the stony meteorites but decrease considerably in the iron and sulphide meteorites. The proportion between the lithophile isotopes, on the one hand, and those with siderophile and chalcophile tendency (M: 56—62), on the other, varies exactly as might be expected. However, the remarkable constancy in the relative abundance of the latter isotopes should be noted. The author will return to this question later.

Igneous rocks. Fig. 21 above illustrates the average abundance of the ferride isotopes in the basalts and in the igneous rocks of the upper lithosphere. The figures for the igneous rocks are from Goldschmidt's work quoted above. The figures for the basalts are recalculated from the works of R. A. Daly (17),

J. H. L. Vogt (119), H. S. Washington (120), and some complementary analyses by the author on rock samples from the Mineralogical Department of the University of Stockholm. The figures for vanadium, chromium and cobalt cannot be regarded as good mean values, but they give a conception of the distribution tendency.

If we assume that the composition of the stony meteorites approximately corresponds to that of the peridotites of the interior of the Earth beneath the basaltic substratum (cf. Buddington (12), it can be said that the relative abundance of the ferrides from the peridotitic to the basaltic stage of evolution has undergone a remarkable alteration. Thus, titanium has increased considerably, chromium, cobalt and nickel, on the other hand, have decreased to the same extent and manganese has remained practically constant. The alterations mentioned involve, *inter alia*, that the even-odd rule, which is strictly valid for the meteorites (peridotites), is not valid for the basalts, especially with regard to the relative abundance of the isotopes of iron, cobalt and nickel.

If the composition of the igneous rocks estimated by Goldschmidt approximates an average of the Earth's crust, we find that the relative abundance of the ferrides in the igneous rocks shows a striking similarity to that of the basalts.

The geochemical features mentioned must not be overlooked when dealing with problems connected with the origin of the upper lithosphere. Since the average composition of the upper lithosphere is influenced by the composition of the sediments, some data on the relative abundance of the ferrides in some sediments are presented below.

Sediments. The relative abundance of the ferride isotopes in the following sediments will be illustrated: marine bottom sediment from the Tyrrhenian Sea, the Mediterranean, post-glacial clay-gyttja from the Viskan Valley, Sweden, Ordovician alum shale, Sweden, and lateritic iron ore, N. Ireland. The relative abundance is illustrated in the diagrams of fig. 22.

In the Mediterranean sediments we find a relative abundance of ferride isotopes, which — apart from some unimportant details — is fairly similar to that in the igneous rocks (fig. 21). However, there are some trends in the distribution that differ from the trends in the igneous rocks and should be noted. The vanadium isotope ($M = 51$) is more abundant than in the igneous rocks. Thus, the content of V^{51}_{23} is greater than that of the two adjacent odd members, $Ti^{50}_{22} + Cr^{50}_{24}$, on the one hand, and Cr^{52}_{24}, on the other. This is quite contrary to the even-odd rule. Further, $Fe^{57}_{26} > Fe^{58}_{26} + Ni^{58}_{28} > Co^{59}_{27} >$ $> Ni^{60}_{28}$, quite as in the igneous rocks.

The post-glacial clay-gyttja (cf. Landergren (70) p. 4 and fig. 2) shows a relative abundance of ferride isotopes, very similar to that of the sediment discussed above and requires no special comment.

The general trend in the abundance of the ferride isotopes in the Ordovician

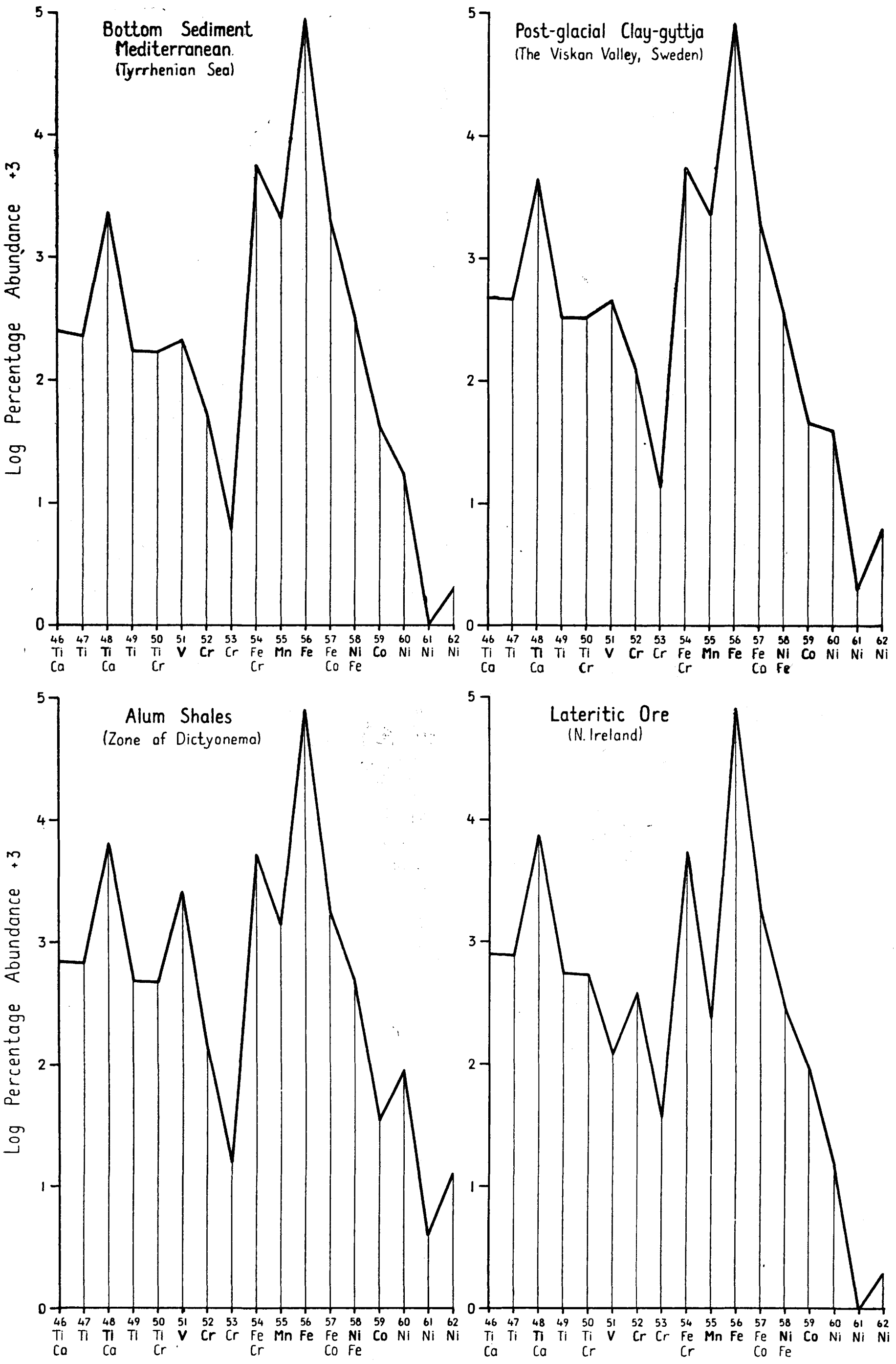

Fig. 22. Diagram of the percentage abundance of the ferride isotopes with mass-numbers 46—62 bottom sediment from the Tyrrhenian Sea (Mediterranean), post-glacial clay-gyttja from the Viskan valley, Sweden, alum shale, Sweden, and lateritic sediment, N. Ireland.

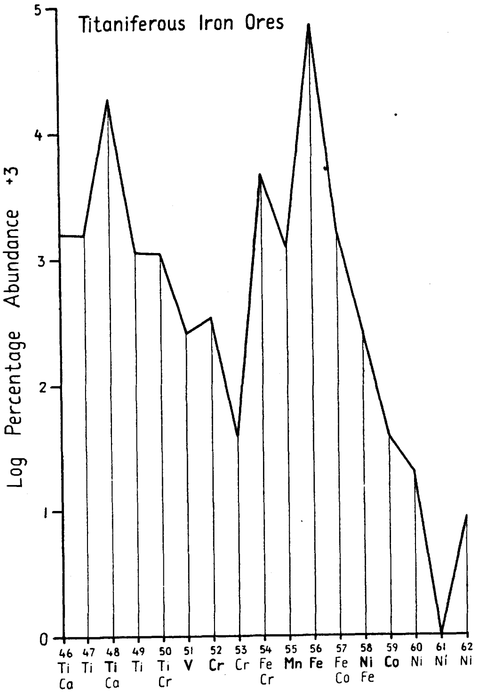

Fig. 23. Diagram of the percentage abundance of the ferride isotopes with mass-numbers 46—62 in titaniferous iron ores.

alum shale is similar to that found in the above-mentioned sediments, but here the content of V^{51}_{23} is appreciable. Further $Co^{59}_{27} < Ni^{60}_{28}$, contrary to the conditions in the other sediments discussed.

As regards the lateritic sediment the abundance of ferrides depends on that in the basalts from which they derive. Thus the similarity between the abundance in the basalts (fig. 21) and that in the laterites shows that no essential alteration in the distribution of the ferrides has taken place on account of the lateritic weathering and the ore-forming processes.

Iron ores. What happens to the ferride isotopes when iron becomes enriched, say, ten times in comparison with the average content of the upper lithosphere? The diagrams in figs. 23—28 are intended to illustrate this.

The relative abundance of the ferride isotopes in the titaniferous iron ores (fig. 23) is fairly similar to the abundance in the basalts, which, on the other hand, is approximately the same as in the gabbros, to which the titaniferous ores in most cases are related genetically. The main difference between the ore and the rocks mentioned is the higher content of titanium in the ore. It should be mentioned, too, that the chromium content of the titaniferous ores is too low compared with that of titanium, so that a deviation from the even-odd rule appears in the relative abundance of the two isotopes $Ti^{49}_{22} > Ti^{50}_{22} + Cr^{50}_{24}$.

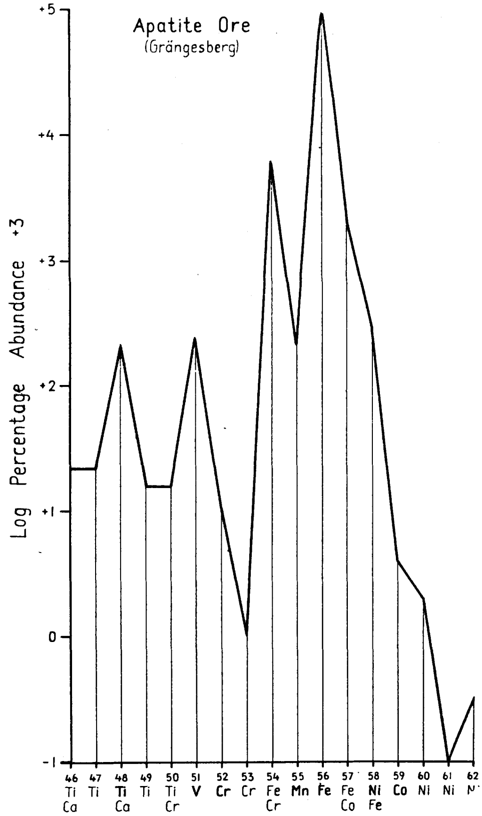

Fig. 24. Diagram of the percentage abundance of the ferride isotopes with mass-numbers 46—62 in apatite iron ores of Grängesberg, Sweden.

The most remarkable feature in the distribution of the ferrides in the apatite ores is the high vanadium content. Thus V^{51}_{23} is much greater than the two adjacent members $Ti^{50}_{22} + Cr^{50}_{24}$ and Cr^{52}_{24}. Further $V^{51}_{23} > Cr^{48}_{20} + Ti^{48}_{22}$ and $V^{51}_{23} > Mn^{55}_{25}$, as seen from fig. 24 above.

Fig. 25 shows the distribution of the ferride isotopes in the oolitic ores. In this ore type we again meet with the characteristic fairly great abundance of the vanadium isotope V^{51}_{23}, which is greater than the abundance of the adjacent members $Ti^{50}_{22} + Cr^{50}_{24}$ and Cr^{52}_{24}, respectively. Further, the isotopes of cobalt and nickel are more abundant than in the apatite ore of Grängesberg (fig. 24).

In the sideritic and the bog ores the abundance of ferride isotopes has decreased considerably as compared with conditions in the oolitic ores, as seen from fig. 26. Thus, the content of vanadium in the sideritic ores is small, so that $Ti^{50}_{22} + Cr^{50}_{24} > V^{51}_{23} > Cr^{52}_{24}$. The abundance of cobalt is approximately the same as in the oolitic ores. In the bog ores the distribution is rather irregular, partly due to the high content of manganese and partly to the low content of

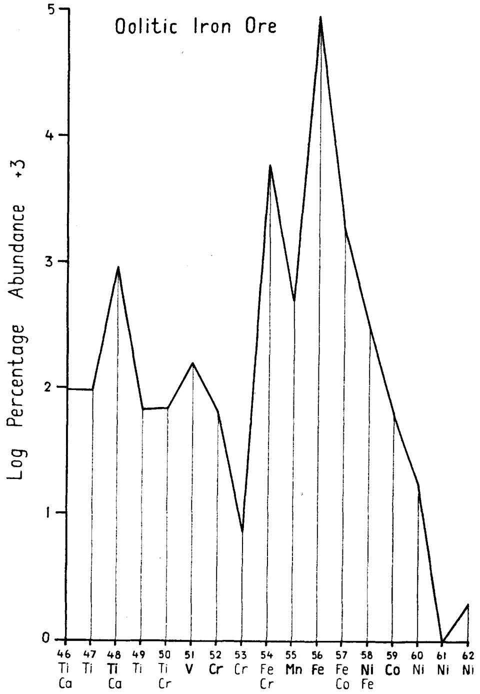

Fig. 25. Diagram of the percentage abundance of the ferride isotopes with mass-numbers 46—62 in oolitic iron ores.

titanium, vanadium and chromium. The distribution of the ferride isotopes in the lateritic ores is illustrated in fig. 22.

Let us turn, finally, to the relative abundance in the pre-Cambrian iron-ore types from central Sweden. The diagrams will be found in figs. 27 and 28. The most characteristic feature that these ores have in common is the great difference in the abundance of iron, on the one hand, and of the other ferrides (in some cases apart from manganese), on the other.

Fig. 27 shows the abundance of ferrides in the skarn and lime-dolomite ores. The diagram of the skarn ores shows a remarkable deficiency in the contents of ferrides, both the lithophile and the chalcophile members. The lime-dolomite ores are characterized by the high content of manganese, and here, again, one can observe that the vanadium isotope is more abundant than the adjacent even-numbered members.

The distribution of the ferride isotopes in the quartz ores is interesting, as seen from the diagrams in fig. 28.

In the banded quartz ores the great abundance of V^{51}_{23} is significant, and $V^{51}_{23} = Ti^{48}_{22} + Ca^{48}_{20}$. Thus, there is a striking similarity in the distribution of the ferrides in the banded quartz ores and in the marine sedimentary oolitic

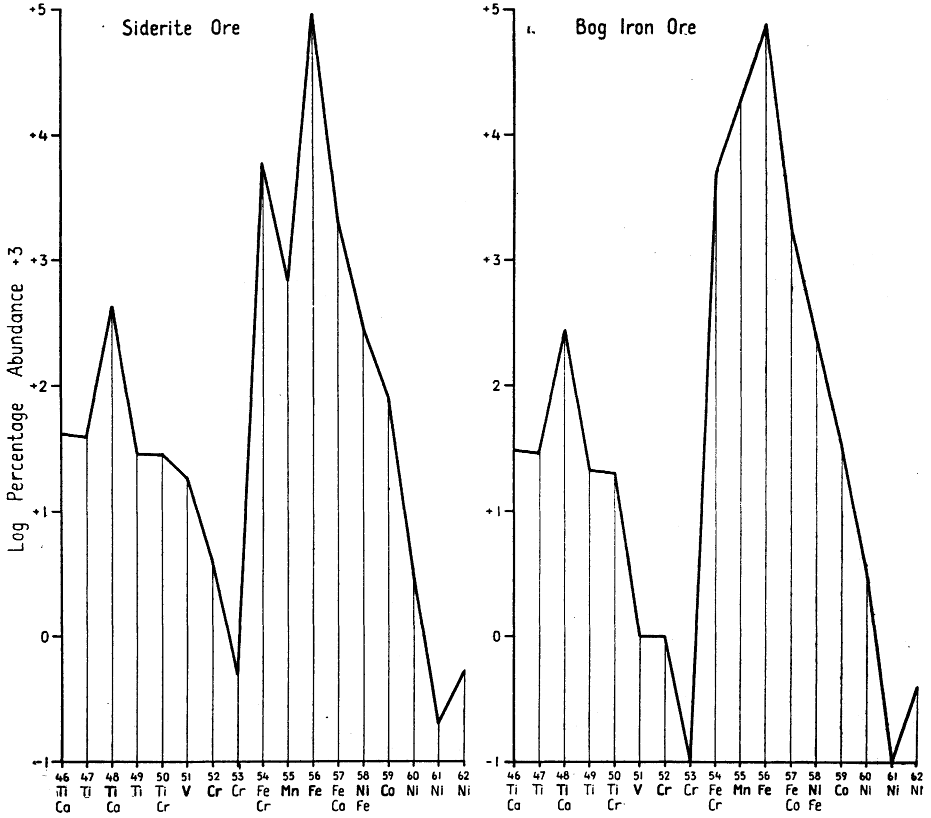

Fig. 26. Diagram of the percentage abundance of the ferride isotopes with mass-numbers 46—62 in siderite ores and in the bog iron ores of Finland.

ore type, but it should be emphasized that the content of ferrides in the oolitic ores is greater than in the banded quartz ores. In the not banded quartz ores the contents of ferrides are low and the diagram shows no feature worth mentioning.

The Relation Fe : Co : Ni.

There are some features in the distribution of the ferrides that should be noted in this preliminary discussion.

As pointed out before, the even-odd rule is strictly valid only in the primary stage of the Earth's evolution — supposing, namely, that the meteorites may be regarded as significant for this stage. After the first differentiation, according to V. M. Goldschmidt (42), the even-odd rule still holds good as regards the distribution of the ferride isotopes in the three phases, the metallic, the silicate and the sulphide phase, respectively. After the second differentiation, the first

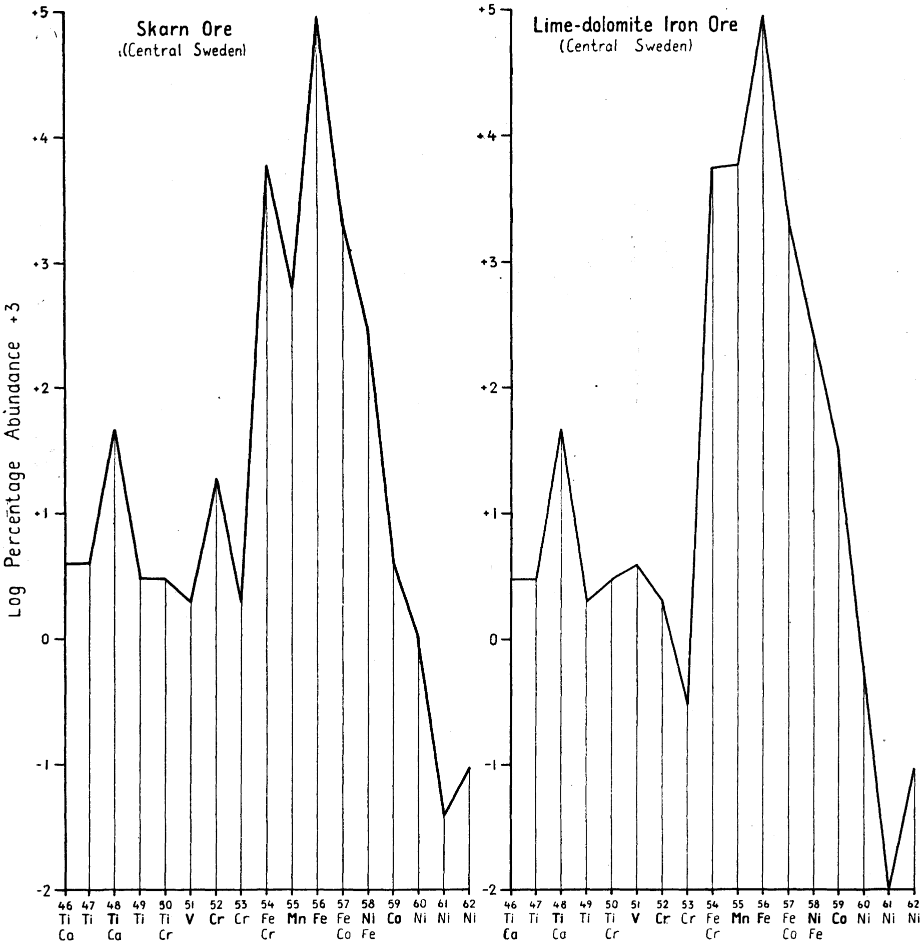

Fig. 27. Diagram of the percentage abundance of the ferride isotopes with mass-numbers 46—62 in skarn and lime-dolomite ores from central Sweden.

of the silicate phase, we find that the basalt — representing the "upper" phase — already shows a relative abundance of ferride isotopes where the even-odd rule is no longer valid. And the more the differentiation processes in the silicate phase proceed, the more deviations are found in the distribution of the ferride isotopes. In no case is the even-odd rule valid and it should be especially noted that the deviations are considerable even for the three members showing the greatest chemical similarity, iron, cobalt, and nickel.

Let us study the ratio Fe : Co : Ni by the aid of Table 58 below, where, for the sake of comparison, the contents of the three metals are given, recalculated to Fe = 100.

As seen from the table, the ratio Fe : Co : Ni changes very rapidly from

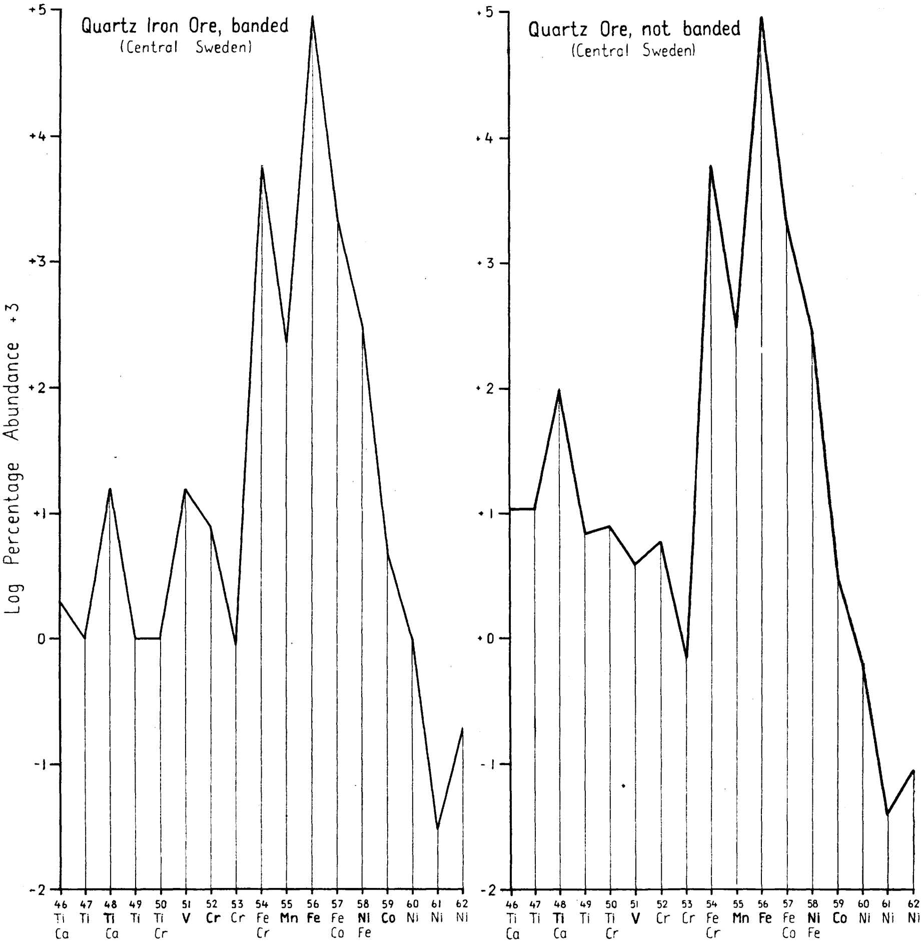

Fig. 28. Diagram of the percentage abundance of the ferride isotopes with mass-numbers 46—62 in banded and not banded quartz iron ores from central Sweden.

the meteorites to the igneous rock series. Not only have the ontents of cobalt and nickel decreased considerably, but the ratio Co : Ni has also increased.

In the sediments the ratio Fe : Co : Ni varies depending on the milieu of sedimentation. Thus, for example, the alum shale and the clay-gyttja show comparatively high contents of nickel, and the ratio Co : Ni is relatively low. The bottom sediment from the Mediterranean has a low content of nickel but the ratio Co : Ni has increased considerably.

The pre-Cambrian iron ores of Central Sweden all show a remarkable deficiency of cobalt and nickel. Apart from the apatite ores from the Grängesberg region, the ores of Central Sweden have a ratio Co : Ni which is > 1. This is

Table 59. **The Distribution of Iron, Cobalt, and Nickel in Meteorites, Rocks, Sediments, and Iron Ores.**

	Fe	Co	Ni	Co/Ni
Meteorites:				
Average	100	0.42	5.4	0.08
Troilites	100	0.34	4.7	0.07
Iron meteorites	100	0.60	9.3	0.065
Stony meteorites	100	0.45	3.4	0.13
Igneous rocks:				
Average	100	0.08	0.2	0.4
Gabbro	100	0.12	0.24	0.5
Granite	100	0.04	0.012	3.3
Basalt	100	0.11	0.23	0.5
Leptite	100	0.09	0.11	0.8
Sediments:				
Ordovician Alum Shale, Sweden	100	0.02	0.4	0.05
Grey Cambrian clay-slate, Sweden	100	0.04	0.07	[1] 0.6
Grey Ordovician clay-slate, Sweden	100	0.12	0.3	[1] 0.4
Post-glacial clay-gyttja, Sweden	100	0.05	0.2	0.25
Bottom sediment (Mediterranean)	100	0.05	0.07	0.7
Lateritic iron sediment	100	0.10	0.06	1.7
Iron ores:				
Titaniferous ore	100	0.05	0.07	0.7
Apatite ore (Central Sweden)	100	0.004	0.009	0.4
Apatite ore (Northern Sweden)	100	0.015	0.03	0.5
Lime ore (Central Sweden)	100	0.003	0.0025	1.2
Skarn ore (Central Sweden)	100	0.004	0.0025	1.6
Quartz ore, banded (Central Sweden)	100	0.005	0.004	1.3
Quartz ore, not banded (Central Sweden)	100	0.003	0.002	1.5
Oolitic ore	100	0.07	0.07	1.0
Sideritic ore	100	0.08	0.01	8.0
Bog ore	100	0.04	0.01	4.0

[1] The figures have been kindly placed at the author's disposal by Dr. P. H. Lundegårdh from an investigation in preparation (75).

also true of the sedimentary iron ores represented by the oolitic, the sideritic and the bog ores.

According to Goldschmidt (45) the almost identical ionic radii of magnesium and nickel (0.78 Å) explain the close association of the two elements. The difference in the ionic radii of magnesium and cobalt (0.82 Å), on the one hand, and the almost equal radii of cobalt and iron (0.83 Å), on the other, likewise explains the close relationship between the two latter elements. Since nickel is enriched in the early crystal fractions rich in magnesium, the ratio cobalt : nickel consequently increases as the crystallization proceeds.

E. B. Sandell and S. Goldich (107) have studied the distribution of some minor constituents in the igneous rocks of the United States, *inter alia* of cobalt and nickel. The relation between cobalt and nickel, on the one hand, and the content of SiO_2, on the other, is shown in two diagrams (p. 183). Here is illustrated the tendency of cobalt and nickel to decrease as the content of SiO_2 increases. Nickel decreases more rapidly than does cobalt where the relation to SiO_2 is more linear. Further, Sandell and Goldich have pointed out that the relation between cobalt and magnesium is more apparent than the relation between cobalt and ferrous iron. This relation between cobalt and magnesium, contrary to that between nickel and magnesium, is linear over a wide magnesium range (p. 178).

This interesting feature corresponds to that found by Goldschmidt (45), as seen from the following figures (in per cent of weight):

	Cr_2O_3	NiO	CoO	MgO
Peridotite (dunite)..	0.5	0.4	0.03	40
Gabbro............	0.05	0.02	0.01	8
Diorite............	0.01	0.005	0.004	3
Granite............	0.003	0.0003	0.001	1

The author has calculated the correlation coefficients (r-values) for the correlation between vandium, chromium, cobalt, and nickel, on the one hand, and Fe^{2+}, Fe^{3+}, Mg^{2+}, and mgf, on the other, by the aid of the data for igneous rocks available in Washington's tables (120). The r-values are as follows:

	N	Fe^{2+}	Fe^{3+}	Mg^{2+}	mgf
V........	145	+0.38	+0.69	+0.06	—0.01
Cr........	276	+0.28	—0.16	+0.41	+0.36
Co.......	22	+0.38		+0.06	
Ni.......	286	+0.32	+0.31	+0.24	+0.12

If the analytical data can be taken for granted, we find that the correlations between Fe^{2+} and V, Cr, Co, and Ni are approximately of the same magnitude and not very high. The correlation between Mg^{2+} and the minor constituents mentioned is very irregular and in bad agreement with the distribution principle advanced by Goldschmidt, *i.e.* that the magnitude of the ionic radii is an important regulating factor. Now it should be emphasized that the r-values may be partly obscured owing to the uncertainty of the chemical estimates of the minor constituents in the igneous rocks and ores.

With reference to the alterations of the ratio Fe : Co : Ni in the meteoritic phases and in the igneous rocks and with reference to the relation between the ratio Co/Ni, on the one hand, and Mg^{2+}/Fe^{2+} (mgf), on the other, it seems very unlikely that the differences in the ionic sizes of the elements in question should have much influence on the ratio in which the two minor constituents cobalt and nickel enter in structures where iron and magnesium are mineral-forming constituents. The former elements will probably enter any structure of Mg-Fe-minerals formed at a certain moment. The ratio Co/Ni in the solid phase will be mainly dependent on the same ratio in the liquid phase. Other factors than differences in ionic size may cause the ratio Co/Ni to alter as crystallization proceeds.

As regards the irregularity in the distribution of cobalt and nickel in the sulphide phase a spectrochemical study of sulphide minerals from the ores of the Skellefte Mining District by S. Gavelin and O. Gabrielson (30) should be mentioned. In view of the chemical properties of cobalt and nickel it can be expected that cobalt preferably enters the pyrite structure and nickel the pyrrhotite structure. However, the authors mentioned have shown that other factors than crystal-chemical properties must be reckoned with for the distribution of cobalt and nickel in ore-forming processes. They write (30), pp. 41—42): "... a separation of Co and Ni by the concentration of Co in pyrite and Ni in pyrrhotite is ... not very pronounced in the ores examined. It is much more common to find a striking co-variance between the values of the various minerals from the same specimen or from the same deposit, there being a certain tendency towards Co-dominance or Ni-dominance in all the sulphide minerals from a certain limited portion of an ore."

"The variations in the Co- and Ni-values of the same mineral are often quite independent of each other even if the samples compared originate from adjacent localities. This involves that also the Co : Ni-quotients in many cases show considerable variations."

Before entering into the special problems connected with the geochemistry of the ferrides, it is necessary to discuss what other factors may influence the distribution of elements in a crystallizing melt.

V. M. Goldschmidt has pointed out that the ionic charge is *inter alia* a factor controlling the distribution of elements on the mineral structures successively appearing as crystallization proceeds (45). Thus, for example Sc^{3+} or Li^+ can replace Mg^{2+} in Mg-minerals but the introduction into the structure is dependent on the magnitude of the electrostatic charge of the ions. The ion with the larger charge (Sc^{3+}) has preference over the ion of lower charge (Li^+), while in the latter case of replacement the electrostatic bond becomes weakened. Consequently Sc^{3+} replaces Mg^{2+} in an early stage of crystallization, *i.e.* at high temperatures, and Li^+ correspondingly in later stages, *i.e.* at lower temperatures. In this phenomenon, called "capturing" by Goldschmidt, the ionic charge and temperature are the two factors regulating the distribution.

Now, if we apply Goldschmidt's static reasoning, we find that temperature is a factor controlling the distribution of two elements of different ionic charge but approximately similar ionic size. But we desire to know if temperature is essential also in cases where we are concerned with the distribution of ions of approximately the same charge and size. This question has been discussed by Frans E. Wickman in a paper on some aspects of the geochemistry of igneous rocks and of differentiation by crystallization (125). Contrary to Goldschmidt, Wickman employs a kinetic reasoning on the distribution of elements and with temperature as an essential feature. Since Wickman's conceptions are of importance for the problems here discussed it may be suitable to give a brief survey of them, mainly by extracts.

As regards the constitution of silicate and oxide melts, Wickman says: "In a melt are present not only ionic forces but also directed covalent bonds, and the atoms and atom-groups bound in this way tend to realize the ideal angles between their valencies, thus often giving rise to a tendency towards a looser packing. On account of the high temperatures, the ions and atom-groups oscillate, and occasionally the oscillation of a single ion will exceed a certain critical value, whereupon it will jump from one place in the lattice to another. Through termal agitation the close-packing of the oxygen ions will also vary with time. It is plausible that the cations prefer to occupy those positions which give them their normal coordination number. The energy required in order to move an ion from a position with a certain coordination number to a neighbouring position with a different coordination number is called the activation energy of migration of the ion (the E-value). From the science of crystal structures it is known that an ion prefers to occur in a coordination which is determined principally by its size, and it is thus evident that the E-value for this coordination number is larger than for any other coordination number. Since an ion can theoretically move to several different coordination numbers, it follows that for a certain coordination number there are several E-values; a tetrahedrally coordinated ion for example can move to a three- or six-coordinated position in a close-packed arrangement. In general, however, there is one E-value which is less than all others, and it is this E-value which is meant when reference is made to the E-value of an ion in a certain coordination. On the other hand, when different ions with different sizes are compared and their coordinations in crystal lattices are examined, it is found that normally only those ions whose diameters fall within a certain interval occur in a certain coordination. It is thus evident that the E-value is greatest at a certain ionic radius and is smaller at both lesser and greater ionic radii. The cations cannot however be distributed at random in the melt; it is reasonable to believe that the relevant parts of Pauling's rules are statistically valid, *i. e.* fluctuations occur, but being disturbances of electroneutrality, they cause the ions to return to equilibrium."

"It can be said that the distinction between a melt and a crystal lies in the degree of order of the ions. In a crystal the degree of order is great and the irregularly arranged ions few, at least at lower temperatures. In a melt, on the other hand, the degree of order is much less. In many cases the melting point may be looked upon as a discontinuous alteration in the degree of order. If f stands for a function indicating the degree of order both in the crystal and the melt at any temperature, then, when $T = O$, $f = l$, *i. e.* at the absolute zero, the order is perfect, and when $T \rightarrow \infty$ then $f = \alpha$, where $O \leq \alpha < 1$, the value of α depending upon the magnitude of the E-value, E. If the E-value is small the ion will readily take up a disordered position, whereas if the E-values are large the degree of order will also be large. The effect of these two variables is expressed by the ratio E/T. This ratio is a pure number if T is multiplied by the constant k (Boltzmann's constant), and the degree of order can thus be written as proportional to f (E/kT). Now the magnitude of the E-value is naturally dependent upon the degree of order, but as a working hypothesis it may be assumed that the E-values of the different ions vary in the same direction and that they preserve their mutual order of magnitude. Of two sorts of ions with the same radius but with different charge then the cation with the greatest charge must have the greatest E-value. A further assumption is valid: that ion which has the lowest E-value, which thus first becomes disordered, is as a rule decisive for the temperature of the melting point (or the position of the alteration point)."

It should be noted that on the whole Wickman's conception is in agreement with those of both Goldschmidt and N. L. Bowen (10). However, many features in the distribution of the elements in Nature are more easily explained if we accept the way of reasoning suggested by Wickman. In the following discussion of special features of the geochemistry of the ferrides and other minor and mineral-forming constituents the author will have occasion to return to the conceptions the outlines of which are given above.

The Significance of the Degree of Oxidation.

As mentioned before, the degree of oxidation (the og-value) is an important quantity when dealing with the rock- and ore-forming processes and hitherto it seems to have been overlooked by petrologists. Through the ratio Fe^{2+}/Fe^{3+} one can obtain a conception of the geochemistry of oxygen, the most abundant element in the lithosphere.

Table 2 on p. 25 shows the statistical data on og and figs 12, p. 47, and 16, p. 49, demonstrate the relation between qv and og in the igneous rocks and iron ores respectively. As pointed out before, the quantities qv and og are symbatic within different ranges of qv. This is in agreement with Goldschmidt's statement (47) regarding the igneous rock series in the Oslo field.

The first question that arises is: What is the cause of the positive correlation between og and qv in the igneous rock series? As a starting point for the discussion one may imagine a magma chamber, where a magma of any composition begins to crystallize, *i. e.* the temperature decreases. The crystallization consequently starts at a certain degree of oxidation. To simplify matters, let us assume that no supply of external oxygen exists.

Now, at a certain temperature magnetite begins to crystallize. If a be the primary content of Fe^{3+} and b that of Fe^{2+}, where $a < b$, the primary ratio $Fe^{3+}/Fe^{2+} = a/b$. When c molecules of magnetite have crystallized the ratio Fe^{3+}/Fe^{2+} gets the value $\frac{a-c}{b-c} < \frac{a}{b}$, *i. e.* the degree of oxidation decreases in the melt.

According to Wickman in his paper quoted above, it is reasonable to believe that all ions with high charges and coordination numbers between four and six have large E-values when in the most favourable coordination. This is certainly true of trivalent iron and it is therefore probable that $E_{Fe^{3+}} > E_{Fe^{2+}}$. In this connection Wickman may be cited again: "During the course ot differentiation one can therefore reckon with a steady production of trivalent iron, which apart from the amount incorporated in the silicate structures forms magnetite, when a sufficient concentration is reached. As a rule the content of divalent iron is sufficiently large to prevent the formation of hematite." (125) p. 385).

Consequently it might be expected that the degree of oxidation would decrease or possibly remain constant during the course of differentiation. An increase in the degree of oxidation under pure endogene conditions is exceedingly unlikely for reasons mentioned.

Nevertheless, the degree of oxidation increases in the igneous rock series, as shown in Table 2 on p. 25. This can be explained in two ways: On the one hand, an oxidation of the crystallizing system may take place due to successive assimilation of external material with a higher degree of oxidation than that of the primary system. On the other hand, a reaction with the volatiles present in the crystallizing system may take place.

However, the latter alternative seems to be the less probable, for reasons which will now be discussed. The two by far most abundant volatiles are H_2O and CO_2. The oxidation of Fe^{2+} to a higher degree of oxidation takes place due to the two reactions:

$$\text{I.}\quad 3\,FeO + H_2O = Fe_3O_4 + H_2$$
$$\text{II.}\quad 3\,FeO + CO_2 = Fe_3O_4 + CO.$$

These two well-known "furnace reactions" have been closely investigated by several authors. The equilibrium constant (K_p) has been calculated at different temperatures by M. Tigerschiöld (115) and is given in Table 60 below.

As seen from the table reactions I and II run in favour of magnetite formation as the temperature decreases. However, the two oxidation processes I and II correspond to the following reduction processes:

$$\text{III.}\quad H_2 + 3\,Fe_2O_3 = 2\,Fe_3O_4 + H_2O \text{ and}$$
$$\text{IV.}\quad CO + 3\,Fe_2O_3 = 2\,Fe_3O_4 + CO_2,$$

the equilibrium constants of which are given in Table 61.

Table 60.

I: $3\,FeO + H_2O = Fe_3O_4 + H_2$

Temperature (Centigrade)	K_p
570	3.85
615	2.27
640	1.75
700	0.97
725	0.78
768	0.54
770	0.53
800	0.41
805	0.40
885	0.22
900	0.20
950	0.14

II: $3\,FeO + CO_2 = Fe_3O_4 + CO$

Temperature (Centigrade)	K_p
627	0.76
662	0.66
720	0.54
863	0.34
963	0.26
1 070	0.19
1 175	0.15

Table 61.

III: $3\,Fe_2O_3 + H_2 = 2\,Fe_3O_4 + H_2O$.

Temperature (Centigrade)	K_p at an og-value of	
	99.7	90.0
527	$3.21 \cdot 10^5$	$6.40 \cdot 10^4$
727	$1.50 \cdot 10^5$	$4.13 \cdot 10^4$
927	$1.01 \cdot 10^5$	$3.43 \cdot 10^4$
1 127	$8.22 \cdot 10^4$	$3.27 \cdot 10^4$

IV: $3\,Fe_2O_3 + CO = 2\,Fe_3O_4 + CO_2$.

Temperature (Centigrade)	K_p at an og-value of	
	99.7	90
527	$1.80 \cdot 10^6$	$3.51 \cdot 10^5$
727	$2.14 \cdot 10^5$	$5.80 \cdot 10^4$
927	$5.83 \cdot 10^4$	$1.97 \cdot 10^4$
1 127	$2.51 \cdot 10^4$	$9.86 \cdot 10^3$

The values of K_p indicate that the reactions in question also run in favour of magnetite formation at any temperature that may reasonably be taken into account. As M. Tigerschiöld has pointed out, reactions III and IV are practically irreversible (115). Thus, we are concerned with redox-systems that have no other influence on the degree of oxidation in the crystallizing system than that discussed before.

Finally, the thermal dissociation of Fe_2O_3 should be mentioned in this connection. The dissociation runs as follows:

$$6\,Fe_2O_3 = 4\,Fe_3O_4 + O_2.$$

The reaction has been investigated by Sosman and Hostetter (10) and the pressure of dissociation of Fe_2O_3 (p) at different temperatures and degrees of oxidation was estimated by M. Tigerschiöld in the paper quoted above. Some of the figures are given below:

Temperature (°C)	p at an og-value of:	
	99.7	90.0
1 027	$4.55 \cdot 10^{-5}$	$6.10 \cdot 10^{-6}$
1 227	$1.81 \cdot 10^{-2}$	$3.17 \cdot 10^{-3}$

Temperature (°C)	p at an og-value of: 99.7	90.0
1 327	0.219	$4.29 \cdot 10^{-2}$
1 527	16.03	3.76
1 727	$5.78 \cdot 10^2$	$1.65 \cdot 10^2$

Thus, heated in air (0.21 atm. of O_2) Fe_2O_3 begins to dissociate a little below 1 325 centigrades to a remarkable extent. At 1 727° C the dissociation has become considerable (of the magnitude 10^2 atm.).

From the figures presented it is evident that mineral facies containing highly oxidized minerals are not stable at the temperatures of a crystallizing magma presumed by R. A. Daly (17) and J. H. L. Vogt (117).

As discussed before, the fractional crystallization of a magma probably takes place at a decreasing degree of oxidation. Since the correlation between qv and og is positive and the degree of oxidation increases as the acidity of rocks increases, it is plausible that the first alternative to explain the increasing degree of oxidation in the igneous rock series, *viz.* the influence of external material in the rock-forming processes, should be taken into account.

Thus, we have to reckon with an endogene-exogene redox system in the lithosphere: Highly oxidized material from the surface of the Earth's crust enters the endogene phase, where a corresponding reduction takes place and oxygen is given off. Consequently, oxygen takes part in the cyclic migration of elements and iron can be looked upon as the "respiratory organ" of the lithosphere.[1]

The arguments of the significance of the degree of oxidation in the igneous rock series can be employed for the iron ores too. The author has chosen the iron-ore types from central Sweden to illustrate that the formation of essential quantities of magnetite and hematite requires a degree of oxidation much higher than that for the igneous rock series, as seen from fig. 16. The upper curve represents the og-values for the iron ores of Central Sweden. There is a strong relationship between qv and og, quite similar to that of the igneous rock series, the lower curve in fig. 16. In fact, the two curves in question run parallel to each other.

If, now, we must reckon with the symbaty between qv and og in the igneous rocks indicating an addition of external material oxidized in the exogene phase in the rock forming-processes as qv increases, it is obvious that this claim should be valid for the formation of iron ores too, especially since their

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[1] Quite recently a very interesting paper by Tom. F. W. Barth has become available: The Distribution of Oxygen in the Lithosphere (Journ. of Geology, vol. 56: 1,1948, pp. 40—49). The author has not the opportunity to discuss Barth's paper in this connection. However, as far as the author can see there is full agreement between Barth's and the author's conceptions regarding the geochemistry of oxygen.

og-values in general are higher than those of the igneous rocks with corresponding qv-values.

Thus, for the formation of iron ores it is not only a question of enrichment of iron, it is also a question of enrichment of oxygen necessary for the formation of ore minerals. Generally the oxidation of iron will take place at the surface of the Earth's crust. However, in such cases where we have to reckon with the formation of sideritic sediments, there seems also to be another source of oxygen which may affect the formation of magnetite: the reaction between Fe^{2+} and the volatiles (H_2O, CO_2) at a moderatly increased temperature (contact metamorphism, for example), as discussed before.

It is plausible, too, that the increasing formation of magnetite in a comparatively late stage of the development of titaniferous iron ores, basalts, diabases, etc., often met with, may be due to reaction between divalent iron ions and volatiles.

To sum up: it is quite unreasonable to assume a primary endogene connection between the formation of iron ores and the formation of igneous rocks, if the distribution of oxygen is to be considered. Generally, the oxidation of iron necessary for the formation of the oxide ore minerals takes place at the surface of the Earth's crust. In some cases of formation of magnetite the reaction between divalent iron and volatiles (H_2O, CO_2) at a moderatly increased temperature, should also be taken into account.

Clearly magmatic differentiation of some kind may take place to a limited extent but the processes are regulated not only by the conditions in the primary magma but also by the composition, quantity and degree of oxidation of the material incorporated in the endogene processes. Phenomena of local significance are, of course, not included in this conception.

In the following discussion it will be shown that many features in the distribution of the elements can be explained by this conception. On the other hand, if we assume that the distribution of the elements in the endogene development are solely or even preferably regulated by pure endogene differentiation processes practically undisturbed by external material the distribution of elements will continue to be a mystery.

Comments on the Distribution of the Ferrides in the Exogene Development.

V. M. Goldschmidt has emphasized (40) that the endogene processes lead to homogeneity of matter, exogene, on the other hand, to separation and consequently to enrichment of elements.

Clearly the by far most important separation and enrichment takes place through the activity of water. The solutions and the changes in their physico-chemical conditions are, therefore, the great factor regulating the distribution of elements.

The pioneer investigations of Goldschmidt and his collaborators should be noted also as regards the geochemistry of sediments. Goldschmidt has laid down the principles for the distribution of elements in the sedimentary development. We can share his opinion that the importance of this field of geochemistry may be judged by the fact that a very great percentage of ores and other useful minerals and rocks is associated with sediments. The processes of weathering, transportation and redeposition of matter at the surface of the Earth's crust involve a great number of chemical reactions including all chemical elements (45).

For the processes in the endogene development the crystal-chemical properties — ionic charge and size — and temperature are, as already mentioned, the controlling factors in the distribution of elements. In the processes of sedimentation the deformability and polarisability of ions are also of importance when considering phenomena of ionic adsorption, as shown by W. Noll (93).

For more detailed information in this part of geochemistry the works by Goldschmidt and Noll quoted above may be referred to. A very valuable survey on this subject is also given by K. Kalle (66).

V. M. Goldschmidt's well-known diagram may serve (45) as a basis for the discussion on the distribution of the ferrides in the sedimentary cycle.

The diagram in fig. 29 is divided into three sections. In the upper section are found elements with relatively large ionic size and low charge. They are the elements that occur in true ionic solutions. The middle section of the diagram shows the ions which preferably precipitate through hydrolysis or remain in solutions as sols. The lowest section of the diagram shows the ions with high ionic charge and small ionic radii. They form complex anions containing oxygen and can remain in true ionic solutions. In the diagram the ferrides are represented by filled circles, the other ions by open circles.

As seen from the diagram, the ferrides, on account of their different charges and sizes, behave differently in solutions. Thus, Mn^{2+}, Fe^{2+}, Co^{2+}, and Ni^{2+} can occur in ionic solutions. As hydrolysates occur Ti^{4+}, V^{3+}, Cr^{3+}, Mn^{4+} and Fe^{3+}. Finally V^{5+} and Cr^{6+} can form complex anions. Consequently, the redox-potential in the solutions is essential for the enrichment and separation of the ferrides during the transport from the weathering milieu to the precipitation milieu.

The ratio Mn/Fe (mf) attracts special interest. The formation of sedimentary iron and manganese ore deposits has been the subject of very important laboratory research, especially by F. Behrend (8). The main results of Behrend's investigations into the conditions during weathering, transportation and redeposition of iron and manganese may, therefore, be mentioned.

By the weathering of rocks iron and manganese become dissolved mainly

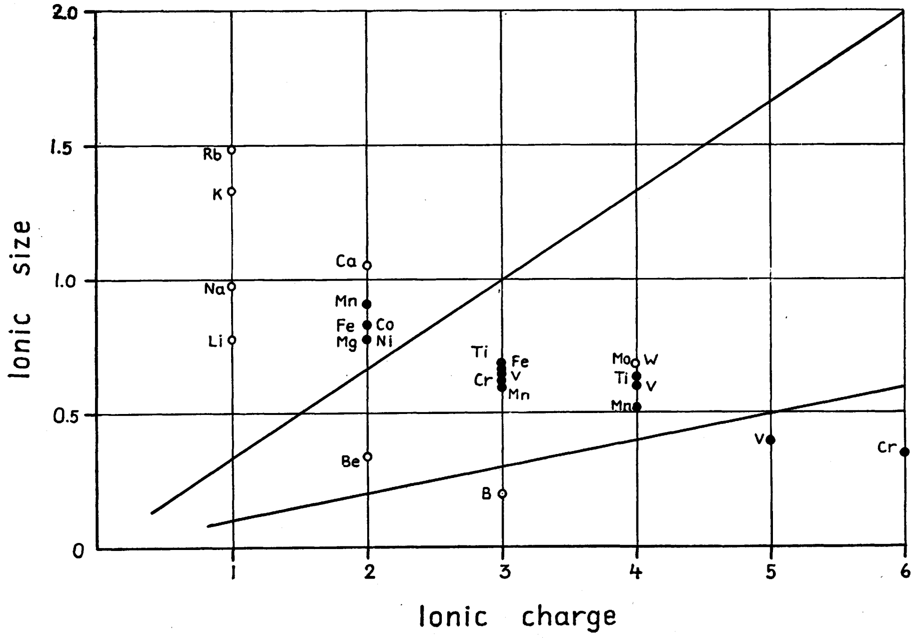

Fig. 29. Diagram of the distribution of elements in solution. (After V. M. Goldschmidt.) Filled circles are ferrides.

as bicarbonates and to some extent also as sulfates. The solubility of manganese is greater than that of iron, and Mn is more stable in solution. When oxidation takes place by the aid of atmospheric oxygen, $Fe\ (OH)_3$ and $Mn\ (OH)_4$ are formed under certain conditions and remain in the solution as sols. The former sol has a feebly basic character, the latter a feebly acid one. The former, therefore, has a positive charge, the latter a negative one. Consequently, the two sols in question either flocculate each other or — if there is a great excess of one of them — the less abundant sol becomes recharged. In the presence of other ions in the solution, flocculation can take place and then in the order manganese -> iron.

During the lateritic weathering process an oxidation takes place. The uni- and divalent cations (Ca, Mg, Co, Ni, K, and Na) dissolve together with SiO_2. Thus the residue becomes enriched in the hydrolysates, *i. e.* Ti^{4+}, V^{3+}, Cr^{3+}, Mn^{4+}, Fe^{3+}, and Al^{3+}.

The manganese sol preferably adsorbs cations, the iron sol preferably anions. The well-known occurrence of cations such as Li, K, Ba, Co, Ni, Zn, Tl, Pb, and W in manganese deposits indicates that these elements are enriched through the adsorbtion of the manganese sol. This has been shown experimentally by N. G. Chatterji and N. R. Dhar (13). The adsorbtion of anions by iron sols is well-known, too. As and Sb, for example, are often enriched in sedimentary iron deposits (cf Goldschmidt (43). The Långban manganese-iron deposit in Central Sweden may be mentioned as an example of enrichment of a number of elements through adsorbtion (se p. 169).

The concentration of hydrogen ions in the transporting solutions is of great importance for the precipitation of iron and manganese. In the table below are shown some p_H -values for precipitation of some hydroxides.

p_H	ion	milieu	p_H	ion	milieu
10	Mg^{2+}		6	Cu^{2+}	rain water
9			5	Al^{3+}	
8	Mn^{4+}	sea water	4		
7	Fe^{2+}	fresh water	3	Fe^{3+}	

The table shows the great effect of changes in the p_H-conditions on the selective precipitation of elements. Thus, for example, a high oxidation potential leads to the precipitation of $Fe(OH)_3$ even at $p_H = 3$. At a high reduction potential, on the other hand, divalent iron becomes dissolved at $p_H \leq 7$. Further, Mn^{4+} and Fe^{3+} can become separated within the p_H-region 3—8 at a high oxidation potential.

As seen from Table 1 on p. 21, the correlation between qv and mf is positive but rather feeble. In many cases there is practically no correlation at all. It is true that the M-values for mf tend to increasing values as qv increases, but the relation between the two quantities is fairly irregular, as mentioned before and as is seen from fig. 14 on p. 48. Again, it is very unlikely that endogene differentiation processes lead to an increase of mf as qv increases in the rock-forming processes. The irregularity in the relation between qv and mf is more likely due to the influence of exogene processes where several factors regulate the magnitude of the ratio mf.

As regards the iron ores investigated, it has been shown that there exists a negative correlation throughout between qv and mf (see Table 10). However, it should be noted that a decrease of qv in the ores generally means an increasing content of carbonate. Thus there is a tendency towards a positive correlation between mf and the content of carbonate in the ores, showing the great importance of the CO_2-pressure in the transporting solutions, which certainly influences the magnitude of mf. Evidently, there are ores rich in carbonate but relatively poor in manganese, on the one hand, and quartz ores relatively rich in manganese, on the other, but if we bear in mind that the ratio mf is also dependent on the magnitude of mf in the primary source of the iron- and manganese-bearing sediments, these exceptions from the rule can be explained.

It is obvious that there are many factors regulating the sediment-forming processes that must be taken into account. As regards the relative abundance of the important ferride group, one has to reckon with the redox potential, the p_H-value, the pressure of CO_2, and the adsorption phenomena in the colloidal stage. Thus the distribution of the ferrides in the rocks and iron ores investigated is seemingly irregular.

Summary.

In this chapter some features of the geochemistry of the ferrides have been discussed. As regards the relative abundance of the ferride isotopes it has been shown that the even-odd rule for the mass-numbers 46—62 holds good only in the meteoritic-peridotitic stage of development but is not valid for the igneous rocks and iron ores mainly occurring in the upper lithosphere. There is a striking similarity between the relative abundance of the ferrides in the basalts, on the one hand, and the bulk of the igneous rocks, on the other.

The sediments and most iron ores show very characteristic deviations in the relative abundance of the ferrides when compared with the abundance in the meteorites, which probably represent the primary distribution.

The proportion Fe : Co : Ni and the ratio Co/Ni in the rocks and ores investigated have been discussed. A conception has been expressed that the ionic size of Co and Ni seem to have no essential influence on the magnitude of the ratio Co/Ni in the upper lithosphere.

V. M. Goldschmidt's and Frans E. Wickman's suggestions have been used as a basis for the discussion on the significance of the magnitude of the degree of oxidation. The increasing values of og as qv increases have been discussed with reference to the conceptions mentioned.

Finally, the principal factors regulating the distribution of the ferrides in the sediment-forming processes have been mentioned.

With the aid of geochemical premises the following conclusions have been drawn:

The formation of igneous rocks and the iron ores associated with these rocks must be regarded as endogene, and processes of differentiation of some kind must be considered to have played a part and have left their geological impression on the rocks and ores. But these endogene processes worked on a material which essentially depended on the quantity, composition, and degree of oxidation of external material which successively entered in the endogene phase of development during the orogenetic cycles within the upper lithosphere. The "igneous" character of the rocks decreases successively towards the most salic members.

As regards the iron-ore formation the primary enrichment of iron occurred mainly in the exogene phase of the cycles. This can explain the seeming irregularity in the relative abundance of the ferrides in the igneous rocks and iron ores.

Chapter V. On the Geochemistry of the Lithophile Elements.

The Significance of the Ratio mc.

In Chapter II in the first part of this book it was pointed out that the ratio mc decreases as qv increases in the igneous rocks. A comparison between the M-values of the two quantities discloses that they are all but inversely proportional, as seen from Tables 1 and 3.

In the iron ores, on the other hand, there seems to be no correlation between qv and mc, which is well illustrated for instance by the iron ores of Central Sweden, as seen from fig. 17 p. 50.

However, there is another feature in the relation between qv and mc in the igneous rocks which is of importance in this connection, and that is the decreasing numerical value of $r_{qv,mc}$ as qv increases. As has been mentioned before, if the negative correlation between qv and mc is a feature in complete agreement with petrological experience and should be regarded as an important distribution principle, the decreasing numerical value of $r_{qv,mc}$ as the acidity of the rocks increases must be looked upon as a distribution principle of the same importance.

Fig. 30 illustrates the relation between qv (abscissa) and $r_{qv,mc}$ (ordinate). As seen from the diagram the r-values for the igneous rocks investigated decrease regularly as qv increases. This feature is significant both for the plutonites and the volcanites, but there is a difference in so far that the r-values of the volcanic rocks decrease more rapidly than those of the plutonic rocks. Further, at a certain qv-value the plutonic rocks have lower r-values than the volcanic rocks. Both the curves for the plutonic rock series and the volcanic rocks converge towards zero. What is the real import of this?

If we employ a crystal-chemical reasoning, it is clear that the ratio mc will decrease as the crystallization of a magma proceeds. The six-coordinated magnesium ion with the radius 0.78 Å will enter the silicates earliest formed. Calcium ions with the radius 1.06 Å and with the coordination numbers 6—9 will begin to crystallize later, preferably as one of the constituents of the plagioclase series. Thus, the two elements behave differently in a crystallizing magma; magnesium enters the dark minerals and calcium preferably the light mineral series.

F. E. Wickman has emphasized that the cause of the occurrence of dark and light minerals is explained by Pauling's rule (125) p. 392): the light minerals have three-dimensional frameworks of linked SiO_4 and AlO_4 tetrahedra and, therefore, only one-quarter of the valency bond is unsatisfied. Magnesium in six-

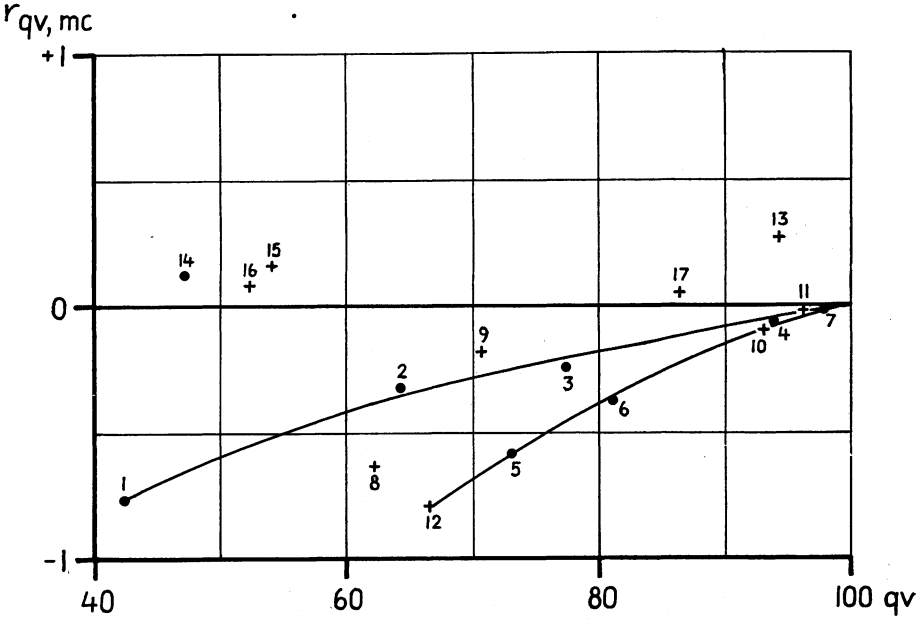

Fig. 30. Diagram and curves showing the decreasing value for $r_{qv,mc}$ as the quartz ratio (qv) increases in the igneous rocks. The r-values for the titaniferous iron ores, the apatite iron ores, and the glacial clay are plotted in the diagram.
Abscissa is the quartz ratio and ordinate $r_{qv,mc}$.
1 peridotites (mean), 2 gabbros (mean), 3 diorites (mean), 4 granites (mean), 5 basalts (mean), 6 andesites (mean), 7 rhyolites (mean), 8 gabbros (Sweden), 9 diorites (Sweden), 10 granites (Sweden), 11 leptites (Sweden), 12 volcanic series (Hawaii), 13 rapakivi granites (Finland), 14 titaniferous iron ores (mean), 15 apatite iron ores from Grängesberg (Sweden), 16 apatite iron ore from Kiruna (Sweden), and 17 glacial clay (Norway).
+ are average values from Fennoscandian regions.

coordination cannot satisfy this, since its contribution is at least one-third, and hence practically no magnesium is found in these alumosilicates.

Consequently, we must reckon with two mineral series in the rock-forming processes: the dark minerals, where the content of magnesium decreases continually as crystallization proceeds (on account of the relatively high E-value of Mg^{2+}), and the series of light alumosilicate minerals, where the valency bond can be neutralized by the large alkali and alkaline earth ions with low charge, thus causing a continuous transition from the calcium-bearing plagioclases to the pure sodium-bearing albite minerals.

Again, magnesium and calcium decrease continuously as qv increases in the rock series and so does the ratio mc, as seen from fig. 13, p. 47. Thus, from a crystal-chemical point of view there are reasons to believe that the correlation between qv and mc also remains practically constant within any range of qv. This would certainly be the case if only fractional crystallization need be taken into account in the rock-forming processes within the upper lithosphere.

The lower r-values for the plutonic rocks compared with those for the volcanic rocks at corresponding qv-values, as seen from fig. 30, indicate that reactions liquid phase $\rightleftarrows$ solid phase may have taken place, resulting in lower r-values for the plutonic rock series. This is in agreement with the "reaction principle" as outlined by N. L. Bowen (10) pp. 54—63).

Let us now turn to the iron ores. In the ores of Central Sweden the values for $r_{qv,mc}$ vary within a considerable range, as is seen from Table 7, p. 34. Fig. 17, p. 50, illustrates the lack of correlation between qv and mc. The average value of $r_{qv,mc}$ for the whole of Central Sweden is practically zero. Finally, the r-values seem to be independent of the concentrations of MgO and CaO, respectively, so that no relation can be established between the numerical value of $r_{qv,mc}$, on the one hand, and the contents of the two oxides mentioned, on the other.

On the whole it seems to be impossible to establish any connection between the correlation between qv and mc in the iron ores and in the igneous rocks. Clearly the greatest interest attaches to the relationship between iron ores of an igneous geological character, on the one hand, and the igneous rocks with which the ores are associated, on the other. The titaniferous iron ores and the apatite iron ores are of that kind. As seen from Table 12, p. 44, the $r_{qv,mc}$ value for the titaniferous iron ores studied is $+ 0.13$. The same values for the apatite ores of Kiruna and Grängesberg are $+ 0.08$ and $+ 0.16$, respectively (Table 7, p. 34). The values in question are plotted in the diagram in fig. 30. The poor agreement between the r-values of the ores and of the igneous rock series is plain enough. If there should exist any closer genetical relationship between the ores and their associated rocks — for instance the titaniferous iron ores and gabbros or basalts — one might expect the ores — regarded as endogene differentiates — to have r-values corresponding to their qv-values at least in the vicinity of the curves for the igneous rock series. Virtually it is not so. On the contrary, even the signs of the r-values are different. If, now, the formation of titaniferous iron ores is to be regarded as the result of pure endogene differentiation, some kind of "crystal sorting" or accumulation of magnetite and ilmenite crystals "under special conditions", why is the relatively strong correlation between qv and mc in the basic rocks lacking in the ore fraction?

If the view-point advocated in this paper is accepted, it is simple to bring the geochemical feature discussed in harmony with field-geological evidence. There is certainly a relationship between the igneous iron ores and their associated rocks. Suppose that a magma — for some reason or other — is split up into two fractions: one ore fraction and one rock fraction. One of these fractions — in this case the ore fraction — shows remarkable deviations from the endogene distribution principles of the elements (qv, mc). In such a case the relationship between the two fractions is unlikely to be a primary one, but it may be secondary, if it can be claimed that the elements primarily present in a magma become distributed according to some special principle. (Deviations from a normal distribution due to alterations of pressure and temperature can be neglected as unimportant.)

What is a secondary relationship between an ore and its associated rock? The crystallization of a magma may be disturbed or take quite a new direction if at some stage of the crystallizing process external material enters into the system. Supposing that, on account of the relation qv,mc, this external material varies or is disordered, and supposing that the composition of this material is such as to favour the formation of an iron ore, the result will be one ore fraction and one rock fraction. The endogene character of the ore fraction is dependent on the composition and quantity of the external material and on the composition, energy and reaction capacity of the primary magma. If now the external material should become completely assimilated by the magma, there would be reasons to expect the correlation coefficients of qv,mc to become fairly uniform in the two fractions formed. Thus, a primary endogene relationship between an iron ore and its associated rock exists if the values for $r_{qv,mc}$ of both ore and rock are uniform, *i. e.* if they correspond to their qv-values. A secondary relationship can exist when the r-values in question are feeble or different for ore and rock, if geological features indicate some general relationship.

N. L. Bowen has pointed out (10) pp. 175—220) that the assimilation capacity of a magma is rather limited. The author can — in the case here discussed — share Bowen's opinion. The disagreement between the values for $r_{qv,mc}$ in the titaniferous iron ores, on the one hand, and their common associated rocks (gabbros, basalts), on the other, at any rate seems to indicate that a complete assimilation is out of question.

The fact that $r_{qv,mc}$ in the titaniferous iron ores shows a marked deviation from those significant for the endogene development indicates that the external material — with varying $r_{qv,mc}$ — that entered in the endogene phase of development was enriched in iron (and probably in titanium).

However, it should be emphasized that the conception regarding the formation of titaniferous iron ores advanced here is based upon the relation between qv and mc in general. Thus, a sample of titaniferous iron ore is compared with an arbitrary sample of basic igneous rocks. If all titaniferous iron ores had a primary endogene relationship to their associated basic rocks, the values for $r_{qv,mc}$ would be uniform. The disagreement between the r-values in question in the ores and the basic rocks, respectively, indicates that at least some of the ores are not genetically related to the basic rocks, *i. e.* the relationship is not generally valid. In order to determine whether in some cases there exists a primary endogene relationship between ore and rock, further investigations will be necessary of deposits of titaniferous iron ores and their associated rocks.

The formation of apatite iron ores can be looked upon in the same way as the formation of titaniferous iron ores. It should be mentioned that the conception on the formation of the apatite iron ores of the Grängesberg region earlier advanced by the author (68) has been confirmed also as regards the relationship between the quantities qv and mc. Thus, the value $r_{qv,mc}$ for the apatite ores is + 0.08 and that for the associated rocks practically zero. Consequently, the relationship cannot be primarily endogene.

The influence of water on the distribution of magnesium and calcium should, finally, be mentioned. It is well known that the content of volatiles increases as qv increases, *i. e.* when the temperature decreases in a magma. It is reasonable, therefore, to believe that pure solutions will occur in the latest stage of an endogene crystallization process. The introduction of sediments into the endogene processes may increase the content of volatiles. Further, the distribution of elements in sediments is regulated by other factors than those regulating the distribution in the endogene processes.

Thus, in sediments we often meet with positive values for $r_{qv,mc}$, as shown in the table below.

	$r_{qv,mc}$	The figures taken from Table No.
Glacial clay	+ 0.05	1
Sideritic iron ore	+ 0.68	11
Skarn ore, Persberg	+ 0.31	7
Skarn ore, Björnberget	+ 0.94	7
Lime ore, Klackberg	+ 0.22	7
Lime ore, Dannemora	+ 0.28	7

In cases where metasomatic solutions have probably been active (skarn and lime ores) the values for $r_{qv,mc}$ also become positive. Thus it is obvious that one has to reckon with a change of sign for the r-values as soon as the distribution of magnesium and calcium to an essential extent is regulated by solutions of some kind. This prompts the question whether the influence of a water phase present at the formation of the acid rock members, for example, might be responsible for the low values for $r_{qv,mc}$? Probably it might, but if this influence should be of decisive importance for the distribution of magnesium and calcium, there would be reasons to believe that the two curves of the decreasing r-values for the plutonic and volcanic rock series, as shown in fig. 30, would converge towards the positive region for $r_{qv,mc}$ and not towards zero.

However, the influence of a water phase, present at the time of the various rock- and ore-forming processes, on the correlation between qv and mc should be taken into account. Clearly the feeble correlation between the two quantities in question in the samples of acid rocks investigated indicates that different factors may influence the magnitude and sign of $r_{qv,mc}$. The low r-values for the acid rocks and the various ore types only indicate that the external material taking part in the rock- and ore-forming processes varied in composition and quantity.

The Alkali Metals.

Lithium and the Ratio Li/Mg. The cations Li^+ and Mg^{2+} are both six-coordinated and their ionic size is practically the same, 0.78 Å. In the rock-forming processes both ions preferably enter stuctures of dark minerals. They do not enter the common feldspar structures, since the cavities in the frameworks of linked SiO_4 and AlO_4 tetrahedra are too large for the relatively small Li^+ and Mg^{2+} ions (cf Wells (123) p. 481).

The difference in ionic charge between the two ions in question indicates that they become separated during the crytallization of a magma. There are consequently reasons to discuss the geochemistry of lithium also in connection with magnesium.

In solution the two elements also behave differently. Lithium preferably remains in the lithosphere, magnesium to a considerable degree in solution. This is demonstrated by the ratio Li/Mg in the upper lithosphere and in sea water:

	$\frac{100\ Li}{Mg}$ (mol. ratio × 100)
Upper lithosphere..................	1.09
Sea water..........................	0.033

Thus, the ratio Li/Mg of the upper lithosphere is about 33 times as large as that of sea water. This indicates that lithium to an appreciable extent is bound to the marine sediments, as established by W. Noll (93).

The geochemistry of lithium has been studied by V. M. Goldschmidt, H. Bauer, and H. Witte (53), and especially by L. W. Strock (111). The last-mentioned investigation contains several interesting data on the distribution of lithium and the relationship to the distribution of magnesium.

Strock has found that the content of lithium in rocks is preferably bound to the dark minerals but not to common feldspars. This is in good agreement with crystal-chemical findings. Several instances of the validity of this rule are mentioned by Strock.

Table 62 contains some data on the distribution of lithium and on the magnitude of the ratio Li/Mg in igneous rocks (according to Strock).

According to Strock the increasing content of lithium and the value for the ratio Li/Mg also when the acidity of the igneous rocks increases indicate that the content of lithium — also in relation to that of magnesium — increases as differentiation proceeds. Further, he expresses the opinion that the substitution $2\ Mg \longleftrightarrow LiR$ takes place, R being a six-coordinated trivalent ion. The increasing lithium content is compared with the increasing content of trivalent ions during the differentiation. He writes: 'Since the content of trivalent iron becomes enriched in the course of fractional crystallization, the ratios Li_2O: MgO and Fe^{3+}: Fe^{2+} seem to run parallel.' (Translated by the author.)

Table 62. **Some Data on the Geochemistry of Lithium**
(after L. W. Strock).

	Li	$\frac{100\text{ Li}}{\text{Mg}}$		Li	$\frac{100\text{ Li}}{\text{Mg}}$
Igneous Rocks:					
Olivine rock	0.00023	0.003	Trachyte	0.007	4.05
Pyroxenite	0.00009	0.005	Liparite	0.0046	5.4
Gabbro	0.00093	0.09			
Diorite	0.0019	0.27	*Sediments:*		
Nepheline syenite	0.0023	1.9	Sandstone	0.0017	0.85
Syenite	0.0014	0.54	Glacial clay	0.012	3.1
Granite	0.014	16.2	Clay schist (Europe)	0.0063	1.8
Basalt	0.00093	0.09	Clay schist (Japan)	0.0038	1.0
Andesite	0.0019	0.43	Marine iron ores	0.0028–0.0035	1.0—2.0
Phonolite	0.0033	3.8	Limestone	0.0028	1.9

F. E. Wickman has studied these very interesting features in the geochemistry of lithium (125) p. 380). He considers the increasing value of Li/Mg during differentiation to be connected with the magnitude of the E-value. According to Wickman there are reasons to believe that $E_{Mg} > E_{Li}$. Thus, lithium is, to a very limited extent, incorporated in minerals formed at high temperatures and takes an essential part in crystallization, preferably at lower temperatures. The minerals to be considered are determined by Pauling's rules. A sufficient quantity of trivalent iron may be present at any temperature.

Strock bases his conclusions on the assumption that the rock-forming processes are mainly due to fractional crystallization. The author considers the premises mentioned to be ambiguous. First, the increasing degree of oxidation as the acidity of the igneous rocks increases cannot be reconciled with any conception that the rock-forming processes are a result of pure fractional crystallization. Secondly, an addition of external material must be assumed to have occurred in the rock-forming processes. Consequently, lithium can become enriched by the addition of sediments, since some of them can be relatively rich in lithium, which was also shown by Strock. The only conclusion that can be drawn regarding the distribution of lithium is that the contribution of this element during the rock-formation is dependent on temperature and on the concentration of Li^+ ions as crystallization proceeds.

When we study Strock's analytical results, it is striking that the content of lithium in the granites investigated is rather irregular — 0.002—0.15 per cent of Li_2O in Variscan granites from Germany. K. Rankama (100) has pointed out that the content of lithium in the pre-Cambrian granites of Fennoscandia seems to be connected with their relative age, so that the content of lithium increases as the age decreases. It is obvious, at any rate, that in general the pre-Cambrian granites show lower contents of lithium than do the younger granites. Some few determinations of lithium in Swedish gneiss-granites of early pre-Cambrian age are in good agreement with the figures for the corresponding granites of Finland investigated by Thure G. Sahama (102).

According to P. H. Lundegårdh, who has studied the pre-Cambrian rocks in a region of Central Sweden (74), the content of lithium is fairly uniform and independent of relative age. The most striking feature, however, is the increasing value of the ratio Li/Mg, as the relative age decreases, of the granites investigated by Lundegårdh, as shown in the following table:

	Relative age	% Li	$\frac{100\ \mathrm{Li}}{\mathrm{Mg}}$
Grey gneiss-granite..........	oldest	0.008	1.4
” ” ”	”	0.01	2.7
Gneiss-granite, porphyric.....	”	0.008	5.5
Red microcline granite.......	younger	0.007	7.0
Red to pink aplite granite....	”	0.003	10.9
Grey aplite granite..........	youngest	0.004	13.6

It is obvious that the increasing value of the ratio Li/Mg is due to a decreasing content of magnesium and not to an increasing content of lithium as the age decreases. On the contrary, lithium shows a feeble tendency to decrease. The author would like to draw attention to this seeming deviation from the normal behaviour of lithium as pointed out by Strock. On the other hand, the explanation is simple if we accept the author's conception that the content of lithium is dependent on the material involved in the rock-forming processes and on the temperature.

The abundance of lithium and the magnitude of the ratio Li/Mg in the leptites of Central Sweden are of interest since these rocks are closely connected with the iron ores of this region.

The vast majority of the leptites investigated have a low content of Li. Thus, 87.5 per cent of the samples show contents < 0.005 per cent Li, and 68 per cent < 0.001 per cent Li. A relatively high content is found in such samples of the leptite formation as either are sediments (the slates of Grythyttan, for example; see Table 24, Nos. 9—11) or in the samples rich in mica (Table 24, Nos. 19—20).

The ratio 100 Li/Mg is generally far below the values for the acid igneous rocks, as seen from Table 62. The few exceptions showing higher values are, as already mentioned, the same as those showing high contents of Li.

It is reasonable to connect the relatively low content of lithium in the leptites with their low content of dark minerals, as suggested by Strock's investigations. However, if the leptites — at any rate some of them — are regarded as acid volcanic rocks, it is strange that the ratio 100 Li/Mg generally displays such low values. Leaving aside the origin of the leptites, we can establish that the values for the ratio 100 Li/Mg in the leptites are in poor agreement with the average value for the acid volcanic rocks mentioned by Strock.

Most of the Swedish geologists who have dealt with the origin of the iron ores of Central Sweden and their relationship to the leptites have been in favour of the opinion that "the iron and manganese ores of Central Sweden always occur in the volcanic rocks, never in true sediments of the upper division and I have come to the conclusion that at least the main mass of the iron and manganese ores of the leptite formation originated through the volcanic processes which produced the leptites and the limestones". (Cited after N. H. Magnusson (79) pp. 334—5.)

Magnusson continues (79) p. 339): "The iron ores of the leptite formation in Central Sweden comprise sedimentary, metasomatic and intrusive ores, all belonging to the same volcanic activity".

Let us study the geochemistry of lithium in the ores of Central Sweden in the light of the opinions cited.

Referring to Tables 23, 25, and 58, we find that the content of lithium in the various ore types of Central Sweden is very low, even when comparing the gangues of the ores with the associated rocks, the leptites.

It is evident that a relationship to "volcanic activity" may be of various kinds. If the leptites associated with the iron ores are regarded as acid volcanic rocks and the relationship in question is a purely magmatic one, the magma must — in the author's opinion — have "split up" into two fractions: one ore-bearing one and one rock fraction (acid). If such a process really can occur, the regularity in the distribution of elements must be considerable, from a crystal-chemical point of view. As regards the distribution of lithium under the conditions mentioned, it is reasonable to expect most of the lithium ions present to become directed into the fraction containing magnesium and trivalent iron, as stated by Strock (111). Obviously it is not so, judging from the analyses. Thus, such a kind of "volcanic relationship" must be considered very unlikely, if the geochemistry of lithium is to be taken into account.

However, there may exist some other relationship between volcanic activity and iron-ore formation. If, for example, volcanic activity played an essential part in the formation of leptites, the residual solutions from the volcanoes may have taken part in the transportation and redeposition of iron sediments. The geochemistry of lithium cannot show if such a relationship can exist or not.

Another problem of some importance should be discussed in this connection. Conceptions have been advanced (Per Geijer (32, 37) and N. Sundius (113, 114) that magmatic residua — either true solutions or volatile-bearing residual magmas enriched in iron and magnesium — emanating from those magma chambers from which granites or leptites were formed, are the source of metasomatic iron ores.

The conceptions mentioned may suitably be subjected to a preliminary discussion, since the geochemistry of lithium can throw some light on the question. Suppose, that the development of a magma has proceeded so far that we can speak of a residuum. For some reason or other (cf., *e. g.*, Pentti Eskola (23) pp. 49 and 59—63) magnesium and iron have remained in solution at this stage of magmatic development. According to Strock (111) and Wickman (125) lithium is to be regarded as a typical "residual" element. The solubility of lithium compounds is greater than that of the corresponding iron or magnesium compounds. Thus, in such a residual magma lithium ions would be enriched. From a crystal-chemical point of view the following conclusion may be drawn: If there is any chance of lithium entering structures of dark minerals, it would clearly be in such a residual magma or solution. Consequently, one would get skarn ores relatively enriched in lithium and the ratio Li/Mg would be fairly large. As far as the author can see, in the light of the analytical data of lithium, there is little support for the conceptions mentioned on the formation of skarn ores.

On the other hand, the distribution of lithium and the magnitude of the ratio Li/Mg in the iron ores of Central Sweden rather seem to be in agreement with those conceptions concerning metasomatic processes, in which iron and magnesium have taken part, that have been expressed by C. E. Tilley and Sir John S. Flett (116).

Lithium seems to be but little abundant in the iron-ore types investigated. In the marine iron sediments and ores the content of lithium seems to increase. In the micaceous hematite ores of Great Rock Mine, Devonshire, Great Britain, the content of lithium is also considerable. In this case, however, the abundance of lithium may be connected with the granites (of the Dartmoor type) with which the ores in question are associated (18). See also Table 45 p. 94.

Rubidium and the Ratio Rb/K. As earlier mentioned V. M. Goldschmidt, H. Bauer and H. Witte have studied the geochemistry of the alkali metals (53). The distribution of rubidium is regulated by the large ionic size of Rb^+, which is 1.49 Å (V. M. Goldschmidt). When we compare the ionic size of K^+ (1.33 Å) with that of Rb^+, the ratio Rb/K may be expected to increase as the crystallization of a magma proceeds and Rb consequently be enriched in the residua.

In the exogene development, too, there will be a tendency to increasing values for Rb/K on account of the greater adsorbtion of rubidium ions in comparison with potassium ions, according to W. Noll (93). Consequently nothing can be said regarding the origin of a material investigated solely on the basis of the magnitude of the ratio Rb/K, since an endogene as well as an exogene development can lead to increasing contents of rubidium and also to incresing values for Rb/K. Now, if these two quantities show a deficiency as compared with the average values for the upper lithosphere, it is likely that such material does not emanate from magmatic residua. It should be mentioned that rubidium preferably enters structures of light minerals (potassium-feldspars and micas) and then substitutes potassium.

As seen from Table 58 the average content of rubidium in all the cases investigated is below the average value for the upper lithosphere (0.03 per cent Rb). In some cases the deficiency of rubidium is considerable. Table 23 establishes that the content of Rb may accidentally increase to considerable values. It is evident that in such cases no conclusions can be drawn regarding the origin.

Lithium and rubidium are both enriched towards the residua in an endogene crystallization process of a magma. It is of interest, therefore, to study the correlation between the two alkali metals in the ores and rocks investigated. The mere fact that the contents of both lithium and rubidium are very low indicates that we are not concerned with magmatic residua. However, lithium and rubidium behave differently in the crystallization of a magma in so far that lithium preferably enters structures of dark minerals, rubidium structures of light minerals. Of course this feature may be taken into account when drawing conclusions regarding the correlation between the two elements in question.

In the exogene development we can reckon with the two alkali metals behaving differently and consequently that the correlation between their contents in sediments can vary.

When studying Tables 23, 24, and 58, we find that there is practically no relationship between the contents of lithium and rubidium. The lacking relationship in question is of special interest in the leptites of Central Sweden (Table 24). In this case, too, the correlation between lithium and rubidium is feeble or practically zero. Again, if the formation of the leptites and the iron ores associated with them is to be connected with volcanic activity, it seems to the author that this relationship probably cannot be referred to a primary magmatic stage.

The Ratio kn. Tables 1—5 and 11 demonstrate that the correlation coefficients of the ratio kn, on the one hand, and the other quantities to which kn is correlated, on the other, are rather feeble on the whole. The most significant correlation is naturally that between qv and kn (Table 1). We find that the value for kn increases as qv increases, which is also illustrated in fig. 15, p. 48. The values for $r_{qv,kn}$ have a positive sign in all the rocks investigated. We also find that the tendency of $r_{qv,kn}$ increases as qv increases in the plutonic rock series. In the volcanic rock series, on the contrary, the tendency decreases as qv increases.

It can be discussed how this remarkable feature in the distribution of the two most abundant alkali metals can be explained. One way of reasoning may be outlined.

Let us first consider the volcanic rock series. The decreasing values of $r_{qv,kn}$ as qv increases may be connected with the quantity of external material added during an endogene rock-forming process. This external material is probably more acid than the primary magma to which it is added. Now, if this material is irregular with regard to the quantities qv and kn, *i. e.* if the value for $r_{qv,kn}$ is low, it is plausible that the rocks formed under such conditions will get a value for $r_{qv,kn}$ depending on the quantity of external material added to the rock-forming system. Since the external material has a high qv compared with the magma and since the r-value in question is low, it is plausible that the rocks formed will get decreasing values for $r_{qv,kn}$ as qv increases, if, that is, time is insufficient to increase $r_{qv,kn}$ to a value corresponding to the temperature of the system.

As regards the plutonic rock series the reasoning can be as follows. Suppose that the time is sufficient to bring the value for $r_{qv,kn}$ in relation to the temperature in this kind of rock formation.

At high temperatures such rocks will be formed where neither sodium nor potassium can enter the minerals formed, on account of their chemical properties (E-values, ionic size). It is plausible, therefore, that both alkalies will become enriched towards a magmatic residuum enriched in silica. Probably no endogene separation of the two alkali metals will take place, on account of the high temperature. Consequently the value for $r_{qv,kn}$ will become or approach zero.

As the temperature decreases in a plutonic rock-forming system the probability for sodium and potassium to become incorporated in structures of rock-forming minerals will increase, and now a separation of the two alkalies can take place thanks to the difference in their chemical proporties. Consequently the conditions will be favourable for increasing r-values as qv increases, *i. e.* at decreasing temperatures. It is evident that the magnitude of $r_{qv,kn}$ is also dependent on the composition and quantity of external material added to the rock-forming system.

It is plain that insufficient data regarding this interesting geochemical feature prevent a more detailed discussion. What has now been said is to be regarded as a preliminary suggestion.

Unfortunately the correlations of the quantity kn cannot be discussed in connection with the majority of the iron ores investigated, on account of the lack of analytical data. Only in the Liassic iron-bearing series of Southern Sweden could the r-values be calculated (Table 11). In these ores the value for $r_{qv,kn}$ is — 0.20. In the glacial clays the value is + 0.17. This indicates that the varying conditions in the sedimentary processes can influence the sign of the correlation coefficient of qv and kn.

In this connection the relationship between potassium and manganese must be discussed. This is of special interest, since there exists a strong geological relationship between the occurrence of manganiferous iron ores and pure manganese ores, on the one hand, and the potassium-bearing associated rocks — the leptites -- on the other, especially in the ore-bearing region of Central Sweden.

However, it should be mentioned that deviations from the relationship in question have also been demonstrated, especially by Per Geijer (32, 37).

The following discussion is based upon some r-values calculated:

$r_{kn,mf}$	in the leptites (Table 5)	+ 0.04
$r_{K,Mn}$	" " " (Table 24)	+ 0.04
$r_{K,Mn}$	" " gangue rocks of the ores (Table 23)	— 0.04

Thus, the r-values mentioned are practically zero.

We shall now return to the correlation kn,mf in the igneous rocks (Table 5). As mentioned before (p. 45), only the correlation between a single pair of variables has so far been dealt with. However, it is essential for the discussion of possible hypotheses regarding the correlation kn,mf to know whether a correlation observed between the two quantities in question can or cannot be accounted for solely by a correlation found between kn,qv and mf,qv respectively. For that reason some partial correlation coefficients between the three variables qv, kn and mf have been calculated, where the quantity qv can be regarded as constant.

The formula for the calculation of the partial correlation coefficients in question is the following (126):

$$r_{kn,mf(qv)} = \frac{r_{kn,mf} - r_{qv,kn} \cdot r_{qv,mf}}{\sqrt{1 - r^2_{kv,kn}} \cdot \sqrt{1 - r^2_{qv,mf}}}$$

Table 63 shows the values for $r_{kn,mf(qv)}$ (I). For the sake of comparison the values for $r_{kn,mf}$ from Table 5 are repeated (II).

In the igneous rock series investigated the partial correlation between the two quantities kn and mf is practically none, with few exceptions.

The relationship between the manganese and manganiferous iron ores, on the one hand, and the associated potassium-bearing rocks (the leptites), on the other, in Central Sweden, has been discussed for many years.

H. E. Johansson (64) regarded the formation of iron ores as an effect of liquid immiscibility between certain components in a silicate melt. According to him a magma was split up into fractions, one enriched *inter alia* in manganese, iron and potassium, and the other *inter alia* in sodium and iron, thus giving rise to manganiferous iron ores associated with potassium-bearing leptites, on the one hand, and iron ores poor in manganese associated with sodium-bearing leptites, on the other.

The author does not intend to discuss this antiquated way of looking upon the formation of iron ores. However, it should be mentioned that Johansson was the first Swedish geologist to pay attention to the geological relationship between manganiferous iron ores and their potassium-bearing associated rocks.

The most moderate and objective opinion on the geological relationship in

Table 63. **Partial Correlation of the Quantities kn and mf.**

Igneous rocks:	I $r_{kn,mf(qv)}$	II $r_{kn,mf}$
Average:		
Peridotites	— 0.14	— 0.14
Gabbros	0	— 0.11
Diorites	+ 0.14	+ 0.19
Granites	+ 0.05	+ 0.10
Basalts	— 0.05	+ 0.11
Andesites	0	+ 0.03
Rhyolites	+ 0.08	+ 0.04
Sweden:		
Gabbros	+ 0.11	+ 0.08
Diorites	+ 0.41	+ 0.40
Granites	+ 0.13	+ 0.14
Leptites	+ 0.06	+ 0.04
Other regions:		
Rapakivi granites (Finland)	+ 0.39	— 0.40
Volcanic series (Hawaii)	+ 0.31	+ 0.30
Sediments:		
Glacial clay (Norway)	+ 0.19	+ 0.17
Iron-bearing sediments (southern Sweden):		
Sideritic-oolitic ore	— 0.06	+ 0.04
Pure sideritic ore	+ 0.04	+ 0.08

question is expressed by Per Geijer and Nils H. Magnusson in their extensive work on the geology of the iron ores of Central Sweden (38). They write (in translation): 'We are of opinion that for the majority of the iron ores such a relationship exists as to allow the formation of the ores to be put in relation to the volcanic activity during the formation of the leptites. Thus, all these ores are — as far as we can find — genetically connected with the igneous activity of the leptite-forming epoch. However, this relationship was certainly not so direct as postulated by Johansson.'

In some important works (5, 6) Helge G. Backlund has expressed the conception that the formation of iron ores in Central Sweden should be connected with the exogene phase of development within the region in question. Thus, contrary to most Swedish geologists who have dealt with the origin of the iron ores, he cannot agree that a chemical relationship between the ore and the associated rock should be connected with endogene processes.

Let us leave aside the question whether volcanic activity played or did not play a part in the formation of iron ores in Central Sweden. That is beside the issue. The question may be asked whether the relationship between manganese and potassium in the ores and their associated rocks, respectively, can be lead back to a primary magmatic stage. The figures showing the magnitude of the correlation coefficients of the two elements in question (Table 63) may give the answer. There seems to be no relationship at all and there are no chemical reasons for such a relationship. The so-called "manganese-criterion", often met with in Swedish geological papers and postulating an endogene relationship between manganese and potassium, must be abolished, as far as the author can see.

On the other hand, a relationship between manganese and potassium in the sediment-forming processes can be easily explained. As stated before (p. 135), tetravalent manganese ions can remain in solution as colloids under favourable conditions. These colloids have a negative charge, according to F. Behrend (8) and others. Thus the colloids have an attractive influence on cations present in the solution. The adsorption of cations by colloids with a negative charge is dependent on *inter alia* the ionic size of the cations, as discussed by W. Noll (93). It is plausible, therefore, that potassium ions (K^+ = 1.33 Å) will become adsorbed by manganese colloids. If the concentration of potassium ions is sufficient, a flocculation of the colloids will take place. A similar way of reasoning can be applied to the enrichment of other cations with large ionic size in connection with the enrichment of manganese (Pb, Ba). It is well known that the enrichment of Pb and Ba is significant in many manganese-bearing ore deposits.

Quite recently the manganese mineralization within a district of northern Sweden has been described by Olof H. Ödman (127). Since the geological conditions in this ore-bearing district indicate that sedimentary processes have played an essential part in the formation of the manganese ore and the associated rocks — leptites — some few data regarding the relationship potassium-manganese will be mentioned.

Two analyses of the leptites and two of the manganese ores are presented in Table 64. The leptites show an excess of potassium, as seen from the table. Further, the aforementioned enrichment of other cations with large ionic size (Pb, Ba), significant for sedimentary manganese ore deposits, can be demonstrated also in this case.

Table 64. **Porphyry, Leptite, and Manganese Ores from the Ultevis District, Jokkmokk, Northern Sweden.** (After Olof H. Ödman.)

	Porphyry	Leptite	Manganese Ores	
SiO_2	73.30	71.75		
TiO_2	0.26	0.40		
Fe_2O_3	2.01	0.48		
FeO	0.51	1.51	4.68	4.88
MnO	0.59	0.52	43.2	12.8
BaO	0.58	nil	0.64	0.59
PbO			1.73	1.25
K_2O	5.73	6.29		
Na_2O	2.51	1.19		
kn	59	78		

Table 65. **Partial Analysis of Hollandite and Psilomelane from Ultevis, Northern Sweden.**

	Hollandite	Psilomelane
SiO_2	0.26	0.23
TiO_2	0.39	0.03
Fe_2O_3	12.58	6.45
MnO	54.50	62.19
BaO	14.28	9.14
PbO	4.32	3.25
K_2O	0.24	1.96
Na_2O	0.06	0.43
kn	61	75

Ödman has pointed out that the geological and chemical features of the manganese ores support the opinion that the ore formation is attributable to the occurrence of tetravalent manganese ions in colloidal solutions.

In the case of some epigenetic ores occurring in the region, Ödman also expresses the opinion that the content of iron and manganese was dissolved from the tuffitic sediments by hydrothermal solutions in connection with the ocurrence of a late pre-Cambrian granite. The epigenetic mineralization is thus the result of a mobilization process during which the sedimentary material was brought into solution.

Thanks to the courtesy of Dr. Ödman two analyses of hollandite and psilomelane have been placed at the author's disposal. The figures are from an investigation of the minerals from the region in question — in preparation — by Dr. Ödman (128).

The analyses illustrate, too, the very close relationship between manganese and potassium in the manganese-bearing minerals the material of which emanates from the sedimentary precipitation of manganese.

Many other examples of the exogene relationship potassium-manganese could be given.

Summary.

This chapter deals with the geochemistry of the elements significant for the igneous rocks, the sediments and the gangues of the iron ores. In this connection the relationship between the formation of igneous rocks and iron ores has been discussed.

The correlation qv,mc has been studied. On the basis of the magnitude of $r_{qv,mc}$ the conception has been expressed that the formation of igneous rocks involves an addition of external material to the endogene rock-forming processes. The differences in the magnitudes of the r-values in question between the igneous rock, on the one hand, and the iron ores, on the other, indicates that the formation of igneous rocks cannot be put in a primary connection with the formation of iron ores.

The geochemistry of the alkali metals lithium, sodium, potassium, and rubidium has been dealt with. Crystal-chemical principles for the distribution of the alkalies have been employed. It has been pointed out that the distribution principle for lithium as the crystallization of a magma proceeds, advanced by L. W. Strock, cannot be taken into account in connection with the formation of the pre-Cambrian iron ores and their associated rocks in Central Sweden. The ores and rocks investigated showing the highest content of lithium are those of pure sedimentary origin.

The content of rubidium and the magnitude of the ratio Rb/K have been discussed. The remarkable deficiency of rubidium in the acid rocks of Central Sweden that are associated with the iron ores has been commented upon. This deficiency indicates that the rocks in question cannot be looked upon as primary igneous rocks. The distribution of both lithium and rubidium strongly support the conception advanced that the relationship between the ores and their associated rocks cannot be of magmatic origin.

Finally, the ratio kn and the correlation between kn and mf have been discussed with special regard to the conditions in Central Sweden. It has been shown that the values for $r_{kn,mf}$ in the igneous rock series investigated are practically zero, indicating that there certainly is no endogene relationship between potassium and manganese. The fact that manganese-bearing iron ores in several cases occur associated with potassium-bearing leptites in Central Sweden is more easily explained as a primary exogene relationship.

Chapter VI. On the Formation of Iron Ores.

Introduction: The Development of the Upper Lithosphere from a Geochemical Point of View.

The evolution of the igneous rocks is looked upon as a link in the cyclic development of the upper lithosphere. The cycles are the orogenetic periods in the Earth's history.

This conception is in agreement with that of modern petrology, the formation of igneous rocks being regarded as the result of a co-operation of endogene and exogene activity. The facies rule (Eskola (20, 21) and the metamorphic differentiation (Eskola (22) are, therefore, regarded as the two fundamental principles regulating the formation of igneous rocks.

From a geochemical point of view V. M. Goldschmidt has advanced the following opinion on the distribution of elements, here cited *in extenso* (40) p. 24): "Im äusseren Stoffwechsel herrscht die quantitative Sonderung der chemischen Stoffe bei weiten über die Mischung ungleichartigen Materials, und die metasomatische Vorgänge im inneren Stoffwechsel können nicht das Material bewältigen und ausgleichend verteilen, das ihnen durch die Sonderungsvorgänge dargeboten wird. Die Produkte der Sedimentbildung und der Metamorphose können auch von Neuem in den äusseren Stoffwechsel einbezogen werden, wodurch eine bedeutende Stoffmenge sich in einem ständigen Kreislauf befindet, der zu immer stärkerer chemischer Sonderung führt."

In his work Stammentypen der Eruptivgesteine (41) V. M. Goldschmidt has emphasized the importance of taking into account the addition of external material in the rock-forming processes. Thus, the endogene differentiation is to an essential extent dependent on the composition and quantity of assimilated material.

By the aid of the geochemical data presented and by the employment of crystal-chemical principles for the distribution of elements, the author has arrived at the conclusion that the principles laid down by V. M. Goldschmidt and P. Eskola and mentioned above can be universally applied to the formation of the igneous rocks.

Here follows a brief survey of the conceptions expressed:

1. Basalts and peridotites are formally regarded as primary igneous rocks derived from magmas through fractional crystallization.

2. The igneous rock series with a qv-value greater than that of basalts and peridotites are formed by the co-operation of endogene and exogene processes. Material from the Earth's crust enters in the endogene phase of development during the orogenetic cycles. This material is inhomogeneous and consequently the distribution of elements can be regarded as irregular.

3. The composition of the igneous rocks is dependent on: 1) the composition and quantity of external material entering in the endogene phase of development; 2) the quantity of a primary magma taking part in the rock-forming processes; 3) the temperature; and 4) the pressure.

4. In the rock-forming processes we must reckon with the migration of cations in the solid state (in agreement with the conceptions expressed by H. Ramberg (99) and the important experimental work of J. A. Hedvall and his co-workers (57), and in solutions.

According to H. Ramberg the migration of cations is mainly attributable to their mobility. We need not consider the presence of solutions essential in this connection. The author can share Ramberg's opinion that the activity of solutions and volatiles has hitherto been overemphasized. However, the activity of solutions in connection with metasomatic processes must not be forgotten.

The successive change in the numerical relationship between the quantity qv, on the one hand, and the other quantities (og, mc, kn, mf, and mgf), on the other, indicates that the formation of igneous rocks did not necessarily take place under purely magmatic conditions. The probability that magmatic conditions ruled at the time of the formation of the rocks decreases as the acidity of rocks increases (increasing qv).

5. Iron plays the part of a "respiratory organ" for the upper lithosphere. The positive value of $r_{qv,og}$ and the increasing value of og as qv increases indicate that the material taking part in the formation of igneous rocks was to quite a considerable extent oxidized at the surface of the Earth's crust.

It goes without saying that fractional crystallization may be taken into account in the formation of igneous rocks. The conception here advanced does not deny that the development of a local series of rocks can be due to a fractional crystallization process. This is a question of temperature. However, it seems unlikely that the formation of the igneous rocks in general should be the result of fractional crystallization of a magma, since the demand for a regular development of the distribution of the rock-forming elements is not satisfied, especially as regards the acid members of the igneous rock series.

The Primary Enrichment of Iron.

As mentioned before, it is convenient to divide the formation of iron ores into two moments. The primary moment is the enrichment of iron and the secondary moment includes the geological processes that give the enrichment product the geological features distinctive of an iron ore.

The most important enrichment of iron takes place at the surface of the Earth's crust and, therefore, the primary exogene enrichment of iron will be briefly discussed.

If we estimate the magnitude of the sedimentary cycle of iron we arrive at the figures presented in Table 66.

Table 66. **Balance of Iron in the Sedimentary Cycle.**

	g per liter sea water
Iron supplied by rock decay	29.2
Iron present in clay sediments	23.2
Iron present in sandstone	0.73
Iron present in limestone and dolomite	0.21
Iron present in sea water	0.000005
Excess of iron	5

As seen from the table, 5 g iron per liter sea-water is available for the formation of iron ores and deep-sea sediments. Since our knowledge of the composition of the latter is fairly scanty no conclusions can at present be drawn as to the quantity of iron taking part in the formation of iron ores. However, it is plausible that most iron is precipitated at the shelf, and the marine shelf sediments show a feeble enrichment of iron.

Nevertheless, an enrichment of iron, say ten times as compared with the average content of iron in the upper lithosphere, essentially due to the activity of surface waters, may give rise to reflections. The question may be asked if a single chain of weathering, transportation and redeposition of iron can give rise to iron-ore deposits of the magnitude of, say, the Minette ores of Lorraine?

According to S. Palmqvist (96, p. 126) the low content of chromium in the siderite of the liassic iron-bearing series of southern Sweden indicates that the sediments did not derive from a gabbroidal magma type. The author cannot agree with Palmqvist's conclusion in this respect for the following reasons: Chromium and iron can be separated, *inter alia* due to the redox-potential in the transporting solutions. Thus, the *absence* of chromium is no indication as to the source of a sediment; the *presence* of this metal, on the other hand, may indicate the source of the sediments. Besides, it should be taken into account, too, that the enrichment of chromium in a marine iron-bearing sediment may be due to the adsorption by the iron-bearing colloids with positive charge at high oxidation potential in the milieu.

J. H. L. Vogt (118) has advanced the opinion that the ratio Mn/Fe in the sedimentary iron ores depends on the source of the sediments. This proposal, too, may be rejected for reasons analogous to those mentioned above.

The author is inclined to discourage conclusions drawn regarding the source of iron in sedimentary iron ores on the basis only of their content of minor constituents. Our present knowledge of the geochemistry of sediments is too incomplete.

Let us return to the question regarding the primary enrichment of iron to an amount sufficient for the formation of iron ores. As mentioned before, the enrichment of iron in the shelf sediments is quite feeble. Thus, the normal sedimentation on the shelf cannot solely account for the formation of marine iron-ore deposits. Two alternatives can be considered. The formation of marine iron ores may be the result of a series of exogene selective enrichments of iron under favourable conditions (climatological, morphological, etc.) or the essential part of the sediment material may derive from rocks rich in iron.

Comments on the Transport of Iron in Solution.

As a result of the weathering processes iron gets into solution as hydrocarbonate. As the oxidation potential increases in the transporting solutions and within certain ranges of concentration of hydrogen ions, iron can also remain in solution as $Fe(OH)_3$-sols. The transport of iron under the conditions mentioned is well known and described in all text-books on chemical geology.

Under what conditions can iron become transported at increased temperatures, say in hydrothermal solutions? The question is indeed intricate, but it is of importance when endeavouring to determine whether hydrothermal solutions can be responsible for the resolution, transport and redeposition of iron.

Many hypotheses have been advanced regarding magmatic residual solutions, pneumotectic residual magmas, etc., and their rôle in the ore-forming processes. Opinions differ considerably regarding the transport of elements in this later stage of magmatic evolution. Valuable contributions to our knowledge on this subject have been made by Cl. Fenner (26), N. L. Bowen (11), and L. C. Graton (54). The author neither has the intention nor the capacity to enter into any discussion on the possible ways in which elements may be transported in the later stages of magmatic development. The following are merely a geochemist's brief comments on the problem.

In the discussions on the endogene transport of iron in solutions more attention has been paid to the *possible* than to the *probable* conditions for this transfer. The problem is not whether iron so to say is able to "sneak away" from its normal range of crystallization during the development of a primary magma and thus remain in solution as a residual element (cf. Eskola (23) pp. 48—50. Such a transfer is unlikely from geochemical point of view for reasons already discussed in the previous chapters. The question is rather whether iron is transferable in solutions under endogene conditions. Suppose, for instance, that a sediment enriched in iron enters in the endogene phase. Can iron under such conditions be remobilized through the activity of solutions? Possibly it could as hydrocarbonate, for example, then being redeposited as siderite when the pressure of CO_2 decreases. Other conditions may also be taken into account for the remobilization of iron in connection with endogene solutions of various kinds. It is dependent *inter alia* on the composition of the material entering in the endogene phase of development. It is useless, therefore, to try to advance hypotheses, since the conditions may vary. Evidently, if a material is enriched in iron and, say, halogens, one might expect iron to become transferred as 'emanations'. However, both Per Geijer (33) and L. C. Graton (54) assert that this kind of transfer of iron is unlikely and the author readily shares their opinion that "the venerable thesis that metals and other components for mineral formation are transferred as volatile compounds of the halogen elements is found to require a great pyramiding of favouring assumptions". (Cited from Graton's paper quoted above, p. 344.)

To sum up: A remobilization of iron in the endogene phase of development may take place under certain conditions depending on the composition of the material entering in the endogene phase, on the content of volatiles present, and on the temperature.

The Secondary Enrichment of Iron.

We have earlier discussed whether the formation of iron ores can be looked upon as a chain of different processes, both exogene and endogene. It is plausible, at any rate, that an endogene phase of development of an iron ore also can involve an enrichment moment. Thus, those iron ores are generally richest in iron where geological features indicate that endogene processes have contributed.

It has been mentioned that the formation of magnetite may be due to reactions at increasing temperatures. The magnetitization of siderite, for instance, involves an essential enrichment of iron (from 48 to 72 per cent of iron), and other alterations of iron compounds might be mentioned in this connection.

In many cases the folding of strata and other tectonic deformations imply a consolidation of the iron content of a deposit, a fact familiar to any ore geologist.

A Theory on the Principles governing Iron-Ore Formation.

If we suppose that the formation of the igneous rocks is brought about by a co-operation of endogene and exogene processes and if the participation of the latter processes in the formation of rocks increases as the acidity of the rocks increases, the probability for a primary endogene relationship between an iron ore and its associated igneous rock will increase as the basicity of a rock increases.

However, on the basis of geochemical premises one arrives at the conclusion that also in the case of basic rocks and their endogene relationship to the titaniferous iron ores it may be uncertain whether this relationship is primary or secondary.

The following geochemical features contradict a primary endogene relationship between the titaniferous iron ores and the basic igneous rocks (gabbros, pyroxenites, basalts, etc.):

1. The high degree of oxidation in the titaniferous iron ores in comparison with that in the igneous rock series with a corresponding qv value.

2. The feeble positive value for $r_{qv,mc}$ in the titaniferous ores compared with the relatively strong negative correlation between qv and mc in the basic igneous rocks.

3. The lack of correlation between TiO_2 and FeO, the positive correlation between TiO_2 and MgO (+ 0.25), and the negative correlation between TiO_2 and Fe_2O_3 (see Table 12) in the titaniferous iron ores investigated. The correlation coefficients mentioned are calculated on the basis of 33 analyses from Washington's work (120).

The results are in poor agreement with those of Pierre Evrard (24) and James R. Balsley Jr (7), the latter having discussed the conditions of the magnetite-ilmenite deposits near Lake Sanford, Essex County, New York. Thus, Evrard has shown that during the differentiation of a titaniferous magma the total number of TiO_2, FeO and Fe_2O_3 mols as well as the number of TiO_2 mols increase continually.

A diagram in Balsley's paper quoted above illustrates that the content of ferromagnesian minerals decreases continually as the content of metallic minerals (magnetite, ilmenite) increases in the gabbro-magnetite-ilmenite rock series of the Lake Sanford district.

The seeming disagreement may be due to the fact that one single principle does not govern the formation of the titaniferous iron ores.

The conclusion is that at any rate some titaniferous iron ores are the result of a co-operation of endogene and exogene processes, the enrichment of iron taking place in the exogene phase of development.

If we take into account the relatively high content of titanium in the iron ores in question and the close relationship between some titaniferous iron ores and anorthosites, it may be discussed whether the lateritic sediments — with an excess of ferrides and Al — might not in the first place be considered in connection with the formation of titaniferous iron ores. However, closer investigations of deposits of titaniferous iron ores are necessary to solve this problem.

The following theory regarding the formation of iron ores is proposed:

The general pre-requisite conditions for iron-ore formation involve a primary enrichment moment in the exogene phase of development during the orogenetic cycles.

Weathering -> resolution of iron -> transport in solutions -> redeposition of iron is the chain of exogene processes leading to enrichment of iron. If the iron-bearing sediments enter in an endogene phase or if endogene activity of some kind influences the sediments, they result in metamorphic iron ores of different kinds: from the ultrametamorphosed or palingenic ores to the weakly metamorphosed sediments, where the primary sedimentary features are still predominant. The geological character of the ores is dependent on the composition of the primary sediment, the kind of exogene activity, the temperature and pressure at which the metamorphic processes take place (cf. Backlund (4).

If we consider the formation of iron ores from this point of view, the obsolete terms "syngenetic" and "epigenetic" ores have lost their significance.

To illustrate the formation of iron ores schematically we can divide the endogene action on the primary iron-bearing sediments into four main categories:

1. Actions mainly due to increasing temperature in connection with the occurrence of igneous rocks: contact metamorphism.

2. Actions mainly due to transference of elements at increased temperature leading to an essential displacement of the equilibrium of the primary system. The reactions may take place in the solid, liquid or gaseous state: metasomatism.

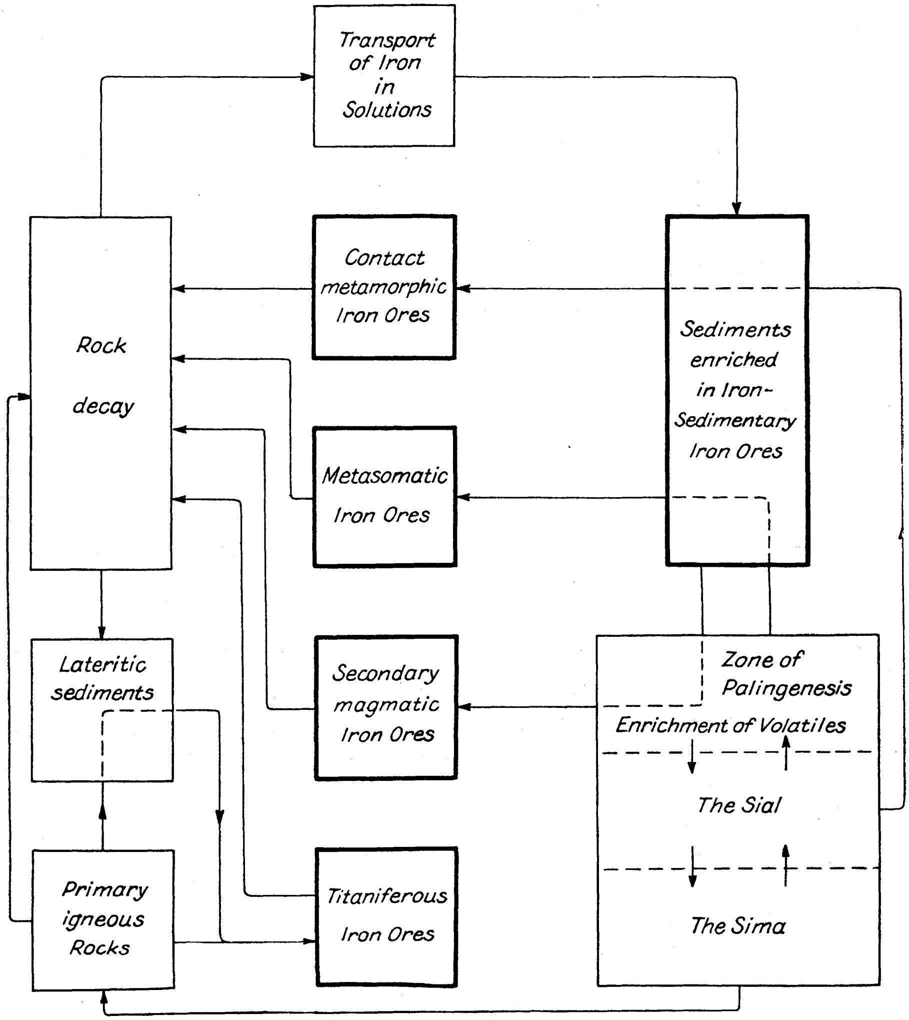

Fig. 31. Diagram illustrating the formation of iron ores in an orogene cycle in the upper lithosphere. The arrows indicate the main course of the processes.

3. The introduction of a primary exogene system into the endogene phase at high temperature leading to the development of a new mineral facies, stable at the temperature of the endogene system. The formation of a secondary mineral facies involves a rearrangement of the primary element association until equilibrium is reached: secondary magmatic or palingenic iron ores.

4. Formation of iron ores in an endogene phase in connection with the formation of basic igneous rocks. The relationship between the iron-ore fraction and the rock fraction can be primary or secondary: the titaniferous iron ores.

The diagram in fig. 33 may serve as an illustration of the formation of iron ores in connection with the cyclic development of the upper lithosphere. The arrows give an idea of the main course of the processes.

Geochemical Comments on the Origin of the Iron Ores of Sweden.

Since most of the research material emanates from the iron-bearing regions of Sweden it may be suitable to give a brief survey of such geochemical features as may be of importance when discussing the origin of the ores.

The Liassic Iron-bearing Series of Southern Sweden. As mentioned before, the iron-bearing sediments of Southern Sweden have been subjected to a geochemical investigation by Sven Palmquist (96). In the author's investigation some statistical calculations are based on Palmquist's chemical analyses. There are some geochemical features which are worth while mentioning in this connection for the sake of comparison with other iron-ore types investigated.

As mentioned before, the author has calculated two different qv-quantities. One (qv) is calculated by means of the content of SiO_2 from which the content of "sand" has been excluded. The other qv-value (qvs) is calculated with the content of sand included.

As seen from Table 11 the influence of the "sandy" part of silica is remarkable in so far as the r-values of qvs are generally lower than those of qv. Thus, for example $r_{qv,mc}$ is + 0.43 for the whole region but $r_{qvs,mc}$ only + 0.24. For the sideritic ores the figures are + 0.68 and + 0.32, respectively. This feature should be taken into account when dealing with the geochemistry of the iron ores — the pre-Cambrian sedimentary (quartz-banded) ores, for instance, — where a sub-division of the content of silica is impossible, for reasons plain enough.

Another geochemical feature worth mentioning is the feeble correlation between the quantities kn and mf. Thus, also in the case of sedimentation of iron under purely marine conditions and with a high value of kn (excess of potassium) the content of manganese in the ores need not necessarily increase. The relationship manganese-potassium in the sedimentary iron-ore formation processes is more complicated, and regulated by several factors. One factor may be that the concentration of both manganese and potassium must have reached a certain point.

The Titaniferous Iron Ores of Sweden. The insufficient geological and chemical research material at present available has prevented statistical computations on the distribution of the major constituents of Swedish titaniferous iron ores. The contents of some minor constituents in a few samples collected are presented in Tables 50—52. They require no special comment.

The pre-Cambrian Iron Ores of Central Sweden. The geology of Central Sweden has been closely investigated and is described in several papers. It is out of question to try to give even a brief survey of the geology of the region. The author begs to refer to the following works: Per Geijer and Nils H. Magnusson: De mellansvenska järnmalmernas geologi (38), Nils H. Magnusson: The Evolution of the Lower Archean Rocks in Central Sweden and their Iron, Manganese, and Sulphide Ores (79), and Nils H. Magnusson: De mellansvenska järnmalmernas omvandlingar i belysning av den geologiska utvecklingen i svionisk tid (81).

The comprehensive work of Geijer and Magnusson is worthy of especial attention. The first part of the book is a general survey of the geology of Central Sweden with special regard to the iron ores. The second part of the book contains a description of all the iron-ore deposits of Central Sweden that are worth mentioning. This is one of the most important and comprehensive descriptions of the ore deposits of a region ever printed. It goes without saying that the author has derived enormous benefit from this work. The tables containing the analytical data on the ore deposits of Central Sweden investigated by the author are grouped according to ore-fields as in the work mentioned.

In this survey will be discussed only those problems pertaining to the origin of ores where geochemical and geological opinions differ.

The iron ores of the region are usually divided into four groups: the quartz ores, the skarn ores, the lime ores, and the apatite ores. In the present paper the primary cause of the formation of all iron ores in Central Sweden is considered to be a sedimentary enrichment of iron. The secondary phase of development can be a more or less accentuated influence of endogene processes.

The content of the minor constituents investigated is very low. This is significant for all iron-ore types. It may be that there are some small differences in the abundance of these elements which may give some indications regarding the origin of the ores, but generally the differences are unimportant, anyway as far as we know at present.

The relative abundance of ferrides shows a remarkable deficiency of titanium, vanadium, chromium, manganese, cobalt, and nickel. Only in certain cases does the content of either manganese or vanadium increase to considerable amounts.

The frequency distribution of manganese in the region is illustrated in the histograms in fig. 11. As seen from the histogram to the left most of the iron ores are extremely poor in manganese. The proportion of manganese and manganiferous iron ores, on the one hand, and iron ores poor in manganese, on the other, is such as to make the ratio Mn/Fe for the region lower than the average value for the same ratio of the upper lithosphere.

The enrichment of vanadium is connected with the enrichment of phosphorus in the iron ores. Consequently, only the apatite iron ores are vanadium-bearing. The region as a whole is rather poor in vanadium.

Thus, the average contents of ferrides are below the corresponding averages for the upper lithosphere. This very remarkable feature is shown in figs 27 and

28, where the relative abundance of the ferride isotopes is shown in diagrams. The enrichment of iron, on the one hand, corresponds to a deficiency of the other ferrides, on the other, indicating that an almost complete separation of them has taken place during the transport of iron in solutions.

The deficiency of lithium and rubidium and the magnitude of the ratio Li/Mg and Rb/K, respectively, indicate that no magmatic residual solution can be put in relation to the formation of iron ores within this region.

There is no relationship between the distribution of the major constituents in the gangues of the ores, on the one hand, and in the associated rocks — the leptites — or the igneous rock series in general, on the other.

There exists no relationship between the quantities kn and mf, either in the ores, in the leptites, or in the igneous rock series.

The irregular fluctuations of the magnitudes of the correlation coefficients calculated indicate that rearrangements of elements have taken place and may be connected with metamorphic processes of various kinds, which have affected the ore bodies.

These are the main geochemical features on which the following discussion is based.

Geijer's and Magnusson's conceptions may serve as a starting point for a preliminary discussion of the origin of the skarn ores.

The skarn ores can be divided into two main groups: ores with a primary skarn, on the one hand, and ores with a secondary or 'reaction' skarn, on the other.

The ores with primary skarn are formed at a fairly high temperature, since the formation of the skarn silicates containing calcium, magnesium, and iron has taken place simultaneously with the formation of the ore minerals magnetite and, occasionally, hematite. The formation of this skarn-ore type is regarded as the result of contact metasomatism (pyrometasomatism) and connected with the activity of a magma. In central Sweden the primary skarn ores are connected with the occurrence of the oldest pre-Cambrian granites of this region, the 'urgranites'.

The ores with a secondary skarn — by far the most common skarn-ore type in central Sweden — are formed at low temperature, since carbonates of calcium magnesium, iron, and manganese, on the one hand, and SiO_2, on the other, can co-exist as stable components of the system. As the temperature increases, the primary equilibrium of the system becomes displaced, so that the formation of skarn silicates and magnetite can take place (the 'reaction' skarn).

It is evident that transition types between primary and secondary skarn ores also occur. A formation of metasomatic skarns, for example, including a rearrangement of iron from ores with 'reaction' skarns, can take place, as shown by Nils H. Magnusson in his work on the geology of the Persberg iron-ore field

(77). The theory for the formation of skarn ores proposed by Magnusson in this work is very important and may therefore be quoted briefly:

The ores of this region fall within two groups. The oldest ore is a lime-bearing skarn-magnetite ore and the younger one is a magnesium-bearing skarn-magnetite ore. The processes which consecutively have acted on a primary iron-bearing sediment, leading to the formation of the skarn ores, are as follows (77) p. 229):

1. The primary precipitation of iron in connection with the formation of the limestones of the region.
2. Rearrangement of iron in connection with folding processes.
3. The formation of the lime-bearing skarns ('reaction' skarns) at the beginning of a regional metamorphism of the leptites.
4. Metasomatic alterations leading to the formation of magnesium-bearing skarn ores and other metasomatic processes (of minor importance in this connection).
5. The occurrence of the oldest pre-Cambrian granites ('urgranites'). The skarn ores become contact-metamorphosed.
6. The occurrence of younger pre-Cambrian granites also leading to contact-metamorphism.

Thus, Magnusson arrives at the conclusion that the formation of the skarn ore types are secondary processes. The primary enrichment of iron has taken place in the exogene phase. The endogene processes which have acted on the primary iron-bearing sediment have only brought about a rearrangement of the primary iron quantity.

The theory proposed by Magnusson for the formation of skarn iron ores agrees with the author's conclusion arrived at on the basis of geochemical premises. Magnusson has further employed and developed his theory for the formation of 'reaction' skarn in several later investigations (78, 82, 83). Thus, the formation of this ore type is due to a displacement of equilibrium, so that a mineral facies stable under the primary exogene conditions, by which iron becomes enriched, tends to form a mineral facies stable under physico-chemical conditions of a secondary endogene phase of development.

The formation of iron ores with primary skarn includes not only a local rearrangement of iron and other elements but also an addition of elements, *i. a.* iron, magnesium, silica (contact metasomatism).

It is well known that the problem of especially the magnesium-metasomatism has caused lively discussions among geologists. As emphasized by P. Eskola (23), Per Geijer (32, 37), Nils H. Magnusson (79) and others, a very remarkable metasomatic alteration of the leptite formation in central Sweden and SW Finland has taken place, involving a considerable addition of magnesium. It has been asserted that this phenomenon is connected with the occurrence especially of the older pre-Cambrian granites of Fennoscandia (the 'urgranites').

In the work by Geijer and Magnusson quoted above the following explanation for the magnesium-metasomatism is given:

Solutions enriched in magnesium (and partly also in iron) have occurred at the intrusion period of the granites. It is further asserted that the magnesium-metasomatism on the whole has reacted in advance of the ascendent granite magma. The separation of the magnesium-bearing solutions — probably emanating from deep-seated magma chambers — is not necessarily connected with the granite magma (the source of the 'urgranites') but with larger magma reservoirs, part of which are the granites in question.

Per Geijer has especially called attention to the relationship between the formation of skarn iron ores and the occurrence of the 'urgranites', in his works on the Riddarhytte ore field (32) and on the Norberg mining district (37). The present investigation of the distribution of some minor constituents has certainly shown that an enrichment of 'granitophile' elements (cf. K. Rankama (100) can take place in samples from the ore fields in question. (The author can refer to the following analyses: Nos. 77—104, Tables 15, 23 and 27.) However, it should be emphasized that the enrichment of elements which may be connected with granites is not by any means of the same magnitude as that in the micaceous hematites from Great Rock Mine, Devonshire, where the ores probably are secondarily connected with the Dartmoor granite. (See tables 44—46, analyses Nos. 9:a—9:f.)

The enrichment of magnesium in connection with the metasomatic alterations of the leptite formation is very remarkable. In the author's opinion it would be fairly surprising if such an enormous transfer of magnesium should be looked upon as an isolated geological phenomenon. On the contrary, it is likely that the magnesium-metasomatism is connected with other simultaneous geological events of regional significance. It is probable, therefore, that the formation of the very abundant 'urgranites' was accompanied by a rearrangement of elements on a large scale for the formation of stable mineral facies. Thus, the author can share the opinions quoted as regards the *cause* of the magnesium transfer by metasomatic processes. However, as regards the *source* of magnesium and iron the author's opinion differs principally from that advanced especially by Geijer in his works quoted above. A simple calculation of the magnitude of a granitic magma necessary for the supply of magnesium, for example, on a large scale leads to incredible figures.

Objections against the transfer of iron and magnesium have been raised by several investigators.

P. Eskola has asserted (for the transfer of magnesium in the presence of silica (23, p. 61): "I know from my own experiments on hydrothermal synthesis in steelbombs that magnesia is practically insoluble when the amount of silica exceeds the metasilicate ratio . . ."

Tilley and Flett have, in their paper quoted above, emphasized that it is difficult to believe that magnesia-rich solutions are available as liquids associated with acid granites.

From a theoretical point of view H. Ramberg has suggested, "that the transport of matter during the metasomatic and metamophic processes in the crust takes place without the help of the so-called volatile substances or other "carriers" which commonly are assumed to be the active agents during the transport of mineral atoms." (99) p. 110).

Geological investigations in the ore-bearing regions of central Sweden by Nils H. Magnusson (79), S. Gavelin (29), and others indicate that the formation of magnesium-bearing skarns, for example, does not necessarily involve an external supply of magnesium. It may just as well be due to a rearrangement of magnesium within a region.

From a geochemical point of view objections have already been raised by the author against the formation of skarn ores in primary connection with the occurrence of igneous rocks.

A brief recapitulation of the author's conception:

A relationship between an endogene process leading to the formation of a skarn ore and one leading to the formation of igneous rocks of some kind is in the author's opinion secondary, and is due to the fact that part of the material which enters into an endogene phase of an orogenetic cycle, is enriched in iron in an earlier exogene phase. Thus, a granite and an iron may belong to the same orogenetic phase of a cycle. A closer relationship should not be reckoned with.

In his admirable work on the geology of the Grythytte field (113) Nils Sundius asserts that the material — containing iron and manganese — forming skarn-iron ores and manganiferous ores emanates from solutions "liberated from the magmas of the hälleflintas (leptites) as these rose towards the surface, the giving off of the solutions being realized at comparatively small depth". Sundius continues: "By this conclusion there will not be denied the possibility in other instances of ore deposits formed later and originating from the 'urgranites' . . ."

In a later work (114) Sundius still suggests that magmatic residual solutions may account for the content of iron, magnesium and silica, these residual solutions originating from magmas of granitic composition. This conception of Sundius' has already been discussed from a geochemical point of view. Thus, D. L. Reynolds comments on this phenomenon in the following way (101) p. 433): "The view that the iron and magnesium are of pneumatolytic or hydrothermal origin is particularly intangible since the field observations that can be adduced as evidence of these processes are the very phenomena that have to be explained. It seems particularly unlikely, however, that the source is to be found in residual magmatic solutions consisting essentially of silica, iron, magnesium and water as Sundius suggests. If granite usually crystallized so as to leave such a curious residual solution, one might expect to find veins and dykes of serpentine rather than pegmatites and aplites, associated with granite."

The author readily shares Dr Reynolds' opinion, for reasons already discussed.

Finally, the distribution of elements in the Långban manganese-iron deposit may serve as an illustration of an ore formation involving a chain of exogene and endogene processes. The geology and mineralogy of this very interesting ore field has been described by Nils H. Magnusson (78).

As regards the distribution of elements in this ore field the abundance of the very elements significant for manganese and iron sols should especially be noted. The great number of elements present in the ores has lead to the formation of a great number of minerals in connection with metamorphic processes in the region. (Cf. Magnusson (78).

Gregori Aminoff (2) has estimated the abundance of the elements in the ores of Långban by means of a very interesting method of estimation based on the frequency of minerals. The second column of Table 67 shows the contents of elements estimated by Aminoff. The third column of the table shows the abundance of elements in the igneous rocks, according to V. M. Goldschmidt (46). In the fourth is found the ratio between the content of elements at Långban and that of the igneous rocks.

On summing up the geochemical character of the iron ores and their associated rocks in Central Sweden the author arrives at the following theory on their origin:

The iron content of the various ore types emanates from iron-bearing sediments.

Several of the ore types have structures showing their primary sedimentary character (the quartz-banded iron ores). Other quartz ores are regarded as feebly metamorphosed sediments.

The skarn ores were formed through endogene processes of various kinds, which metamorphosed the primary iron-bearing sediments.

The apatite iron ores were formed through the ultrametamorphosis of a material in which the enrichment of iron took place in a cycle within the upper lithosphere, and where this enrichment occurred in the exogene phase of the cycle. The apatite ores are called secondarily magmatic or palingenetic. The geochemistry of this ore type has already been described by the author in an earlier paper (68).

The author suggests that there is no primary magmatic relationship between the iron ores and their associated rocks. The leptites are regarded as metamorphic rocks, most of them at least of sedimentary origin. (Cf. Walter Larsson (72).

Residual solutions from a magma of granitic composition cannot be regarded as the primary source of iron or account for any transfer of iron from the magma.

Table 67. **The Abundance of Elements in the Långban Manganese Ore, Sweden.**
(After Gregori Aminoff.)

Element	Långban (L)	Upper Lithosphere (u)	L/u
1 H	0.3		
3 Li	0.01	0.0065	1.5
4 Be	0.3	0.0006	500
5 B	0.1	0.0003	333
6 C	0.7	0.032	22
8 O	32.0	46.6	0.69
9 F	0.6	0.03	20
11 Na	0.5	2.83	0.18
12 Mg	5.3	2.09	2.5
13 Al	0.5	8.13	0.06
14 Si	10.0	27.7	0.36
15 P	0.01	0.08	0.13
16 S	2.4	0.052	46
17 Cl	0.2	0.048	4.2
19 K	0.3	2.59	0.12
20 Ca	6.7	3.63	1.8
22 Ti	0.2	0.44	0.45
23 V	0.1	0.015	6.7
24 Cr	0.01	0.02	0.5
25 Mn	12.0	0.1	120
26 Fe	8.1	5.0	1.6
27 Co[1]	0.001	0.004	0.25
28 Ni[1]	0.001	0.01	0.1
29 Cu	2.2	0.01	220
30 Zn	0.8	0.004	200
33 As	3.8	0.0005	7,600
42 Mo	0.3	0.0015	200
51 Sb	1.1	0.0001	11,000
56 Ba	1.5	0.025	60
74 W	0.4	0.0002	2,000
82 Pb	9.1	0.0016	5,700
83 Bi	0.5	0.00002	25,000

chamber. However, there may in certain cases be a secondary relationship between granites and ores. This may lead to a rearrangement of the primary iron content and metasomatic alterations of the ores. In such cases the formation of skarn ores, for instance, and the formation of granite may be considered syn-orogenic processes, *i. e.* they belong to the same phase of a cycle.

The theory here proposed is in agreement with that of Nils H. Magnusson regarding the formation of skarn ores and presented in his work on the geology of the Persberg ore field quoted before. As regards the main principles governing the formation of the iron ores of the region it is in agreement with H. G. Backlund's conception of the geological pre-requisites for the formation of the ores in the region (6 p. 85): "Dass sie alle aber im Laufe der relativ langen tektogenen

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[1] The contents of Co and Ni have been determined by the present author on ore specimens.

Entwicklung (= Revolution) des Geosynklinalraumes neben den tektonischen Deformation mehr oder weniger zur stofflichen und mengenmässigen Verschiebungen des Metallgehalts innerhalb und in der nächsten Umgebung der vorher angelegten Erzkörper mitgewirkt haben dürften, kann wohl keinem Zweifel unterliegen und wird sowohl durch Chemismus und Textur als auch durch stetig neuentstandene Mineralparagenesen bewiesen".

The Apatite Iron Ores of Northern Sweden. These ores are considered to be of magmatic origin. Many geologists have discussed the ores and their origin. The important investigations by Per Geijer are fundamental and the apatite iron ores of Northern Sweden are described in several works (31, 34, 35, 36). In two interesting papers Geijer has further discussed the similarity in the geological appearence significant to all the apatite-bearing ores of the so-called Kiruna type (34, 36).

A certain geological similarity between the apatite ores of Northern Sweden and those of the Grängesberg region in Central Sweden is pointed out by R. Looström (73).

It may be suitable to give a brief survey of Geijer's conceptions of the most significant geological features of the ores that may be of special interest.

The apatite iron ores of the Kiruna type are considered to be formed through magmatic differentiation. The relationship between the ores and their wall rock is significant. The ores are connected with volcanic rocks showing a limited variation in chemical composition between acid and intermediate rock types. The Kiruna ores, for instance, are associated with the syenite porphyries occurring in the region.

The geological occurrence of the ores indicates that the differentiation took place in magma chambers close beneath the surface.

Geijer asserts that a volatile phase co-operated in some way in the differentiation processes, so that a fraction rich in iron and phosphorus was separated and intruded as a pneumotectic residual magma. The occurrence of amygdule-fillings of hornblende, magnetite, sphene, and apatite, the combination of ore minerals and apatite with quartz and carbonates in certain ore bodies, and the abundance of boron in others, strongly supports the assumption of the activity of a volatile phase in connection with the ore-forming processes.

The temperature of the magma at the time of the intrusion varied within certain limits. Differences in the pneumatolytic and hydrothermal activity in connection with the intrusion account for the variation in temperature.

For the sake of comparison there follows a survey of the main geochemical features of the ores from Northern Sweden and those of the Grängesberg ores:

1. The mean for the quantity qv is 52.4 for Kiruna, 54.1 for Gällivare, and 54.1 for Grängesberg.

2. The means for the quantity mc for Kiruna, Gällivare and Grängesberg are 63.7, 70.3, and 68.1, respectively.

3. The values for $r_{qv,mc}$ are as follows: Kiruna + 0.08, Gällivare — 0.03, and Grängesberg + 0.16.

4. The mean for the degree of oxidation is 90.1 for Kiruna, 90.1 for Gällivare, and 91.7 for Grängesberg.

5. The means for the ratio mf are as follows: Kiruna and Gällivare 0.1 and Grängesberg 0.3.

6. The distribution of the ferrides shows an excess of vanadium of approximately the same magnitude for all the apatite ores. The content of cobalt and nickel is higher in the apatite ores of Northern Sweden than that of the apatite ores of Central Sweden. All the ores are poor in titanium and manganese.

The distribution of vanadium, manganese, cobalt, and nickel in the two phases magnetite/gangue in the ores of Northern Sweden is of interest. It has been pointed out that there is a certain relationship between the content of P and the ratio P_2O_5/SiO_2, on the one hand, and the magnitude of the distribution coefficients magnetite/gangue for manganese, cobalt and nickel (but not for vanadium), on the other, which is seen from Table 32, where the correlation coefficients are given. The relationship in question is as follows: an increase in the content of phosphorus in the gangue leads to an increase in the content of Mn, Co and Ni entering in the magnetite.

7. The content of lithium is low in the apatite ores and so is the ratio Li/Mg.

8. The content of rubidium and the ratio Rb/K are below the average for the igneous rocks.

9. The content of boron in the ores investigated is low both in the ores of Northern Sweden and in those of Central Sweden.

A few comments follow on those features of the Kiruna ores which, according to Geijer, are significant for a primary magmatic differentiation process.

The presence of volatiles in the ore magma is of great interest. There is, as a matter of fact, a striking anomaly in the course of differentiation as emphasized by N. L. Bowen, who asserts (10 p. 172): "Certain magmas such as the highly silicic or highly alkalic are, in virtue of their character as residual liquids, the natural home of concentration of volatiles. But the oxide ore bodies, like the ultrabasic rocks, are a very unnatural place to expect concentration of volatiles. It is probable that not all masses of the oxide ores are crystal accumulations. Some are perhaps the result of a secondary rearrangement of the rock materials by circulating solution, but that any of them are the result of the injection of a molten magma, even a 'wet' magma, is exceedingly unlikely."

Thus even the very presence of a volatile phase in the ore fraction indicates that a primary differentiation of a syenitic magma is a doubtful explanation of the origin of the Kiruna ores. However, there are other geochemical features which indicate that the origin of the Kiruna ores cannot be regarded as the result of a primary magmatic differentiation and which should be discussed.

If a magma is divided into an ore fraction and a rock fraction, the elements are distributed according to their chemical properties. If we regard the relationship between the quantities qv and mc, we find that $r_{qv,mc}$ approaches zero in the apatite iron ores. It is in striking disagreement to the values for $r_{qv,mc}$ in the igneous rock series with a corresponding qv-value. The author will pay special attention to the comparison with the igneous rock series, since Geijer asserts that the ores crystallized in exactly the same way as a normal igneous rock (31) p. 260).

The degree of oxidation in the Kiruna ores is higher than in igneous rocks within any qv-range, as seen from fig. 16 on p. 49. If, now, a primary magma has been split up into two fractions, one ore fraction and one rock fraction, it is quite natural to wonder where is the source of oxygen sufficient for the formation of such an enormous amount of magnetite as in the case of the Kiruna ore body. One might perhaps imagine that most of the oxygen available entered the ore fraction. In such a case the rock fraction, *i. e.* the syenite porphyries, would show a deficiency in the degree of oxidation. It is not so, as far as can be seen from the analyses in Geijer's work (31) p. 33). Thus analyses Nos. III, IV, V and VI show the following og-values: 86.7, 89.7, 90.5 and 83.0. The average value is 87.5. (For the sake of comparison the following figures of the syenites of the world should be mentioned: qv = 86.8, og = 86.7, mc = 44.1 and $r_{qv,mc}$ — 0.38.) Thus, the author asserts that the degree of oxidation cannot be regarded as significant for an igneous rock fraction formed under primary magmatic conditions.

According to Geijer the volatile components present in the ore fraction lowered the temperature of consolidation, so that this fraction could be injected as a residual magma. One can reckon with temperatures approximately of the same magnitude as those of the rock component, *i. e.* the syenite porphyries. L. W. Strock has pointed out (111) that rocks of syenitic composition can be relatively enriched in lithium. As already mentioned, lithium enters structures of the dark minerals, replacing magnesium. It is, therefore, reasonable to assume that lithium would be enriched in the ore fraction, which is enriched in both magnesium and iron. The content of lithium in the ores and the ratio Li/Mg should consequently show relatively high values. This is not the case. For reasons discussed before it is unlikely that the ore fraction should be a primary residual magma.

A similar way of reasoning could be employed regarding the content of rubidium and the ratio Rb/K.

To sum up: All the geochemical features indicate that the author's conception regarding the formation of the apatite iron ores of Central Sweden (Grängesberg) can be applied also to the origin of the apatite iron ores of Northern Sweden. Thus, we are concerned with secondary magmatic phenomena.

A material primarily enriched in iron, vanadium, phosphorus and volatiles entered in an endogene phase of development in an orogenic cycle. In this phase a simultaneous rock-forming process took place: the formation of the syenites. The result is a secondary magmatic relationship between the syenites and the ores. In this way is explained the presence of a volatile phase in the ore fraction. Several geochemical features indicate that the primary enrichment of iron took place in an exogene phase of development. Thus, the following way of reasoning can be employed:

If we accept a cyclic development of the upper lithosphere it is reasonable to assume that exogene material of various composition can enter into an endogene phase of development, for example, such a sediment enriched in iron, phosphorus, vanadium, and volatiles — a combination of elements often met with in certain marine iron-bearing sediments.

When this material enters into the endogene stage it will tend to form a mineral facies stable at the increased temperature. We may call it the magnetite-apatite-silicate facies in agreement with Eskola's facies rule. It is plausible that the composition of this secondary endogene mineral facies deviates considerably from the primary exogene facies, since the composition of the former will be regulated by a (secondary) metamorphic differentiation (Eskola). This presupposes a rearrangement of cations to an extent depending on their chemical properties. In fact, we find such a tendency of transfer of cations in the iron ores of Kiruna, for example, since manganese, cobalt and nickel enter the magnetite structure to an amount which is in relationship with the ratio SiO_2/P_2O_5. If now the sequence is the following: exogene enrichment of iron, phosphorus, vanadium, volatiles, etc. → endogene metamorphic differentiation, leading to the development of a stable magnetite-apatite-silicate facies, the conditions for the formation of an apatite iron ore are present. The geological features — secondary from this point of view — can naturally vary within certain limits, as emphasized by Geijer, but the composition of the primary exogene material, the source of the apatite ores, should mainly be accounted for by these varying geological features.

This conception may be considered to disagree with Geijer's theory regarding the formation of the apatite iron ores of the Kiruna type. But only superficially. Thus, the author can readily share Geijer's opinion that endogene processes were essential for the formation of the ores in question and also that there may exist a magmatic relationship between the ores and their associated igneous rocks. The author can further agree with Geijer in his conception that the formation of the ores took place at high temperatures before the injection of an ore fraction. The distribution of the manganese, cobalt and nickel of the magnetite and the gangue respectively indicates this. Thus, the problem is not whether the ores should be regarded to be the products of endogene processes. They certainly are. The problem is rather: Are the endogene processes responsible for the primary enrichment of iron? Probably not, in the author's opinion.

All the geochemical features indicate that the enrichment of iron took place *before* those endogene phenomena which have obscured these trends and which have given the iron ores the indisputable geological character of what we call a magmatic ore.

Comments on the Conditions during the pre-Cambrian Evolution. According to A. Holmes (61) the age of the Earth is about 3,000 M. y. The highest age estimates based on material from the Archean formations hitherto arrived at are below 2,000 M. y. Thus, if the estimates mentioned can be taken for granted one half to one third of the Earth's history had elapsed before the formation of the Archean rocks. Consequently there would be but little reason to look upon the formation of pre-Cambrian rocks from an "anti-actualistic" point of view.

In an interesting theoretic study on the condensation of water on the cooling Earth by Risto Niino (89), the author discusses the time necessary for a temperature fall from, say, 400 degrees Centigrade to about 30 degrees Centigrade. On the most probable of premises the time of this temperature fall presupposed for the condensation of the water should be surprisingly short and of the magnitude $2 \cdot 10^4$ years.

As regards the distribution of the major constituents in igneous rocks and ores and their relationship to each other as dealt with in this investigation, no geochemical indications bespeak any principal difference between pre-Cambrian material and that of younger age. (Se Tables 53—55.)

In the distribution of some minor constituents investigated some differences may perhaps in some cases indicate a certain difference between pre-Cambrian iron ores and those of younger age. Thus, there is a tendency to decreasing contents in the pre-Cambrian material, cf. Kalervo Rankama (100). Since our knowledge of the geochemistry of the sediments, especially, is still quite scanty, a discussion on these problems must be deferred. If the author should propose any hypothesis, it would be that we must certainly assume that biogenic processes contributed to the enrichment of some minor constituents in the pre-Cambrian evolution, but on a comparatively small scale. The difference in the conditions for weathering processes in pre-Cambrian times compared with those existing in later times, due to the differences in climatological factors, must also be considered.

The opinion advanced by Pentti Eskola in his inspiring work on the problems here touched upon may serve as a summary of our knowledge of to-day (23) p. 70): "To a certain extent the actualistic method is applicable even to the very oldest rocks known, and all that can be said is that volcanism and plutonism in the earliest geological times acted on larger scale than ever in later times".

Summary.

1. The material studied in this investigation is mainly from the Swedish iron-ore bearing regions. This material has been supplemented with samples of iron ores from other regions.

The iron ores have been analysed mainly by means of spectrochemical methods and the special technique introduced by V. M. Goldschmidt and his collaborators has been applied. Methods elaborated in the Geochemical laboratory of the Geological Survey have also been employed.

Available chemical analyses of igneous rocks, titaniferous iron ores from various regions, and a great number of ores from Swedish ore fields have been subjected to statistical computations. A brief survey of the material and the methods used is given in the first chapter.

2. The distribution of some significant major constituents, their statistical data and the geochemical features of the igneous rocks and iron ores are briefly discussed in the second chapter.

The quartz ratio (qv) is the quantity to which other statistical quantities are referred and correlated. Correlation coefficients have been estimated between other quantities, too, but they are of minor interest in this connection. The only relationship of any importance in connection with the origin of Swedish iron ores is that between the two quantities kn and mf.

The degree of oxidation has proved to be a quantity of great importance and its relationship to the quartz ratio has been given special attention. The increasing value of og as qv increases has proved to be essential when discussing the origin of ores and igneous rocks as well as the relationship between them.

The ratio MgO/CaO is discussed and so is the interesting geochemical feature that the magnitude of the ratio mc decreases fairly regularly as qv increases in the igneous rock series, whereas the numerical value of the correlation coefficient for qv,mc ($r_{qv,mc}$) decreases continually as qv increases. On the basis of the magnitude of $r_{qv,mc}$ the division of plutonites and volcanites has been awarded a real geochemical sense and is illustrated by a diagram in fig. 31.

The iron ores subjected to statistical elaboration show remarkable deviations with regard to $r_{qv,mc}$. Thus, there seems to be no relationship between the igneous rock series, on the one hand, and the iron ores on the other.

The finding that the ratio Mn/Fe (mf) has but feeble relationship to the quantity qv in the igneous rock series in general is of interest. Thus, no endogene distribution principle governing the ratio Mn/Fe can be discovered in the igneous rock series. In the iron ores, on the other hand, the concentration of carbonate ions seems to have some influence on the magnitude of the ratio Mn/Fe. The lack of endogene relationship between the quantities mf and kn, both in the igneous rocks and in the iron ores hitherto investigated, is of interest.

A special table shows the statistical quantities for the titaniferous iron ores.

(Table 12). Here special attention should be paid to the deviation of $r_{qv,mc}$ as compared with the corresponding values for the igneous rocks.

Table 11 contains the statistical data for the Liassic iron-bearing sediments in Southern Sweden.

All the statistical data on the major constituents of the iron ores and the igneous rocks are found in Tables Nos. 1—14.

3. In the third chapter the minor constituents investigated are presented and preliminarily discussed. The elements involved in the investigation are 1) the ferrides (Ti, V, Cr, Mn, Fe, Co, and Ni); 2) the alkali metals lithium, rubidium, and potassium; and 3) beryllium, boron, molybdenum, and tungsten. The tables showing the contents of the minor constituents are grouped according to regions.

4. In part two of this volume the main geochemical features of the material investigated are discussed in connection with the problems relating to the origin of the oxide iron ores and the relationship between the formation of igneous rocks and the formation of iron ores.

In the fourth chapter the geochemistry of the ferrides is discussed. A survey is given of the distribution of the ferride isotopes (mass-numbers 46—62) and some features in the relative abundance of the triade Fe-Co-Ni are mentioned. Further, the distribution of the ferrides is put in relation to their chemical properties.

In this connection the degree of oxidation has been dealt with. The conclusion is arrived at that the increasing value for og as the acidity of rocks increases means an introduction of external material into the endogene rock-forming processes. This material is assumed to have oxidized in the exogene phase of development. The relatively high value for og in the iron ores disagrees with the conception that magnetite can be formed under purely endogene conditions in connection with the formation of igneous rocks, since the degree of oxidation in the latter is too low to permit of any considerable formation of magnetite. Thus, it is suggested that the pre-requisite condition for the formation of iron ores in general is an exogene enrichment of iron. This material may then enter an endogene phase of development or endogene processes of various kinds may have acted on the primary exogene enrichment product for the formation of those iron ores which have a more or less decided endogene geological character.

5. The fifth chapter deals with the geochemistry of the lithophile elements investigated. Here the problems presented by the relationship between the ore-forming and the rock-forming processes is the principal subject for discussion.

Geochemical features indicate that a primarily endogene relationship between the two processes mentioned is generally unlikely. Even a primarily endogene relationship between the titaniferous iron ores and the basic igneous rocks can be the subject for discussion. There may in many cases exist a secondary relationship between ores and their associated rocks due to the fact that material exogenically enriched in iron enters an endogene phase of development in an orogenic cycle simultaneously and in connection with a rock-forming process.

6. Chapter six presents the geochemical premises for the theory proposed on the principles governing the formation of iron ores, which is schematically illustrated in a diagram of the development within a cycle.

Finally, the theory proposed is employed in a discussion on the origin of the pre-Cambrian iron ores of Sweden. A special study is made of the conceptions advanced by several Swedish geologists. The apatite iron ores of the Kiruna district are closely discussed and a comparison is made between the geochemical and geological aspects of the problem of the origin.

A few comments on the problem connected with the conditions during pre-Cambrian time completes part two.

The death of V. M. Goldschmidt closes a chapter in the history of geochemistry. Goldschmidt drew up the outlines of the principles governing the distribution of the elements in the various phases of the evolution of the Earth. That was a masterpiece. The influence in the fields of chemistry, mineralogy and geology cannot yet be surveyed.

However, as geochemical investigations proceed — including those where geochemistry should be employed — points of disagreement appear on the principles governing the distribution of elements, on the one hand, and the classic conceptions on the evolution of the upper lithosphere, on the other. It is true that modern petrology and modern geochemistry tend towards conceptions that in many respects deviate from the decidedly "plutonic" one on the formation of rocks and ores.

If we look upon the matter from a decidedly geochemical point of view, however, and use the methods available that may throw light upon the many problems connected with the development of our globe, we find that our exact knowledge is at present fairly small also as regards essential physico-chemical and crystal-chemical data, and that ambiguous conclusions might be drawn. Thus, we have insufficient knowledge of the physico-chemistry of solutions, we know but little regarding the pre-requisites for the formation of minerals, our knowledge on the distribution of elements in the various kinds of sediments is surprisingly scanty, etc.

Seen from this point of view the results of the present investigation are unsatisfactory. The author is aware of this as also of the fact that the opinions voiced on the pre-requisites for iron-ore formation and its connection with the development of the upper lithosphere may be subjected to criticism in many quarters.

However, if this work prompts further studies of this important and interesting matter the author will feel very satisfied and then, perhaps, the present investigation has not been in vain.

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