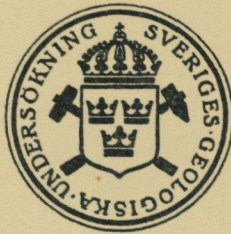


RUDYARD FRIETSCH

TRACE ELEMENTS
IN MAGNETITE AND HEMATITE
MAINLY FROM NORTHERN SWEDEN



STOCKHOLM 1970

SVERIGES GEOLOGISKA UNDERSÖKNING

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ABSTRACT

The paper deals essentially with the geochemical properties of the iron ores of Norrbotten county, Northern Sweden, as obtained by spectrochemical analysis of the constituent oxide minerals (magnetite and hematite) in the different types of ore and rock. It complements earlier work by Landergren (1943, 1948) which dealt mainly with the iron ores of Central Sweden. The geochemistry of the apatite iron ores of Northern Sweden, however, suggests a magmatic origin rather than a "sedimentary-palingenic" one as proposed by Landergren. Furthermore the similar geochemical composition of the magnetite in the skarn iron ores and the stratified, usually siliceous iron ores in Northern Sweden indicates that the two types of ore have the same origin.

For comparative purposes iron oxides in the iron ores of Northern Finland and the Lahn-Dill area of Western Germany were investigated spectrochemically. The paper also includes a compilation of magnetite and hematite analyses reported in the literature.

1. INTRODUCTION AND PREVIOUS WORK

The present investigation deals mainly with the distribution of the trace elements in magnetite and hematite taken from different types of iron ore in the county of Norrbotten, Northern Sweden. By analyzing these oxides and not the whole ore a reliable basis is obtained for an interpretation of the geochemical features of the ore itself. If other minerals than the iron oxides are included in the analysis, it is not possible to make a fair comparison of the geochemistry of the different deposits as the mineral associations, even within the same type of ore, show rather great variations.

Knowledge of the distribution of the trace elements in magnetite and hematite in an iron ore is of importance for understanding the conditions during which the ore formed. The formation of a mineral is controlled by temperature and pressure, and by the concentrations and physical properties of the elements available. Elements present in small amounts substitute for the main elements or occur as accessory minerals. The amount of minor elements entering the lattice of a mineral is thus to a large extent determined by the physico-chemical conditions existing during its formation. Consequently differences in the mode of formation of the iron ore types in Norrbotten should be reflected by differences in the trace element distribution in magnetite and hematite. Thus the main aim of the present investigation was to find out if there existed significant differences in the trace element distribution in the iron oxides of different types of iron ore in Norrbotten. The existence of such differences could be of use in genetical studies, for example, when the mineralogical composition, mode of occurrence etc. are ambiguous, the minor elements in the iron oxides may give a hint as to which type of ore a given ore body belongs. This reasoning is further applicable to iron ore boulders found in glacial drift; in many cases the mineralogical features of these do not enable their source to be established with certainty. Geochemically, however, it may be possible to indicate the type of ore to which the boulders belong and hence the source from which they derive. The same reasoning can be applied to iron ore pebbles in conglomerates; to say from which type of ore the pebbles derive is in many cases impossible from their macroscopic features alone, but a study of the trace elements of the iron oxides may give some clue.

Geochemical data on the iron ores of Norrbotten are rather scarce. The pioneer work by Landergren (1948) on the geochemistry of the iron ores of Sweden includes data on the content of the ferrides (Ti, V, Cr, Mn, Fe, Co, Ni) and of Li, Mg, K, Rb, Be, B, Mo, W, Y and the lanthanides in a few deposits of the apatite iron ores in Norrbotten. The determinations are mostly on samples of ore, but there are also some on magnetite and hematite. Only the apatite iron ores in Norrbotten were investigated in this study. Hegemann &

Albrecht (1954) in their extensive study of the geochemical properties of different types of iron ore from different parts of the world, made some determinations of the trace element content in magnetite and hematite from the apatite iron ores in Northern Sweden. The results, however, are given in diagrams and show only the range of the contents of different elements. The apatite iron ores and the skarn iron ores in the Svappavaara area, ESE of Kiruna, have been geochemically investigated by the present author (Frietsch 1966). The analyses were made on magnetite and hematite, and also on the gangue and on the whole ore. Values are given for the ferrides and Si, Al, Ca and Mg. This work also includes a few determinations of the content of the ferrides in unseparated samples of iron ores NE of Kiruna and of the ferrides and sulphur in magnetite from the Stora Sahavaara skarn iron ore.

In the present paper the trace elements in magnetite and hematite from 109 localities in the county of Norrbotten (fig. 1) are reported. Representatives of all types of iron ore have been investigated. The deposits differ greatly in size, but all, irrespective of their economic value, have been given the same importance. Deposits with greatest economic value and currently being mined are the apatite iron ores. These are called iron ores of the Kiruna type after their most important representative, the iron ore at Kiruna. They contain both magnetite and hematite. 23 deposits of this type have been investigated. The magnetite in the syenite-porphyrries which form the host rock of some apatite iron ores has been investigated in a few deposits. Genetically connected with ores of the Kiruna type, but formed at a later stage and at a lower temperature, are some hematite (-magnetite) ores, called ores of the Hauki type in this paper. These have been investigated from 6 deposits. The largest group investigated, the skarn iron ores, include 42 deposits. They are made up of magnetite and in two deposits also of hematite. Samples of stratified, usually quartz-rich, magnetite ores have been taken from 15 deposits. The investigation also includes some magnetite deposits which, from their general appearance and mineralogical composition, could not be assigned to any of the above mentioned types. These iron ores are of unknown origin and show, in some respects, similarities with iron ores of the Kiruna type and with skarn iron ores. It was therefore expected that the trace element distribution in the magnetite might give an indication as to which of the two types of ore these deposits really belong. The iron oxides in basic magmatic rocks of both intrusive and extrusive origin have been investigated from 7 localities. Magnetite has been analyzed from 3 localities where the mode of formation is due to metasomatic processes: in some altered basic volcanics and in the leptite in the Nautanen copper deposit. From two localities hematite occurring in conglomerates as pebbles and in the matrix has been investigated. Finally, magnetite found in pegmatites and granites in gneisses of unknown origin has been analyzed from two localities.

For comparative purposes the trace elements in magnetite and hematite from some iron ores in Northern Finland and Western Germany have been analyzed. Those from Northern Finland include the magmatic magnetite ores in the Misi area (three deposits); the Taporova hematite-(magnetite) deposit which is most likely of metasomatic origin; the skarn iron ore at Rautuvaara which is similar to the skarn iron ores in Norrbotten, and the jaspilitic magnetite iron ores in the Kittilä area. From Central Finland the magnetite occurring in an amphibolite in the Hällinmäki copper deposit (contact-pneumatolytic in origin) has been analyzed. From Western Germany, magnetite and hematite in the exhalation iron ore deposits in the Lahn-Dill area have been investigated.

The analytical results are compiled in the tables 6–15. In connection with these a short description of the characteristic features of the different types of ore and rock together with an interpretation of their genesis is given. The tables include 289 analyses of which 227 are new; 16 were published by Landergren (1948) and 46 by Frietsch (1966). The 289 analyses comprise 220 determinations of magnetite, 44 of hematite, 13 of magnetite ore, 4 of hematite ore, 2 of syenite-porphry, 2 of siderite and 4 of the gangue associated with magnetite ore. Of these 43 analyses of magnetite, 15 of hematite, 2 of magnetite ore and 2 of hematite ore have formerly been published in the papers by Landergren and Frietsch.

Most of the samples investigated in this work were collected by the author and his co-workers. For some iron ore deposits the samples were obtained by courtesy of the mining companies owning them. I want therefore to express my sincere gratitude to Mr. E. Carlsson, Stora Kopparbergs Bergslags Aktiebolag; Mr. T. Eriksson, A. Johnson & Co. Handels Aktiebolag; Mr. P. Forsell and Mr. N. Marinder, Luossavaara-Kiirunavaara Aktiebolag, and Mr. P. V. Villner, Tuolluvaara Gruvaktiebolag. Without the co-operation of these persons the purpose of the investigation, namely a survey of the geochemistry of all the known iron ores in the Norrbotten county, could not have been fulfilled. I am also obliged to Mr. J. Nuutilainen, Rautaruukki Osakeyhtiö, who kindly supplied samples from some of the iron ore deposits in Northern Finland.

Mr. P. Padget has kindly corrected the English of the manuscript.

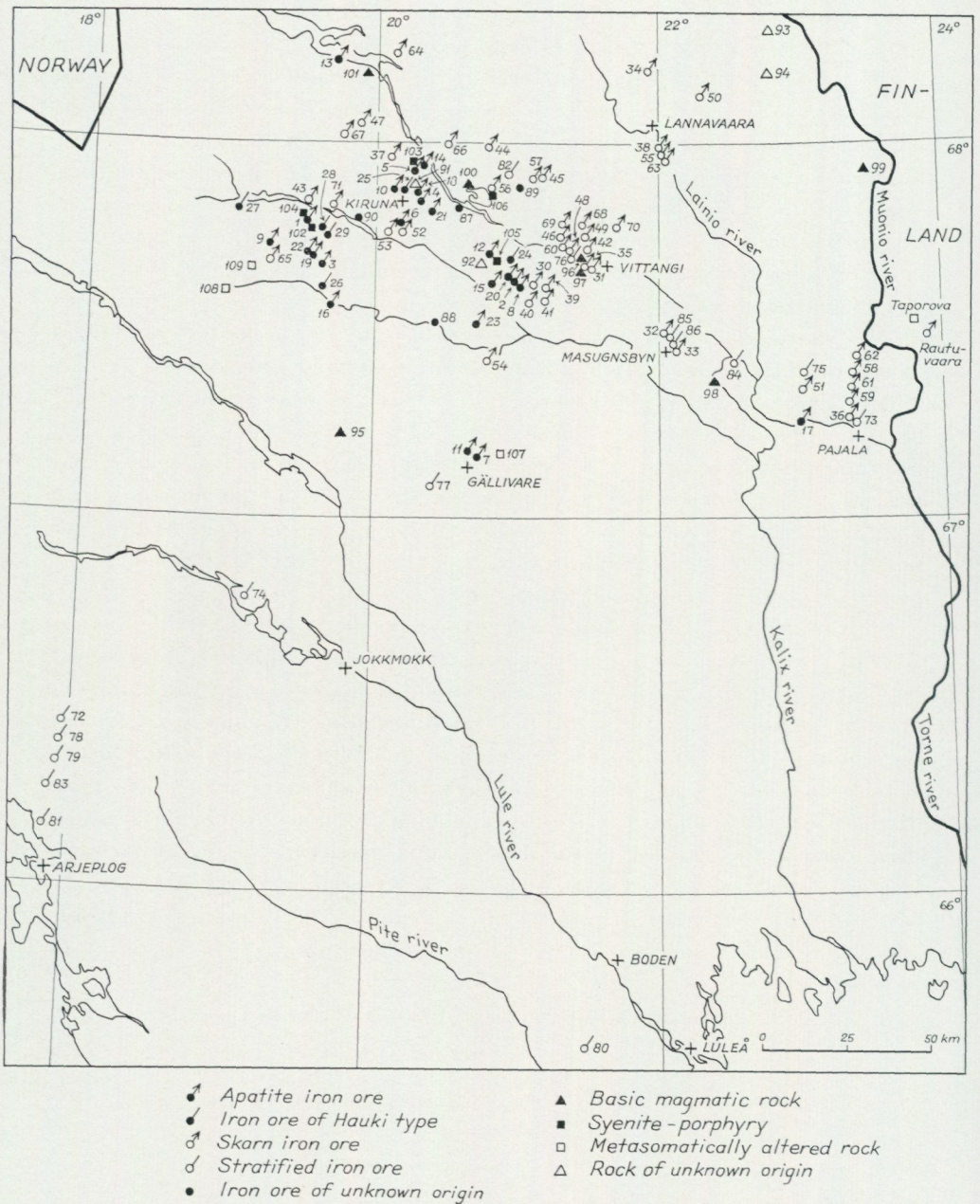


Fig. 1. Map showing the location of the iron ores and rocks investigated in Norrbotten county, Northern Sweden. The numbers indicating the different localities are the same as in tables 6-13.

List of localities:

Apatite iron ores

1. Ekströmsberg
2. Gruberget
3. Harrejaure
4. Haukivaara
5. Henry
6. Kiirunavaara
7. Koskullskulle
8. Leveäniemi
9. Luopuware
10. Luossavaara
11. Malmberget
12. Mertainen
13. Nakerivaara
14. Nukutus
15. Painirova
16. Pattovare
17. Peräjävaara
18. Rektorn
19. Renhagen
20. Tansari
21. Tuolluvaara
22. Tjåorika
23. Ylipääsnjaska

Iron ores of the Hauki type

24. Ainasjärvi
25. Haukivaara
26. Kuosatjvare
27. Larkimvare
28. Pidjastjåkko
29. Skåukemjokk

Skarn iron ores

30. Alpha
31. Haren
32. Isovaara (Masugnsbyn)
33. Junosuando (Masugnsbyn)
34. Juolovanjärvet
35. Kallokajärvi
36. Karhujärvi
37. Keskinen Käyrävaara
38. Kevus (Lannavaara)

39. Kiilavaara
40. Koivujärvi
41. Kulleri
42. Kuusi Nunasvaara
43. Laukujärvi
44. Luovinjunanen (Älvgruvan)
45. Maattavaara
46. Mänty Vathanvaara
47. Njuotjamavare
48. Nunasjärvenmaa
49. Nälkävuoma
50. Paljasjärvi
51. Pellivuoma
52. Rakkurijoki
53. Rakkurijärvi
54. Salmivaara
55. Sattavaara (Lannavaara)
56. Sautusvaara
57. Sekkujoki
58. Stora Sahavaara (Kaunisvaara)
59. Suksivuoma
60. Svanbolandet
61. Södra Sahavaara (Kaunisvaara)
62. Tapulivuoma (Kaunisvaara)
63. Teltaja (Lannavaara)
64. Tjavelk
65. E. Tjärrojäkka
66. Tjärro
67. Toppi
68. Valkkijoki
69. Vathanvaara
70. Venetvuoma
71. Vieto

Stratified iron ores

72. Hejka (Tjegelvass)
73. Jupukka
74. Kallak
75. Käymäjärvi
76. W. Nunasvaara
77. Peltovaara
78. Rappen (Tjegelvass)

79. Rebak (Tjegelvass)
80. Ristjäl'n
81. Sakka (Tjegelvass)
82. E. Sautusvaara
83. Skomern (Tjegelvass)
84. Tornefors
85. Vuoma (Masugnsbyn)
86. Vähävaara (Masugnsbyn)

Iron ores and rocks of unknown origin

87. Altavaara
88. Killingi
89. Leppäkoski
90. Puoltsa
91. Doktors kulle
92. Saurusvaara
93. Masankijärvi
94. Suijavaara

Basic magmatic rocks

95. Akkavare
96. Jälketkurkkio
97. Kallokajärvi
98. Lauttakoski
99. Saarikoski
100. Saivo
101. Tjabrak

Syenite-porphyrries

102. Ekströmsberg
103. Hopukka
104. Kaipak
105. Mertainen
106. Sautusvaara

Metasomatically altered rocks

107. Nautanen
108. Läfte
109. Tjårråive

2. ELEMENTS INVESTIGATED AND ACCURACY OF DATA

The material investigated consists of rock samples and drillcores in about equal amounts. These were crushed, the magnetite being separated magnetically and the hematite by heavy liquids. At the laboratory of the Geological Survey of Sweden the separated iron oxides were subjected to a spectrochemical analysis with the tapemethod and direct reading. The isoformation was made by grinding with a spectroscopic buffer (Danielsson 1967). The following elements were determined: Si, Al, Ca, Mg, Mn, Ti, Ba, Sr, Ni, Co, Cr, V, Cu, Zn, Mo, Pb, and Ag. Pb and Ag were determined only in a small number of samples. The determination of Si, Al, Ca, and Mg must be considered as a semiquantitative estimation; of these elements the analytical error is smallest for Mg. For Ni, Co, Cr, Cu, Zn, Mo, Pb, and Ag the error is about ± 10 per cent and for Mn, Ti, Ba, Sr, and V about ± 20 per cent. For a restricted number of samples a spectrographical analysis was made recording B, Be, Ga, Sn, Sb, and Cd photographically. The error for these elements is about ± 20 per cent. As has been mentioned in the preceding chapter some of the analyses of magnetite and hematite listed in the present paper have been taken from the works of Landergren (1948) and Frietsch (1966). These analyses were also made spectrochemically, the values of the different elements being obtained photometrically. The error for these analyses is about of the same magnitude as for the analyses made in the present investigation. For further information see the works cited.

For some of the samples the separation of the iron oxides is somewhat incomplete. When the separation was repeated the purity of the samples was not much improved (as judged from the analytical results) which is most possibly due to the fact that the iron oxides and admixed minerals occur as a fine intergrowth. The purity of the samples is best estimated from the silica content in the analyses in table 6-15. As silica is not known to enter magnetite and hematite in any appreciable amounts the silica content found in the analyses means that the iron oxides in the samples are contaminated with quartz or silicates. Table 1 shows the distribution of the content of SiO_2 in the analyses, and it is seen that the purity of magnetite is somewhat better than for hematite. Thus 42 per cent of the magnetites and only 32 per cent of the hematites contain less than 1 per cent SiO_2 . 84 per cent of the magnetite samples contain less than 5 per cent SiO_2 , for hematite the corresponding value is somewhat lower, 76 per cent. Of the different types of ore and rock investigated the magnetites in the apatite iron ores, the Misi iron ores (in Finland), the iron ores of unknown origin and the gneisses show the lowest values. This is also the case for the hematite in the ores of the first mentioned type. The highest contents of SiO_2 are found in ores and rocks where the content of magnetite or hema-

Table 1. The distribution of the SiO₂ content in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Type of ore or rock	Magnetite				Hematite						
		n	% SiO ₂				n	% SiO ₂				
			<1	1-5	5-10	>10		<1	1-5	5-10	>10	
Magmatic	Basic magmatic rock, N. Sweden	8		63	25	12	1	100				
	Syenite-porphry, N. Sweden	5		40		60						
	Apatite iron ore, N. Sweden	53	75	25			23	52	35	9	4	
	Iron ore, Misi, N. Finland	3	67	33								
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Germany	3		67	33		4		75	25		
	Iron ore, Kittilä, N. Finland	3			33	67						
	Stratified iron ore, N. Sweden	28	18	33	21	28						
	Skarn iron ore, N. Sweden	77	36	54	6	4	2		50	50		
	Skarn iron ore, Rautuvaara, N. Finland	1		100								
Metasomatic	Iron ore, Hauki type, N. Sweden	1		100			7		40	20	40	
	Leptite, Nautanen, N. Sweden	2	50	50								
	Altered basic volcanics, N. Sweden	2		100								
	Iron ore, Taporova, N. Finland	1		100			2		100			
	Amphibolite, Hällinmäki, C. Finland	1		100								
Unknown	Iron ore, N. Sweden	10	60	40								
	Conglomerate, N. Sweden						2		50	50		
	Gneiss, N. Sweden	2	100									
	All ores and rocks	200	42	42	7	9	41	32	43	16	9	

tite is rather low and where the iron oxides are finely divided. Thus the magnetites from the basic magmatic rocks, syenite-porphyrines, skarn iron ores, stratified iron ores and the iron ores in the Kittilä area (in Finland) show the highest contents of SiO₂.

As the purpose of the present investigation is to determine the content of the minor elements in magnetite and hematite and from these results to find significant geochemical characteristics for the different types of ores and rocks in Norrbotten, the conclusions drawn concerning their geochemistry are less

certain if the samples of magnetite and hematite are contaminated with other minerals. If the samples analyzed contain impurities in the form of minerals which lack the trace elements sought, a "dilution" of the content of these elements in the iron oxides will be the result. If, on the other hand, the minerals admixed with the iron oxides contain a high content of the trace elements in question, higher values than the true ones will be obtained for these elements in the analyses. Knowledge of the mineralogical composition of the ore or rock in which the iron oxides are located is, in many cases, rather imperfect and consequently a certain prediction of which minerals might occur as impurities cannot always be given. The effect of the presence of different impurities will however be discussed below. The content of the trace elements in the different minerals which occur as impurities is shown in tables 2 and 4; the values are taken from the current literature.

Quartz occurs in fairly large amounts in the stratified iron ores, the iron ores of the Hauki type (both in Northern Sweden), the Taporova iron ore and the ores in the Kittilä area (both in Northern Finland), and in the iron ores in the Lahn-Dill area (Western Germany). Many of the high SiO_2 -values in the analyses from these deposits are without doubt due to the presence of quartz. As quartz does not contain any trace elements the presence of this mineral means that lower values than the true ones are represented in analyses of the iron oxides.

Potassium feldspar in analyses which show high SiO_2 -values is present in the altered basic volcanics in Northern Sweden and the iron ore at Taporova. According to Howie (1955) and Engel & Engel (1960) potassium feldspar does not contain any appreciable amounts of trace elements besides strontium, barium, and rubidium, barium reaching the highest amounts. The relatively large amount of barium in the analyzed magnetite and hematite in Taporova (table 14) is, however, largely due to impurities of barite which has not been removed by the separation.

Plagioclase in those analyses which show high SiO_2 -values is present in samples of basic magmatic rocks and syenite-porphyrries, both from Northern Sweden. The only trace elements known to occur in fairly high amounts in plagioclase are strontium and barium, of which the former shows the higher values (Wager & Mitchell 1951, Howie 1955, Nesterenko et al. 1958, Sen et al. 1959). For the other elements in the iron oxides in the above mentioned rocks the presence of plagioclase has a "diluting" effect on the analytical values.

Pyroxene and amphibole occur in fairly large amounts in the basic magmatic rocks, the skarn iron ores, the stratified iron ores, the iron ores of unknown origin (all in Northern Sweden), and in the iron ores in the Misi area (in Northern Finland). Furthermore, in the skarn iron ores phlogopite and serpentine are rather common. All the above mentioned minerals are often

intimately interwoven with the iron oxides and are difficult to separate, and consequently some of the samples analyzed might be contaminated with them. The high content of magnesium found in the above mentioned ores and rocks (table 20) might thus in some cases be due to impurities of magnesium-bearing silicates. To a certain degree also the manganese contents found in the analyses can be due to the admixed dark silicates. As seen from table 2 these minerals usually contain some manganese. In the skarn iron ores and the stratified iron ores manganese-rich silicates are occasionally encountered (p. 33). From table 2 it is also evident that the content of chromium and nickel in the dark silicates, especially the pyroxenes, is relatively high, and if these minerals are admixed with the iron oxides they can affect the analytical results of these elements, giving too high values. The content of titanium, cobalt, copper, zinc, and vanadium in the dark silicates is too low to be given any consideration in this connection.

In order to find out if the content of magnesium and manganese obtained by the spectrochemical analysis is due to contaminations of dark silicates or if it is really sited in the lattice of the iron oxides, six samples of magnetite from skarn iron ore, stratified iron ore, and iron ore of unknown origin which are rather high in magnesium and partly in manganese, were investigated by a microprobe at the laboratory of the Geological Survey. The analytical values obtained by this method (table 3) have an error of ± 20 per cent. From the table it is seen that there is a good agreement between the contents obtained by spectrochemical analysis and microprobe analysis. This means that in the 6 magnetite samples investigated the magnesium and manganese content found by the spectrochemical analysis is really sited in the magnetite and is not due to contaminations of magnesium-manganese-bearing silicates. It is interesting to note that the microprobe analysis shows that in some of the samples taken from the skarn iron ores there are relatively great variations in the magnesium content meaning that the magnetite in this type of ore is heterogeneous in composition.

Pyrite and pyrrhotite occur with magnetite in relatively large amounts in the skarn iron ores, in some of the stratified iron ores, in the iron ores Altavaara and Killingi (both of unknown origin), in the leptite at Nautanen (all in Northern Sweden), and in the iron ores of the Misi area. These sulphides are usually accompanied by small amounts of chalcopyrite. The content of certain trace elements which are known to enter these sulphides is given in table 4 and from this it is seen that the content of cobalt and nickel in pyrite and pyrrhotite is sometimes relatively high. If the separation of the magnetite is incomplete and sulphides remain in the sample, the figures of these elements in the analyses may be too high. It has already been pointed out by the present author (Frietsch 1966, p. 272) that the content of cobalt in the magnetite in the skarn iron ore at Stora Sahavaara (table 8) is directly related to the con-

Table 2. The content of some elements in pyroxene, amphibole and biotite according to current literature

Author	p. p. m. of							
	Cr	Ti	Ni	Co	Cu	Zn	V	Mn
<i>Orthopyroxene</i>								
Ishimori (1950)	2800							
Ross et al. (1954)	2500-4500	20-2000	400- 800	40- 80			30- 100	600-1600
Howie (1955)	<2- 300		8- 650	25-100			10- 200	2000-8000
Sen et al. (1959)	4- 140		<3- 60	12- 85			<5- 200	
Turekian & Carr (1960) ..	93-1650		310-10000					
<i>Clinopyroxene</i>								
Lundegårdh (1946)	5	<100	50	130			300	
Ishimori (1950)	34-3000							
Wager & Mitchell (1951)	<1-3000		<1- 200	15- 60	<10-1000		<5- 300	1500-6000
Wedepohl (1953)						19- 79		
Howie (1955)	10- 800		10- 650	25- 65			25- 400	600-3700
Storm & Holland (1957) ..			8- 123					
Nesterenko et al. (1958) ..	10- 30		30	40			50	
Sen et al. (1959)	15- 500		<3- 55	40- 60			200- 480	
Turekian & Carr (1960) ..	215-1800		380- 1400	74-118				
<i>Amphibole</i>								
Wedepohl (1953)						250-1600		
Howie (1955)	10- 650		15- 1000	25- 70			80- 600	300-1850
Sen et al. (1959)	2- 370		<3- 80	12- 45			90-1000	
Tauson & Kravchenko (1960)						8- 710		
<i>Biotite</i>								
Howie (1955)	15- 75		35- 65	35- 50			75- 350	850
Nesterenko et al. (1958) ..	100		100	40			100	
Sen et al. (1959)	5- 125		<5- 90	15- 70			55- 400	
Engel & Engel (1960)	100- 350		40- 120	25- 55	9- 160		200- 700	60-2000

Table 3. The content of magnesium and manganese in magnetite in some iron ores in Northern Sweden determined by spectrochemical analysis and microprobe analysis

Sample No.	Type of ore	Locality	Spectrochemical analysis		Microprobe analysis	
			% MgO	% MnO	% MgO	% MnO
1361	Skarn iron ore	Haren	5.0	0.025	4.3	0.07
1354	Skarn iron ore	Junosuando	4.5	0.125	5.3-6.2	0.22
1320	Skarn iron ore	Pellivuoma	4.5	0.625	3.8	0.77
1318	Skarn iron ore	Salmivaara	8.5	0.05	5.7-8.5	0.14
1305	Stratified iron ore	Tornefors	3.5	0.45	5.9	0.21
903	Iron ore of unknown origin	Puoltsa	2.9	0.11	5.6	0.13

tent of these sulphides as shown by the sulphur content in the analyses (*ibid.*, table 33).

Summarizing the above it can be concluded that impurities in the iron oxide samples due to incomplete separation can effect the analytical results for certain elements. If quartz and feldspar are present in the samples of the iron oxides, lower values than the true ones are obtained for all elements besides strontium and barium, the content of which may be higher due to presence of feldspars. If dark silicates are present as impurities in the samples, higher values than the true ones are found in the analyses for magnesium and to a lesser degree for manganese, chromium, and nickel. The presence of pyrite and pyrrhotite means too high contents of cobalt and nickel in the analyses. This matter will be further discussed in a review of the different trace elements in the iron oxides analyzed.

To obtain an estimate of how the minerals admixed with the iron oxides affect the analytical values for the different elements, 11 samples have first been analyzed and then the separated iron oxides in each. The results are shown in table 5, where the ratio between the content of the different elements in the iron oxide and the ore or rock has been calculated. It must, however, be pointed out that the ratios in the table for the different deposits are not directly comparable as the content of the iron oxides in the ore or rock is rather different, the apatite iron ores having the highest iron content. From the table it is obvious that complete separation is necessary to obtain fair values for the content of the trace elements in the iron oxides. If this is not done, erroneous values may be the result. As might be expected the content of SiO_2 , Al_2O_3 , CaO , Mg , Mn , Sr , and Ba decreases when a separation is made. For the samples from Kiirunavaara and Junosuando there is however a higher value for manganese in the magnetite than in the unseparated ore. The increase of barium in the hematite from Skåukemjokk as compared to the whole ore is due to an enrichment of barite accompanying the hematite in

Table 4. The content of some elements in pyrite, pyrrhotite and chalcopyrite taken from current literature

Author	p. p. m. of					
	Cr	Ti	Ni	Co	V	Mn
<i>Pyrite</i>						
Gavelin & Gabrielson (1947) ..			<10(1000)	<100(4000)		100-900
Fleischer (1955)		0-200(600)	0-100(25000)	0-500(>25000)	0-50(1000)	0-10(1000)
Nesterenko et al. (1958)			30	70		
Hawley & Nichol (1961)	12-160	96-1450	11-2500	310-13300	55	
<i>Pyrrhotite</i>						
Gavelin & Gabrielson (1947) ..			<10(850)	<10(2000)		100-900
Fleischer (1955)			0-200(74700)	0-200(8500)		0-500(3000)
Nesterenko et al. (1958)			30	50		
Hawley & Nichol (1961)	8- 27		10-16500	72-1500	94-100	
<i>Chalcopyrite</i>						
Gavelin & Gabrielson (1947) ..			<10(100)	<10(1000)		<100
Fleischer (1955)			0-10(2000)	0(2000)		0-50(20000)
Nesterenko et al. (1958)			10	60		
Hawley & Nichol (1961)	9- 79	57-310	7-370	55-490	55	

Figures in parenthesis denote a maximum value compared to the usual value.

Table 5. The ratio between the content of some elements in magnetite and hematite and the whole ore or rock

Type of ore or rock	Locality	Sample No.	Mineral	SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo
Apatite iron ore	Henry	1380	Hematite	0.5	0.5	<0.8	(1)	(1)	1	1	0.7	1.4	1	(1)	1.3	1.2	0.7	1
Apatite iron ore	Kiirunavaara	1385	Magnetite	1	1	(1)	(1)	6	1.3	<0.06	(1)	1.3	1.7	(1)	1.5	1.5	3	>1
Apatite iron ore	Nakerivaara	1211	Magnetite					0.4	1.9			1.3	1.9	(1)	1.8			
Apatite iron ore	Nakerivaara	1213	Magnetite					0.4	1			1.3	1.9	(1)	1.5			
Apatite iron ore	Nakerivaara	1214	Magnetite					0.5	1.6			1.2	1.8	(1)	1.8			
Iron ore of Hauki type	Skåukemjokk	1372	Hematite	(1)	0.5	(1)	(1)	(1)	(1)	3	1	(1)	(1)	(1)	3	2.5	(1)	0.5
Skarn iron ore	Junosuando	1360	Magnetite	0.6	(1)	0.5	1	1.8	(1)	>1	>1	0.5	0.3	(1)	2	0.5	0.5	(1)
Skarn iron ore	Rautuvaara	1387	Magnetite	<0.3	0.6	0.2	0.3	1	1	(1)	>1	1.2	1.2	>1	1.5	0.7	0.7	(1)
Iron ore of unknown origin	Altavaara	832	Magnetite									1.5	1.3		1.5			
Syenite-porphry	Ekströmsberg	1369	Magnetite	(1)	(1)	1	0.8	<1	1	0.7	1	2	2	2.3	1.7	4	>1	(1)
Syenite-porphry	Hopukka	1376	Magnetite	(1)	(1)	<0.5	0.7	(1)	1	0.7	0.5	>1	1.3	(1)	1.1	0.5	(1)	(1)

Figures in parentheses denote that the contents in both the separated iron oxide and the whole ore or rock are below (above) the lower (upper) limit of the sensitivity of the determination.

the separation. Nickel, cobalt, and vanadium are more concentrated in the iron oxides than in the whole ore or rock. In the sample from Junosuando there is less nickel and cobalt in the magnetite than in the ore. This is most likely due to the fact that the admixed sulphides (mostly pyrite) are removed by the separation causing a decrease in the content of these elements. The content of titanium is not changed by the separation but in some samples the element may be enriched in the magnetite phase. For copper, zinc, and molybdenum the ratios are ambiguous and no conclusions can be drawn.

3. ORES AND ROCKS INVESTIGATED

3.1. Northern Sweden

3.1.1. APATITE IRON ORES

The apatite iron ores in Northern Sweden, or ores of the Kiruna type as they are also called, consist of magnetite and less commonly of hematite. Magnetite is the primary mineral from which hematite has been formed by oxidation. The content of phosphorus represented by apatite is usually quite high, up to 1–2 per cent and sometimes 4–5 per cent. Occasionally it is rather low (less than 0.1 per cent). Tremolite-actinolite and diopside usually occur in small amounts. Apart from these no other minerals are found in amounts worth mentioning. Some deposits are, however, relatively rich in calcite. The content of titanium (mostly as sphene but occasionally as ilmenite) is less than 0.1 per cent. The ore forms elongated, tabular bodies or occurs as schlieren forming an irregular net-work in the wall rock when it has an intrusive mode of appearance. The wall rocks are volcanics of intermediate or acid composition, more or less metamorphosed. The ore originated, in the opinion of Geijer (1931b, 1935), by a magmatic differentiation in which volatiles played a decisive role. While the main part of the enclosing wall rock crystallized the ore remained in solution and separated as a later phase with low viscosity.

The trace elements in the iron oxides in the following 23 deposits of the apatite iron ores in Northern Sweden have been investigated: Ekströmsberg, Gruvberget, Harrejaure, Haukivaara, Henry, Kiirunavaara, Koskullskulle (part of Malmberget), Leveäniemi, Luopuvara, Luossavaara, Malmberget (Gällivare), Mertainen, Nakerivaara, Nukutus, Painirova, Pattovare, Peräjävaara, Rektorn, Renhagen, Tansari, Tuolluvaara, Tjåorika, and Ylipääsnjaska (fig. 1). All these deposits except Nakerivaara have in common the features given above. In the Nakerivaara deposit the wall rock is a gneissose diorite consisting of oligoclase and hornblende. The trace elements of the iron oxides in these deposits are shown in table 6.

Table 6. The content of some elements in magnetite and hematite in the apatite iron ores in Northern Sweden

Sample No.	Mineral	Weight % of			p. p. m. of												
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo	
1 ¹ Ekströmsberg																	
1362	Magnetite	<1	0.3	0.5	<3000	200	1800	<90	17	140	120	<20	1100	50	100	10	
1367	Magnetite	1	0.4	0.5	<3000	1400	<600	<90	17	120	40	<20	800	40	50	<10	
1367	Hematite	1	0.4	2.5	<3000	<200	<600	<90	51	<20	<20	<20	900	30	50	10	
1368	Hematite	3	0.4	1.0	<3000	<200	4200	<90	17	140	40	<20	900	40	50	10	
2. Gruvberget																	
440 ²	Magnetite	0.20	0.10	1.4	2940	>2400	60			220	110	<10	600				
441 ²	Magnetite	0.10	0.15	1.0	3480	>2400	240			210	130	<10	700				
442 ²	Magnetite	0.30	0.05	0.25	780	1800	60			360	100	<10	350				
439 ²	Magnetite	0.65	0.20	0.65	1200	>2400	600			160	140	<10	950				
444 ²	Magnetite	0.25	0.10	0.10	960	600	600			210	120	<10	1300				
442 ²	Hematite	>3.0	0.25	>3.0	1500	2200	<60			<10	<10	<10	600				
436 ²	Hematite	0.35	0.05	0.75	420	<80	<60			<10	30	<10	350				
437 ²	Hematite	<0.05	0.05	0.85	240	<80	<60			<10	40	<10	400				
432 ²	Hematite	0.45	0.20	0.35	1200	<80	180			10	40	<10	500				
433 ²	Hematite	0.50	0.15	0.50	1260	<80	240			40	40	<10	550				
434 ²	Hematite	0.35	0.20	<0.05	120	<80	<60			<10	40	<10	350				
435 ²	Hematite	0.15	0.15	<0.05	60	<80	180			<10	40	<10	400				
438 ²	Hematite	1.2	0.50	0.40	3000	>2400	780			250	130	<10	200				
443 ²	Hematite	0.65	0.50	0.20	840	<80	540			<10	50	<10	800				
3. Harrejaure																	
1444	Magnetite	<1	<0.1	<0.5	<3000	200	600	<90	<17	290	140	<20	700	20	70	<10	
1444	Hematite	5	0.3	1.0	<3000	<200	15500	<90	<17	20	<20	<20	1000	20	100	10	
1445	Magnetite	<1	0.2	<0.5	<3000	200	600	<90	<17	270	100	<20	800	90	<50	<10	
1446	Magnetite	<1	0.1	<0.5	<3000	600	<600	<90	17	320	80	<20	900	80	80	<10	
1447	Magnetite	<1	<0.1	<0.5	<3000	600	<600	<90	<17	170	70	<20	800	40	90	<10	

Table 6 (continued)

Sample No.	Mineral	Weight % of			p. p. m. of												
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo	
4. Haukivaara																	
630 ³ 1365	Hematite ore Hematite	<1	<0.1	<0.5	<3000	78 <200	900 600				50 40	<10 <20	<10 <20	400 1000		20 <50	20
5. Henry																	
1379	Hematite	2	0.3	<0.5	<3000	<200	1200	360	17	40	<20	<20	1400	50	50	10	
1380	Hematite	1	0.2	8	<3000	<200	2400	90	170	200	80	<20	900	60	300	10	
1380	Hematite ore	2	0.4	>10	<3000	<200	2400	90	240	140	80	<20	700	50	450	10	
1381	Hematite	1	0.3	3.5	<3000	<200	2400	<90	68	90	40	<20	1000	60	150	<10	
6. Kiirunavaara																	
1 ⁴	Magnetite					450				200	130		1300				
2 ⁴	Magnetite					800				170	130		1800				
3 ⁴	Magnetite					800				230	130		2300				
4 ⁴	Magnetite					600				200	130		1400				
1384	Magnetite	1	0.1	1.0	<3000	200	1800	<90	20	230	60	<20	1300	60	100	20	
1385	Magnetite	1	0.3	<0.5	<3000	1200	3000	<90	<17	250	120	<20	1900	60	150	10	
1385	Magnetite ore	1	0.3	<0.5	<3000	200	2400	1530	<17	200	70	<20	1300	40	50	<10	
7. Koskullskulle																	
1441	Magnetite	<1	0.3	<0.5	<3000	400	1800	<90	<17	180	160	<20	1200	10	60	<10	
8. Leveäniemi																	
718 ²	Magnetite	0.45	0.30	0.10	480	400	480			230	110	<10	1050				
719 ²	Magnetite	0.20	0.30	1.5	2100	300	300			230	140	<10	1000				
720 ²	Magnetite	0.20	0.60	0.10	1500	700	1350			200	120	<10	>1500				
721 ²	Hematite	0.20	0.10	1.5	300	<60	300			<10	<10	<10	1150				
722 ²	Hematite	0.80	0.55	1.1	1200	1000	3350			300	70	<10	1500				

9. Luopuvare																
1522	Magnetite	<1	0.5	<0.5	<3000	<200	600	<90	<17	220	60	<20	900	50	<50	<10
1522	Hematite	>10	1.0	<0.5	<3000	<200	12000	400	<17	40	40	<20	1000	70	50	<10
1523	Magnetite	1	0.3	<0.5	<3000	<200	4800	100	<17	70	40	<20	400	20	50	<10
10. Luossavaara																
5 ⁴	Magnetite					400				170	100		1700			
6 ⁴	Magnetite					400				170	100		1300			
7 ⁴	Magnetite					400				230	110		1800			
1386	Magnetite	<1	0.2	1.5	<3000	200	1200	<90	17	200	60	<20	1300	20	100	10
11. Malmberget (Gällivare)																
8 ⁴	Magnetite					500				330	110		1300			
9 ⁴	Magnetite					500				130	130		1300			
10 ⁴	Magnetite					700				180	140		1300			
11 ⁴	Magnetite					400				170	130		2300			
12 ⁴	Magnetite					500				170	130		1100			
12 ⁴	Hematite					800				30	30		300			
13 ⁴	Hematite					900				140	110		1000			
14 ⁴	Magnetite					700				170	130		1300			
14 ⁴	Hematite					900				10	10		200			
1440	Magnetite	<1	0.2	<0.5	<3000	<200	1200	<90	<17	170	100	<20	1600	20	70	<10
1442	Hematite	<1	0.2	<0.5	<3000	<200	<600	540	17	70	<20	<20	650	40	50	10
1443	Magnetite	<1	<0.1	<0.5	<3000	<200	<600	<90	<17	100	110	<20	1000	10	<50	<10
12. Mertainen																
896	Magnetite	0.12	0.14	0.17	540	700	250			220	90		700	10		<10
897	Magnetite	0.13	0.15	0.20	300	600	300			240	100		700	15		<10
898	Magnetite	0.35	0.30	0.40	900	600	1200			220	90		700	100		<10
899	Magnetite	0.45	0.20	0.40	1200	600	1300			220	120		1000	100		<10
900	Magnetite	0.30	0.20	0.50	600	800	700			250	130		800	<10		<10
901	Magnetite	0.40	0.25	0.40	1200	900	1200			230	150		1600	15		<10
13. Nakerivaara																
1211	Magnetite ore					450	630			610	140	<10	1100			
1212	Magnetite ore					450	2300			620	130	<10	1300			
1213	Magnetite ore					380	750			580	100	<10	1100			

Table 6 (continued)

Sample No.	Mineral	Weight % of			p. p. m. of											
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo
13. Nakerivaara (continued)																
1211	Magnetite	<1	0.3	<0.5	<3000	200	1200	<90	17	800	260	<20	2000	60	150	<10
1213	Magnetite	3	1.0	<0.5	12000	200	2400	<90	17	800	260	<20	2000	20	100	10
1214	Magnetite	<1	0.3	<0.5	6000	200	1200	90	17	700	180	<20	2000	40	100	<10
14. Nukutus																
887 ³	Magnetite ore					400	1800			140	60	<10	800			
1378	Magnetite	1	0.2	1.5	<3000	<200	600	<90	17	180	120	20	1000	40	50	30
15. Painirova																
892	Magnetite	0.30	0.18	1.0	480	500	500			200	60		1400	280		<10
893	Magnetite	0.65	0.55	0.45	2100	600	900			200	90		1700	30		<10
894	Magnetite	0.85	0.35	1.0	1380	500	900			200	100		1400	70		<10
895	Magnetite	0.60	0.28	0.85	1080	500	700			170	80		1300	15		<10
16. Pattovare																
1448	Magnetite	<1	0.1	<0.5	<3000	400	<600	<90	<17	270	180	<10	1850	10	<50	<10
1449	Magnetite	<1	0.2	<0.5	<3000	400	<600	<90	<17	140	130	<10	2100	10	<50	<10
17. Peräjävaara																
1286	Magnetite	4	0.3	4	<3000	200	6000	90	85	170	100	<20	1500	20	200	<10
1287	Hematite	8	0.2	0.5	<3000	200	5400	<90	<17	140	100	<20	1500	10	100	<10
18. Rektorn																
888 ³	Magnetite ore					650	420			160	50	<10	900			
1363	Magnetite	1	0.5	<0.5	<3000	<200	3000	90	<17	560	20	<20	1400	40	50	10
1363	Hematite	8	2.2	2	6000	1000	3600	180	17	30	120	<20	1300	20	50	<10
1364	Hematite	<1	<0.1	<0.5	<3000	<200	4800	<90	<17	<20	<20	<20	1700	20	<50	20

19. Renhagen																
1519	Magnetite	3	0.3	<0.5	<3000	800	1200	<90	34	80	40	<20	500	20	<50	<10
1520	Magnetite	3	0.2	1.0	<3000	800	2400	<90	<17	80	100	<20	500	20	100	<10
1521	Magnetite	4	1.2	<0.5	<3000	1000	4800	<90	<17	80	60	<20	600	180	50	20
20. Tansari																
428 ²	Magnetite	0.20	0.10	0.15	180	300	1150			170	120		1200			
429 ²	Magnetite	1.1	0.30	0.80	900	600	5350			210	140	<10	>1500			
430 ²	Magnetite	0.60	0.20	0.50	720	500	4500			220	120	<10	>1500			
431 ²	Magnetite	0.35	0.15	0.45	780	200	1500			190	90	<10	1400			
21. Tuolluvaara																
1437	Magnetite	<1	0.1	<0.5	<3000	<200	600	<90	<17	260	100	<20	1350	30	350	>10
1438	Magnetite	<1	0.2	<0.5	<3000	200	1200	<90	<17	310	190	<20	600	30	150	<10
1439	Magnetite	<1	0.2	<0.5	<3000	<200	<600	<90	<17	180	100	<20	900	25	100	<10
22. Tjåorika																
1450	Magnetite	<1	<0.1	<0.5	<3000	600	600	<90	<17	100	80	<20	800	<10	<50	<10
1451	Magnetite	<1	<0.1	<0.5	<3000	200	1200	<90	<17	90	50	<20	500	10	<50	<10
23. Ylipääsnjaska																
1464	Magnetite	3	0.9	<0.5	<3000	1800	1800	90	17	240	120	20	2500	70	100	<10
1465	Magnetite	2	0.6	<0.5	<3000	1400	<600	<90	17	60	20	<20	1800	50	50	<10

¹ Refers to the number in fig. 1.² Previously published by Frietsch (1966), table 32.³ Ibid., table 40.⁴ Previously published by Landergren (1948), table 31.

3.1.2. IRON ORES OF THE HAUKI TYPE

Related to the apatite iron ores are some economically unimportant hematite deposits of hydrothermal, metasomatic origin. These represent a later stage in the magmatic differentiation that gave rise to the main mass of the deposits of the Kiruna type. They formed at lower temperatures and were accompanied by a greater amount of volatiles than the apatite iron ores. The first member of this type to be described was found in the Lower Hauki series NE of Kiruna, hence the name of the Hauki type used in this paper.

This type of ore is encountered in six deposits: Ainasjärvi, Haukivaara, Kuosatjsvare, Larkimvare, Pidjastjåkko, and Skåukemjokk (fig. 1). It is also possible that part of the Leppäkoski iron deposit belongs to this type (p. 38). The ore is made up of hematite but in Ainasjärvi magnetite is also encountered. In the opinion of the author (Frietsch 1967a, p. 10) the hematite is in most cases probably of primary origin and not secondary as in the apatite iron ores. The content of phosphorus and sulphur in the ore is very low. Evidence for the hydrothermal origin of the ore is based on the fact that the ore is always accompanied by metasomatic alteration of the acidic or intermediate volcanic host rock. The metasomatic alteration leads to the formation of quartz, sericite, chlorite, and calcite together with small or accessory amounts of barite, fluorite, allanite, tourmaline, and zircon. These minerals are also encountered in the ore but to a lesser degree. The ore occurs as small elongated bodies or as tiny veinlets intruding the host rock. In some cases the ore replaces the host rock. The deposits differ somewhat from each other in mode of appearance and mineralogical composition as is evident from the descriptions given below.

Ainasjärvi is made up of a breccia which the present author (Frietsch 1966, p. 268) considers to be of tectonic origin. The ore minerals are thought to be metasomatic. The matrix in the breccia consists of magnetite, hematite, quartz, and biotite together with small amounts of tourmaline and allanite. The wall rock is an albite porphyrite which occurs as almost totally silicified fragments in the breccia. Adjacent to the hematite-bearing part of the breccia (but not the magnetite-bearing part) the porphyrite is sericitized. The tectonic brecciation of the porphyrite facilitated circulation of the ore-bearing solutions and metasomatic alteration of the host rock.

The hematite ore bodies at *Haukivaara*, NE of Kiruna, occur in the Lower Hauki series here represented by strongly schistose syenite-porphyrines and sericite quartzites. These rocks are often fragment-bearing and breccia-like in appearance. They are completely altered and consist of quartz and sericite with subordinate amounts of chlorite and calcite. In small or accessory amounts occur apatite, sphene-leucoxene, tourmaline, allanite, barite, and fluorite. The ore forms small lenses in the sericite quartzites and follows the schistosity of the rock. The ore is a fine-grained, schistose hematite with small

Table 7. The content of some elements in hematite and magnetite in the iron ores of the Hauki type in Northern Sweden

Sample No.	Mineral	Weight % of			p. p. m. of											
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo
24. Ainasjärvi																
723 ¹	Magnetite	3.0	>1.0	0.35	1800	500	1800			170	60	130	500			
724 ¹	Hematite	3.0	0.35	<0.05	120	<80	1250			<10	<10	20	<50			
25. Haukivaara																
629 ²	Hematite ore					80	1320			<10	<10	20	<50			
1366	Hematite	1	0.1	<0.5	<3000	<200	<600	90	<17	<20	<20	20	<50	10	<50	10
1377	Hematite	10	0.2	<0.5	<3000	<200	<600	450	17	<20	<20	20	100	70	<50	20
26. Kuosatjvare																
1292	Hematite	>10	>3	<0.5	<3000	<200	1200	>7200	170	<20	<20	<20	<50	90	<50	<10
27. Larkimvare																
1528	Hematite	3	0.3	<0.5	<3000	<200	<600	180	<17	<20	<20	<20	<50	50	<50	<10
28. Pidjastjåkko																
1371	Hematite	8	1.0	<0.5	<3000	<200	1200	90	51	<20	<20	<20	50	80	<50	10
29. Skåukemjokk																
1372	Hematite	>10	0.1	<0.5	<3000	<200	<600	270	17	<20	<20	<20	300	50	<50	10
1372	Hematite ore	>10	0.2	<0.5	<3000	<200	<600	90	17	<20	<20	<20	100	20	<50	20

¹ Previously published by Frietsch (1966), table 32.

² Ibid., table 40.

fragments of the sericite quartzite. Admixed with the hematite is quartz and sericite and occasionally chlorite. Accessory minerals include tourmaline, barite, allanite, and zircon. The ore bodies and the alteration of the wall rock are considered by Geijer (1931b, 1935) to be due to a late stage hydrothermal process in the magmatic activity that gave rise to the apatite iron ores at Kiirunavaara and Luossavaara.

Kuosatjvare (Kuosajs) has previously been described by Geijer (1931a) and Frietsch (1966). It has a conglomerate- or breccia-like appearance with fragments of hematite, silicified porphyry, quartz and sericite schist. The matrix consists of quartz, hematite, muscovite and occasionally barite, tourmaline, zircon, and an allanite-like mineral. According to Geijer *Kuosatjvare* is a clastic deposit representing an accumulation of material derived from an ore similar to those at Haukivaara. In spite of the fact that the ore at *Kuosatjvare* is conglomerate-like in appearance it cannot be ruled out that it has a tectonic origin and that the ore formation is related to this. Immediately north of the deposit runs a big fault stretching NW-SE and it is possible that the mineral association in *Kuosatjvare* can be related to this huge tectonic zone.

The *Larkimvare* ore occurs as veins measuring up to 1 dm across in a somewhat sericitized, quartz-bearing porphyry. These veins have sharp contacts with the wall rock. The ore mineral is hematite and occurs mainly as euhedral grains up to 0.5 mm in size and partly with the form of octahedra. The hematite also contains small, irregular remnants of magnetite, which together with the octahedral form of the hematite grains probably indicate that magnetite was the primary mineral.

The ore at *Pidjastjåkko* (Frietsch 1967a, p. 12) is made up of small, fine-grained hematitic lenses in a quartz-bearing porphyry. The border between the ore and the host rock is mostly sharp but may be diffuse when the ore replaces the host rock. The porphyry shows a varying degree of alteration with the formation of sericite, quartz, and fluorite. Tourmaline, allanite, and zircon occur in accessory amounts. In the hematite all the minerals mentioned, except tourmaline and zircon, are encountered.

Skåukemjokk (Skuokimjokk) described by Geijer (1931a) and Frietsch (1967a, p. 12) forms a small body of fine-grained, partly siliceous hematite in a quartz-bearing porphyry. The host rock is partly crushed and has undergone metasomatic alteration including the formation of sericite and quartz. An argillitic alteration product is also encountered.

The trace elements in the iron oxides of the iron ores of the Hauki type are given in table 7.

3.1.3. SKARN IRON ORES

The skarn iron ores in Northern Sweden form lenses concordant with the strike of the host rocks. The latter consist of sediments and basic volcanics. In many deposits the ore is associated with limestone. The ore mineral is

Table 8. The content of some elements in magnetite and hematite in the skarn iron ores in Northern Sweden

Sample No.	Mineral	Weight % of			p. p. m. of												
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo	
30. Alpha																	
445 ¹	Magnetite	0.85	0.45	0.70	960	1000	1300			<10	10	20	50				
31. Haren																	
1361	Magnetite	5	1	<0.5	30000	200	600	<90	<17	30	60	40	300	120	<50	<10	
32. Isovaara (Masugnsbyn)																	
1315	Magnetite	6	0.4	1.5	15000	1600	1200	<90	<17	40	60	<20	900	50	200	10	
33. Junosuando (Masugnsbyn)																	
1354	Magnetite	3	<0.1	<0.5	27000	1000	<600	<90	<17	<20	80	<20	100	70	100	<10	
1360	Magnetite	3	<0.1	1.0	21000	1400	<600	90	17	20	100	<20	100	250	50	<10	
1360	Magnetite ore	5	<0.1	2	21000	800	<600	<90	<17	40	400	<20	50	500	100	<10	
1498	Magnetite	<1	<0.1	<0.5	6000	600	<600	<90	<17	<20	40	<20	200	20	<50	<10	
1499	Magnetite	1	<0.1	<0.5	6000	400	<600	<90	<17	60	40	40	200	140	<50	<10	
1500	Magnetite	3	<0.1	<0.5	9000	200	<600	<90	<17	180	150	<20	900	220	50	<10	
1501	Magnetite	<1	0.2	<0.5	<3000	800	<600	<90	<17	90	80	<20	600	50	50	<10	
34. Juolovanjärvet																	
1352	Magnetite	1	0.4	<0.5	<3000	400	1800	90	<17	60	100	20	300	50	100	<10	
35. Kallokajärvi																	
1374	Magnetite	1.0	0.6	<0.5	<3000	<200	600	<90	<17	40	120	200	300	50	100	<10	
36. Karhujärvi																	
1460	Magnetite	<1	0.7	<0.5	9000	800	1200	<90	<17	60	140	30	400	25	100	<10	
1461	Magnetite	2	0.7	<0.5	15000	1000	1800	<90	<17	20	140	40	300	30	100	<10	

Table 8 (continued)

Sample No.	Mineral	Weight % of			p. p. m. of												
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo	
37. Keskinen Käyrävaara																	
1452	Magnetite	2	0.3	<0.5	6000	1200	<600	<90	<17	40	40	<20	200	40	90	<10	
1453	Magnetite	1	0.3	<0.5	<3000	<200	<600	<90	<17	60	30	<20	150	10	50	<10	
38. Kevus (Lannavaara)																	
1493	Magnetite	1	0.7	<0.5	3000	2200	<600	<90	<17	100	20	100	300	20	<50	<10	
1494	Magnetite	1	0.6	<0.5	<3000	3200	600	<90	<17	80	40	20	200	20	<50	<10	
39. Kiilavaara																	
448 ¹	Magnetite	0.60	0.40	0.15	7200	400	600			<10	80	<10	50				
40. Koivujärvi																	
447 ¹	Magnetite	0.45	0.55	0.30	840	1400	3000			20	50	20	350				
41. Kulleri																	
1012 ¹	Magnetite	2.0	0.60	0.10	>12000	500	1800			<10	20	<10	>1500				
42. Kuusi Nunasvaara																	
1308	Magnetite	>10	1.7	4.0	<3000	1000	1800	90	51	50	100	230	150	30	200	10	
43. Laukujärvi																	
1321	Magnetite	2	0.6	4.0	6000	400	1200	90	34	360	210	<20	2300	20	250	<10	
1322	Hematite	6	0.8	<0.5	30000	1000	<600	90	<17	80	400	<20	200	50	100	10	
44. Louvinjunanen (Älvgruvan)																	
1454	Magnetite	<1	0.2	<0.5	<3000	400	1200	<90	<17	220	60	<20	1000	10	50	<10	
1455	Magnetite	<1	0.1	<0.5	<3000	200	600	<90	<17	120	30	<20	1000	20	<50	<10	

45. Maattavaara																
1482	Magnetite	3	0.5	<0.5	<3000	400	<600	<90	<17	140	60	20	100	70	50	<10
46. Mänty Vathanvaara																
1310	Magnetite	5	0.7	1.5	6000	800	1200	<90	<17	40	20	70	400	30	100	10
47. Njuotjamavare																
1313	Magnetite	4	0.2	<0.5	24000	1200	<600	<90	<17	60	60	<20	50	20	50	<10
1314	Magnetite	3	0.3	<0.5	6000	1200	<600	<90	<17	20	40	<20	<50	30	50	10
48. Nunasjärvenmaa																
1312	Magnetite	7	0.6	0.5	9000	<200	<600	<90	<17	20	40	<20	50	150	100	<10
49. Nälkävuoma																
1468	Magnetite	1	0.4	<0.5	<3000	400	<600	<90	<17	340	60	420	1600	40	50	<10
50. Paljasjärvi																
1458	Magnetite	<1	0.2	<0.5	<3000	200	600	<90	<17	220	100	<20	900	<10	50	<10
1459	Magnetite	<1	0.2	<0.5	<3000	<200	600	<90	<17	200	80	<20	800	10	<50	<10
51. Pellivuoma																
1320	Magnetite	4	0.1	<0.5	27000	4900	<600	360	17	20	60	<20	<50	130	100	<10
52. Rakkurijoki																
1383	Magnetite	3	0.3	<0.5	12000	200	600	<90	<17	220	160	120	1900	50	100	<10
53. Rakkurijärvi																
1382	Magnetite	1	<0.1	<0.5	12000	200	600	<90	<17	80	40	20	200	30	50	<10

Table 8 (continued)

Sample No.	Mineral	Weight % of			p. p. m. of											
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo
54. Salmivaara																
1318	Magnetite	8	1.3	<0.5	51000	400	1200	<90	<17	<20	100	50	250	200	50	<10
1319	Magnetite	7	0.7	<0.5	42000	200	1200	<90	<17	<20	70	<20	150	400	<50	10
55. Sattavaara (Lannavaara)																
1353	Magnetite	2	0.8	1	6000	4900	<600	90	17	<20	20	<20	200	220	100	<10
56. Sautusvaara																
1280	Magnetite ore					310	1200			130	150	50	60			
1281	Magnetite ore					350	1000			80	150	50	170			
1282	Magnetite ore					390	1800			50	160	60	70			
1284	Magnetite ore					310	1500			150	20	70	550			
1477	Magnetite	1	0.4	<0.5	<3000	<200	<600	<90	<17	20	40	20	200	20	50	<10
1479	Magnetite	<1	0.2	<0.5	<3000	<200	<600	<90	<17	240	80	40	1800	20	<50	<10
57. Sekkujoki																
401	Magnetite ore					700				50	70	10	570	<100	<100	<10
1483	Magnetite	<1	0.2	<0.5	<3000	200	<600	<90	<17	100	60	<20	1300	50	50	<10
58. Stora Sahavaara (Kaunisvaara)																
815 ²	Magnetite	0.7	0.15	0.18	14400	300	<60			20	60	<10	<50	10	50	<10
816 ²	Magnetite	1.1	0.15	0.05	12000	800	<60			30	50	<10	<50	80	100	<10
817 ²	Magnetite	0.8	0.25	<0.01	12600	1000	600			20	190	30	<50	90	50	<10
818 ²	Magnetite	1.1	0.25	<0.01	18000	1000	<60			30	150	<10	<50	120	50	<10
819 ²	Magnetite	1.3	0.20	0.14	14400	800	200			80	140	20	200	160	50	<10
820 ²	Magnetite	1.4	0.20	0.15	7800	400	100			30	60	<10	150	60	<50	<10
821 ²	Magnetite	2.3	0.50	1.4	2400	500	500			80	20	<10	100	45	50	<10
822 ²	Magnetite	0.9	0.25	0.04	15000	>2400	1200			70	60	40	<50	25	50	<10
823 ²	Magnetite	0.8	0.25	0.04	18000	1000	500			30	40	<10	150	25	150	<10

824 ²	Magnetite	1.5	0.20	0.14	18600	500	350			50	190	30	50	90	50	<10
825 ²	Magnetite	1.5	0.25	0.50	8400	1600	300			30	<10	30	<50	85	50	<10
826 ²	Magnetite	1.0	0.50	0.09	15000	800	150			40	190	70	50	60	50	<10
827 ²	Magnetite	1.0	0.20	0.10	18600	400	<60			20	80	<10	50	40	100	<10
59. Suksivuoma																
1462	Magnetite	<1	0.3	0.5	<3000	<200	1200	<90	17	300	80	<20	1200	30	100	<10
1463	Magnetite	3	0.1	1.5	<3000	<200	1800	<90	51	260	60	<20	1100	20	100	<10
60. Svanbolandet																
1311	Magnetite	<1	0.1	<0.5	<3000	1000	600	<90	<17	60	50	140	800	70	100	<10
61. Södra Sahavaara (Kaunisvaara)																
1491	Magnetite	2	<0.1	<0.5	18000	800	<600	<90	<17	<20	80	<20	<50	20	50	<10
1492	Magnetite	<1	<0.1	<0.5	<3000	800	<600	<90	<17	60	60	<20	50	10	50	<10
62. Tapulivuoma (Kaunisvaara)																
1489	Magnetite	<1	0.1	<0.5	<3000	200	<600	<90	<17	290	140	<20	700	20	50	<10
1490	Magnetite	<1	<0.1	<0.5	9000	200	<600	<90	<17	140	120	<20	400	10	<50	<10
63. Teltaja (Lannavaara)																
1495	Magnetite	<1	0.2	<0.5	<3000	1600	<600	<90	<17	90	50	<20	300	10	<50	<10
1496	Magnetite	1	0.1	<0.5	<3000	5000	<600	90	<17	370	100	20	600	20	50	<10
1496	Hematite	4	0.4	<0.5	<3000	400	1800	90	<17	20	<20	<20	900	60	50	<10
1497	Magnetite	<1	0.1	<0.5	<3000	2200	<600	<90	<17	<20	20	<20	200	20	50	<10
64. Tjavelk																
1316	Magnetite	6	0.4	<0.5	27000	800	600	<90	17	150	80	<20	1900	170	100	<10
1317	Magnetite	10	0.3	<0.5	36000	1000	600	<90	17	340	200	<20	1200	375	<50	<10
65. E. Tjärrojåkka																
1524	Magnetite	2	0.4	<0.5	<3000	200	4800	<90	<17	260	100	<20	2100	20	50	<10
1525	Magnetite	2	0.4	<0.5	<3000	<200	1800	<90	<17	270	120	<20	2100	30	50	<10

Table 8 (continued)

Sample No.	Mineral	Weight % of			p. p. m. of												
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo	
66. Tjärro																	
1456	Magnetite	<1	0.1	<0.5	<3000	200	1200	<90	<17	190	80	50	1200	20	50	<10	
1457	Magnetite	<1	0.2	<0.5	<3000	1000	2400	<90	<17	300	120	100	1400	20	100	10	
67. Toppi																	
1529	Magnetite	2	<0.1	0.5	<3000	400	<600	<90	<17	40	<20	<20	<50	30	<50	<10	
68. Valkkijoki																	
1469	Magnetite	1	0.3	<0.5	<3000	600	1200	<90	<17	30	20	140	700	120	50	<10	
69. Vathanvaara																	
1309	Magnetite	10	1	1	6000	200	600	180	17	30	30	<20	600	110	50	<10	
70. Venetvuoma																	
1466	Magnetite	1	0.1	<0.5	6000	800	600	<90	17	20	40	<20	50	30	100	<10	
1467	Magnetite	<1	1	<0.5	<3000	600	600	<90	<17	30	<20	<20	<50	110	50	<10	
71. Vieto																	
1487	Magnetite	<1	0.3	<0.5	<3000	600	<600	90	<17	80	50	<20	2800	30	50	<10	
1488	Magnetite	<1	0.2	<0.5	<3000	200	1200	<90	<17	110	40	<20	2300	10	50	<10	

¹ Previously published by Frietsch (1966), table 32.

² The values for Mn, Ti, Ni, Co, Cr and V previously published by Frietsch (1966), table 33.

magnetite whilst hematite is almost totally lacking. The content of phosphorus occurring as apatite is as a rule lower than 0.1 per cent but reaches this value in some deposits and very exceptionally amounts to values between 1 and 2 per cent. The sulphur content, which is bound up in pyrite, pyrrhotite, and to a small extent chalcopyrite, is usually higher than 1 per cent. The ore is accompanied by dark silicates rich in calcium and magnesium or magnesium, the most common minerals being tremolite-actinolite, diopside, phlogopite, and serpentine. In the Sattavaara deposit the silicates are manganese-bearing and here fayalite also occurs. An interlayering of magnetite and dark silicates is a rather common feature in the ore. The skarn iron ores have, by Geijer (1918b, 1929, 1931a, 1935 and Geijer & Magnusson 1952), been considered pyrometasomatic. A sedimentary origin has, however, been postulated by T. Eriksson (1954), Ödman (1957), and Frietsch (1966, 1967b).

The following 42 skarn iron ore deposits have been investigated: Alpha, Haren, Isovaara, Junosuando, Juolovanjärvet, Kallokajärvi, Karhujärvi, Keskinen Käyrävaara, Kevus, Kiilavaara, Koivujärvi, Kulleri, Kuusi Nunasvaara, Laukujärvi, Luovinjunanen (Älvgruvan), Maattavaara, Mänty Vathanvaara, Njuotjamavare, Nunasjärvenmaa, Nälkävuoma, Paljasjärvi, Pellivuoma, Rakkurijoki, Rakkurijärvi, Salmivaara, Sattavaara, Sautusvaara, Sekkujoki, Stora Sahavaara, Suksivuoma, Svanbolandet, Södra Sahavaara, Tapulivuoma, Teltaja, Tjavelk, E. Tjärrojåkka, Tjärro, Toppi, Valkkijoki, Vathanvaara, Venetvuoma, and Vieto (fig. 1). Some of these deposits belong to rather long narrow zones of iron ore. Thus Isovaara and Junosuando belong to the Masugnsbyn zone; Stora Sahavaara, Södra Sahavaara, and Tapulivuoma to the Kaunisvaara zone; Kevus, Sattavaara, and Teltaja to the Lannavaara zone. The trace element content of the iron oxides in the skarn iron ores is shown in table 8.

3.1.4. STRATIFIED IRON ORES

The stratified, usually siliceous iron ores in Northern Sweden consist of magnetite and occasionally of hematite. The ore contains pyrite and pyrrhotite in small amounts. In some deposits sulphur contents as high as 5 per cent are encountered. The content of phosphorus is less than 0.1 per cent. The ore minerals are intercalated with quartz and dark silicates rich in iron or in some cases rich in calcium and magnesium. The most common silicates are hornblende, grünerite-cummingtonite, clinoenstatite, hedenbergite, and almandite. Occasionally diopside and phlogopite occur. In the Marjarova and Käymäjärvi deposits (NW of Pajala; not investigated in the present work) a manganese-bearing fayalite is found. The general appearance of the ore is the same as for the skarn iron ores, i. e. the ore forms lenses concordant with the strike of the enclosing basic volcanics and sedimentary rocks. The stratified iron ores are regarded as sedimentary by Geijer (1925, 1929, 1931a), T. Eriksson

Table 9. The content of some elements in magnetite in the stratified iron ores in Northern Sweden

Sample No.	Mineral	Weight % of			p. p. m. of												
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo	
72. Hejka (Tjegelvass)																	
1539	Magnetite	8	1.1	<0.5	<3000	3600	<600	180	51	50	120	90	100	10	50	<10	
73. Jupukka																	
1306	Magnetite	>10	2.1	2.0	24000	3700	2400	360	34	<20	20	40	200	20	100	10	
74. Kallak																	
1297	Magnetite	6	0.5	<0.5	6000	1600	1200	<90	<17	20	40	<20	50	20	100	<10	
1298	Magnetite	>10	0.5	<0.5	<3000	2900	600	90	<17	<20	40	<20	50	30	100	<10	
1299	Magnetite	>10	0.6	0.5	6000	4800	600	90	17	20	60	<20	50	30	200	<10	
75. Käymäjärvi																	
1307	Magnetite	6	0.2	<0.5	<3000	2800	1200	990	<17	40	60	<20	50	20	100	<10	
76. W. Nunasvaara																	
1295	Magnetite	4	1.3	<0.5	<3000	<200	3000	<90	<17	100	40	390	400	40	150	20	
77. Peltovaara																	
1531	Magnetite	3	1.4	<0.5	<3000	200	4200	<90	17	140	60	80	1800	10	50	<10	
1532	Magnetite	3	0.8	0.5	<3000	400	4800	<90	17	220	120	<20	2200	<10	50	<10	
78. Rappen (Tjegelvass)																	
1538	Magnetite	>10	1.7	<0.5	<3000	4800	600	360	34	40	80	60	50	20	250	<10	
79. Rebak (Tjegelvass)																	
1302	Magnetite	4	0.3	<0.5	<3000	2400	<600	90	17	60	140	50	100	70	100	<10	
1303	Magnetite	6	0.7	0.5	<3000	4800	600	<90	17	100	220	240	100	40	150	10	
1537	Magnetite	7	0.8	<0.5	<3000	3300	<600	<90	17	40	80	80	50	10	<50	<10	

80. Ristjäl'n																
1300	Magnetite	3	1.8	<0.5	6000	400	9600	<90	17	270	120	1200	3800	300	300	10
1301	Magnetite	2	1	0.5	6000	1400	5400	<90	17	<20	20	<20	250	20	150	10
81. Sakka (Tjegelvass)																
1533	Magnetite	>10	0.3	<0.5	<3000	2700	<600	<90	<17	20	60	20	<50	<10	350	<10
1534	Magnetite	>10	0.7	1.0	3000	7000	1200	90	17	40	120	100	50	<10	150	<10
1535	Magnetite	7	1.5	1.0	<3000	7200	1800	90	17	80	140	160	100	10	100	<10
82. E. Sautusvaara																
1296	Magnetite	3	0.2	<0.5	<3000	600	<600	<90	<17	90	80	<20	100	60	100	<10
83. Skomern (Tjegelvass)																
1536	Magnetite	7	0.5	<0.5	<3000	3800	600	<90	<17	20	80	<20	<50	<10	100	<10
84. Tornefors																
1304	Magnetite	>10	1.7	<0.5	33000	200	4200	180	<17	<20	80	<20	250	30	50	<10
1305	Magnetite	5	0.4	1.0	21000	3500	600	90	<17	30	70	<20	200	60	150	<10
85. Vuoma (Masugnsbyn)																
1502	Magnetite	<1	0.4	<0.5	<3000	1200	<600	90	<17	90	100	20	50	70	150	<10
1503	Magnetite	<1	0.4	<0.5	<3000	600	600	90	<17	30	100	<20	50	20	50	<10
1504	Magnetite	1	0.4	<0.5	<3000	400	<600	<90	<17	30	60	<20	500	70	50	<10
1505	Magnetite	<1	0.2	<0.5	<3000	600	600	<90	<17	170	20	<20	500	20	100	<10
86. Vähävaara (Masugnsbyn)																
1506	Magnetite	<1	<0.1	<0.5	<3000	3100	<600	90	<17	120	240	<20	50	280	100	<10
1507	Magnetite	<1	<0.1	<0.5	<3000	200	<600	<90	<17	<20	60	200	300	40	50	<10

son (1954), and Ödman (1957). In the opinion of Geijer they are metamorphic chemical sediments, as is indicated by their typical sedimentary appearance and by the occurrence of metamorphosed granules of greenalite or some other iron silicate in the Käymjärvi deposit.

The following 15 deposits belonging to the stratified iron ores have been investigated geochemically in the present work: Hejka, Jupukka, Kallak, Käymjärvi, W. Nunasvaara, Peltovaara, Rappen, Rebak, Ristjäl'n, Sakka, E. Sautusvaara, Skomern, Tornefors, Vuoma, and Vähävaara (fig. 1). Of these, Vuoma and Vähävaara belong to the Masugnsbyn zone and Hejka, Rappen, Rebak, Sakka, and Skomern to the Tjegelvass zone. The trace element content in magnetite in the stratified iron ores is shown in table 9.

3.1.5. IRON ORES AND ROCKS OF UNKNOWN ORIGIN

Iron ore. The three main types of iron ore in Norrbotten, namely apatite iron ore, skarn iron ore, and stratified, siliceous iron ore are distinguished partly on the basis of their mineralogical-chemical composition (the amounts of apatite, dark silicates, sulphides and quartz) partly on the nature of the enclosing host rock. To distinguish the stratified iron ores from the other two types is not difficult as they differ in general appearance and composition from the apatite iron ores and the skarn iron ores. The division between the two latter types is, in most cases, quite clear, but the deposits Altavaara, Killingi, and Puoltsa (fig. 1), show, in some respects, similarities with both the apatite iron ores and the skarn iron ores, and it is not possible to say to which of the two types the deposits should be assigned.

The *Altavaara* deposit has, by Geijer (1931a), been referred to the skarn iron ores, while Ödman (1957) on the map of Norrbotten marked the deposit as an apatite iron ore. The ore, which is covered by glacial drift, is known from older drillings and from drillings made in 1964 by the Geological Survey of Sweden. According to B. Eriksson (1965) it is a lean magnetite ore (the grade not exceeding 30 per cent iron) partly apatite-bearing and partly rich in sulphides (mostly pyrite). To a limited extent the magnetite is accompanied by an amphibole skarn (common hornblende). The wall rock is made up of amphibolites which in part are gneissose. The ore is concordant with the strike of the host rock. The contents of sulphur and phosphorus vary within wide limits. The sulphur content is on an average about 0.4 per cent but sometimes as much as 5 per cent. The content of phosphorus is on an average 0.4 per cent, but occasionally 2 per cent. The ambiguous features of the ore make classification uncertain. The amphibolitic host rock, the concordant appearance of the ore and the occasional high sulphide content point to a skarn iron ore. The relatively high content of phosphorus, however, suggests affinities with an

apatite ore, but in Norrbotten there are some deposits among the skarn iron ores which show a relatively high content of phosphorus. Thus Karhujärvi contains 0.1–0.8 % P (Frietsch 1963), Laukujärvi 0.34 % P (Berglund 1924), Vuoma 0.06–0.2 % P (Frietsch 1963) and Koivujärvi 0.05–0.1 % P (Frietsch 1966). Recent investigations show that the deposits Rakkurijoki and Vieto are to some extent relatively rich in phosphorus. According to P. Forsell (oral communication) the mean phosphorus content in Rakkurijoki is 0.1 per cent but in some parts of the ore body the values vary between 0.1 and 0.3 per cent and occasionally attain 1 to 2 per cent. In Vieto, currently being investigated by diamond drilling, similar phosphorus contents as in Rakkurijoki are found.

An iron ore deposit which is also transitional between the apatite iron ore type and the skarn iron ore type is *Puoltsa*, discovered by the Geological Survey of Sweden in 1960. The ore, which does not outcrop and which is only known from drill-holes, consists of magnetite in amphibole skarn. The skarn occurs disseminated in the magnetite but mainly as huge masses outside the magnetite. The ore is free from sulphides and the content of phosphorus low, less than 0.01 per cent. The wall rock is mainly a syenite-porphiry with some greenstone and granite. The ore forms rather irregular bodies, and the proportion of ore to skarn and wall rock is very variable. The possibility that the deposit belongs to the apatite iron ores is supported by the fact that the wall rock is a syenite-porphiry and that the ore is irregularly distributed in this rock. On the other hand, the ore is free from apatite, a feature which is also known from other apatite iron ores. This is, for example, the case when the main part of the ore forms a breccia, the ore minerals veining the rock ($P < 0.1$ %; Frietsch 1966). But in these ores parts rather rich in apatite are also always found. The possibility that *Puoltsa* belongs to the skarn iron ore type is indicated by the richness in skarn, which is a typical feature for this type of ore, and to some degree by the enclosing greenstone. On the other hand the ore lacks sulphides, which are normally present in the skarn ores.

The *Killingi* deposit is, by Geijer (1931a), assigned to the apatite iron ores, and in his opinion it resembles some varieties in the Malmberget ore field. The wall rock is a coarse gneissose leptite of syenitic character. It is veined by a skarn consisting partly of hornblende, partly of pyroxene, epidote and feldspar. The ore is made up of magnetite intermingled with pyrite, hornblende, and apatite. According to Ibach (1944) the ore forms two lenses with a N-S strike. Analyses of drill-cores gave the following values: 53–61 % Fe, 0.25–0.44 % Mn, 2.20 % CaO, 1.50–2.90 % MgO, 7.02–11.00 % SiO_2 , 1.30–1.70 % TiO_2 , 0.02–2.15 % S, and 0.004–0.62 % P. That the deposit is an apatite iron ore is indicated by the character of the wall rock and the relatively high content of phosphorus (up to 0.62 % P), but as has been mentioned above when discussing the Altavaara ore, there are some skarn iron ores in Norrbotten which have phosphorus contents of this magnitude. The assignment of *Killingi*

to the skarn iron ore group is supported by the rather high content of pyrite and by the richness in skarn.

The above remarks indicate that the deposits Altavaara, Killingi, and Puoltsa from their mineralogical-chemical character and mode of appearance are intermediate between the apatite iron ores and the skarn iron ores. The content of trace elements in magnetite in these deposits is shown in table 10. The conclusions that can be drawn from these values when considering to which of the two types of iron ore the deposits should be assigned are discussed on p. 110.

The *Leppäkoski* deposit (fig. 1) is made up of two types of somewhat different magnetite ore. The following description is based on papers by Petersson (1900) and B. Eriksson (1963). In the northwestern part of the deposit there is an albite porphyrite which is cut by veins of magnetite. Some of these are a few meters wide but most are rather narrow. The ore-bearing zone has, according to Petersson, a width of about 5 meters. Some fissures filled with amphibole, carbonate, and small amounts of sulphides are also encountered. An analysis given by Petersson shows 59.49 % Fe, 0.010 % P, 0.04 % S, and 3.42 % CaCO_3 . In general appearance (magnetite veining the wall rock) the ore is similar to the apatite iron ores. To the southeast there occurs a magnetite-rich, strongly schistose, fragment-bearing rock in which the fragments, mostly rounded, are made up of albite-rich rocks with a varying, often high content of magnetite, fine-grained rocks rich in muscovite, and quartzitic rocks partly rich in magnetite. The albite-rich fragments consist of albite with subordinate amounts of muscovite, biotite, and magnetite. They also contain tourmaline and rutile. The mica-rich fragments consist of albite, quartz, biotite, and muscovite with small amounts of opaque minerals, rutile, zircon, and apatite. The quartzitic fragments contain quartz with magnetite and small amounts of biotite, tourmaline, rutile, and feldspar. The matrix between the fragments consists of magnetite and biotite. Adjacent to the fragment-bearing rock in the eastern part occurs a 2 meters wide, fine-grained hematite which contains small intercalations of jasper quartzite and sometimes aggregates of quartz. An analysis of the hematite given by Petersson shows 52.52 % Fe, 0.038 % P, and 0.06 % S. The wall rocks of the fragment-bearing rock and the hematite are an albite porphyrite (to the east) and sedimentary rocks (to the west). The origin of the ore in this part of the deposit is somewhat uncertain but the occurrence of muscovite and tourmaline in the altered fragments in the fragment-bearing rock and the siliceous hematite points to a metasomatic mode of formation. This is also supported by two chemical analyses of the fragment-bearing rock which show 0.45–0.80 % BaO, probably as barite. The fragment-bearing rock has a conglomerate-like appearance but can also be interpreted as a tectonic breccia. The general appearance and chemical composition is rather similar to some iron ores of the Hauki type (p. 24). If the fragment-

bearing rock in Leppäkoski is a tectonic breccia its existence could, as in the Ainasjärvi deposit belonging to the Hauki type of ore, have facilitated the circulation of the ore-bearing solutions. The geochemical determinations of the Leppäkoski deposit are shown in table 10. The interpretation of the analyses is given on p. 112.

Conglomerate. Conglomerates sometimes contain iron ore pebbles, the origin of which is often rather obscure, especially if they lack distinct mineralogical features. The trace elements of the iron oxides in the pebbles might however be expected to give a hint as to the type of ore from which the pebbles are derived. In the present work hematite pebbles in the conglomerates at Doktors kulle and Saurusvaara (fig. 1) have been investigated geochemically.

The sample from *Doktors kulle* is taken from a 4 to 5 meters thick basal conglomerate in the Upper Hauki series NE of Kiruna. The conglomerate is underlain by the metasomatically altered Lower Hauki series (p. 24) which in turn is underlain by the volcanics which form the host rock of the Kiirunavaara and Luossavaara apatite iron ores. The conglomerate is overlain by a graywacke, a phyllitic slate, and a quartzitic sandstone, all belonging to the Upper Hauki series. The conglomerate is rich in hematite which occurs both in the matrix and in the pebbles. Regarding the origin of the pebbles Geijer (1931a, p. 204) says: "Some of these may be derived from the underlying Hauki hematite ores, but probably a large part comes from exposed and maritized parts of the main ore body of Luossavaara."

At *Saurusvaara* has been met with a conglomerate containing a 0.5 meter thick intercalation rich in hematite occurring both in the matrix and as pebbles up to some decimeters in size. The conglomerate is overlain by quartzitic schist and quartzitic sandstone which show lithological similarities to the rocks in the above mentioned Upper Hauki series. The conglomerate is underlain by volcanics of intermediate composition. The general appearance of this conglomerate is thus similar to that at Doktors kulle.

The trace elements of the hematite in the two conglomerates investigated are shown in table 10, and their significance is discussed on p. 112.

Gneiss. The trace elements of two samples of magnetite occurring in quartzfeldspar-biotite-gneisses along the Swedish-Finnish border in the northern part of Norrbotten (fig. 1) have been investigated. According to Ödman (1957) these rocks are of late Karelian age but their origin is unknown. The investigated iron oxides occur in granitic or pegmatitic veins in the gneisses. In *Masankijärvi* a pegmatite contains up to 1 decimeter large crystals of magnetite. In *Suijjavaara* the host rock is a biotite gneiss with intercalations of granite. Some parts of the granite contain small amounts of magnetite forming crystals up to 1 centimeter in size. The trace elements of the magnetites investigated are shown in table 10 and their significance discussed on p. 113.

Table 10. The content of some elements in magnetite and hematite in iron ores and rocks of unknown origin in Northern Sweden

Sample No.	Mineral	Weight % of			p. p. m. of											
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo
<i>Iron ore</i>																
87. Altavaara																
832	Magnetite ore									55	60	50	400			
832	Magnetite									80	80		600			
832	Gangue									20	20		130			
1480	Magnetite	<1	0.2	<0.5	<3000	6400	<600	360	<17	50	50	<20	1200	<10	<50	<10
1481	Magnetite	<1	0.2	<0.5	<3000	400	600	<90	<17	80	80	40	700	10	<50	<10
88. Killingi																
1530	Magnetite	<1	1.1	<0.5	<3000	400	3000	<90	<17	80	40	<20	1100	20	50	<10
89. Leppäkoski (Northeastern part)																
398	Magnetite ore					150				100	45	<20	200	<10	<50	20
399	Magnetite ore					200				65	60	<20	410	<10	<50	10
400	Magnetite ore					1500				25	50	<20	20	300	200	10
1484	Magnetite	<1	0.2	<0.5	<3000	<200	<600	<90	<17	120	50	<20	200	30	50	20
(Southeastern part)																
1182	Magnetite ore	22.5	4.9	0.2	600	300	3550	80		40	30	120	200			
1485	Magnetite	1	0.3	<0.5	<3000	<200	<600	270	<17	80	60	120	500	20	<50	<10
1486	Magnetite	1	0.2	<0.5	<3000	<200	<600	90	<17	120	60	120	400	20	<50	<10
90. Puoltsa																
902	Magnetite	1.15	0.42	0.10	15000	500	500			270	100	<20	1100	<10		<10
903	Magnetite	0.90	0.55	0.10	17500	900	1200			280	120	<20	1200	<10		<10
904	Magnetite	1.15	0.50	0.09	15000	1000	800			320	120	<20	2100	<10		<10
905	Magnetite	0.47	0.30	0.15	2700	300	600			230	60	<20	2200	<10		<10

<i>Conglomerate</i>																
91. Doktors kulle																
1285	Hematite	9	1.3	<0.5	<3000	200	6000	180	17	40	30	20	800	80	160	10
<i>Saurusvaara</i>																
1357	Hematite	1	0.3	<0.5	<3000	3100	1200	90	<17	<20	<20	<20	1000	60	<50	<10
<i>Gneiss</i>																
93. Masankijärvi																
1356	Magnetite	<1	0.4	<0.5	<3000	1200	1200	<90	<17	70	60	<20	500	20	100	<10
<i>Suijavaara</i>																
1355	Magnetite	<1	0.4	<0.5	<3000	2200	1200	90	<17	200	100	20	1600	50	250	<10

3.1.6. BASIC MAGMATIC ROCKS

Magnetite occurring in basic magmatic rocks in Norrbotten county has been investigated spectrochemically from Akkavare, Jälketurkkio, Kallokajärvi, Lauttakoski, Saivo, and Tjabrak. In Kallokajärvi the rock is possibly of extrusive origin, in the other localities of intrusive origin. Further a sample of hematite from a gabbro at Saarikoski has been investigated for trace elements. The situation of these localities is shown in fig. 1.

Akkavare is, according to Geijer (1930), made up of small concentrations of magnetite and ilmenite in a norite which consists of plagioclase, pyroxene (diplage and hypersthene), and small amounts of apatite and biotite. Hornblende and spinel occasionally occur, too.

In *Jälketurkkio* the rock investigated is a magnetite-bearing metadiabase. According to B. Eriksson (oral communication) the diabase forms long intrusions following the strike of the enclosing sedimentary and basic volcanic rocks. The diabase consists of plagioclase (usually andesine, but varying from albite to labradorite), hornblende with remnants of diopside, and minor quantities of magnetite and sphene. The plagioclase is often strongly scapolitized. The amounts of magnetite and sphene are directly correlated.

The sample from *Kallokajärvi* is made up of a magnetite forming narrow layers in an amphibolite possibly representing a metamorphic volcanic rock of basic composition. The magnetite stratification seems to be a primary feature. The amphibolitic rock consists of actinolite and magnetite together with small amounts of apatite and carbonate, the latter mineral being in some cases secondary.

At *Lauttakoski* a soap-stone partly rich in magnetite has been investigated. According to N. A. Shaikh (oral communication) the rock consists of talc and chlorite (delessite) with minor amounts of carbonate (mostly dolomite) and magnetite. The origin of the rock is somewhat dubious but it seems to be an alteration product of a basic or ultrabasic rock.

The hematite sample from *Saarikoski* is taken from a pyroxene-rich gabbro in part rather coarse. The gabbro is partly anorthositic and rich in plagioclase. It is cut by pegmatites from which the hematite investigated has been taken. The hematite forms lumps up to some decimeters in size. The microscope shows that the hematite contains abundant laths of ilmenite which in turn have inclusions of hematite. To a less extent the hematite contains laths of magnetite which have been partly martitized.

In *Saivo* occurs a 50–60 meters wide zone with a coarse skarn rich in magnetite. The wall rock of the skarn is a red, fine- to medium-grained feldspar-rich rock of quartz-syenitic composition. It contains plagioclase of undetermined composition and perthitic feldspar together with small amounts of quartz and tremolite-actinolite in accessory amounts. To the west the rock becomes porphyritic with phenocrysts of an acid plagioclase and microcline; the matrix

Table 11. The content of some elements in magnetite and hematite in basic magmatic rocks in Northern Sweden

Sample No.	Mineral	Weight % of			p. p. m. of												
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo	
95. Akkavare																	
1290	Magnetite	3	2.1	0.5	3000	400	3600	180	51	<20	80	60	2600	40	200	10	
1291	Magnetite	>10	>3.0	0.5	27000	2000	18000	180	85	230	260	560	2700	250	350	10	
96. Jälketkurkkio																	
1224	Diabase	44.6	12.5	9.5	34800	1400	14000	720		100	65	30	1000				
1293	Magnetite	2	0.5	0.5	<3000	<200	11400	<90	<17	70	120	<20	4000	140	200	10	
97. Kallokejärvi																	
1373	Magnetite	2	0.8	<0.5	6000	<200	3600	<90	<17	300	190	>2000	1500	40	100	<10	
98. Lauttakoski																	
1375	Magnetite	6	0.3	<0.5	18000	<200	6000	<90	<17	420	420	>2000	700	70	100	10	
99. Saarikoski																	
1294	Hematite	<1	0.4	<0.5	<3000	1600	>30000	<90	<17	40	100	<20	1200	40	700	30	
100. Saivo																	
1415	Magnetite	1	<0.1	<0.5	<3000	200	30000	<90	<17	120	140	480	2000	60	800	30	
101. Tjabrak																	
1288	Magnetite	5	>3.0	<0.5	3000	200	5400	90	51	200	230	380	1100	20	200	10	
1289	Magnetite	6	0.5	1.5	9000	600	<600	<90	<17	80	120	<20	200	190	100	<10	

consists of plagioclase with small amounts of microcline. The quartz-syenite in the eastern part is strongly tectonized and cut by centimeterwide fissures filled with amphibole. These are straight and border distinctly upon the quartz-syenite. The skarn with the magnetite has the same general appearance as the smaller fissure-fillings and in mode of formation seems to be rather similar to them. The skarn is built up of tremolite-actinolite and diopside. In the skarn titanite, ankerite, and a red not yet identified mineral occur besides magnetite. The skarn minerals and the magnetite are intimately intergrown, sometimes forming large crystal aggregates up to 50 centimeters in size. Under the microscope the magnetite is anisotropic with two crossing systems of twin lamellæ, the anisotropy possibly being due to a high content of titanium in the magnetite (proved by a microprobe analysis). In the magnetite occur laths of hematite and ilmenite, both with small amounts of exsolved magnetite (?). Chalcopyrite is found in accessory amounts.

To the west of the above described feldspar-rich rocks and the skarn-magnetite zone is a gabbro. In the vicinity of the quartz-syenite and the skarn-zone a rather coarse hybrid rock is found. This might be interpreted as a result of an influence on the gabbro effected by the quartz-syenite.

The magnetite-bearing skarn at Saivo is of uncertain origin. It seems, however, plausible to connect it with the gabbro, an interpretation supported by the presence of ilmenite in the magnetite in the skarn. It is probable that the skarn and magnetite together with quartz-syenite represent a later stage in the magmatic activity that gave rise to the gabbro, the order of formation being gabbro – quartz-syenite – skarn and magnetite.

Tjabrak is, according to Petersson (1900), made up of small concentrations of titaniferous magnetite occurring in olivine-bearing gabbro. The magnetite is mixed with pyroxene and plagioclase and occasionally with rather large amounts of pyrite. An analysis shows 53.26 % Fe, 0.156 % P, and 2.60 % TiO₂.

The trace element contents in the iron oxides in the above mentioned rocks are shown in table 11.

3.1.7. SYENITE-PORPHYRIES

In Ekströmsberg, Hopukka, Kaipak (Njakak), Mertainen, and Sautusvaara (fig. 1) the magnetite in syenite-porphyrines has been spectrochemically analyzed.

According to Geijer (1931a, 1931b) the apatite iron ores in Northern Sweden seem to originate from the same magma as the volcanics forming the host rock of the ores, and he has found this presumption to be supported by the behaviour of the magnetite in the volcanics. In the syenite-porphyrines in some deposits a late differentiation phase rich in magnetite occurs. The magnetite appears partly in the matrix of the magnetite-syenite-porphyrines and partly in nodules

Table 12. The content of some elements in magnetite in syenite-porphyrines in Northern Sweden

Sample No.	Mineral	Weight % of			p. p. m. of												
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo	
102. Ekströmsberg																	
1369	Magnetite	>10	>3	1.0	9000	<200	10800	180	51	60	40	280	500	40	50	<10	
1369	Porphyry	>10	>3	1.0	12000	200	10200	270	51	30	20	120	300	10	<50	<10	
103. Hopukka																	
1376	Magnetite	>10	>3	<0.5	6000	<200	9600	360	17	20	50	<20	800	10	<50	<10	
1376	Porphyry	>10	>3	1.0	9000	<200	9600	540	34	<20	40	<20	700	20	<50	<10	
104. Kaipak																	
1370	Magnetite	>10	2.2	<0.5	<3000	<200	1500	90	17	160	40	60	1000	80	50	10	
105. Mertainen																	
1518	Magnetite	3	0.7	<0.5	<3000	800	2400	<90	<17	100	100	<20	1250	20	100	<10	
106. Sautusvaara																	
1478	Magnetite	1	0.5	<0.5	<3000	<200	600	<90	<17	120	50	800	1500	40	50	<10	

(vesicle fillings) in the porphyries. "The characteristic features of the magnetite-syenite-porphyries are, chemically, their composition of alkaline feldspar (generally very decidedly sodic) and magnetite, and texturally, the late crystallization of the magnetite" (Geijer 1931b, p. 33). The nodules usually consist of hornblende and magnetite with apatite and sphene. Both for the magnetite-syenite-porphyries and the nodules there was thus, during the solidification of the rock, a rest solution with a high content of magnetite. While the nodules "are not, in their nature, directly comparable to the ore bodies, there is so much of similar relations that it cannot be doubted that the physico-chemical conditions which, in these two types of concentration of magnetite etc. have caused the separation, must have been closely related". ". . . the substances that formed the main ore bodies were fractionated out, as a separate magma, from its mother magma under the influence of volatile constituents". "The vesicle-fillings may be regarded as *in situ* examples of a related although not quite identical form of fractionation" (Geijer 1960, p. 37). In both the magnetite-syenite-porphyries and in the nodules in the syenite-porphyries the formation of the magnetite, in the opinion of Geijer, is thus in principle rather similar to the formation of the magnetite in apatite iron ores.

In Ekströmsberg, Hopukka, and Kaipak the magnetite occurs in magnetite-syenite-porphyries. In Sautusvaara the magnetite in pebbles of a magnetite-syenite-porphyry in a conglomerate west of the skarn iron ore has been determined. In Mertainen the syenite-porphyry is rich in nodules containing magnetite and hornblende. The trace element content of these magnetites is shown in table 12.

3.1.8. METASOMATICALLY ALTERED ROCKS

Altered basic volcanics. From *Läffa* and *Tjärråive* (fig. 1) magnetite occurring in metasomatically altered basic volcanic rocks has been spectrochemically analyzed (table 13). Both occurrences are imperfectly known but according to G. Nilsson (oral communication) the basic volcanics have been bleached due to a metasomatic action, which in *Tjärråive* seems to be related to a zone of tectonization. In *Läffa* the magnetite is mostly found in nodules but occasionally in small veinlets. In *Tjärråive* it occurs as veinlets. In both places the metasomatic alteration of the basic volcanics resulted in a breaking down of the dark silicates (mainly hornblende), all elements in these except iron being removed. The iron left behind changed to magnetite. The main element added during the alteration is potassium entering microcline in the bleached zones of the rock. This mode of formation of the magnetite is rather similar to that in the leucodiabases in Norrbotten. These rocks are considered by Padget (1959) and the present author (Frietsch 1966) as metasomatically formed from basic rocks in the vicinity of tectonic zones. The dark minerals in the basic rocks

Table 13. The content of some elements in magnetite in metasomatically altered rocks in Northern Sweden

Sample No.	Mineral	Weight % of			p. p. m. of											
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo
107. Nautanen																
1358	Magnetite	<1	0.3	<0.5	<3000	1400	1200	180	<17	<20	60	<20	400	200	150	<10
1359	Magnetite	1	0.5	<0.5	<3000	1200	600	450	17	40	60	<20	1100	60	100	<10
108. Läfte																
1527	Magnetite	1	0.4	<0.5	<3000	400	1200	90	<17	30	40	<20	800	10	50	<10
109. Tjårråive																
1526	Magnetite	2	0.9	<0.5	<3000	400	1200	<90	<17	200	100	<20	1800	10	50	<10

are destroyed, and leucodiabases rich in albite with some quartz and amphibole have been formed. In these rocks magnetite is sometimes encountered which by the present author is believed to emanate from the iron in the dark silicates in the original basic rock. In the formation of the leucodiabases the main element added is sodium, in Läfte and Tjäreåve potassium.

A similar mode of formation of magnetite has been described by Slobodskoy (1963) from the Kolyvansk intrusive massif in the northwestern part of Gornyy Altai. During a postmagmatic alteration (autometamorphism) of the massif some iron from the dark minerals in the rocks (mainly granodiorite) was released and recrystallized both as epidote and magnetite. Due to the low temperature of the alteration the new-formed magnetite is relatively poor in trace elements. Further Hagner & Collins (1967) showed from the Ausable district, New York, that during a regional metamorphism the dark iron-bearing silicates (clinopyroxene and hornblende) in a granite gneiss were broken down and the iron released formed magnetite. This process is connected with albitization and shearing.

Nautanen. In Nautanen (fig. 1) the magnetite occurs in a schistose leptite rich in biotite and with small amounts of garnet. The leptite is probably of sedimentary origin. The rock has been affected by a later mineralization which resulted in the formation of scapolite, quartz, tourmaline, hornblende, garnet, epidote, apatite, calcite, and zeolites together with ore minerals such as chalcopyrite, magnetite, pyrite, bornite, and molybdenite. The ore minerals occur partly as small veinlets together with quartz, tourmaline etc. and partly as disseminations. According to Geijer (1918a, 1931a), the ores of the Nautanen district have been deposited by hot, probably gaseous emanations the quantitatively most important result of which is a regional scapolitization. The mineralization is believed by Geijer to have been caused by the 'late Archean' Lina granite.

Two samples of magnetite from Nautanen have been analyzed for the trace elements (table 13). Sample No. 1358 is a quartz-rich magnetite-vein with small amounts of sulphides, and sample No. 1359 is a leptite in which the magnetite occurs equally distributed.

3.2. Iron ores in Northern Finland

Misi area. The magnetite in the *Kärväsvaara*, *Puro* and *Raajärvi* iron ores in the Misi area, about 60 kilometers east of Rovaniemi in Northern Finland, has been investigated geochemically (table 14). The deposits belong to the same type of ore. A detailed description of the Misi ores has recently been given by Nuutilainen (1968). *Kärväsvaara* is made up of magnetite with tremolite and some chlorite, talc, carbonate, apatite, and pyrite. An analysis of the

ore shows, according to Nuutilainen, 0.06 % V_2O_3 , 6.06 % MgO, 0.01 % CoO, 0.09 % NiO, 1.04 % S, and 0.19 % P_2O_5 . The ore occurs in quartzite, mica-schist and mica-hornblende-gneiss, which are surrounded by granite and gabbro. In the vicinity of the ore there are further small bodies of gabbro and albitite. The last mentioned rock is almost totally composed of albite and considered by Nuutilainen to be an intrusive. Puro is a rather small deposit consisting of magnetite associated with tremolite, chlorite and pyrite. The ore occurs in a chlorite-tremolite rock surrounded and cut by albitites. Raajärvi is made up of magnetite with small amounts of pyrite. The gangue consists of chlorite, tremolite, serpentine and phlogopite. The ore is enclosed in a serpentinite in the vicinity of which occur dolomites and albitites. An analysis of the ore shows, according to Nuutilainen, 0.13 % V_2O_3 , 11.20 % MgO, 0.01 % CoO, 0.016 % NiO, 0.11 % S, and 0.37 % P_2O_5 .

The following age relation between the wall rock and the iron ores in the Misi area has been established: (oldest) sediments (quartzite, mica-schist, dolomite) – gabbro – albitite – serpentinite – ore. Regarding the mode of formation of the ore the following features are relevant. The ore bodies always occur in connection with the albitites. Furthermore they seem to be connected with the older sediments. They are, however, also related to tectonic zones which mainly strike NW–SE but in part E–W. Thus Kärvasvaara is bordered by fault-planes striking in these directions. Nuutilainen considers the Misi ores to be magmatic and genetically related to the gabbros, serpentinites, and albitites, and to belong to the same differentiation series. The ores crystallized at a low hydrothermal temperature from a late hydromagma rich in mineralizers.

Kolari area. From the iron ores *Rautuvaara* and *Taporova* in Northern Finland samples of magnetite and hematite have been investigated for trace elements (table 14). These deposits lie near the Swedish-Finnish border about 18 kilometers N of the parish of Kolari and about 20 kilometers ENE of the Tapulivuoma skarn iron ore deposit on the Swedish side of the border (fig. 1). Of these two deposits *Rautuvaara* resembles the skarn iron ores in Norrbotten. The ore consists of magnetite with small amounts of pyrite and pyrrhotite and accessory amounts of chalcopyrite. The ore forms several lenses which follow the strike of the host rock, here made up of basic volcanics and quartzites. The immediate wall rock of the ore is, on the one side, amphibolites and mica-schists, on the other, black schists and limestones. This series of volcanics and sediments is enclosed in a gneissose monzonite.

The ore at *Taporova*, being quite different from that at *Rautuvaara*, is rather lean. It is made up of hematite with small amounts of finely divided magnetite in a quartz-muscovite-microcline-schist which sometimes contains sillimanite and biotite. Tourmaline and zircon are also found in accessory amounts. A comparatively large amount of barite (up to 10 per cent) is a conspicuous feature of the rock. T. Mikkola (1960) and Schmidt (1960) consider the ore

Table 14. The content of some elements in magnetite and hematite in ores and rocks in Finland

Sample No.	Mineral	Weight % of			p. p. m. of											
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo
IRON ORES, NORTHERN FINLAND																
<i>Misi area</i>																
Kärväsvaara																
1389	Magnetite	<1	0.3	<0.5	<3000	800	<600	<90	<17	500	150	<20	800	<10	50	<10
Puro																
1416	Magnetite	2	0.2	<0.5	<3000	<200	1200	<90	<17	250	40	<20	600	70	50	<10
Raajärvi																
1388	Magnetite	<1	0.4	<0.5	12000	800	600	<90	<17	80	140	<20	1500	<10	50	<10
<i>Kolari area</i>																
Rautuvaara																
1387	Magnetite	3	0.8	0.5	6000	800	1200	<90	17	70	140	20	150	250	100	<10
1387	Magnetite ore	>10	1.3	2.5	18000	300	1200	<90	<17	60	120	<20	100	350	150	<10
Taporova																
1423	Magnetite	3	0.6	<0.5	<3000	600	<600	2520	68	120	40	220	200	30	50	<10
1423	Hematite	3	0.7	<0.5	<3000	600	5400	3150	68	<20	<20	180	300	<10	50	<10
1422	Hematite	4	1.3	<0.5	<3000	350	8400	>4500	119	<20	<20	280	350	<10	50	<10
<i>Kittilä area</i>																
Haurespää																
1417	Magnetite	>10	0.2	0.5	<3000	400	<600	<90	51	20	<20	<20	50	20	<50	10
1417	Gangue	>10	0.1	2	<3000	4400	<600	<90	119	<20	<20	<20	<50	20	<50	<10

1418	Magnetite	>10	0.1	0.5	<3000	<200	<600	90	68	20	20	<20	<50	40	50	<10
1418	Gangue	>10	<0.1	1.0	<3000	3700	<600	<90	85	<20	<20	<20	<50	<10	<50	<10
Pitslomankuru																
1421	Siderite	>10	3	<0.5	9000	23000	5400	270	<17	60	<20	80	200	40	<50	<10
Silmänpaistama																
1419	Mangano-siderite	>10	2	0.5	9000	93000	1200	630	17	50	40	<20	<50	60	<50	<10
1420	Magnetite	9	1.3	<0.5	<3000	27000	600	450	<17	80	20	80	400	70	50	<10
1420	Gangue	>10	2.3	1.0	6000	85000	1200	720	51	50	40	<20	<50	70	<50	<10
AMPHIBOLITE, CENTRAL FINLAND Hällinmäki																
1390	Magnetite	1	0.7	<0.5	<3000	800	1800	<90	<17	120	80	<20	200	200	150	10

to be sedimentary but as the author has pointed out (Frietsch 1967a) it is possible that the present mineral composition is due to metasomatic action, the deposit being in many places cut by granitic and pegmatitic dikes.

Kittilä area. About 40 kilometers ENE of the parish of Kittilä in Northern Finland a vast area of basic volcanics is encountered. These contain irregular intercalations of jasper quartzites in which the stratified magnetite iron ore deposits at Porkonen and Pahtavaara are found. Associated with the jasper quartzites are siderites and mangano-siderites. The jasper quartzites and associated rocks are considered by E. Mikkola (1941) and Kaitaro (1949) to have been formed in connection with the magmatic activity that gave rise to the enclosing basic volcanics. From the Porkonen-Pahtavaara area some samples comprising magnetite ore, mangano-siderite and siderite have been investigated geochemically in the present work (table 14). The samples from *Haurespää* are taken from a stratified magnetite ore rich in quartz and with subordinate amounts of siderite. The samples from *Silmänpaistama* are taken from a mangano-siderite which besides carbonates contains chlorite, iron oxides, and a little minnesotaite. A similar rock has been described by Hytönen et al. (1966) from Petäjäseltä which is to the north of Silmänpaistama. The rock contains, according to these authors, 6.30 per cent MnO, and the siderite has the composition $(\text{Fe}_{0.65}\text{Mn}_{0.22}\text{Mg}_{0.10}\text{Ca}_{0.03})\text{CO}_3$. The sample from *Pitslomankuru* is a siderite with a comparatively small content of manganese. The rock is built up of siderite, quartz, chlorite, muscovite, and small amounts of iron oxides.

Hällinmäki. Hällinmäki, in the nearhood of Virtasalmi, S of Pieksämäki, in Central Finland, is a sulphide ore situated in a partly garnet-bearing diopside-amphibolite, probably of sedimentary origin. The amphibolite is surrounded and intruded by a quartzdiorite. The ore minerals are chalcopyrite and to a lesser extent cubanite and occasionally some bornite and molybdenite, all occurring as irregular veinlets in an andradite skarn or disseminated in the amphibolite. The skarn also contains small lumps of magnetite. The trace element content of the magnetite is shown in table 14. The sulphides and the magnetite are of contact-pneumatolytic origin, the source rock being the enclosing quartzdiorite (Hyvärinen 1968).

3.3. Iron ores in the Lahn-Dill area, Western Germany

The iron ores in the geosynclinal basins at Lahn and Dill in Western Germany are considered by Schneiderhöhn (1941), Lippert (1953), and Borchert (1960) to be exhalative sedimentogeneous formations connected with a basic volcanism. The ores lie mainly as a horizon between basic volcanics of the Upper Middle Devonian and tuffites, limestones, and schists of the Upper Devonian. An epigenetic origin for the ores has, however, been proposed by Lehman

(1949) who considered them to be intrusive and to have similarities with iron ores of the Kiruna type. A theory of a "metasomatic" mode of formation of the ores has been proposed by Hentschel (1960) who considered them to have been formed from the basic volcanics which have taken up water from the geosyncline and have been split into a chlorite-albite-quartz-calcite-rich phase forming the wall rock and a phase rich in iron oxides. This 'metasomatic' interpretation is thus, in principle, somewhat similar to what has been stated about the mode of formation for the magnetite in Läfte and Tjårråive and in the leucodiabases in Norrbotten (p. 46).

The ores in the Lahn-Dill area, being in part stratified, are predominantly hematitic with a large amount of quartz. In some cases calcite is a major mineral. Chlorite occurs in subordinate amounts. Occasionally small amounts of dolomite, siderite, and pyrite are found. Another ore variety is made up of magnetite which differs from the hematite ore in having a higher content of pyrite. The distribution of hematite and magnetite seems, in most cases, to be a primary feature. Thus in the Lahn area the magnetite occurs in connection with a dark schist indicating a reducing milieu, but where this schist is missing hematite is encountered. In the Dill area, on the other hand, cases are known in which hematite has been changed to magnetite by the action of a keratophyre (Grube Köningszug, cf. Schneiderhöhn 1941) and an intrusive diabase (Grube Falkenstein).

The samples investigated spectrochemically (table 15) are taken from two mines: Grube Falkenstein in the Dill area and Grube Lindenberg in the Lahn area.

Table 15. The content of some elements in magnetite and hematite in iron ores in the Lahn-Dill area, Western Germany

Sample No.	Mineral	Weight % of			p. p. m. of											
		SiO ₂	Al ₂ O ₃	CaO	Mg	Mn	Ti	Ba	Sr	Ni	Co	Cr	V	Cu	Zn	Mo
Falkenstein																
1470	Hematite	7	<0.1	1.5	<3000	1000	<600	90	34	80	20	<20	300	100	100	40
1471	Hematite	5	2.1	<0.5	<3000	600	<600	180	17	100	40	<20	400	50	100	<10
1472	Magnetite	5	1.6	<0.5	<3000	1800	<600	<90	17	40	<20	<20	300	10	100	10
Lindenberg																
1473	Hematite	1	0.9	<0.5	<3000	<200	<600	90	17	140	20	<20	500	70	100	<10
1474	Hematite	2	1.3	<0.5	<3000	<200	<600	<90	17	200	40	<20	400	100	100	10
1475	Magnetite	2	0.2	0.5	<3000	<200	<600	<90	17	200	<20	<20	<50	20	<50	30
1476	Magnetite	7	0.5	1.5	<3000	<200	<600	<90	34	80	<20	<20	<50	40	50	<10

4. MINOR CONSTITUENTS IN MAGNETITE AND HEMATITE

4.1. Trace element substitutions in a crystal lattice

The entry of trace elements into a mineral is governed by several factors of which the temperature and pressure, the physical properties of the elements, and the chemical environment are important. The physical properties for the elements are the valency, the radii of the ions and the nature of their chemical bonds. The laws governing the entry of trace elements into minerals and the behaviour of these elements during a magmatic differentiation has been investigated by Goldschmidt (1937, 1954), Ahrens (1952, 1953), Shaw (1953), Ringwood (1955), Taylor (1965), and Nockolds (1966). Reviews of the theories proposed are given by Shaw (1964) and Taylor (1965). The behaviour of the trace elements when substituting for the main elements is governed by the rules established by Goldschmidt. According to these elements with the same ionic radii and the same charge could substitute for each other; and differences up to 15 per cent in the ionic radii are tolerable. If the ions have the same size but different charges the ion with the higher charge will be incorporated in a crystal lattice in preference to the ion with lower charge. If the charges are the same but the ionic radii differ the ion with a smaller radius will be incorporated in preference to the larger ion. The Goldschmidt Rules show however certain limitations; they are only applicable to elements which have mainly ionic bonds. If covalent bondings are prevalent the elements show certain deviations from the behaviour expected according to the Goldschmidt Rules. A quantitative measure of the degree of ionic bonding – covalent bonding was given by Ahrens (1952, 1953), Ringwood (1955), and Nockolds (1966). Ahrens used the ionization potential to indicate the anion affinity and pointed out that a cation with lower ionization potential (anion affinity) forms more ionic bonds than a cation with a higher ionization potential. Ringwood (1955, p. 193) used the electronegativity as a measure of the degree of ionic or covalent bonding: "Whenever diadochy in a crystal is possible between two elements possessing appreciably different electronegativities the element with the lower electronegativity will be preferentially incorporated because it forms a stronger and more ionic bond than the other". ". . . when diadochy occurs between elements possessing similar electronegativities the Goldschmidt Rules may be applied". Nockolds (1966) calculated the degree of covalent bonding for different elements and used the relative total bonding energies to predict the behaviour of different elements. "When two cations of the same valency are capable of substitution in a crystal lattice, the one having the greater relative total bonding energy will be incorporated preferentially. When two cations of different valency, involving coupled substitution, are capable of substitution in a crystal lattice, that substitution will take place preferentially whose sum of relative total bonding energies is the greater" (ibid. p. 272).

It is evident from the above that the behaviour of the trace elements when substituting for the main elements in a mineral is governed by the physical properties of the elements, namely, the size, charge and the type of bonding for the different ions. The behaviour of the trace elements is however also controlled by the chemical environment, as an element, as Taylor (1965, p. 186) pointed out, behaves differently in magmas of varying composition.

The crystal-chemical properties which have been used by the above mentioned authors are compiled for certain elements in table 16. These parameters will be used later in the text when discussing the entry of elements into the lattice of magnetite and hematite.

Table 16. Crystal-chemical parameters for certain elements

	r	e	I ¹	I ²	I ³	I ⁴	E
Si ⁴⁺	0.42	1.8	8.15	16.34	33.5	45.1	380
Al ³⁺	0.51	1.5	5.98	18.82	28.4		300
Ga ³⁺	0.62	1.5	6.00	20.51	30.7		264
Cr ³⁺	0.63	1.6	6.76	16.49	31.0		321
Fe ³⁺	0.64	1.8	7.87	16.18	30.6		246
Mg ²⁺	0.66	1.2	7.64	15.03			202
Ti ⁴⁺	0.68	1.6	6.82	13.57	27.5	43.2	348
Ni ²⁺	0.69	1.8	7.63	18.15			197
Mo ⁴⁺	0.70	1.6	7.10	16.15	27.1	46.4	
Sn ⁴⁺	0.71	1.8	7.34	14.63	30.49	40.7	300
Co ²⁺	0.72	1.7	7.86	17.05			183
Cu ²⁺	0.72	2.0	7.72	20.29			
Zn ²⁺	0.74	1.5	9.39	17.96			170
V ³⁺	0.74	1.4	6.74	14.65	29.3		299
Fe ²⁺	0.75	1.65	7.87	16.18			178
Mn ²⁺	0.80	1.4	7.43	15.64			174
Ca ²⁺	0.99	1.0	6.11	11.87			200
Sr ²⁺	1.18	1.0	5.69	11.03			191
Pb ²⁺	1.20	1.6	7.42	15.03			138
Ag ⁺	1.26	1.8	7.57				71
Ba ²⁺	1.34	0.9	5.21	10.00			180

r = ionic radius
 e = electronegativity
 I = ionization potential
 E = relative total bonding energy after Nockolds (1966)

} after Taylor (1965)

4.2. Magnetite

Magnetite belongs to the spinel group, the unit cell contains 32 oxygen ions and 24 cations of which 8 cations are in 4-fold coordination and 16 cations are in 6-fold coordination. The spinels occur in two structural types namely normal and inverse depending in the distribution of the cations in 4-fold or

6-fold coordination. The general formula can be written $R_8^{2+}R_{16}^{3+}O_{32}$ where R^{2+} is Fe^{2+} , Mg^{2+} , Zn^{2+} , Mn^{2+} etc., and R^{3+} is Fe^{3+} , Al^{3+} , Cr^{3+} etc. The magnetite is of the invernal type with 8 R^{3+} in 4-fold coordination and 8 R^{2+} and 8 R^{3+} in 6-fold coordination, and the formula of magnetite should thus be written $Fe^{3+}(Fe^{2+}Fe^{3+})O_4$ (Nicholls 1955, Deer et al. 1962).

It is a well known fact that titanium is found in appreciable amounts in magnetite. At higher temperatures there exists a solid solution series between magnetite and ulvöspinel (Fe_2TiO_4); according to Nicholls (1955) and Nagata (1961) the ionic replacement in this series takes the form $2Fe^{3+} = Fe^{2+} + Ti^{4+}$. Other elements are also known to enter the magnetite lattice and some of these will modify the magnetic properties and the lattice constant of magnetite: manganese and titanium cause the lattice constant to increase, the opposite being the case if magnesium, cobalt, nickel, aluminum, and chromium (which substitute for Fe^{2+} and Fe^{3+}) enter the lattice (Nicholls 1955, Basta 1957). According to Deer et al. (1962, pp. 68–69) "small amounts of Al substitute for Fe^{3+} : generally similar small proportions of Ca, Mn, and Mg replace Fe^{2+} , but continuous replacement between Mg and Fe^{2+} to magnesioferrite can occur." The same authors mention "V and Cr substituting for Fe^{3+} , often in appreciable amounts." "In the divalent group, in addition to the major elements replacing Fe^{2+} (Mg, Mn and some Ca), minor amounts of Ni, Co and Zn may occur." Wager & Mitchell (1951) showed that in magnetite Cu, Ni, Co, and Mn substitute for Fe^{2+} , and Ga, Cr, and V for Fe^{3+} . Hegeman & Albrecht (1954) pointed out that Al, Ga, V, Cr, Ti, Mn, Zn, Ni, and Co enter the magnetite lattice. Howie (1955) reported V and Zn entering magnetite in the Madras charnockite series, further Ga, Cr, Mo and Sn are supposed to substitute for Fe^{3+} and Ni and Co for Fe^{2+} . Gjelsvik (1957) found that in titaniferous iron ores Cr, Ni, V, and Cu are enriched in magnetite in comparison to coexisting ilmenite. Similarly Lister (1966) showed that in early differentiated iron ores magnetite contains higher amounts of chromium, vanadium and aluminum than ilmenite, which means that these elements substitute for Fe^{3+} in magnetite and not for Fe^{2+} in ilmenite.

Analyses of the trace elements in magnetite occurring in different types of iron ores and rocks taken from the current literature are compiled in table 17. It must, however, be pointed out that the values are not directly comparable as the analyses have been performed by different laboratories using different methods. Furthermore, the purity of the magnetite may be in question in some cases. The values give, nevertheless, an estimate of the elements entering the magnetite lattice. It should be noted that magnetite in titaniferous iron ores is placed in the table under the title "Magnetite in rocks" with the sub-title "Basic intrusives" since it would be unfortunate to divide the titaniferous magnetites into two groups, a division which would only be based on the relative amount of magnetite.

Table 17 (continued)

Author	Locality	SiO ₂	Al ₂ O ₃	Ga	Cr	MgO	Li	TiO ₂	Ni
Acid intrusives									
Howie (1955)	Madras, India	0.11	0	70– 120	250– 2000	0.13		2.78	<2– 500
Tauson & Krawtchenko (1957)	Central Tian-Schan, U.S.S.R.								
Rabinovich et al. (1958)	E. Transbaikal, U.S.S.R.								
Marmo (1959)	Sierra Leone, W. Africa							0.17– 1.17	
Sen et al. (1959)	S. California, U.S.A.			100	250				20
Theobald & Thompson (1962)	Different, U.S.A.								
Intermediate intrusives									
Howie (1955)	Madras, India	0.05– 0.14	0.16– 1.32	10– 20	450– 4500	0.08– 0.11		1.51– 7.41	200– 3000
Rabinovich et al. (1958)	E. Transbaikal, U.S.S.R.								
Marmo (1959)	Sierra Leone, W. Africa							0.19– 1.97	
Sen et al. (1959)	S. California, U.S.A.			70– 120	200– 3000				10– 200
Theobald & Thompson (1962)	Different, U.S.A.								
Basic intrusives									
Foslie (1928)	Ekersund-Soggendal, Norway	0.62	2.39		600	0.81		1.45	
Hutton (1945)	Taraniki, New Zealand								
Mogensen (1946)	Ulvön, Sweden	1.61	2.70		6100 1350	3.00 1.08		18.2 2.50	
Vaasjoki (1947)	Otanmäki, Finland							1.63	
Hjelmqvist (1950)	Taberg, Sweden	1.81	6.16			4.37		15.30	
Wager & Mitchell (1951)	Skaergaard, E. Greenland			20– 60	<1– 200		<1		<2– 300
Wedepohl (1953)	Hoher Hagen								
Vincent & Phillips (1954)	Skaergaard, E. Greenland	0.23– 1.80	0.41– 1.16		0– 900	0.06– 1.98		15.08– 28.09	
Howie (1955)	Madras, India	0.48	0.02– 2.43	15– 55	1500– 15000	0.34– 0.39		6.38 0.5–	150– 3100
Gjelsvik (1957)	Sunnmøre, Norway	0.1– 3.6			<35– 13000	<0.65– 3.5		3.72– 6.07	<80– 1200
Lundegårdh (1957)	Kramsta, Sweden								
Storm & Holland (1957)	Lambertville, N.J., U.S.A.								96– 383
Wilkinson (1957)	New South Wales, Australia	0.33– 2.85	2.31– 3.55		0– 2600	0.79– 2.33		26.76– 29.66	
Vincent et al. (1957)	Different	0.03– 0.2	1.39– 3.1		0– 1800	0.5– 3.61		9.36– 21.87	
Sen et al. (1959)	S. California, U.S.A.			50– 120	55– 12000				20– 350
Vaasjoki & Heikkinen (1962)	Different	0.05– 2.15	0.16– 3.15		70– 500	0.30– 5.18		0.92– 9.71	80– 850
Theobald & Thompson (1962)	Different, U.S.A.								
Lister (1966)	Ontario-Quebec, Canada		0.02– 1.1		20– 4680	0.3– 2.0		0.17– 21.0	
Ultrabasic intrusives									
Lundegårdh (1947)	E. Uppland, Sweden				<0.5			4.2	<0.5
Du Rietz (1956)	Different, N. Sweden	10.5– 12.4	0.67– 1.3		34000– 54000	14.28– 15.1 2.85			900– 3900 10000– 81400
Fawley (1959)	Tanganyika, E. Africa								
Marmo (1959)	Sierra Leone, W. Africa							0.20– 0.24	

Table 17 (continued)

Author	Locality	SiO ₂	Al ₂ O ₃	Ga	Cr	MgO	Li	TiO ₂	Ni
Exhalative rocks									
Zies (1938)	Valley of Ten Thousand Smokes, U.S.A.							0.005	100
Hegemann & Albrecht (1954)	Different		0.0003– 0.06	<10	0– 2	0– 0.07		0.003– 0.02	0– 150
Lava rocks									
Ishimori (1950)	Different, Japan				6– 120				
Rabinowitsch et al. (1958)	E. Transbaikal, U.S.S.R.							0.48	
Marmo (1959)	Sierra Leone, W. Africa								
Fissure fillings									
Hegemann & Albrecht (1954)	Alps		0.04– 0.6	<10	20– 2000	0.003– 1.3		0.008– 3.2	10– 3000
Sedimentary rocks									
Marmo (1959)	Sierra Leone, W. Africa							0.27– 0.41	
Origin not stated									
Newhouse & Glass (1936)	Different	0.14– 1.22	0– 6.72			0.10– 6.65		0– 7.57	
Basta (1957)	Different	1.22	tr.– 1.54		0	0.19– 0.49		tr.– 0.36	
Basta (1959)	Different	0.13– 1.55	0.14– 15.14		0– 68	1.85– 7.18		0.05– 6.98	

4.3. Hematite

In hematite the lattice is made up of oxygen (ions) and Fe³⁺ and other cations in 6-fold coordination. Few elements are known to enter the hematite lattice. Hegemann & Albrecht (1954) pointed out that magnetite takes up a greater number of elements and sometimes in greater amounts than hematite due to the different crystal-chemical properties of these two minerals. The same opinion is maintained by Kisvarsanyi & Proctor (1967, p. 460): "Theoretically, a primary hematite crystallizing from the same melt as magnetite should contain smaller amounts of trace elements than the magnetite. This is predictable from the crystal structure, because hematite has fewer positions with varied properties available for substitution than magnetite." According to Deer et al. (1962, p. 22) in hematite "a small amount of MnO and FeO may be found, while

Mo	Sn	Co	Cu	Zn	V	Zr	MnO	Sc	Y	CaO	La	Pb	Rb
<i>Exhalative rocks</i>													
400	40	200	2300	4700			0.13					50	
	<10- 60	0- 20	100- 2000	<10- 3000	0- 100		0.03- 0.2					<10- 80	
<i>Lava rocks</i>													
5													
<i>Fissure fillings</i>													
		10- 300	0- 50		10- 2500		0.03- 1.0					<10- 20	
<i>Sedimentary rocks</i>													
							0.21						
<i>Origin not stated</i>													
					1800		0.03- 0.29			0.10			
					0- 670		0.06- 1.82			tr. 0- 0.94			

any appreciable SiO₂ and Al₂O₃ probably represent contamination. Hematites particularly rich in Mn have been described from the Ardennes (Bourguignon and Toussaint, 1955). "In natural material TiO₂ is usually reported, but any large amounts may be due to the intergrowth of ilmenite." In table 18 analyses of hematite taken from the current literature are compiled. Only a relatively small number of analyses is available. As in the case of the analyses of magnetite in table 17 the hematite analyses are not necessarily comparable and the purity of the samples analyzed is in some cases questionable. From table 18 it is seen that in addition to the elements mentioned above only magnesium, nickel and vanadium are found in appreciable amounts in hematite.

Table 18. The content of trace elements in hematite in iron ores and rocks according to current literature

(For elements in the oxide form the values are given in weight %/o, for the others in p. p. m.)

Author	Locality	SiO ₂	Al ₂ O ₃	Cr	MgO	TiO ₂	Ni	Mo	Co	Cu	Zn	V	MnO	CaO
<i>Hematite in iron ores</i>														
Sedimentary														
Hegeman & Albrecht (1954)	Different		0.29- 9.5	0- 14	0.16- 0.5	0.1- 0.7	0- 500		0- 8	0- 150		150- 2000	0.13- 0.7	
Beneslawskij (1957)	Not given		~15											
Volcanic-sedimentary														
Hegeman & Albrecht (1954)	Different		0.08- 6	0- 2	0.02- 0.8	0- 0.03	0- 300		0- 15	0- 300		0- 2000	0- 0.05	
Hydrothermal														
Hegeman & Albrecht (1954)	Different		0.06- 2	0- 2	0.015- 0.8	0- 0.08	0- 150		0- 70	0- 400		0- 150	0- 0.01	
Kisvarsanyi & Proctor (1967)	Pilot Knob, Miss., U.S.A.		1.61	1	0.003	0.123	1	59	11	1	100	3	0.001	
Kisvarsanyi & Proctor (1967)	Cedar Hill, ibid.		0.12	1	0.011	0.039	10	1	11	1	200	3	0.004	
Contact-pneumatolytic														
Palache (1935)	Franklin, N. J., U.S.A.												0.98	
Minguzzi (1950)	Elba, Italy					< 0.03- 0.074							< 0.025- 0.05	
Hegeman & Albrecht (1954)	Different		0.06- 0.6	0- 7	0.002- 0.02	0- 0.002	0- 20		0- 60	0- 2		0- 50	0- 0.002	

<i>Hematite in rocks</i>												
Exhalative rocks												
Montalto (1940) Hegeman & Albrecht (1954)	Etna, Italy Different	0.24	0.04– 0.28	0– 2	0.02 0– 0.008	0.34 0– 0.008	8– 70	0– 200	10– 300	0– 2000	0.007– 0.2	
Fissure fillings, quartz-veins												
Hegeman & Albrecht (1954)	Alps		0.08– 0.36	0– 15	0– 0.002	3.3– 8.2	10– 60	10– 60	0– 60	250– 1500	0.001– 0.007 0.31– 22.8	0.30– 0.50
Bourguignon & Toussaint (1955)	Ardennes, Belgium	0.80– 9.40			<0.1	1.8– 6						
Weibel & Bambauer (1958)	Alps, Switzerland											
Pegmatites												
Hegeman & Albrecht (1954)	Different		0.06– 1	0– 2	0.001– 0.015	0.0015– 0.02	0– 2	0– 50	0– 200	0– 150	0.0008– 0.002	
Intermediate intrusives												
Papp (1927)	Bernece, Hungary					0.10						
<i>Origin not stated</i>												
Simpson (1937)	Inglehope, W. Australia	0.41	1.26								0.19	
<i>Synthetical</i>												
Caillère et al. (1960)			~ 11									

5. DISTRIBUTION OF TRACE ELEMENTS IN MAGNETITE AND HEMATITE

The contents of the different trace elements in magnetite and hematite in the iron ores and rocks in Northern Sweden, Finland, and Western Germany investigated in the present work is presented in tables 6–15. In the following pages the elements are reviewed in order of their increasing ionic radii. Tables 19–25 give the arithmetic mean content and the range of the elements in the iron oxides in the different ores and rocks. The description of each trace element begins with a discussion concerning its crystal-chemical properties followed by a review of its distribution in magnetite and hematite in other iron ores and rocks as known from the current literature.

5.1. Silica

Silica is only found in a small number of the magnetite and hematite analyses reported in the literature and in these the content is mostly low. In some analyses of magnetite from basic intrusives silica contents up to several per cent have however been obtained (table 17). High SiO_2 -contents have been found by Bourguignon & Toussaint (1955) in a manganese hematite (table 18). As silica due to its crystal-chemical properties is not expected to enter either magnetite or hematite it cannot be excluded that the relative high silica contents reported are due to impurities.

The SiO_2 -contents in the magnetites and hematites investigated in the present work have been discussed on p. 10.

5.2. Aluminum

Aluminum has a small ionic radius (0.51 Å), low electronegativity and ionization potential values and a high relative total bonding energy as compared to Fe^{3+} . It differs still more from Fe^{2+} except that the electronegativity values are somewhat closer to each other (table 16). Aluminum is therefore not expected to enter the lattice of either magnetite or hematite. These minerals are consequently rather low in aluminum in most cases, as seen from tables 17 and 18. In magnetite from some contact-pneumatolytic and sedimentary iron ores, however, rather high contents of this element are reported, in the first mentioned type of ore up to 9.5 % Al_2O_3 (cf. table 17). The highest aluminum contents are found in titaniferous magnetite in basic intrusives, this possibly being due to the fact that the magnetite in the latter has got admixed with other spinel components. In hematite the aluminum content is mostly low, but Hegemann & Albrecht (1954) have reported up to 9.5 % Al_2O_3 in sedimentary ores. The figure reported by Beneslawskij (1957) from bauxite-ores

is remarkably high (about 15 % Al_2O_3). Caillère et al. (1960) have also synthesized a hematite containing up to 11 % Al_2O_3 . In all these cases the high aluminum content in the iron oxides may be due to contaminations. It is possible that other mineral phases admixed with the iron oxides have been analyzed.

The content of aluminum in magnetite and hematite in the samples investigated in the present work is usually relatively low. As seen from table 19 it is less than 1 % Al_2O_3 in most cases. In those samples where the content is above this value, as in the basic magmatic rocks and the syenite-porphyrines, it is possibly due to feldspar impurities, being indicated by the relatively high silica contents (table 1). Also the value of 1.3 % Al_2O_3 found in the hematite in the conglomerate at Doktors kulle seems to be due to impurities, as the analysis shows 9 % SiO_2 (table 10), but in this case the impurities consist of muscovite. From the Al_2O_3 values given in table 19 no conclusions regarding the distribution of aluminum in the iron oxides in the different kinds of ore and rock can be drawn as it is not certain if the aluminum is sited in the lattice of the iron oxides or if it occurs as impurities in the form of feldspar or other aluminum-bearing minerals.

5.3. Chromium

Cr^{3+} has an ionic radius (0.63 Å) very similar to that of Fe^{3+} and associates therefore with ferric iron. Cr^{3+} has, however, a low electronegativity value and a high relative total bonding energy value (table 16) and will consequently in a crystal lattice be preferentially incorporated to Fe^{3+} . This is in accordance with what is known about the behaviour of chromium in magmatic rocks. Thus in a fractional crystallization chromium is depleted at an early stage, the ultrabasic and basic rocks always being rich in this element. This is further applicable to the magnetites formed by fractional crystallization. According to Landergren (1948) chromium preferentially enters the magnetite structure in the titaniferous iron ores. In the Skaergaard intrusion iron ores have not formed before a middle stage of the fractionation (Wager & Mitchell 1951), and are consequently low in chromium compared to the earlier formed magnetites which are more chromium-rich. This statement is confirmed by Vincent & Phillips (1954). In the Madras series, as shown by Howie (1955), and in the batholith in S. California, as shown by Sen et al. (1959), the decrease of the chromium content in the magnetite during the fractionation of the magma is less pronounced, and the magnetites in the later phases are still relatively rich in chromium.

As seen from table 17 the content of chromium in magnetite in iron ores reported in the literature is rather low, in most cases below the content of the upper lithosphere (90 p. p. m., according to Shaw 1964). In some contact-

Table 19. The content of aluminum and chromium in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Occurrence	Mineral (M = magnetite H = hematite)	% Al ₂ O ₃			p. p. m. Cr		
			n	Mean	Range	n	Mean	Range
Magmatic	Basic magmatic rock, N. Sweden	M	8	>1.3	0.3 ->3	8	>690	<20->2000
	Basic magmatic rock, N. Sweden	H	1	0.4		1	<20	
	Syenite-porphry, N. Sweden .	M	5	>1.9	0.5 ->3	5	230	<20- 800
	Apatite iron ore, N. Sweden ..	M	54	0.3	0.05-1.2	44	11	≤20
	Apatite iron ore, N. Sweden ..	H	23	0.4	0.05-2.2	21	<20	
	Iron ore, Misi, N. Finland	M	3	0.3	0.2 -0.4	3	<20	
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Ger- many	M	3	0.8	0.2 -1.6	3	<20	
	Iron ore, Lahn-Dill, W. Ger- many	H	4	1.1	<0.1 -2.1	4	<20	
	Iron ore, Kittilä, N. Finland ..	M	3	0.5	0.1 -1.3	3	30	<20- 80
	Stratified iron ore, N. Sweden	M	28	0.8	0.2 -2.1	28	90	<20-1200
	Skarn iron ore, N. Sweden ..	M	77	0.4	<0.1 -1.7	77	40	<20- 420
	Skarn iron ore, N. Sweden ..	H	2	0.6	0.4 -0.6	2	<20	
	Skarn iron ore, Rautuvaara, N. Finland	M	1	0.8		1	20	
Metasomatic	Iron ore, Hauki type, N. Sweden	M	1	1		1	130	
	Iron ore, Hauki type, N. Sweden	H	7	>0.7	0.1 ->3	7	<20	
	Leptite, Nautanen, N. Sweden	M	2	0.4	0.3 -0.5	2	<20	
	Altered basic volcanics, N. Sweden	M	2	0.7	0.4 -0.9	2	<20	
	Iron ore, Taporova, N. Fin- land	M	1	0.6		1	220	
	Iron ore, Taporova, N. Fin- land	H	2	1.0	0.7 -1.3	2	230	180- 280
	Amphibolite, Hällinmäki, C. Finland	M	1	0.7		1	<20	
Unknown	Iron ore, Altavaara, N. Sweden	M	2	0.2		2	25	<20- 40
	Iron ore, Killingi, N. Sweden	M	1	1.1		1	<20	
	Iron ore, Leppäkoski, N. Swe- den	M	3	0.2	0.2 -0.3	3	80	<20- 120
	Iron ore, Puoltsa, N. Sweden	M	4	0.4	0.3 -0.55	4	<20	
	Conglomerate, Doktors kulle, N. Sweden	H	1	1.3		1	20	
	Conglomerate, Saurusvaara, N. Sweden	H	1	0.3		1	<20	
	Gneiss, N. Sweden	M	2	0.4		2	10	≤20

pneumatolytic ores chromium contents of this magnitude have been found. Only the magnetites in the ultrabasic and basic magmatic rocks have chromium contents which lie significantly above the content of this element in the upper lithosphere. This is due to their early crystallization. The highest values (up to 54000 p. p. m. Cr) have been reported by Du Rietz (1956) from magnetites in peridotites. In the ultrabasic and basic volcanics the high chromium

contents in the magnetite might be due to the presence of chromite and magnesiochromite. The only magnetites in intermediate or acid intrusives which contain appreciable amounts of chromium are those occurring in the charnockite series in Madras (Howie 1955) and in the batholith of S. California (Sen et al. 1959). Further the magnetite in the late fissure fillings of the Alps contains, according to Hegemann & Albrecht (1954), up to 2000 p. p. m. Cr.

Hematite takes up very little chromium. As seen from table 18 the chromium content of hematite in both iron ores and rocks is well below that for the upper lithosphere. In this respect there seems to be a fundamental difference between magnetite and hematite. The fact that chromium substitutes for ferric iron in magnetite but not in hematite must be due to the different crystal-chemical properties of these minerals and possibly to different modes of formation, at least in the case of hematite formed by magmatic processes. Thus hematite seems to be connected with late stages of magmatism, often in association with pneumatolytic or hydrothermal processes when the ore solutions are depleted in chromium.

In the magnetites and hematites analyzed in the present work the content of chromium is, in most cases, below the content of the upper lithosphere as seen from table 19. The highest values have been obtained from magnetites in the basic magmatic rocks where some samples contain more than 2000 p. p. m. The hematite from the gabbro at Saarikoski forms an exception as the content is below 20 p. p. m. This is in accordance with what has been said above about the restricted ability of hematite to take up chromium. The syenite-porphyrries also have rather high values approaching 800 p. p. m. Cr. It is interesting to note the low chromium content of the apatite iron ores which have been derived from the same magma as the syenite-porphyrries but are formed at a later stage in the differentiation. This means that chromium was depleted early in the differentiation when the porphyries were formed. It is, however, remarkable that the chromium content is so relatively high in hydrothermal ores of the Hauki type since these formed at an even later stage in the same differentiation. The author (Frietsch 1966, p. 272) has explained this as a consequence of the metasomatic mode of formation of the ore. The same feature is also encountered in other deposits formed metasomatically. Thus rather high chromium contents are found in the iron oxides in Taporova: 180–280 p. p. m. in hematite and 200 p. p. m. in magnetite. In the Leppäkoski deposit the southeastern part of which is similar to the Hauki iron ore type (p. 38), a chromium content of 120 p. p. m. is found in the magnetite. From the above it is clear that magnetite in the early magmatic differentiates in Norrbotten is relatively rich in chromium and that the same holds for some late formed, metasomatic iron ores.

In both the skarn iron ores and the stratified iron ores in Northern Sweden the chromium content is somewhat higher than in the other types of ore rock

investigated in this work but still not above the content in the upper lithosphere. It is somewhat higher in the stratified ores with a mean of 90 p. p. m. than in the skarn iron ores with a mean of 40 p. p. m. Sometimes, however, rather high contents of chromium are found in these ores, up to 420 p. p. m. in the skarn ores and up to 1200 p. p. m. in the stratified ores. To some extent these extreme values can be explained as due to impurities of dark, magnesium-bearing silicates which are rather rich in chromium (table 2), but the low contents of silica and magnesium seem to exclude the existence of such impurities. It seems reasonable, therefore, to conclude that the partly high chromium contents in magnetite in the skarn ores and stratified ores are primary features.

5.4. Magnesium

Mg^{2+} is smaller in size (0.66 Å) than Fe^{2+} but these two ions are, in spite of the size difference, known to substitute for each other in a great number of minerals. Mg^{2+} has, however, compared to Fe^{2+} a lower electronegativity value, a somewhat lower ionization potential value and a higher value for the relative total bonding energy (table 16). It forms therefore more ionic bonds with oxygen than Fe^{2+} . In fractional crystallization magnesium is separated at an early stage. This feature is applicable to the magnetite formed in the Skaergaard intrusion. Here Vincent & Phillips (1954) showed that the magnesium content in the magnetite decreases rapidly in the later stages. In the Madras charnockites there is, however, no change in the magnesium content in magnetite during the differentiation, the content being relatively low in magnetite in all rock members (Howie 1955).

Magnesium enters magnetite in iron ores, mostly in small amounts, but there are exceptions as may be seen from table 17. Thus Hegemann & Albrecht (1954) reported magnetite in the volcanic-sedimentary ores with up to 2 % MgO and in the hydrothermal ores approaching 1.7 % MgO. In the skarn iron ore deposit Stora Sahavaara in Northern Sweden, which is considered by the present author to be sedimentary, the magnetite contains 2.6 % MgO (Lundberg 1967). The highest magnesium contents are found in contact-pneumatolytic deposits from which values of up to 14 % MgO have been reported. In magnetite occurring in rocks the magnesium content is also rather low in most cases, though the magnetites in basic and ultrabasic rocks form an exception. In these the MgO content mostly varies between 2 and 5 %, the highest value being reported by Du Rietz (1956) from chromium-bearing magnetites in peridotites. In the basic and ultrabasic rocks the high magnesium content in magnetite is, like the high aluminum and chromium contents, due to admixture of other spinel components in the magnetite. A relatively high magnesium content (up to 1.3 % MgO) has been reported from magnetite in fissure fillings in the Alps (Hegemann & Albrecht 1954).

Hematite in iron ores and rocks does not contain large amounts of magnesium (table 18), the highest contents (up to 0.8 % MgO) being reported by Hegemann & Albrecht (1954) from volcanic-sedimentary ores and hydrothermal ores. The low magnesium content in hematite is naturally due to the fact that Mg^{2+} and Fe^{3+} , in spite of their similarity in size, are different in charge and other physical properties (table 16) and consequently do not replace each other.

The content of magnesium in magnetite and hematite investigated in the present work (table 20) is low compared to the content of this element in the upper lithosphere (5.15 % MgO = 31000 p. p. m. Mg, according to Shaw 1964). In most types of ores and rocks the magnesium content is less than 3000 p. p. m. (0.5 % MgO) which is the lower sensitivity limit of the spectrographical determination. This unfortunately means that no conclusions concerning the variations of the magnesium content can be drawn in these cases. In the magnetite in the basic magmatic rocks the content is, however, higher with values up to 27000 p. p. m. Mg (4.5 % MgO). In the skarn iron ores and the stratified iron ores the magnesium values are sometimes high with maximum of 51000 p. p. m. Mg (8.5 % MgO) for the first type and 33000 p. p. m. (5.5 % MgO) for the second type. In some cases the high magnesium contents are due to impurities of magnesium-bearing silicates as shown by the fact that the high values often are found in those analyses where the content of silica is rather high. In rather many analyses the magnesium content seems not to be correlated to the content of silica, meaning that magnesium, at least in part, enters magnetite. The location of the magnesium in the magnetite lattice from some skarn iron ores and stratified iron ores has been established with the aid of the microprobe (p. 13). The high magnesium contents are not due to contaminations of magnesium-bearing silicates. The same is true for the magnetite in the Puoltsa deposit (of unknown origin) where magnesium contents up to 17500 p. p. m. (2.9 % MgO) have been found spectrochemically.

5.5. Titanium

Ti^{4+} is intermediate in size (0.68 Å) between Fe^{3+} and Fe^{2+} . Ti^{4+} has the same electronegativity value as Fe^{2+} but lower than that for Fe^{3+} (table 16). Ti^{4+} has a lower ionization potential value and a higher value of the relative total bonding energy than Fe^{2+} and Fe^{3+} . Therefore titanium forms more ionic bonds with oxygen than iron and is concentrated in the early stages of a fractional crystallization. In consequence the magnetite found in basic and ultrabasic intrusives is always rich in titanium.

According to Deer et al. (1962, p. 68) "a considerable amount of Ti can enter the magnetite structure, there being a continuous relationship between

Table 20. The content of magnesium and titanium in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Occurrence	Mineral (M = magnetite H = hematite)	p. p. m. Mg			p. p. m. Ti		
			n	Mean	Range	n	Mean	Range
Magmatic	Basic magmatic rock, N. Sweden	M	8	8600	<3000-27000	8	9800	<600-30000
	Basic magmatic rock, N. Sweden	H	1	<3000		1	>30000	
	Syenite-porphry, N. Sweden ..	M	5	3900	<3000- 9000	5	5000	600-10800
	Apatite iron ore, N. Sweden	M	54	1900	180-12000	54	1500	<600- 6000
	Apatite iron ore, N. Sweden	H	23	1800	60- 3000	22	2600	<600-15500
	Iron ore, Misi, N. Finland	M	3	5000	<3000-12000	3	700	<600- 1200
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Germany	M	3	<3000		3	<600	
	Iron ore, Lahn-Dill, W. Germany	H	4	<3000		4	<600	
	Iron ore, Kittilä, N. Finland	M	3	<3000		3	400	≤600
	Stratified iron ore, N. Sweden ..	M	28	5300	<3000-33000	28	1800	<600- 9600
	Skarn iron ore, N. Sweden	M	77	9600	<3000-51000	77	900	<600- 4800
	Skarn iron ore, N. Sweden	H	2	15800	<3000-30000	2	1000	<600- 1800
	Skarn iron ore, Rautuvaara, N. Finland	M	1	6000		1	1200	
Metasomatic	Iron ore, Hauki type, N. Sweden	M	1	1800		1	1800	
	Iron ore, Hauki type, N. Sweden	H	7	<3000		7	700	<600- 1200
	Leptite, Nautanen, N. Sweden ..	M	2	<3000		2	900	600- 1200
	Altered basic volcanics, N. Sweden	M	2	<3000		2	1200	
	Iron ore, Taporova, N. Finland ..	M	1	<3000		1	<600	
	Iron ore, Taporova, N. Finland ..	H	2	<3000		2	6900	5400- 8400
	Amphibolite, Hällinmäki, C. Finland	M	1	<3000		1	1800	
Unknown	Iron ore, Altavaara, N. Sweden ..	M	2	<3000		2	450	≤600
	Iron ore, Killingi, N. Sweden	M	1	<3000		1	3000	
	Iron ore, Leppäkoski, N. Sweden	M	3	<3000		3	<600	
	Iron ore, Puoltsa, N. Sweden	M	4	12500	2700-17500	4	700	300- 1000
	Conglomerate, Doktors kulle, N. Sweden	H	1	<3000		1	6000	
	Conglomerate, Saurusvaara, N. Sweden	H	1	<3000		1	1200	
	Gneiss, N. Sweden	M	2	<3000		2	1200	

magnetite and the ulvöspinel molecule, Fe_2TiO_4 ". In these minerals the iron-titanium substitution occurs according to the reaction $2\text{Fe}^{3+} = \text{Fe}^{2+} + \text{Ti}^{4+}$ (Nicholls 1955, Nagata 1961). Buddington & Lindsley (1964) and Abdullah (1965) showed that the titanium content in magnetite coexisting with ilmenite can be used as a geological thermometer; the titanium content in magnetite increases with increasing temperature.

In hematite "TiO₂ is usually reported, but any large amount may be due to the intergrowth of ilmenite" (Deer et al. 1962, p. 22). At elevated tempera-

tures there is a complete solid solutions series between these minerals (Ramdohr 1926, Posnjak & Barth 1934). According to Nicholls (1955) the iron-titanium substitution in hematite occurs in the form given above for this substitution in magnetite.

The titanium content of the upper lithosphere is, according to Shaw (1964), 1.68 % TiO_2 = 10000 p. p. m. Ti. As seen from table 17 the titanium content in magnetite in iron ores is in most cases below this value, not exceeding 1 % TiO_2 . From some contact-pneumatolytic deposits Pavlov & Tschuprynina (1955) reported up to 2.9 % TiO_2 . The magnetite in the basic and ultrabasic intrusives is, in almost all cases, rich in titanium with contents of up to 30 % TiO_2 . Naturally the high amounts reported are often due to the presence of ulvöspinel or ilmenite. Fairly high contents of titanium in magnetite have also been found in intermediate intrusives (up to 7.4 % TiO_2), in the fissure fillings in the Alps (up to 3.2 % TiO_2) and in pegmatites (up to 1.7 % TiO_2).

The titanium contents found in hematite are lower than in magnetite, usually not exceeding 0.1 % TiO_2 (table 18). Hegemann & Albrecht (1954) however reported up to 0.7 % TiO_2 in sedimentary iron ores and up to 8.2 % TiO_2 in the fissure fillings in the Alps.

As seen from table 20 the mean content of titanium in magnetite and hematite in most of the different iron ores and rocks investigated in the present work is below 2000 p. p. m. (0.34 % TiO_2). High values are only obtained in the iron oxides in the basic magmatic rocks with up to 30000 p. p. m. (5 % TiO_2) or more. At least in part these high contents are due to the presence of ilmenite in the samples analyzed. Comparatively high titanium contents are further found in the magnetite of the syenite-porphyrines (mean value 5000 p. p. m.) and in the hematite of the apatite iron ores (mean value 2600 p. p. m.), the Taporova ore (mean value 6900 p. p. m.), and the conglomerate at Doktors kulle (6000 p. p. m.). It should be pointed out that in the apatite iron ores and in the Taporova deposit there is a higher content of titanium in hematite compared with magnetite. A similar feature has been reported by Landergren (1943) from the apatite iron ores in Central Sweden: the hematite ores contain 6800 p. p. m. Ti and the magnetite ores 2300 p. p. m. Ti (mean values). These values refer to the whole ore and are thus not comparable to those found in the iron oxides in the apatite iron ores in the present investigation.

5.6. Nickel

The content of nickel in the upper lithosphere is 80 p. p. m. (Shaw 1964). As seen from table 17 only a small number of analyses of the nickel content in magnetite in iron ore are reported, but these show that the content is in most cases less than this value or of about the same magnitude. Hegemann & Al-

brecht (1954), however, reported up to 250 p. p. m. Ni in volcanic-sedimentary deposits and up to 180 p. p. m. Ni in contact-pneumatolytic deposits. Nickel values above the average content of this element in the upper lithosphere are found in the magnetites in magmatic rocks. In a fractional crystallization the content of nickel tends to fall, and this is applicable to the nickel content in magnetite as shown from the Skaergaard intrusion by Wager & Mitchell (1951), the Madras charnockite series by Howie (1955), the batholith in S. California by Sen et al. (1959) (table 29, p. 96), and the Lambertville diabase by Storm & Holland (1957). The highest nickel values are reported from the ultrabasic magmatic rocks. Fawley (1959) described a nickeliferous magnetite (in a serpentinite) containing more than 8 per cent Ni although the average content is less than 1 per cent. In the magnetite in basic intrusives nickel contents up to several thousands p. p. m. are recorded. The magnetite in the intermediate and acid intrusives shows lower nickel values but above the average content of this element in the upper lithosphere. Furthermore, the magnetite in the fissure fillings in the Alps is relatively rich in nickel. Hegemann & Albrecht have reported up to 3000 p. p. m. Ni.

Analyses of the nickel content in hematite are still rather few in the literature as compared with magnetite. In hematite in iron ores it seems that the values are somewhat higher than the average content of the upper lithosphere, the highest values (up to 500 p. p. m.) being reported by Hegemann & Albrecht in sedimentary ores. Regarding the nickel content in hematite in rocks no conclusion can be drawn because of the scarcity of analyses, but the contents seem to lie below the value for the upper lithosphere.

As seen from table 21 the nickel content in the magnetites and hematites investigated in this work is of about the same magnitude as the average content in the upper lithosphere, but in most cases it is somewhat higher. The highest values occur in the magnetite in the magmatic iron ores in the Misi area in Northern Finland, where the mean value is 280 p. p. m. This might, however, partly be due to contaminations with pyrite (cf. p. 48). According to Nuutilainen (1968, p. 46) the pyrite associated with magnetite in the Kärvasvaara ore in this area contains some nickel and cobalt. The nickel content in the magnetite in the apatite iron ores in Northern Sweden is almost of the same magnitude (mean value = 220 p. p. m.), the highest value in these being 800 p. p. m. Otherwise the content of nickel in the iron oxides in the different types of ore and rock investigated shows so small variations that no significant conclusions about the distribution of this element can be drawn. It should also be pointed out that the nickel content in magnetite in the basic magmatic rocks in Norrbotten is low compared to the usually high value for nickel in magnetite in this type of rock from other parts of the world. There is an obvious difference between magnetite and hematite in the samples investigated, hematite being low in nickel compared to magnetite. The nickel

Table 21. The content of nickel and molybdenum in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Occurrence	Mineral (M = magnetite H = hematite)	p. p. m. Ni			p. p. m. Mo		
			n	Mean	Range	n	Mean	Range
Magmatic	Basic magmatic rock, N. Sweden	M	8	180	<20-420	8	23	<10-30
	Basic magmatic rock, N. Sweden	H	1	40		1	30	
	Syenite-porphry, N. Sweden ..	M	5	90	20-160	5	6	≤10
	Apatite iron ore, N. Sweden	M	67	220	60-800	41	7	<10-30
	Apatite iron ore, N. Sweden	H	25	70	<20-300	12	8	<10-20
Iron ore, Misi, N. Finland	M	3	280	80-500	3	<10		
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Germany	M	3	100	40-200	3	15	<10-30
	Iron ore, Lahn-Dill, W. Germany	H	4	130	80-200	4	15	<10-40
	Iron ore, Kittilä, N. Finland	M	3	40	20-80	3	7	≤10
	Stratified iron ore, N. Sweden ..	M	28	70	<20-260	28	6	<10-20
	Skarn iron ore, N. Sweden	M	77	100	<20-360	73	5	≤10
	Skarn iron ore, N. Sweden	H	2	50	20-80	2	8	≤10
Skarn iron ore, Rautuvaara, N. Finland	M	1	70		1	<10		
Metasomatic	Iron ore, Hauki type, N. Sweden	M	1	160		-		
	Iron ore, Hauki type, N. Sweden	H	7	<20		6	10	<10-20
	Leptite, Nautanen, N. Sweden ..	M	2	25	<20-40	2	<10	
	Altered basic volcanics, N. Sweden	M	2	120	30-200	2	<10	
	Iron ore, Taporova, N. Finland ..	M	1	120		1	<10	
	Iron ore, Taporova, N. Finland ..	H	2	<20		2	<10	
	Amphibolite, Hällinmäki, C. Finland	M	1	120		1	10	
Unknown	Iron ore, Altavaara, N. Sweden ..	M	3	70	50-80	2	<10	
	Iron ore, Killingi, N. Sweden	M	1	80		1	<10	
	Iron ore, Leppäkoski, N. Sweden	M	3	100	80-120	3	10	<10-20
	Iron ore, Puoltsa, N. Sweden	M	4	280	230-320	4	<10	
	Conglomerate, Doktors kulle, N. Sweden	H	1	40		1	10	
	Conglomerate, Saurusvaara, N. Sweden	H	1	<20		1	<10	
Gneiss, N. Sweden	M	2	140	70-200	2	<10		

content in hematite does not usually exceed 50 p. p. m. The only exception is the hematite in the ores from the Lahn-Dill area, where the content varies between 80 and 200 p. p. m.

5.7. Molybdenum

According to Shaw (1964) the content of molybdenum in the upper lithosphere is 1 p. p. m. Molybdenum is found to be concentrated in magnetite as shown by Howie (1955) and Rabinovich et al. (1958). According to Howie

molybdenum is probably replacing Fe^{3+} in magnetite. The ionic radius of Mo^{4+} (0.70 Å) is, however, somewhat larger than that of Fe^{3+} . As seen from table 17 molybdenum in magnetite is reported from acid, intermediate, and basic intrusives. The highest values are those in the acid rocks with contents up to 150 p. p. m. As shown from the Madras series by Howie (1955) and from the batholith in S. California by Sen et al. (1959) the molybdenum content in magnetite is highest in the late phases of the differentiation. Wager & Mitchell (1951) showed, on the other hand, that in the Skaergaard intrusion the molybdenum content in magnetite has not changed during the fractional crystallization. From the apatite iron ores in Southeastern Missouri a low content of molybdenum (3 p. p. m.) has been recorded by Kisvarsanyi & Proctor (1967). The hematite in the metasomatic iron ores connected with the apatite iron ores in the same area contains, according to these authors, up to 60 p. p. m. Mo.

In table 21 it is seen that the content of molybdenum in the magnetites and hematites investigated in the present work is mostly below the sensitivity of the spectrographic determination (10 p. p. m.). Somewhat higher values have been found in the iron oxides in the basic magmatic rocks (up to 30 p. p. m.) and in the iron ores in the Lahn-Dill area (up to 40 p. p. m.). There seems to be a tendency for hematite to have a somewhat higher molybdenum content than magnetite.

5.8. Cobalt

Co^{2+} is intermediate in size (0.72 Å) between Fe^{2+} (0.75 Å) and Mg^{2+} (0.66 Å) and replaces these elements in a crystal lattice. According to Taylor (1965, p. 173) Co^{2+} enters "early Fe^{2+} positions, although not to the same extent as nickel. Thus nickel is depleted at a faster rate, the Ni/Co ratio falls during fractionation and the Fe/Co ratio tends to rise". That the content of cobalt compared to iron decreases during a fractional crystallization is shown by the behaviour of this element in magnetite in the Skaergaard intrusion (Wager & Mitchell 1951) and in the batholith in S. California (Sen et al. 1959). In both rock series the cobalt content in magnetite is higher in the earlier than in the later phases (cf. table 29, p. 96). However, according to Howie (1955), the content of cobalt in magnetite in the Madras charnockite series has not changed during the differentiation (table 29).

The cobalt content of the upper lithosphere is, according to Shaw (1964), 27 p. p. m. As seen from table 17 the cobalt content in magnetite in iron ores is somewhat higher than this value. The highest value (up to 500 p. p. m.) has been reported by Hegemann & Albrecht (1954) from contact-pneumatolytic deposits. In magnetite in rocks the cobalt content is relatively high but mostly not exceeding 300 p. p. m. The highest value (1000 p. p. m.) is reported from the basic rock members in the batholith in S. California (Sen et al. 1959).

In hematite the cobalt content is clearly lower than in magnetite, as seen from table 18. It is of the same magnitude as the content of this element in the upper lithosphere or somewhat higher.

The cobalt content in the magnetites and hematites investigated in the present paper is, in most cases, higher than the content of this element in the upper lithosphere (table 22). In magnetite the highest values are met with in the basic magmatic rocks (with a maximum value of 420 p. p. m.). Comparatively high cobalt contents (100 p. p. m. or higher) are found in the magnetite in the skarn iron ores, the apatite iron ores, the Misi iron ores and stratified iron ores. As has been pointed out earlier (p. 13), the cobalt content in the iron oxides in the skarn ores, the stratified ores and the Misi ores might partly be due to impurities of cobalt-bearing pyrite and pyrrhotite. Low cobalt contents (20 p. p. m. or less) are found in the magnetite in the Kittilä iron ores.

In comparison with magnetite there is a clear tendency for hematite to contain less cobalt. In rather many hematite samples the content is less than 200 p. p. m. There are, nevertheless, exceptions, e. g., the hematite in the skarn iron ore at Laukujärvi which contains 400 p. p. m. Co (table 8).

5.9. Copper

Cu^{2+} is in size (0.72 Å) similar to Fe^{2+} and should enter the magnetite lattice, but Cu^{2+} has higher values for electronegativity and ionization potential than Fe^{2+} (table 16), meaning that the Fe-O bond is more ionic than the Cu-O bond. Copper will thus, compared to iron, be concentrated in the later phases of magmatic differentiation. According to Wager & Mitchell (1951) the copper content in magnetite in the Skaergaard intrusion increases during the fractionation, being highest in the late phases. Vincent & Phillips (1954), however, reported a rather irregular variation of the copper content in the magnetite in this rock series.

The copper content in the upper lithosphere is 70 p. p. m. (Shaw 1964). Only a few analyses of the copper content in magnetite are available in the literature. Fairly high copper contents in magnetite in iron ores have been reported by Hegemann & Albrecht (1954) from volcanic-sedimentary deposits (up to 600 p. p. m. Cu), hydrothermal deposits (up to 150 p. p. m. Cu) and contact-pneumatolytic deposits (up to 150 p. p. m. Cu). In magnetite in basic intrusives and exhalative rocks values much above the copper content of the upper lithosphere have been found.

As seen from table 18 Hegemann & Albrecht (1954) reported comparatively high copper contents in hematite in different iron ores and rocks, the highest values (up to 400 p. p. m.) occurring in hematite in hydrothermal ores.

Table 22. The content of cobalt and copper in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Occurrence	Mineral (M = magnetite H = hematite)	p. p. m. Co			p. p. m. Cu		
			n	Mean	Range	n	Mean	Range
Magmatic	Basic magmatic rock, N. Sweden	M	8	200	80-420	6	60	20-140
	Basic magmatic rock, N. Sweden	H	1	100		1	40	
	Syenite-porphry, N. Sweden	M	5	60	40-100	5	40	10- 80
	Apatite iron ore, N. Sweden	M	67	120	<20-260	40	40	<10-180
	Apatite iron ore, N. Sweden	H	25	50	<20-120	14	40	<10- 90
	Iron ore, Misi, N. Finland	M	3	110	40-150	2	30	<10- 70
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Germany	M	3	<20		3	20	10- 40
	Iron ore, Lahn-Dill, W. Germany	H	4	30	20- 40	4	80	50-100
	Iron ore, Kittilä, N. Finland	M	3	15	≤20	3	40	20- 70
	Stratified iron ore, N. Sweden . .	M	28	100	20-260	25	40	<10-300
	Skarn iron ore, N. Sweden	M	77	80	<20-200	50	60	<10-400
	Skarn iron ore, N. Sweden	H	2	205	<20-400	2	60	50- 60
	Skarn iron ore, Rautuvaara, N. Finland	M	1	140		-		
Metasomatic	Iron ore, Hauki type, N. Sweden	M	1	60		-		
	Iron ore, Hauki type, N. Sweden	H	7	<20		6	60	10- 90
	Leptite, Nautanen, N. Sweden . .	M	2	60	40-100	2	130	60-200
	Altered basic volcanics, N. Sweden	M	2	70		2	10	
	Iron ore, Taporova, N. Finland . .	M	1	40		1	30	
	Iron ore, Taporova, N. Finland . .	H	2	<20		2	<10	
	Amphibolite, Hällinmäki, C. Finland	M	1	80		-		
Unknown	Iron ore, Altavaara, N. Sweden . .	M	3	70	50- 80	2	8	≤10
	Iron ore, Killingi, N. Sweden	M	1	40		1	20	
	Iron ore, Leppäkoski, N. Sweden . .	M	3	60	50- 60	3	25	20- 30
	Iron ore, Puoltsa, N. Sweden	M	4	100	60-120	4	<10	
	Conglomerate, Doktors kulle, N. Sweden	H	1	30		1	80	
	Conglomerate, Saurusvaara, N. Sweden	H	1	<20		1	60	
	Gneiss, N. Sweden	M	2	80	60-100	2	35	20- 50

The copper content in magnetite and hematite in iron ores and rocks investigated in the present work is shown in table 22. Here, the only analyses considered are those in which chalcopyrite and other copper minerals could not be detected macroscopically or microscopically. The copper values in both magnetite and hematite are, in most cases, below the copper content in the upper lithosphere. The highest values are found in magnetite in skarn iron ores

(up to 400 p. p. m. Cu) and stratified iron ores (up to 300 p. p. m. Cu), the mean for both types being below the average copper content of the upper lithosphere. Otherwise the copper content in magnetite and hematite in the different types of ore and rocks is rather similar. There seems to be no difference in the copper content between magnetite and hematite.

5.10. Zinc

Zn^{2+} being of the same size (0.74 Å) as Fe^{2+} should, according to the Goldschmidt Rules, substitute for this ion in a crystal lattice. The lower value of the ionization potential and the somewhat higher value of the relative total bonding energy for Fe^{2+} (table 16) indicate that this element forms more ionic bonds than zinc. This is, however, offset by the smaller electronegativity of Zn^{2+} compared to Fe^{2+} . Zn^{2+} will, according to Taylor (1965, p. 179), "enter late Fe^{2+} positions and the Zn^{2+}/Fe^{2+} ratio will increase during fractionation in silicate melts". According to Wedepohl (1953) zinc in basic rocks enters pyroxene and magnetite, in acid rocks biotite and amphibole. Howie (1955) showed that in the Madras series zinc appears to be concentrated in magnetite from basic and intermediate rocks.

As seen from table 17 the amount of zinc found in magnetite in iron ores, except for the contact-pneumatolytic deposits, is below the average zinc content of the upper lithosphere estimated to 40 p. p. m. (Shaw 1964). In the magnetite in the contact-pneumatolytic iron ores zinc contents up to 9000 p.p.m. were recorded by Hegemann & Albrecht (1954). In magnetite in magmatic rocks rather high values of zinc are reported. The content of about 1 per cent Zn found by Wager & Mitchell (1951, table B) in the magnetite in the Skaergaard intrusion is the highest recorded. It seems to be too high, later investigations by Vincent & Philips (1954) showing values between 750 and 1700 p. p. m. Zn to be present. The highest value obtained is from magnetite in the late-formed fayalite-ferrogabbro. Further zinc contents up to several thousands of p. p. m. have been found in magnetite in exhalative rocks.

Zinc in hematite has only been reported from the iron ores of the Hauki type in Southeastern Missouri. Kisvarsanyi & Proctor (1967) showed mean values up to 200 p. p. m. Zn in the hematite in these ores.

The zinc content in magnetite and hematite in the different iron ores and rocks investigated in this paper is shown in table 23. The content is in almost every case above that for the upper lithosphere. The highest values are met with in the basic magmatic rocks, where the zinc content in magnetite reaches 800 p. p. m. and in hematite 700 p. p. m. Otherwise the variation in the iron oxides in the different ores and rocks is rather small. No differences between the zinc content in magnetite and hematite have been traced.

Table 23. The content of zinc and vanadium in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Occurrence	Mineral (M = magnetite H = hematite)	p. p. m. Zn			p. p. m. V		
			n	Range	Range	n	Mean	Mean
Magmatic	Basic magmatic rock, N. Sweden	M	8	260	100-800	8	1850	200-4000
	Basic magmatic rock, N. Sweden	H	1	700		1	1200	
	Syenite-porphry, N. Sweden . . .	M	5	60	<50-100	5	1000	500-1250
	Apatite iron ore, N. Sweden . . .	M	32	100	<50-350	67	1300	300-2500
	Apatite iron ore, N. Sweden . . .	H	11	110	<50-300	25	800	200-1500
	Iron ore, Misi, N. Finland	M	3	50		3	1000	600-1500
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Germany	M	3	60	<50-100	3	120	<50- 300
	Iron ore, Lahn-Dill, W. Germany	H	4	100		4	400	300- 500
	Iron ore, Kittilä, N. Finland . . .	M	3	33	≤50	3	160	<50- 400
	Stratified iron ore, N. Sweden ..	M	28	150	<50-350	28	440	<50-3800
	Skarn iron ore, N. Sweden	M	73	90	<50-250	77	600	<50-2900
	Skarn iron ore, N. Sweden	H	2	80	50-100	2	550	200- 900
	Skarn iron ore, Rautuvaara, N. Finland	M	1	100		1	150	
Metasomatic	Iron ore, Hauki type, N. Sweden	M	-			1	500	
	Iron ore, Hauki type, N. Sweden	H	6	<50		7	80	<50- 300
	Leptite, Nautanen, N. Sweden ..	M	2	130	100-150	2	750	400-1100
	Altered basic volcanics, N. Sweden	M	2	50		2	1300	800-1800
	Iron ore, Taporova, N. Finland ..	M	1	50		1	200	
	Iron ore, Taporova, N. Finland ..	H	2	50		2	330	300- 350
	Amphibolite, Hällinmäki, C. Finland	M	1	150		1	200	
Unknown	Iron ore, Altavaara, N. Sweden ..	M	2	<50		3	850	700-1200
	Iron ore, Killingi, N. Sweden . . .	M	1	50		1	1100	
	Iron ore, Leppäkoski, N. Sweden	M	3	33	≤50	3	370	200- 500
	Iron ore, Puoltsa, N. Sweden . . .	M	-			4	1650	1100-2200
	Conglomerate, Doktors kulle, N. Sweden	H	1	160		1	800	
	Conglomerate, Saurusvaara, N. Sweden	H	1	<50		1	1000	
	Gneiss, N. Sweden	M	2	180	100-250	2	1050	500-1600

5.11. Vanadium

Vanadium, mostly occurring as V^{3+} , has almost the same ionic radii (0.74 Å) as Fe^{2+} but is larger than Fe^{3+} and is consequently captured in Fe^{2+} positions while it enters late Fe^{3+} positions. V^{3+} has a lower value of electronegativity and ionization potential and a higher relative total bonding energy than Fe^{3+} (table 16). It thus forms more ionic bonds with oxygen than Fe^{3+} . According to Taylor (1965, p. 169) "the entry of V^{3+} into Fe^{2+} positions leads to difficulty in maintaining charge balance, in minerals such as olivine, and in fact

vanadium was not detected in Skaergaard olivines, entering instead pyroxenes and the ore minerals, preferring magnetite to ilmenite".

The content of vanadium in the upper lithosphere is, according to Shaw (1964), 100 p. p. m. Table 17 shows that the vanadium content in magnetite in iron ores and rocks reported in the literature is mostly above this value. Relatively high contents are found in the volcanic-sedimentary and contact-pneumatolytic iron ores, and in fissure fillings in the Alps. The highest values are, however, found in magnetite in the magmatic rocks. As has already been pointed out by Luyken & Kirchberg (1944) and Landergren (1948) the titaniferous magnetites are richer in vanadium than other magnetites. According to Taneda (1950) the content of V_2O_3 in magnetite in basic rocks, except for alkaline basalts, is higher than in acid ones. In the titaniferous magnetites in basic and ultrabasic rocks the content of vanadium is roughly between 2000 and 10000 p. p. m., the highest value being 14000 p. p. m. The magnetite in the Madras series and the batholith in S. California contains between 1000 and 6000 p. p. m., the acid members of these rocks series showing the lowest contents. In the Skaergaard intrusion there is a marked decrease in the vanadium content in the magnetite during the differentiation as shown by Wager & Mitchell (1951) and Vincent & Phillips (1954). The magnetites in the Skaergaard intrusion contain on the whole a lower content of vanadium than the magnetites in the above mentioned rocks series (cf. table 29, p. 96).

The content of vanadium in hematite in iron ores and rocks (table 18) is in most cases higher than the vanadium content of the upper lithosphere. In the contact-pneumatolytic and hydrothermal iron ores, however, vanadium contents lower than 50 p. p. m. are found.

In the magnetites and hematites investigated in the present work the content of vanadium is, in almost every case, above that of the upper lithosphere (table 23). The highest values are found in the basic magmatic rocks with a mean content of 1850 p. p. m. Furthermore, the mean content of 1300 p. p. m. in the magnetite in the apatite iron ores is rather high. Low values are found in the magnetite in the Lahn-Dill ores (mean value 120 p. p. m.) and still lower in the hematite in the iron ores of the Hauki type (mean value 80 p. p. m.). For the samples investigated there seem to be only smaller differences between the content of vanadium in magnetite and hematite. In the apatite iron ores, the iron ores of the Hauki type, and the skarn iron ores there is, however, a tendency for vanadium to show higher contents in magnetite than in hematite, but the opposite is found in the Lahn-Dill ores and in the Taporova ore.

5.12. Manganese

Mn^{2+} which has a somewhat larger ionic radius (0.80 Å) than Fe^{2+} is known to substitute for this ion in magnetite. The relative total bonding energy for Mn^{2+} and Fe^{2+} is almost equal (table 16), pointing to a similarity between

these ions, but Mn^{2+} has compared to Fe^{2+} , a lower value for electronegativity and ionization potential, and the Mn-O bond is thus more ionic than the Fe-O bond. Consequently Mn^{2+} should be depleted at a faster rate than Fe^{2+} in fractional crystallization. The analyses given by Howie (1955) show that the manganese content in magnetite in the different members of the Madras charnockite series has not been subject to any change during the differentiation. According to Vincent & Phillips (1954) the manganese content in magnetite in the early and intermediate rock members of the Skaer-gaard intrusion is almost similar (roughly 1500–3000 p. p. m.), but has increased in the late-formed fayalite-gabbro (5000–8000 p. p. m.).

As Mn^{2+} and Fe^{3+} are different in size, charge and other physical properties (table 16) the possibility for manganese to enter the hematite lattice is restricted, and as will be shown below, the manganese content in hematite is fairly low.

The manganese content in the upper lithosphere is, according to Shaw (1964), 1000 p. p. m. (0.13 % MnO). As seen from table 17 the manganese content in magnetite in iron ores is about of this magnitude but with slight variations above and below this value. High contents (up to 2.6 % MnO = 20000 p. p. m.) are only found in magnetite in the contact-pneumatolytic deposits. Relatively low contents have been reported from the volcanic-sedimentary ores, further Hegeman & Albrecht (1954) found only up to 0.02 % MnO (150 p. p. m. Mn) in the sedimentary ores. Other authors, on the other hand, have reported relatively high values (up to 0.87 % MnO = 6700 p. p. m. Mn) from this type of ore. In magnetite in rocks the manganese content is mostly equal to the content of this element in the upper lithosphere, only basic intrusives showing higher values (somewhat more than 1 % MnO).

In hematite the manganese content is lower than in magnetite (table 18), in most cases being below the manganese content of the upper lithosphere. Astonishingly high values are, however, reported by Bourguignon & Tuossaint (1955) from quartz-veins in the Ardennes. According to these authors up to 17.6 % MnO replaces iron in the hematite structure without modifying it.

In the magnetite and hematite in the iron ores and rocks investigated in the present work the content of manganese is mostly below that of the upper lithosphere (table 24). The highest values are found in the magnetite in the Kittilä ores, the skarn iron ores, and the stratified iron ores. To what extent these high contents are sited in the lattice or are due to impurities cannot always be determined. In the Kittilä ores the high manganese content is possibly due to impurities of mangano-siderite associated with the magnetite. In the skarn iron ores and the stratified iron ores the manganese content found in the analyses is partly due to admixture of pyroxene and amphibole which usually contain some manganese (cf. table 2). Furthermore, in both types of ore manganese-rich silicates are known to occur occasionally as in the skarn ore

Table 24. The content of manganese and calcium in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Occurrence	Mineral (M=magnetite H=hematite)	p. p. m. Mn			% CaO		
			n	Mean	Range	n	Mean	Range
Magmatic	Basic magmatic rock, N. Sweden ..	M	8	500	<200- 2000	8	0.5	<0.5 -1.5
	Basic magmatic rock, N. Sweden ..	H	1	1600		1	<0.5	
	Syenite-porphry, N. Sweden	M	5	200	<200- 800	5	0.4	<0.5 -1.0
	Apatite iron ore, N. Sweden	M	67	700	<200- 2400	54	0.5	0.1 -4.0
	Apatite iron ore, N. Sweden	H	25	500	<200- 2400	23	1.2	<0.05-8.0
	Iron ore, Misi, N. Finland	M	3	600	<200- 800	3	<0.5	
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Germany ..	M	3	700	<200- 1800	3	0.8	<0.5 -1.5
	Iron ore, Lahn-Dill, W. Germany ..	H	4	500	<200- 1000	4	0.6	<0.5 -1.5
	Iron ore, Kittilä, N. Finland	M	3	9100	<200-27000	3	0.4	≤0.5
	Stratified iron ore, N. Sweden	M	28	2500	<200- 7200	28	0.4	<0.5 -2.0
	Skarn iron ore, N. Sweden	M	77	900	<200- 5000	77	0.4	0.04-4.0
	Skarn iron ore, N. Sweden	H	2	700	400- 1000	2	<0.5	
	Skarn iron ore, Rautuvaara, N. Finland	M	1	800		1	0.5	
Metasomatic	Iron ore, Hauki type, N. Sweden ..	M	1	500		1	0.4	
	Iron ore, Hauki type, N. Sweden ..	H	7	<200		7	<0.5	
	Leptite, Nautanen, N. Sweden	M	2	1300	1200- 1400	2	<0.5	
	Altered basic volcanics, N. Sweden ..	M	2	400		2	<0.5	
	Iron ore, Taporova, N. Finland	M	1	600		1	<0.5	
	Iron ore, Taporova, N. Finland	H	2	500	350- 600	2	<0.5	
	Amphibolite, Hällinmäki, C. Finland	M	1	800		1	<0.5	
Unknown	Iron ore, Altavaara, N. Sweden	M	2	3400	400- 6400	2	<0.5	
	Iron ore, Killingi, N. Sweden	M	1	400		1	<0.5	
	Iron ore, Leppäkoski, N. Sweden ..	M	3	<200		3	<0.5	
	Iron ore, Puoltsa, N. Sweden	M	4	700	300- 1000	4	0.1	0.09-0.15
	Conglomerate, Doktors kulle, N. Sweden	H	1	200		1	<0.5	
	Conglomerate, Saurusvaara, N. Sweden	H	1	3100		1	<0.5	
	Gneiss, N. Sweden	M	2	1700	1200- 2200	2	<0.5	

Sattavaara and the stratified ore Marjarova. As has been mentioned earlier (p. 13) the analytical values obtained by a microprobe analysis are similar to those found spectrochemically. This means that manganese, at least in some of the samples of skarn iron ore and stratified iron ore, is really sited in the magnetite.

In the iron oxides in the other types of iron ore and rock investigated manganese is rather equally distributed. In accordance with the above there seems

to be a tendency for hematite to contain less manganese than magnetite. In the conglomerate from Saurusvaara the content is, however, comparatively high (3100 p. p. m. Mn), and this value forms an exception.

5.13. Calcium

Ca^{2+} differs in size and other physical properties both from Fe^{2+} and Fe^{3+} and is consequently not to be expected to enter magnetite or hematite. From tables 17 and 18 it is seen that significant amounts of calcium have not been reported to occur in these minerals, the only exception being the titaniferous magnetite in the basic intrusives, which in part is relatively rich in calcium (up to 2.6 % CaO). This feature is possibly due to the admixture of other mineral components in this type of magnetite.

In the magnetite and hematite investigated in the present work the calcium content is, in most cases, below the sensitivity of the spectrographic determination (0.5 % CaO). Higher values are, however, found in some ores and rocks (table 24), but these are most possibly due to contaminations with calcium-bearing minerals in the analyzed samples: apatite in the apatite iron ores, calcite in the Lahn-Dill ores and partly in the apatite iron ores, pyroxene and amphibole in the skarn ores, stratified ores and the basic magmatic rocks, plagioclase in the basic magmatic rocks and syenite-porphyrries.

5.14. Strontium and barium

The large size of Sr^{2+} and Ba^{2+} in comparison with Fe^{2+} and Fe^{3+} prevents the entry of these elements into magnetite or hematite. The contents of strontium and barium in the analyses of magnetite and hematite investigated in this paper are also low (table 25). In some of the analyzed samples high barium contents have been obtained, but these are due to contamination with barite, as in the hematite in the iron ores of the Hauki type and in the hematite and magnetite in the iron ore at Taporova. The high content of barium in the magnetite in Nautanen is also possibly related to contaminations with barite, a mineral which is commonly associated with magnetite at this locality (oral communication by F. Ros). Furthermore, the hematite of the apatite iron ores has higher barium contents (up to 540 p. p. m.) than the magnetite (up to 90 p. p. m.), which is in accordance with the fact that the secondary formation of hematite from magnetite in this type of ore is followed by a new-formation of barite (cf. Frietsch 1967a).

The content of strontium in the magnetites and hematites analyzed in this work is rather low, being of the magnitude of 17 p. p. m. or less. In the apatite iron ores, the iron ores of the Hauki type, and the iron ore at Taporova somewhat higher values are met with. This feature is possibly due to the admixture in the samples of barite containing some strontium.

Table 25. The content of strontium and barium in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Occurrence	Mineral (M = magnetite H = hematite)	p. p. m. Sr			p. p. m. Ba		
			n	Mean	Range	n	Mean	Range
Magmatic	Basic magmatic rock, N. Sweden ..	M	8	23	<17- 85	8	90	<90-180
	Basic magmatic rock, N. Sweden ..	H	1	<17		1	<90	
	Syenite-porphry, N. Sweden	M	5	17	<17- 51	5	144	<90-360
	Apatite iron ore, N. Sweden	M	32	18	<17- 85	32	60	≤90
	Apatite iron ore, N. Sweden	H	12	38	<17-180	12	180	<90-540
	Iron ore, Misi, N. Finland	M	3	<17		3	<90	
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Germany ..	M	3	23	17- 34	3	<90	
	Iron ore, Lahn-Dill, W. Germany ..	H	4	21	17- 34	4	100	90-180
	Iron ore, Kittilä, N. Finland	M	3	43	17- 68	3	200	<90-450
	Stratified iron ore, N. Sweden	M	28	19	<17- 51	28	150	<90-990
	Skarn iron ore, N. Sweden	M	60	13	<17- 51	60	70	<90-360
	Skarn iron ore, N. Sweden	H	2	<17		2	90	
	Skarn iron ore, Rautuvaara, N. Finland	M	1	17		1	<90	
Metasomatic	Iron ore, Hauki type, N. Sweden ..	H	6	49	<20-180	5	>1380	90->7200
	Leptite, Nautanen, N. Sweden	M	2	13	≤17	2	320	180-450
	Altered basic volcanics, N. Sweden ..	M	2	<17		2	60	≤90
	Iron ore, Taporova, N. Finland	M	1	68		1	2520	
	Iron ore, Taporova, N. Finland	H	2	94	68-119	2	>3820	3150->4500
	Amphibolite, Hällinmäki, C. Finland	M	1	<17		1	<90	
Unknown	Iron ore, Altavaara, N. Sweden	M	2	<17		2	200	<90-360
	Iron ore, Killingi, N. Sweden	M	1	<17		1	<90	
	Iron ore, Leppäkoski, N. Sweden ..	M	3	<17		3	140	<90-270
	Conglomerate, Doktors kulle, N. Sweden	H	1	17		1	180	
	Conglomerate, Saurusvaara, N. Sweden	H	1	<17		1	90	
	Gneiss, N. Sweden	M	2	<17		2	70	≤90

5.15. Other elements (gallium, tin, silver and lead)

The contents of the elements B, Be, Ga, Sn, Sb, Zr, Cd, Pb, and Ag have only been determined in a small number of iron oxide samples investigated in the present work and are listed in table 26. In all analyses the contents of B, Be, Sb, Zr, and Cd are below the sensitivity of the spectrochemical determination, and as these elements are not known to enter magnetite or hematite the significance of these values will not be discussed.

Gallium. Ga^{3+} is in size (0.62 Å) similar to Fe^{3+} and replaces this ion in

magnetite. For Ga^{3+} the electronegativity is lower and the relative total bonding energy higher than for Fe^{3+} (table 16), meaning that the Ga-O bond is more ionic than the Fe-O bond. The ionization potential values are, however, the same for both ions.

According to Shaw (1964) the gallium content of the upper lithosphere is 19 p. p. m. As seen from table 17 gallium is present in higher amounts than this value in magnetite in iron ores and rocks. Hegemann & Albrecht (1954) reported up to 500 p. p. m. Ga in contact-pneumatolytic iron ores and up to 20 p. p. m. Ga in volcanic-sedimentary iron ores. In magnetite in rocks gallium is only found in magmatic intrusives where the content varies between 10 and 120 p. p. m. Ga. The analyses given by Howie (1955) and Sen et al. (1959) show that there is a slight increase of the gallium content in magnetite during the differentiation of the Madras charnockites and the batholith in S. California, the magnetite in the early formed basic rock members showing the lowest values. This means that Ga^{3+} is not simply following Fe^{3+} in magnetite in these rock series. As the Ga-O bond is more ionic than the Fe-O bond, Ga^{3+} should be depleted at a faster rate than Fe^{3+} in a fractional crystallization. As no analyses of the gallium content in hematite are available in the literature, no conclusions of the ability of gallium to substitute for trivalent iron in this mineral can be drawn.

The gallium content in the different types of iron ore and rock investigated in the present paper shows only small variations, being roughly about 20 p. p. m. (table 26). The highest value (40 p. p. m. Ga) is found in the titaniferous magnetite from Akkavare. The only hematite analysis shows a value of 10 p. p. m. Ga.

Tin. Sn^{4+} which in size (0.71 Å) is intermediate between Fe^{3+} and Fe^{2+} is reported to occur in magnetite in small amounts. The tin content of the upper lithosphere is, according to Shaw (1964), 2 p. p. m. As seen from table 17 tin is in some cases concentrated in magnetite in iron ores and rocks. According to Howie (1955) the magnetite in the basic charnockites in the Madras series contains up to 50 p. p. m. Sn and in the intermediate charnockites up to 20 p. p. m. Sn. Tin is probably replacing Fe^{3+} in the magnetite. The decrease of the tin content in this fractional crystallization is in accordance with the fact that Sn^{4+} has a lower ionization potential value and a higher relative total bonding energy value than Fe^{3+} (table 16), and tin should therefore be concentrated in the earlier phases compared to trivalent iron. In exhalative rocks the magnetite contains up to 60 p. p. m. Sn. Extremely high tin contents (up to 9000 p. p. m.) in magnetite have been found by Hegemann & Albrecht (1954) in contact-pneumatolytic iron ores. From the silver mines in Hällefors (Central Sweden), belonging to the same type of ore, Sundius et al. (1966) reported a magnetite containing 200 p. p. m. Sn. No analyses of the tin content in hematite are available in the literature.

Table 26. The content of B, Be, Ga, Sn, Sb, Zr, Cd, Pb, and Ag in magnetite and hematite in iron ores and rocks from Northern Sweden

Type of ore or rock	Sample No.	Locality	Mineral	p. p. m. of								
				B	Be	Ga	Sn	Sb	Zr	Cd	Pb	Ag
Basic magmatic rock	1289	Tjabrak	Magnetite	< 10	< 10	20	< 10	< 100	< 300	< 100		
Basic magmatic rock	1291	Akkavare	Magnetite	< 10	< 10	40	< 10	< 100	< 300	< 100		
Basic magmatic rock	1294	Saarikoski	Hematite				50					10
Basic magmatic rock	1415	Saivo	Magnetite									10
Iron ore of Hauki type	1292	Kuosatjvare	Hematite	< 10	< 10	10	< 10	< 100	< 300	< 100		
Stratified iron ore	1298	Kallak	Magnetite	< 10	< 10	< 10	< 10	< 100	< 300	< 100		
Stratified iron ore	1301	Ristjälän	Magnetite	< 10	< 10	20	< 10	< 100	< 300	< 100		
Skarn iron ore	1314	Njuotjamavare	Magnetite	< 10	< 10	20	< 10	< 100	< 300	< 100		
Skarn iron ore	1315	Isovaara	Magnetite	< 10	< 10	15	< 10	< 100	< 300	< 100		
Skarn iron ore	815-827	Stora Sahavaara	Magnetite				< 10				< 10	
Apatite iron ore	1362	Ekströmsberg	Magnetite	< 10	< 10	20	< 10	< 100	< 300	< 100		
Apatite iron ore	1363	Rektorn	Magnetite	< 10	< 10	20	< 10	< 100	< 300	< 100		
Apatite iron ore	1385	Kiirunavaara	Magnetite	< 10	< 10	30	< 10	< 100	< 300	< 100		
Apatite iron ore	896-901	Mertainen	Magnetite				< 10				10-15	
Apatite iron ore	892-895	Painirova	Magnetite				< 10				10-20	
Iron ore of unknown origin	902-905	Puoltsa	Magnetite				< 10				< 10-20	

As seen from table 26 the magnetite in the different types of iron ore and rock investigated in the present work contains less than 10 p. p. m. Sn. In the hematite in the gabbro at Saarikoski a content of 50 p. p. m. Sn has been found.

Silver. In the hematite at Saarikoski and in the magnetite at Saivo, both being titaniferous and occurring in connection with gabbro, a silver content of 10 p. p. m. has been found. The presence of silver in these iron oxides is somewhat unexpected. In the literature no analyses of magnetite and hematite containing silver have been reported. Ag^+ has a large ionic radius (1.26 Å) and should thus not replace either Fe^{3+} or Fe^{2+} . According to Taylor (1965) Ag^{2+} (with a radius of 0.89 Å) may enter into Fe^{2+} positions; this feature might explain the presence of silver in the magnetite at Saivo.

Lead. Pb^{2+} with a large ionic radius (1.20 Å) is not expected to enter magnetite or hematite. The lead content of the upper lithosphere is, according to Shaw (1964), 15 p. p. m. In magnetite in some types of iron ore and rock there has, however, occurred a concentration of this element (table 17). Hegemann & Albrecht (1954) reported as much as up to 500 p. p. m. in contact-pneumatolytic iron ores and up to 50 p. p. m. in sedimentary iron ores. In magnetite in rocks relatively high lead contents are found in the charnockites in Madras (up to 80 p. p. m.) and in the exhalative rocks (up to 80 p. p. m.). No information about the lead content in hematite is available in the literature.

Only a few determinations of the lead content in magnetite in iron ores have been made in the present work (table 26). The content in these does not exceed 20 p. p. m. Pb.

6. SOME GEOCHEMICAL FEATURES OF MAGNETITE AND HEMATITE IN IRON ORES AND ROCKS, MAINLY FROM NORTHERN SWEDEN

6.1. Typochemical elements

The range of the content of the different trace elements in magnetite and hematite in the iron ores and rocks investigated in the present work is considerable. As has been demonstrated in the preceding chapter some elements occur more or less in similar amounts in the iron oxides in the different iron ores and rocks. In many cases it is thus not possible to find any relationship between the distribution of the trace elements in the iron oxides and the origin of the latter. This concerns especially hematite which, due to its crystal-chemical properties, has a more restricted ability to take up trace elements than magnetite (p. 62). As a rule hematite takes up smaller amounts of chromium,

nickel, cobalt, vanadium, manganese, and partly titanium but higher amounts of molybdenum than magnetite. Magnetite is more fitted for genetical considerations. This mineral shows differences in the trace element distribution in some cases which are related to differences in the mode of formation. Figs. 2 and 3 show 10 of the 15 analyzed elements which are of interest in this respect in the iron oxides in iron ores and rocks in Northern Sweden, Finland, and Western Germany. The elements are Cr, Mg, Ti, Ni, Mo, Co, Cu, Zn, V, and Mn. The columns in the diagrams are of different importance as the number of analyses (n) within these varies between 1 and 77. Thus, for example, in fig. 2 " $n=8$, only 6 Cu" for the basic magmatic rocks means that there are 8 analyses of all elements except for copper, of which there are 6 analyses. The contents are given in a logarithmic scale. The elements in magnetite which show variations in the contents depending on the mode of formation are mainly Cr, Mg, Ti, and Ni (table 27). The other elements are more or less uniformly distributed in the different kinds of ores and rocks. Higher values of chromium than in the other types of ore and rock investigated are found in the magnetite of the basic magmatic rocks, syenite-porphyrines, skarn iron ores, stratified iron ores, and in some of the metasomatically formed iron ores (Ainasjärvi, belonging of the Hauki type of ore, and Taporova in Northern Finland). Magnesium shows relatively high values in the basic magmatic rocks, skarn iron ores, stratified iron ores, and in the iron ores in the Misi area (in Northern Finland). In the basic magmatic rocks and syenite-porphyrines the titanium content is fairly high. Relatively high nickel contents are found in the basic magmatic rocks, apatite iron ores, and the Misi ores. Cobalt has been enriched in the basic magmatic rocks. Higher values of zinc than in the other types of ore and rocks are found in the basic magmatic rocks. The stratified iron ores and the iron ores in the Kittilä area (in Northern Finland) show enrichment of manganese.

Relatively low contents of some trace elements in magnetite are found in the volcanic-sedimentary and metasomatic deposits. A low content of titanium has been obtained in the Lahn-Dill ores, the Kittilä ores, and the Taporova ore. In the Kittilä ores and in Nautanen the magnetite is poor in nickel. In the Lahn-Dill ores the cobalt content is low. A low copper content is found in the altered basic volcanics.

When considering the trace element variations in hematite in the different types of ore and rocks investigated in this work, it is seen from fig. 3 that the hematite in the metasomatic iron ore at Taporova is comparatively rich in chromium. The hematite in the skarn iron ores is richer in magnesium and cobalt than the hematite in the other types of iron ore and rock investigated. The hematite in the basic magmatic rocks is relatively rich in zinc.

Low contents of trace elements in hematite are found in the metasomatically formed Hauki iron ores and Taporova ore. Both are low nickel, cobalt, and

M A G N E

M a g m a t i c

V o l c a n i c -

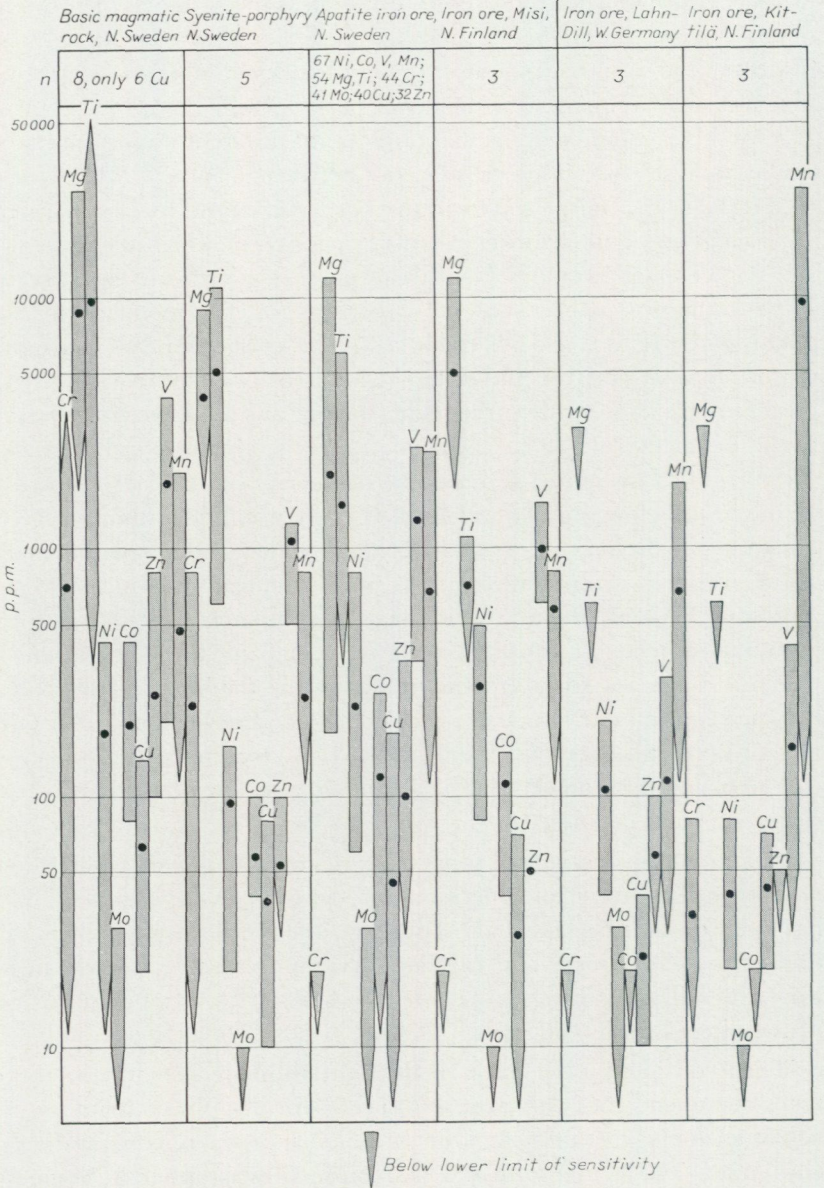
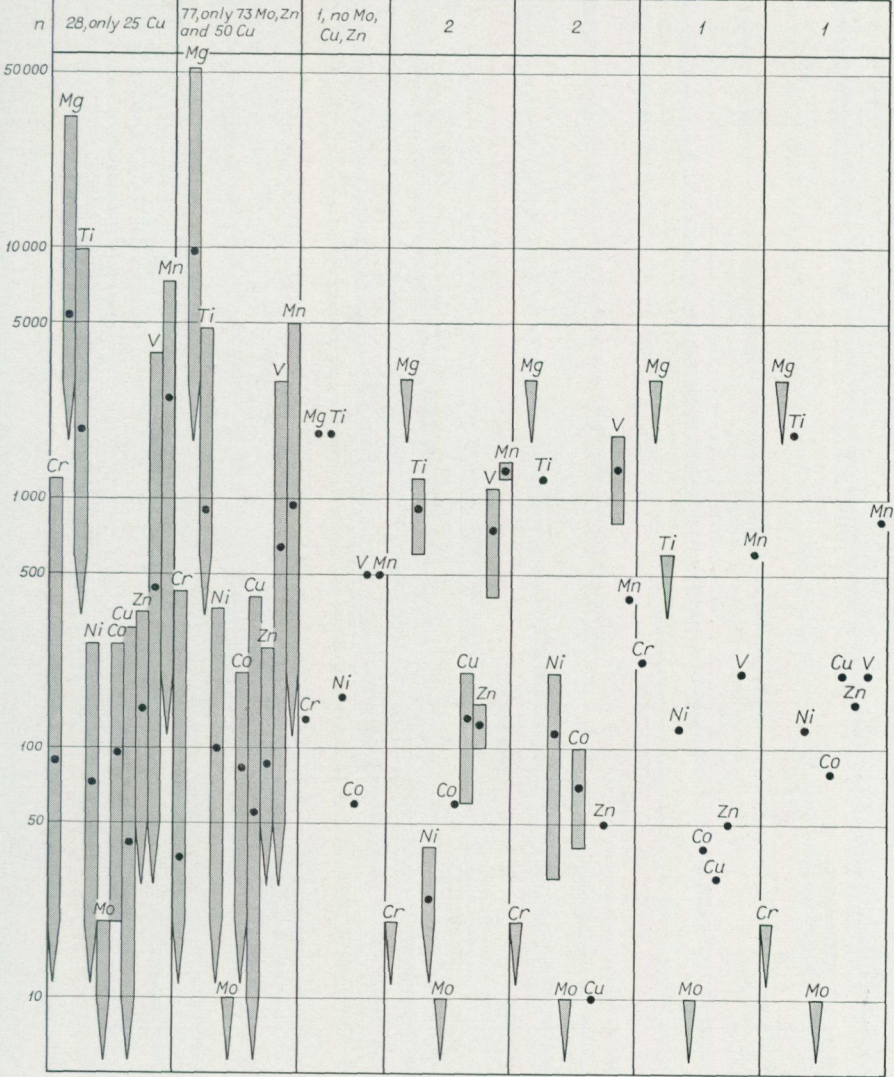


Fig. 2. The contents of some trace elements in magnetite in iron ores and rocks, mainly from Northern Sweden. For the meaning of "n", number of analyses, see the text.

T I T E

sedimentary Metasomatic

Stratified iron ore, N. Sweden | Skarn iron ore, N. Sweden | Iron ore, Hauki type, N. Sweden | Leptite, Nautanen, N. Sweden | Altered basic volcanics, N. Sweden | Iron ore, Taporova, N. Finland | Amphibolite Hällinmäki, C. Finland



▲ Above upper limit of sensitivity • Mean value

H E M A T I T E

M a g m a t i c V o l c a n i c - s e d i m e n t a r y M e t a s o m a t i c

Basic magmatic Apatite iron ore, Iron ore, Lahn- Skarn iron ore, Iron ore, Hauki Iron ore, Tapo-
 rock, N. Sweden N. Sweden Dill, W. Germany N. Sweden type, N. Sweden rova, N. Finland

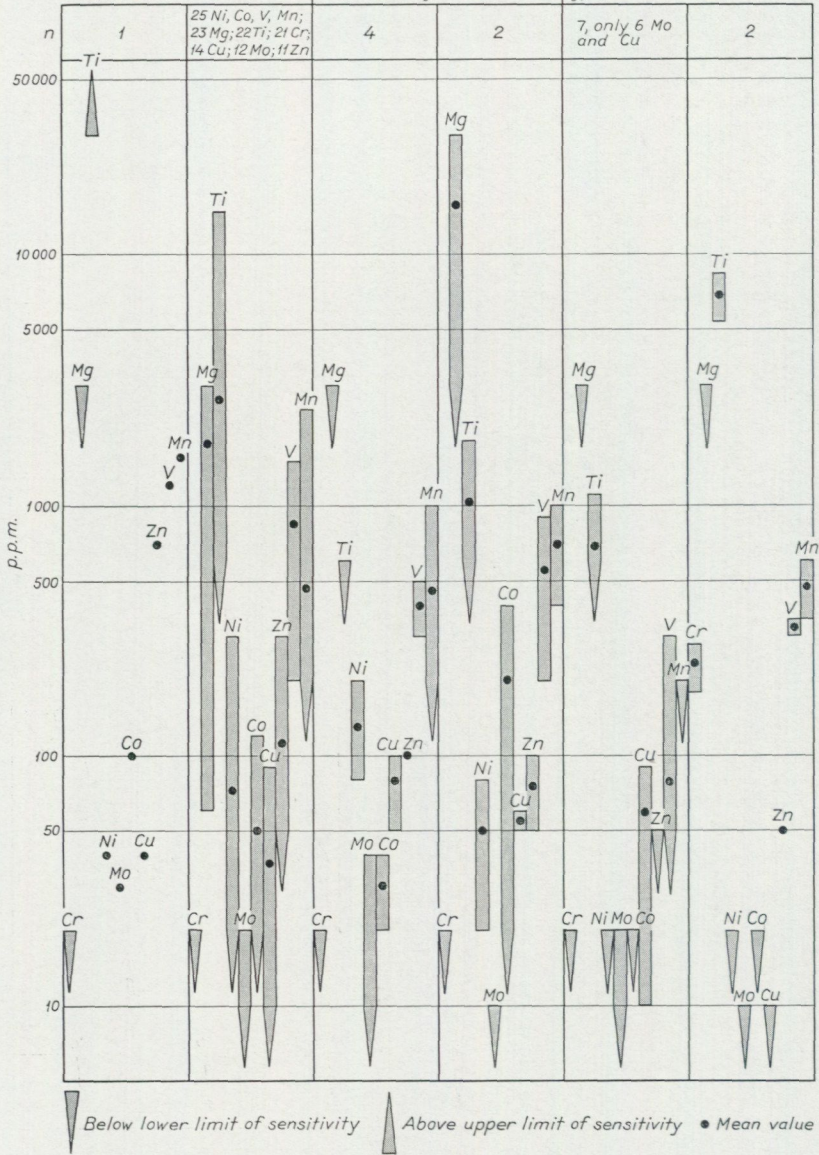


Fig. 3. The contents of some trace elements in hematite in iron ores and rocks, mainly from Northern Sweden.

zinc. Furthermore, the Hauki ores are low in titanium, vanadium, and manganese and the Taporova ore low in molybden and copper. The hematite in the Lahn-Dill ores is poor in titanium. In the skarn iron ores a low content of molybdenum is found.

Thus it is evident that only the magnetite of the basic magmatic rocks differs definitely in trace element distribution from the magnetite in other iron ores and rocks. It has a higher content of trace elements (table 27). On the other hand the iron oxides in some of the metasomatic and volcanic-sedimentary deposits are characterized by a rather low content of trace elements. In the metasomatic deposits this concerns mainly hematite.

Summarizing the above it seems impossible, on the mere basis of the content of a single element in the iron oxides, to separate different types of ore and rock, as the values obtained are rather similar. If the contents of several elements are considered simultaneously, however, such a division can, in some cases, be made. Examples are given on p. 109.

6.2. Ratio of some element pairs

As shown in the preceding section the absolute values of the trace elements in magnetite and hematite investigated in the present work are in most cases not related to the genesis of the iron ores and rocks in which the iron oxides are sited. The same lack of relationship is found if the ratios between the mean contents of some elements in the iron oxides are considered. In table 28 are shown the ratios for Co/Ni, Cr/V, Zn/V, Ti/V, and Co/V. These ratios are more or less of the same magnitude in the different types of iron ores and rocks. The quotients for some other element pairs (as Cr/Ni, Cr/Co, Cr/Ti, Cr/Zn, Ni/V, etc.) have been reviewed but are not presented as they show still smaller variations than the ratios of the element pairs listed in table 28.

6.2.1. THE Co/Ni RATIO

The ratio between the cobalt and nickel contents in the upper lithosphere is 0.3. These two elements enter Fe^{2+} and Mg^{2+} positions. According to Taylor (1965, p. 171) "on the basis of size, and melting point data for the oxides, the sequence of entry into crystal lattices should be Mg^{2+} , Ni^{2+} , Co^{2+} , Fe^{2+} ". ". . . the Mg-Ni-Fe relationship is that expected from the electronegativity values. Thus, Ni enters early Fe rather than Mg positions." "The larger size of Co^{2+} will restrict the entry of cobalt into magnesium positions to a greater degree than for nickel. A greater similarity is apparent between Co and Fe, but the smaller size of Co^{2+} cause it to enter early Fe^{2+} positions, although not to the same extent as nickel. Thus nickel is depleted at a faster rate, the Ni/Co ratio falls during fractionation, and the Fe/Co ratio tends to rise"

Table 27. The distribution of some trace elements in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Occurrence	Magnetite										Hematite										
		Cr	Mg	Ti	Ni	Mo	Co	Cu	Zn	V	Mn	Cr	Mg	Ti	Ni	Mo	Co	Cu	Zn	V	Mn	
Magmatic	Basic magmatic rock, N. Sweden	+	+	+	+		+		+										+			
	Syenite-porphry, N. Sweden	+		+																		
	Apatite iron ore, N. Sweden				+																	
	Iron ore, Misi, N. Finland		+		+																	
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Germany			-			-															
	Iron ore, Kittilä, N. Finland			-	-								+									
	Stratified iron ore, N. Sweden	+	+										+									
	Skarn iron ore, N. Sweden	+	+											+		-	+					
Metasomatic	Iron ore, Hauki type, N. Sweden	+														-	-		-	-	-	-
	Leptite, Nautanen, N. Sweden				-																	
	Altered basic volcanics, N. Sweden								-													
	Iron ore, Taporova, N. Finland	+		-										+		-	-	-	-	-	-	-
	Amphibolite, Hällinmäki, C. Finland																					

+ = comparatively high content.

- = comparatively low content.

Table 28. The ratio of certain element pairs in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Occurrence	Mineral (M = magnetite H = hematite)	Co/Ni	Cr/V	Zn/V	Ti/V	Co/V
Magmatic	Basic magmatic rock, N. Sweden	M	1.1	0.4	0.1	5.3	0.1
	Basic magmatic rock, N. Sweden	H	2.5	<0.02	0.6	>25.0	0.08
	Syenite-porphry, N. Sweden	M	0.7	0.2	0.06	5.0	0.06
	Apatite iron ore, N. Sweden	M	0.5	0.01	0.08	1.2	0.09
	Apatite iron ore, N. Sweden	H	0.7	<0.02	0.1	3.3	0.06
	Iron ore, Misi, N. Finland	M	0.4	<0.02	0.05	0.7	0.1
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Germany	M	<0.2	<0.2	0.5	<5.0	<0.2
	Iron ore, Lahn-Dill, W. Germany	H	0.2	<0.05	0.3	<1.5	0.08
	Iron ore, Kittilä, N. Finland	M	0.4	0.2	0.2	2.5	0.1
	Stratified iron ore, N. Sweden	M	1.4	0.2	0.3	4.1	0.2
	Skarn iron ore, N. Sweden	M	0.8	0.06	0.1	1.5	0.1
	Skarn iron ore, N. Sweden	H	4.0	<0.04	0.1	1.8	0.4
	Skarn iron ore, Rautuvaara, N. Finland ..	M	2.0	0.1	0.7	8.0	0.9
Metasomatic	Iron ore, Hauki type, N. Sweden	M	0.4	0.3	—	3.6	0.12
	Iron ore, Hauki type, N. Sweden	H	—	<0.3	<0.6	8.8	<0.3
	Leptite, Nautanen, N. Sweden	M	2.4	<0.03	0.2	1.2	0.08
	Altered basic volcanics, N. Sweden	M	0.6	<0.02	0.04	0.9	0.05
	Iron ore, Taporova, N. Finland	M	0.3	1.1	0.3	<3.0	0.2
	Iron ore, Taporova, N. Finland	H	—	0.7	0.2	20.9	<0.06
	Amphibolite, Hällinmäki, C. Finland ..	M	0.7	<0.1	0.8	9.0	0.4
Unknown	Iron ore, Altavaara, N. Sweden	M	1.0	0.03	<0.06	0.5	0.08
	Iron ore, Killingi, N. Sweden	M	0.5	<0.02	0.05	2.7	0.04
	Iron ore, Leppäkoski, N. Sweden	M	0.6	0.3	0.09	<1.6	0.2
	Iron ore, Puoltsa, N. Sweden	M	0.4	<0.02	—	0.4	0.06
	Conglomerate, Doktors kulle, N. Sweden	H	0.8	0.03	0.2	7.5	0.04
	Conglomerate, Saurusvaara, N. Sweden	H	—	<0.02	<0.05	1.2	<0.02
	Gneiss, N. Sweden	M	0.6	0.02	0.2	1.1	0.08

(ibid., p. 173). The value of the Co/Ni ratio is a useful index for determining the stage of fractionation reached as pointed out by Lundegårdh (1946), Landergrén (1948), and Davidson (1962).

In a fractional crystallization the Co/Ni ratio in magnetite formed at different stages tends to rise, as shown by Wager & Mitchell (1951) from the Skaergaard intrusion and by Howie (1955) from the Madras charnockite series. In the magnetite in the Skaergaard intrusion nickel is abundant in the early differentiates and absent in the later ones, while cobalt persists (table 29). In the Madras series nickel is concentrated in the magnetite in the earlier

Table 29. The content of V, Co, and Ni in magnetite from some differentiated igneous rock series

		Differentiation of parental rock →													
Skaergaard intrusion, Wager & Mitchell (1951, table B)	V	2000	800	300	<5	<5									
	Co	80	80	60	30	3									
	Ni	300	100	<2	<2	<2									
	Co/Ni	0.3	0.8	>30	>15	>1.5									
Madras series, Howie (1955, p. 761)	V	2000	1500	4500	5000	1350	6000	1250	1000	1500	800	650	4000	150	2000
	Co	200	150	80	125	135	300	150	60	500	50	170	100	5	170
	Ni	2000	3100	150	320	360	3000	200	30	250	100	500	120	<2	400
	Co/Ni	0.1	0.05	0.5	0.4	0.4	0.1	0.8	2	2	0.5	1.7	0.8	>2.5	0.4
Batholith, S. California, Sen et al. (1959, p. 69)	V	6000	4500	50	5000	5000	6000	3500	2200	3500	1750	2500	1100		
	Co	210	200	1000	150	210	70	60	50	30	40	40	40		
	Ni	225	215	320	20	350	200	30	125	70	10	25	20		
	Co/Ni	0.9	0.9	3.1	7.5	0.6	0.4	2.0	0.4	0.4	4.0	1.6	2.0		

formed rock members, cobalt being not much changed during the differentiation. In the batholith from S. California, however, the contents of cobalt and nickel in magnetite have decreased to the same degree during the differentiation (table 29), and consequently the Co/Ni ratio does not show the same characteristic increase as in the two other above mentioned rock series.

The Co/Ni ratio in magnetite and hematite in the iron ores and rocks investigated in the present work is mostly lower than unity (table 28). Higher values are only found in the iron oxides in the basic magmatic rocks and the stratified iron ores, further in hematite in the skarn iron ores and in the magnetite from Nautanen. The lowest ratio is obtained in the Lahn-Dill ores. The range of the ratio in the magmatic, volcanic-sedimentary, and metasomatic iron oxides is almost the same in all groups, and the Co/Ni ratio is thus unrelated to the genesis of the iron oxides.

There seems to be a tendency for hematite to have a somewhat higher ratio in the same type of iron ore or rock which is due to the fact that hematite has a restricted ability to take up nickel.

It is interesting to note that the Co/Ni ratio in magnetite in the syenite-porphyrries, the apatite iron ores, and the Hauki ores, all belonging to the same magmatic activity and formed in the order indicated (p. 113), has not been subject to any change. The ratio in the apatite iron ores (0.5 for magnetite and 0.7 for hematite) is similar to that found in the apatite iron ores in Central Sweden, for which Landergren (1948) reported a Co/Ni ratio of 0.4. This value, however, comprises the whole ore and not the iron oxides proper.

The contents of cobalt and nickel in the analyzed iron oxides in the different types of iron ore and rock presented in tables 6–15 are compiled diagrammatically in fig. 4. From this it is evident that a positive correlation exists between these elements in the basic magmatic rocks and in the apatite iron ores, though rather weak in the latter. For the iron oxides in the other types of iron ore or rock no relationship between the cobalt and nickel contents can be detected. The diagram also shows the restricted ability of hematite compared with magnetite to take up these elements. Only hematite in the apatite iron ores shows relatively high contents of cobalt and nickel, partly being of the same magnitude as in magnetite in this type of ore.

The Co/Ni ratio for the single analyses of the iron oxides in the different types of iron ore and rocks is presented in fig. 5. The diagram does not comprise samples with contents of cobalt and nickel below the sensitivity of the spectrographical determination (less than 20 p. p. m.), and thus the number of analyses presented in the diagram is smaller than in the diagram in fig. 4. From fig. 5 it is seen, in accordance with what has been said above, that the Co/Ni ratio in most types of ore and rocks is below unity, the basic magmatic rocks and the stratified iron ores forming exceptions. Further a smaller part of the analyses of the skarn iron ores has a Co/Ni ratio higher than unity. In

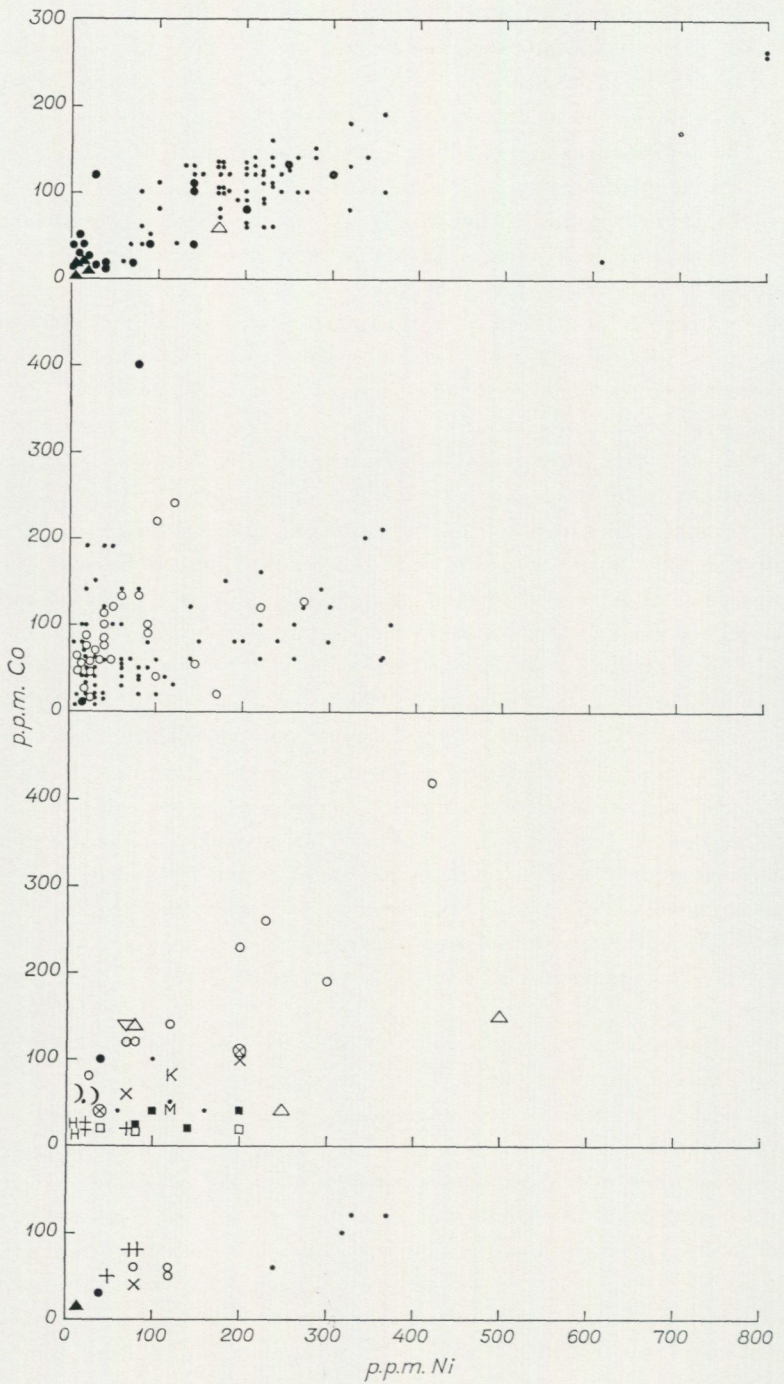


Fig. 4. Relationship between cobalt and nickel in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden.

- Magnetite } apatite iron ore, N. Sweden
- Hematite } apatite iron ore, N. Sweden

- △ Magnetite } iron ore of the Hauki type,
- ▲ Hematite } N. Sweden

- Magnetite } skarn iron ore, N. Sweden
- Hematite } skarn iron ore, N. Sweden
- Magnetite, stratified iron ore, N. Sweden

- Magnetite } basic magmatic rock,
- Hematite } N. Sweden
- Magnetite, syenite-porphry, N. Sweden
- ⊗ Magnetite, altered basic volcanics, N. Sweden
- × Magnetite, gneiss, N. Sweden
-) Magnetite, leptite, Nautanen, N. Sweden
- + Magnetite, iron ore, Kittilä, N. Finland
- M Magnetite } iron ore, Taporova, N. Finland
- H Hematite } iron ore, Taporova, N. Finland
- △ Magnetite, iron ore, Misi, N. Finland
- ▽ Magnetite, iron ore, Rautuvaara, N. Finland
- K Magnetite, amphibolite, Hällinmäki,
C. Finland
- Magnetite } iron ore, Lahn-Dill,
- Hematite } W. Germany

- + Magnetite, iron ore, Altavaara, N. Sweden
- × Magnetite, iron ore, Killingi, N. Sweden
- Magnetite, iron ore, Leppäkoski, N. Sweden
- Magnetite, iron ore, Puoltsa, N. Sweden
- Hematite, conglomerate, Doktors kulle, N. Sweden

- ▲ Hematite, conglomerate, Saurusvaara,
N. Sweden

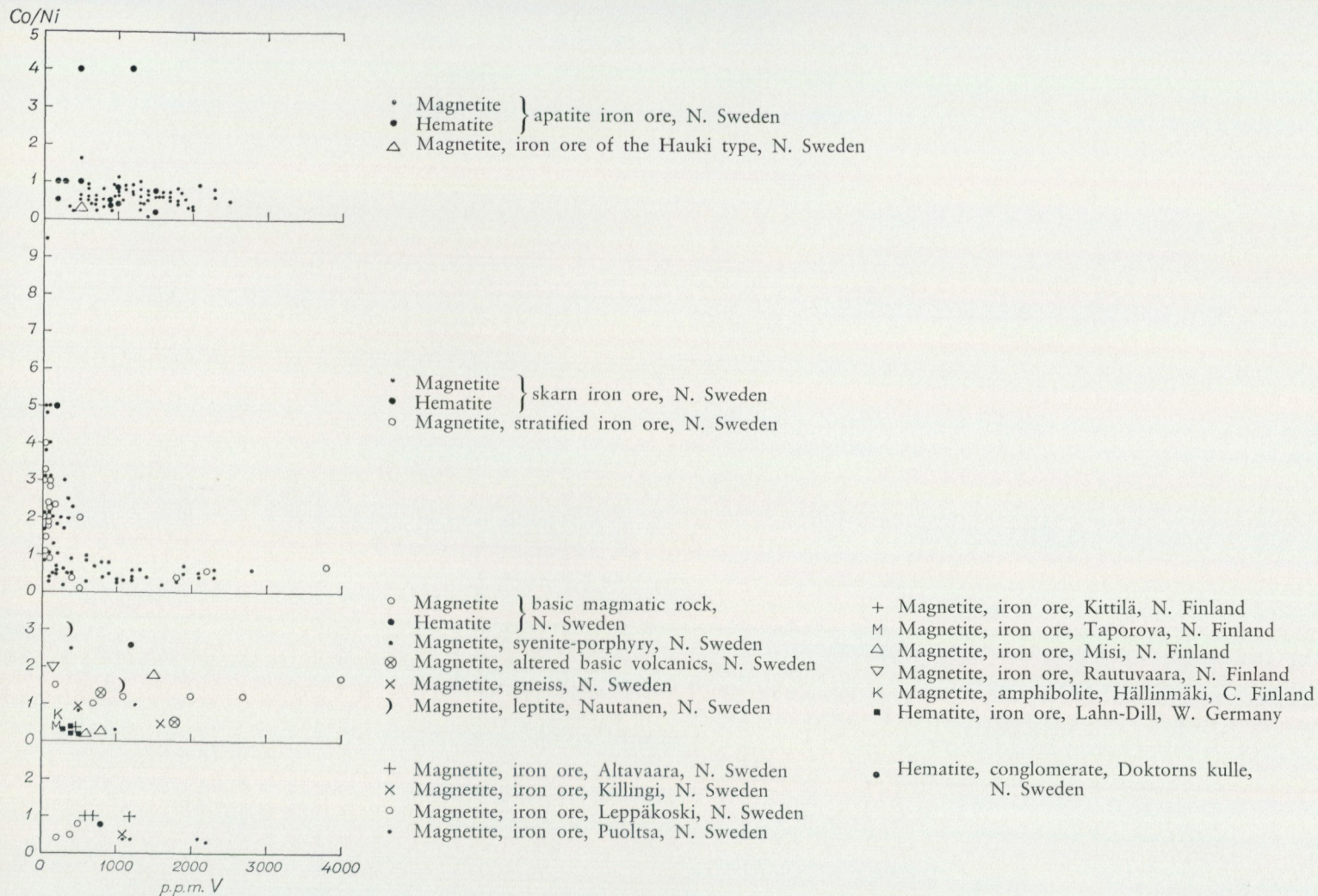


Fig. 5. Relationship between the Co/Ni ratio and the vanadium content in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden.

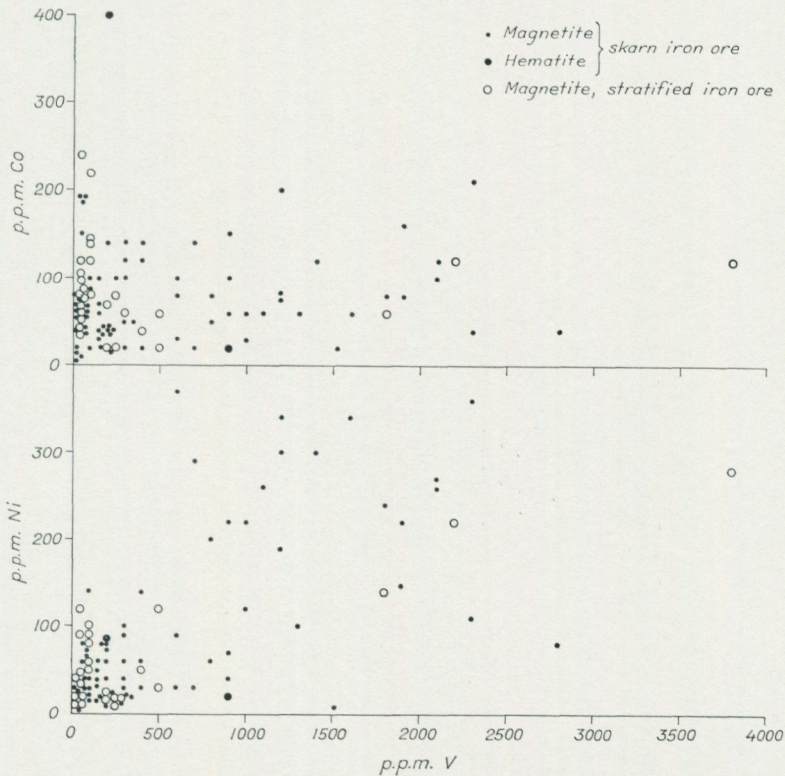
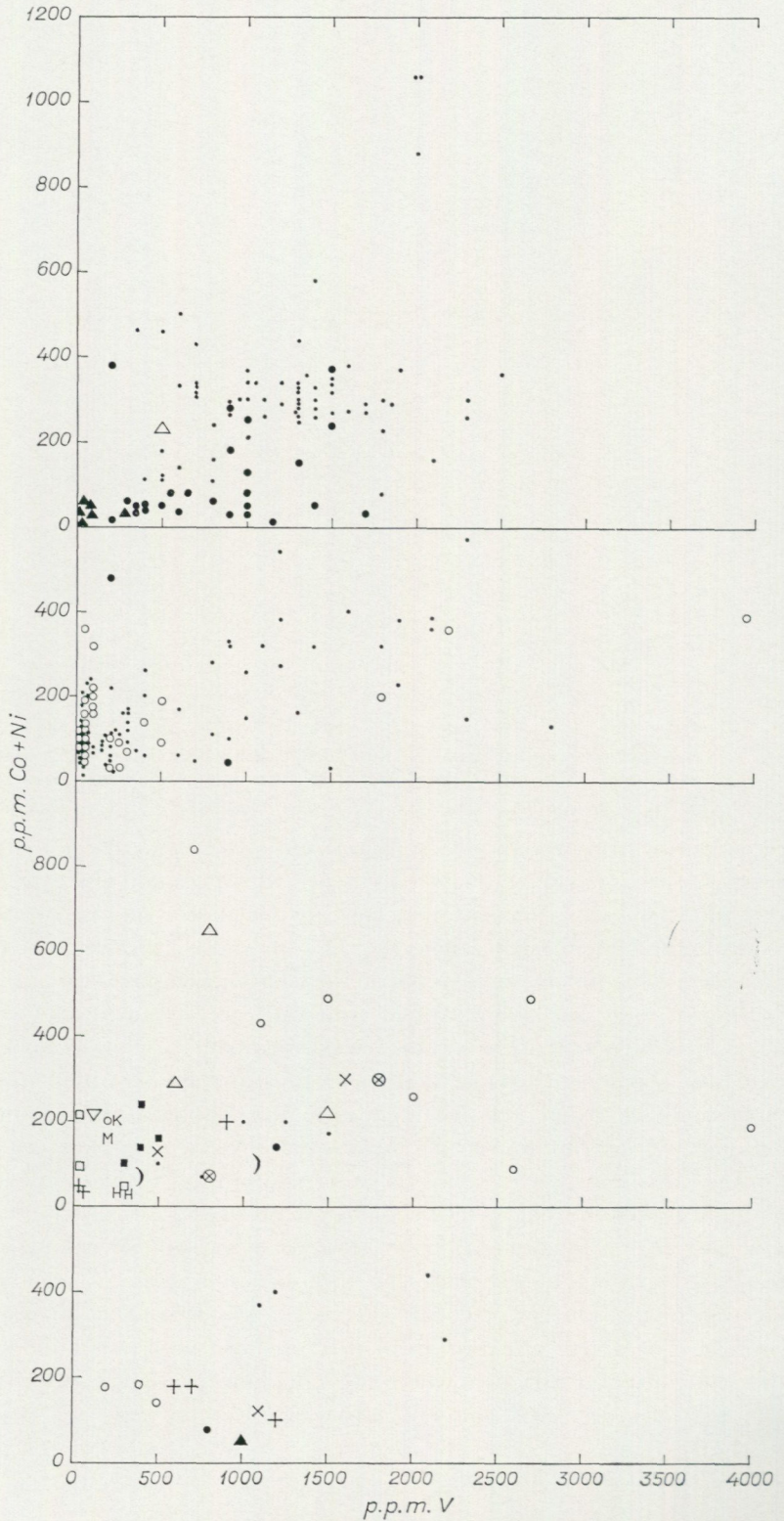


Fig. 6. Relationship between cobalt and vanadium and between nickel and vanadium in the iron oxides in skarn iron ores and stratified iron ores in Northern Sweden.

the stratified iron ores and in the skarn iron ores a ratio above unity is, however, only found in those analyzed samples which contain less than about 500 p. p. m. V. This is a characteristic feature for these types of ore and serves to distinguish them from other types of ore and rock investigated. The explanation for this feature seems to be that nickel and vanadium in the skarn iron ores and the stratified iron ores accompany each other. From fig. 6 it is seen that there exists a weak positive correlation between these elements in magnetite in the skarn iron ores and the stratified iron ores; in those analyses where relative high vanadium contents (higher than about 500 p. p. m.) are found even the highest nickel contents are also encountered. On the other hand, there seems to be no relationship between cobalt and vanadium, as seen from fig. 6. The cobalt contents are equally distributed between low and high vanadium contents. The total amount of cobalt and nickel compared to vanadium seems to be without importance: as seen from fig. 7 the sum of the amount of cobalt and nickel is independent of the vanadium content. The above remarks mean that in those samples of the skarn iron ores and stratified iron ores where the vanadium content is more than about



- Magnetite } apatite iron ore, N. Sweden
- Hematite } apatite iron ore, N. Sweden

- △ Magnetite } iron ore of the Hauki type,
- ▲ Hematite } N. Sweden

- Magnetite } skarn iron ore, N. Sweden
- Hematite } skarn iron ore, N. Sweden
- Magnetite, stratified iron ore, N. Sweden

- Magnetite } basic magmatic rock,
- Hematite } N. Sweden
- Magnetite, syenite-porphry, N. Sweden
- ⊗ Magnetite, altered basic volcanics, N. Sweden
- × Magnetite, gneiss, N. Sweden
-) Magnetite, leptite, Nautanen, N. Sweden
- + Magnetite, iron ore, Kittilä, N. Finland
- M Magnetite } iron ore, Taporova, N. Finland
- H Hematite } iron ore, Taporova, N. Finland
- △ Magnetite, iron ore, Misi, N. Finland
- ▽ Magnetite, iron ore, Rautuvaara, N. Finland
- K Magnetite, amphibolite, Hällinmäki,
C. Finland
- Magnetite } iron ore, Lahn-Dill,
- Hematite } W. Germany

- + Magnetite, iron ore, Altavaara, N. Sweden
- × Magnetite, iron ore, Killingi, N. Sweden
- Magnetite, iron ore, Leppäkoski, N. Sweden
- Magnetite, iron ore, Puoltsa, N. Sweden
- Hematite, conglomerate, Doktors kulle, N. Sweden

- ▲ Hematite, conglomerate, Saurusvaara,
N. Sweden

Fig. 7. Relationship between the contents of (Co+Ni) and V in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden.

500 p. p. m., vanadium is followed by a relatively high nickel content and a relatively low content of cobalt giving a Co/Ni ratio below unity. In those samples where the vanadium content is less than about 500 p. p. m. the nickel and cobalt contents are also low, but in a part of these the cobalt content exceeds that of nickel giving Co/Ni ratios higher than unity.

6.2.2. THE Cr/V RATIO

The ratio between the content of chromium and vanadium in the upper lithosphere is 0.9. According to the value of electronegativity and ionization potential V^{3+} should form more ionic bonds with oxygen than Cr^{3+} . For the latter ion the relative total bonding energy is, however, higher than for V^{3+} . According to Taylor (1965) the smaller size of Cr^{3+} causes it to enter earlier stages in a magmatic differentiation than V^{3+} , thus counteracting the more covalent bond of Cr^{3+} , and the Cr^{3+}/V^{3+} (which falls) is thus a useful index of the fractionation in basic rocks. An interesting investigation concerning the behaviour of the Cr/V ratio in some contact-pneumatolytic magnetite ores in the New Jersey Highlands has been made by James & Dennen (1962). These authors showed that chromium increases and vanadium decreases in the magnetite when going away from the center of the structural and magmatic activity, the Cr/V ratio being low near the center and high away from it.

As the content of chromium in most of the magnetites and hematites investigated in the present work is lower than 20 p. p. m. and the content of vanadium much higher, the ratio between the means of these elements is fairly low, in most cases below 0.1 (table 28). A relatively high ratio (0.4) is, however, met with in the basic magmatic rocks. Ratios higher than 0.1 are also found in the magnetite in the syenite-porphyrries (0.2) and in some of the metasomatic iron ores. The magnetite in the Hauki ore type has a ratio of 0.3, and in the Taporova ore the magnetite has a ratio of 1.1 and the hematite a ratio of 0.7. In the Leppäkoski deposits some parts of which show similarities with the Hauki ores, the magnetite has a ratio of 0.3. Furthermore, the magnetite in the stratified iron ores and the Kittilä ores a Cr/V ratio of 0.2.

6.2.3. THE Zn/V RATIO

The ratio between the content of zinc and vanadium in the upper lithosphere is 0.4. These elements have the same ionic radius (0.74 Å), but V^{3+} has lower values for the electronegativity and the ionization potential and a higher value for the relative total bonding energy than Zn^{2+} . In a fractional crystallization vanadium will therefore be preferentially incorporated and the Zn/V ratio should thus tend to increase. According to Kisvarsanyi (1966 and Kisvarsanyi & Proctor 1967) the Zn/V ratio in magnetite in the apatite iron ores in southeastern Missouri depends on the temperature. In the middle of the ore body,

where the temperature is supposed to be the highest, the ratio is lower (with a value of about 0.1) than in the marginal, low-temperature part of the ore body (where the ratio is about 0.5).

The ratio between the mean content of zinc and vanadium in magnetite and hematite investigated in the present work is lower in the magmatic iron ores and rocks than in ores and rocks of volcanic-sedimentary and metasomatic origin. The magmatic iron oxides have a Zn/V ratio of 0.1 or less, except for the hematite in the basic magmatic rocks having a ratio of 0.6 (table 28). In the volcanic-sedimentary and metasomatic iron oxides the ratio varies between 0.1 and 0.8. In the altered basic volcanics a value lower than 0.1 has, however, been encountered.

6.2.4. THE Ti/V RATIO

Hegemann & Albrecht (1954) compared the Ti/V ratio in all igneous rocks (2.9) with the same ratio in different iron ore types obtained from analyses comprising the whole ore. They found that only in the intramagmatic and contact-pneumatolytic ores does a preponderance of titanium over vanadium exist, the Ti/V ratio in these two types being higher than 2.9. For the other iron ore types the Ti/V ratio covers a wide interval but is in the main lower than 2.9.

The ratio between the mean content of titanium and vanadium in the magnetites and hematites investigated in the present work varies mostly between 1 and 5 (table 28). Higher values are found in the hematite in the basic magmatic rocks, the Hauki iron ores, the Taporova iron ore, and the conglomerate at Doktors kulle. The same relationship is found in the magnetite in the Rautuvaara skarn iron ore and in the amphibolite at Hällinmäki. A low ratio (0.7) is obtained in the magnetite in the Misi iron ores. As the Ti/V ratio in the iron oxides of magmatic, volcanic-sedimentary, and metasomatic origin seems to be rather similar on the whole, this ratio is unfitted for drawing genetical conclusions about the origin of the iron oxides. In all cases the values are decidedly lower than the ratio between the content of titanium and vanadium in the upper lithosphere, which according to the values taken from Shaw (1964) is as high as 100 (10000 p. p. m. Ti/100 p. p. m. V).

6.2.5. THE Co/V RATIO

The ratio between the cobalt and vanadium content in the upper lithosphere is 0.3. The ratio between the mean content of these elements in magnetite and hematite investigated in the present work is mostly below 0.1 (table 28). Only in the stratified iron ores, the skarn iron ores, and the metasomatically formed Hällinmäki and Taporova deposits the Co/V ratios are somewhat higher than 0.1.

Table 30. The concentration-coefficient of some trace elements in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Occurrence	Mineral (M=magnetite H=hematite)	Cr	Mg	Ti	Ni	Co	Cu	V	Zn	Mn	Sr	Ba
			(90	31000	10000	80	27	70	100	40	1000	450	250)
			Concentration-coefficient										
Magmatic	Basic magmatic rock, N. Sweden	M	>7.7	0.3	1.0	2.3	7.4	0.9	18.5	6.5	0.5	0.05	0.4
	Basic magmatic rock, N. Sweden	H	<0.2	<0.1	>3.0	0.5	3.7	0.6	12.0	17.5	1.6	<0.04	<0.4
	Syenite-porphry, N. Sweden	M	2.6	0.1	0.5	1.1	2.2	0.6	10.0	1.5	0.2	0.04	0.6
	Apatite iron ore, N. Sweden	M	0.1	0.06	0.2	2.8	4.4	0.6	13.0	2.5	0.7	0.04	0.2
	Apatite iron ore, N. Sweden	H	<0.2	0.06	0.3	0.9	1.9	0.6	8.0	2.8	0.5	0.08	0.7
	Iron ore, Misi, N. Finland	M	<0.2	0.2	0.07	3.5	4.1	<0.4	10.0	1.3	0.6	<0.04	<0.4
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Germany	M	<0.2	<0.1	<0.06	1.3	<0.7	0.3	1.2	1.5	0.7	0.05	<0.4
	Iron ore, Lahn-Dill, W. Germany	H	<0.2	<0.1	<0.06	1.6	1.1	1.1	4.0	2.5	0.5	0.05	0.4
	Iron ore, Kittilä, N. Finland	M	0.3	<0.1	0.04	0.5	0.6	0.6	1.6	0.8	9.1	0.1	0.8
	Stratified iron ore, N. Sweden	M	1.0	0.2	0.2	0.9	3.7	0.6	4.4	3.8	2.5	0.04	0.6
	Skarin iron ore, N. Sweden	M	0.4	0.3	0.09	1.3	3.0	0.8	6.0	2.3	0.9	0.03	0.3
	Skarin iron ore, N. Sweden	H	<0.2	0.5	0.1	0.6	7.4	0.8	5.5	1.9	0.7	<0.04	0.4
	Skarn iron ore, Rautuvaara, N. Finland	M	0.2	0.2	0.1	0.9	5.2	-	1.5	2.5	0.8	0.04	<0.4
Metasomatic	Iron ore, Hauki type, N. Sweden	M	1.4	0.06	0.2	2.0	2.2	-	5.0	-	0.5	-	-
	Iron ore, Hauki type, N. Sweden	H	<0.2	<0.1	0.07	<0.3	<0.7	0.9	0.8	<1.3	<0.2	0.1	5.5
	Leptite, Nautanen, N. Sweden	M	<0.2	<0.1	0.09	0.3	2.2	0.9	7.5	3.3	1.3	0.03	1.3
	Altered basic volcanics, N. Sweden	M	<0.2	<0.1	0.1	1.5	2.6	<0.1	13.0	1.3	0.4	<0.04	0.2
	Iron ore, Taporova, N. Finland	M	2.4	<0.1	<0.06	1.5	1.5	0.4	2.0	1.3	0.6	0.2	10.1
	Iron ore, Taporova, N. Finland	H	2.6	<0.1	0.7	<0.3	<0.7	0.1	3.3	1.3	0.5	0.2	>15.3
	Amphibolite, Hällinmäki, C. Finland	M	<0.2	<0.1	0.2	1.5	3.0	-	2.0	3.8	0.8	<0.04	<0.4
Unknown	Iron ore, Altavaara, N. Sweden	M	0.3	<0.1	0.05	0.9	2.6	0.1	8.5	<1.3	3.4	<0.04	0.8
	Iron ore, Killingi, N. Sweden	M	<0.2	<0.1	0.3	1.0	1.5	0.3	11.0	1.3	0.4	<0.04	<0.4
	Iron ore, Leppäkoski, N. Sweden	M	0.9	<0.1	<0.06	1.3	2.2	0.3	3.7	0.8	<0.2	<0.04	0.6
	Iron ore, Puoltsa, N. Sweden	M	<0.2	0.4	0.07	3.5	3.7	<0.1	16.5	-	0.7	-	-
	Conglomerate, Doktors kulle, N. Sweden	H	0.2	<0.1	0.6	0.5	1.1	1.1	8.0	4.0	0.2	0.04	0.7
	Conglomerate, Saurusvaara, N. Sweden	H	<0.2	<0.1	0.1	<0.3	<0.7	0.9	10.0	<1.3	3.1	<0.04	0.4
	Gneiss, N. Sweden	M	0.1	<0.1	0.1	1.8	3.0	0.5	10.5	4.5	1.7	<0.04	0.3

6.3. Enrichment of trace elements

In table 30 are listed the concentration-coefficients for the trace elements in magnetite and hematite in the different iron ores and rocks investigated in the present work. This coefficient (= clarke of concentration) has been obtained by dividing the mean content of an element in the iron oxide with the content of this element in the upper lithosphere. Thus a coefficient higher than 1 means an enrichment of the element in the iron oxide as compared with the upper lithosphere. From table 30 it is seen that there is an enrichment of cobalt, vanadium, and zinc in the iron oxides in almost every type of ore and rock, only the Hauki ores and the Kittilä ores being poor in these elements. A great number of the iron oxides are further enriched in nickel. Manganese is only enriched in a few types of ore and rock. A concentration of chromium is found in magnetite in the basic magmatic rocks and the syenite-porphyrries as well as in the metasomatically formed magnetite in the Hauki ores and in the likewise formed magnetite and hematite in the ore at Taporova. Barium is enriched in the iron oxides of the Hauki ores and the Taporova ore and in the magnetite at Nautanen, which in all cases is due to contamination with barite. Titanium is only concentrated in the hematite in basic magmatic rocks (at Saarikoski) which is due to a contamination of ilmenite. Copper is enriched in the hematite in the Lahn-Dill ores and the conglomerate at Doktors kulle. Magnesium and strontium do not show enrichments in any type of ore or rock.

The above remarks mean that the concentration-coefficients for the trace elements in magnetite and hematite, like the absolute values of the trace element content and the ratio of some element pairs, are unrelated to the mode of formation of these minerals and thus cannot be used for genetical considerations.

For certain geochemical considerations Shaw (1964) proposed the use of a coefficient, called "le coefficient d'accumulation des elements en trace" or shorter "le coefficient d'accumulation". This ratio, hereafter called the accumulation-coefficient, is obtained by dividing the sum of the values of the concentration-coefficients of the trace elements in consideration by the number of elements. The accumulation-coefficient gives thus a rough estimate if a rock or mineral is "rich" or "poor" in trace elements. For the iron oxides in the different types of iron ore and rock investigated in the present work the accumulation-coefficient has been calculated for the ferrides (chromium, titanium, nickel, cobalt, vanadium, and manganese) and for the elements magnesium, zinc, and copper. The values are shown in table 31.

The accumulation-coefficient for the ferrides is, in almost every type of iron ore and rock, higher than 1. The highest values (2-6) are found in the magmatically formed iron oxides. In the volcanic-sedimentary and metasomatic iron oxides the accumulation-coefficient mostly varies between 1 and 2; the lowest values being found in the Lahn-Dill ores, the Hauki ores, the Taporova ore and in the magnetite in the amphibolite at Hällinmäki. A low value

Table 31. The accumulation-coefficient for the ferrides (Cr, Ti, Ni, Co, V and Mn) and for Mg, Zn and Cu in magnetite and hematite in iron ores and rocks, mainly from Northern Sweden

Origin	Occurrence	Mineral (M=magnetite H=hematite)	Ferrides	Mg, Zn, Cu	All elements
Magmatic	Basic magmatic rock, N. Sweden	M	6.2	2.5	5.0
	Basic magmatic rock, N. Sweden	H	3.5	6.1	4.4
	Syenite-porphiry, N. Sweden	M	2.8	0.7	2.1
	Apatite iron ore, N. Sweden	M	3.5	1.1	2.7
	Apatite iron ore, N. Sweden	H	2.0	1.1	1.7
	Iron ore, Misi, N. Finland	M	3.1	0.5	2.2
Volcanic-sedimentary	Iron ore, Lahn-Dill, W. Germany	M	0.7	0.6	0.7
	Iron ore, Lahn-Dill, W. Germany	H	1.2	1.3	1.3
	Iron ore, Kittilä, N. Finland	M	2.0	0.5	1.5
	Stratified iron ore, N. Sweden	M	2.1	1.5	1.9
	Skarn iron ore, N. Sweden	M	2.0	1.6	1.9
	Skarn iron ore, N. Sweden	H	2.4	1.1	2.0
Skarn iron ore, Rautuvaara, N. Finland	M	1.5	1.4 ¹	1.4 ¹	
Metasomatic	Iron ore, Hauki type, N. Sweden	M	1.9	0.06 ²	1.6 ²
	Iron ore, Hauki type, N. Sweden	H	0.4	0.7	0.5
	Leptite, Nautanen, N. Sweden	M	1.9	1.4	1.6
	Altered basic volcanics, N. Sweden	M	3.0	0.5	2.2
	Iron ore, Taporova, N. Finland	M	1.3	0.6	1.1
	Iron ore, Taporova, N. Finland	H	1.3	0.5	1.1
Amphibolite, Hällinmäki, C. Finland	M	1.3	1.9	1.3	
Unknown	Iron ore, Altavaara, N. Sweden	M	2.6	0.5	1.9
	Iron ore, Killingi, N. Sweden	M	2.4	0.5	1.8
	Iron ore, Leppäkoski, N. Sweden	M	1.4	0.4	1.1
	Iron ore, Puoltsa, N. Sweden	M	4.1	0.3 ³	3.6 ³
	Conglomerate, Doktors kulle, N. Sweden	H	1.8	1.7	1.8
	Conglomerate, Saurusvaara, N. Sweden	H	2.4	0.7	1.9
	Gneiss, N. Sweden	M	2.9	1.7	2.5

¹ Not Cu. ² Not Zn and Cu. ³ Not Zn.

is further obtained in the magnetite in the Leppäkoski ore, a deposit similar in some respects to the Hauki ores (p. 38). In the magnetite in the Lahn-Dill ores and in the hematite in the Hauki ores the coefficient is below unity meaning a strong impoverishment of the ferrides in comparison to the upper lithosphere.

Hematite has a lower accumulation-coefficient for the ferrides than magnetite in the basic magmatic rocks, the apatite iron ores, and the Hauki ores. The opposite is the case in the Lahn-Dill ores and the skarn iron ores. In the Taporova deposit the coefficient is the same for both minerals.

In conclusion, the above means that magnetite and hematite in the iron ores and rocks investigated have, in most cases, been enriched in the ferrides as

compared with the composition of the upper lithosphere. This concerns especially the magmatic iron oxides. In some volcanic-sedimentary and metasomatic iron oxides there is, however, a ferride deficiency, meaning that the processes giving these oxides have been depleted in the ferrides. As there is a clear difference in the accumulation-coefficient between the magmatic iron oxides and the otherwise formed iron oxides, this coefficient might thus be a useful genetical index.

From table 31 it is seen that accumulation-coefficient for the three elements magnesium, zinc, and copper is usually below unity. Only for the basic magmatic rocks high values have been found. Relatively high values are met with in the skarn iron ores and the stratified iron ores, the hematite in the conglomerate at Doktors kulle, the magnetite in gneisses of unknown origin and in the magnetite in the amphibolite at Hällinmäki.

If the accumulation-coefficient for the ferrides and magnesium, zinc, and copper is calculated for the iron oxides in the different types of iron ore and rock, the value is mainly influenced by the ferrides, and the third row in table 31 shows more or less the same values as the accumulation-coefficient comprising merely the ferrides. Only two values including all elements are below unity, namely, the magnetite in the Lahn-Dill ores and hematite in the iron ores of the Hauki type, which further emphasizes the above statement regarding the deficiency of trace elements in the activity giving rise to these ores.

7. CLASSIFICATION OF CERTAIN IRON ORES AND ROCKS OF UNKNOWN ORIGIN IN NORTHERN SWEDEN BY MEANS OF THE TRACE ELEMENTS IN THE IRON OXIDES

The iron ores Altavaara, Killingi, and Puoltsa in Northern Sweden show similarity in general appearance and mineralogical composition with both the apatite iron ores and the skarn iron ores (p. 36). In the following pages an attempt will be made to assign these deposits to one of these ore types using the trace element distribution in the magnetite.

If the geochemical features of the magnetite in the apatite iron ores and the skarn iron ores are reviewed, it is found that the magnetite in the apatite iron ores has higher contents of nickel, molybdenum, and vanadium but lower contents of chromium and magnesium than the magnetite in the skarn iron ores (fig. 2). This relationship does not lack limitations as the contents of these elements in the two types of ore in many cases overlap each other. But the higher content of chromium in the skarn ores seems to be significant. If a value higher than 20 p. p. m. Cr is found in magnetite, it thus means that a skarn ore is present. There are, however, several skarn iron ores with less than 20 p. p. m. Cr. Other criteria though less significant are the compara-

tively high contents of magnesium in the magnetite in the skarn iron ores and the relatively high contents of vanadium in magnetite in the apatite iron ores. Unfortunately there are rather high contents of magnesium in some of the apatite iron ores and rather high contents of vanadium in some of the skarn iron ores, but as seen from fig. 5 a value less than about 500 p. p. m. V means that the magnetite emanates from a skarn iron ore because none of the magnetites in the apatite iron ores (except one sample from Gruvberget) have such a low value. In the skarn ores the molybdenum content in magnetite is 10 p. p. m. or less, but in the apatite ores values up to 30 p. p. m. are found.

Furthermore it is possible, from the nickel-cobalt ratio in the magnetite, to make a distinction between the two types of ore. Fig. 4 shows that magnetites in the apatite iron ores and the skarn iron ores to some extent cover the same field, i. e. they have the same contents of nickel and cobalt but values less than 100 p. p. m. for both elements are confined to the skarn ores. The Co/Ni ratio in the magnetite also differs in the two types of ore, the mean in the apatite ores being 0.5 and in the skarn ores 0.8 (table 28). These values are not directly applicable to a single sample as the ratios have a rather wide range in both types. As seen from fig. 5 the apatite ores always have a ratio below unity, which is also the case with most of the analyses in the skarn ores. There are also analyses of the skarn ores for which the ratio is above unity. A Co/Ni ratio higher than unity is thus always confined to a magnetite in the skarn ores.

The field geological, mineralogical and chemical properties characterizing the apatite iron ores and the skarn iron ores are summarized in table 32.

The *Altavaara* deposit has the general appearance of a skarn iron ore but differs from this type by having in part a rather high content of apatite (p. 36). The trace elements in the magnetite show that the deposit, in spite of this feature, belongs to the skarn ores, this being indicated by the relatively high content of chromium (up to 50 p. p. m.) and the comparatively low contents of nickel (50–80 p. p. m.) and cobalt (50–80 p. p. m.). In fig. 4 showing the distribution of nickel and cobalt, the analyses from *Altavaara* fall outside the field covered by the apatite iron ores. This means that *Altavaara* is a skarn ore deposit similar to *Karhujärvi*, *Koivujärvi*, *Laukujärvi*, *Rakkurijoki*, *Vieto*, and *Vuoma* which also contain apatite in small amounts (p. 37), this, however, not being the case with most skarn ore deposits.

For the *Killingi* and *Puoltsa* deposits no certain assignment to the apatite iron ores or to the skarn iron ores can be made on the basis of the trace element distribution in the magnetite. In *Killingi* relatively low contents of nickel (80 p. p. m.) and cobalt (40 p. p. m.) point to a skarn ore. In *Puoltsa* the high content of magnesium (up to 17500 p. p. m.) indicates a skarn ore. The content of the other trace elements gives no clue as to which of the two ore types these deposits should be referred. Thus in figs. 4, 5, and 7 showing

Table 32. Field geological, mineralogical and chemical properties characterizing the apatite iron ores and the skarn iron ores in Northern Sweden

Ore type	Appearance	Host rock	Ore mineral	Gangue	In ore		In magnetite					
					% P	% S	Cr	Ni	p. p. m. Mo Co		V	Co/Ni
<i>Apatite iron ore</i>	Stratiform, intrusive	Volcanics, mostly of acid or intermediate composition	Magnetite, hematite	Apatite, (calcite, Ca-Mg-silicates)	0.01-5	<0.1	≤20	60-800	<10-30	<20-260	350-2500	0.1-1
<i>Skarn iron ore</i>	Stratiform	Basic volcanics and sediments	Magnetite	Ca-Mg- and Mg-silicates, (sulphides)	<0.1	1-5	<20-420	<20-360	≤10	<20-200	<50-2900	0.1-9.5

the distribution of cobalt, nickel, and vanadium, the analyses from Killingi and Puoltsa fall within the field common both for the apatite iron ores and the skarn iron ores.

The geochemical features of the iron ore at *Leppäkoski* may now be reviewed. The northwestern part of the deposit is, in general appearance, rather similar to the apatite iron ores and the southeastern part shows mineralogical and chemical similarities with the iron ores of the Hauki type (p. 38). As seen from table 10 the magnetite sample from the northwestern part is on the whole rather poor in trace elements. In comparison with the apatite iron ores it is obvious that the magnetite is poorer in all trace elements. This is especially the case with vanadium, the value of 200 p. p. m. being less than in any of the samples of the apatite iron ores. The lowest value is here 350 p. p. m. from Gruvberget. To be an ore of the Kiruna type the northwestern part of the *Leppäkoski* ore is thus exceptionally poor in trace elements, especially vanadium. The magnetite in the southeastern part is characterized by a relatively high content of chromium (120 p. p. m.) in which respect it resembles the magnetite in the Hauki iron ores. Furthermore, the contents of cobalt and vanadium are the same as in the magnetite in these ores, but the contents of titanium, nickel, and manganese are lower in the *Leppäkoski* magnetite. The relatively high content of chromium in this part of the deposit seems, as in the Hauki ores and the Taporova deposit, to be a result of the metasomatic action forming the ore. The content of barium (in barite) found in the magnetite analyses is relatively high (90–270 p. p. m.), which is also the case in the iron ores of the Hauki type and in the iron ore at Taporova.

From a geochemical point of view the southeastern part of the *Leppäkoski* ore is rather similar to the Hauki ores and the Taporova ore. A metasomatic mode of formation is therefore most likely for this part of the deposit, the fragment-bearing rock found here (p. 38) being best interpreted as a zone of tectonic disturbance facilitating the action of the ore-forming solutions. For the northwestern part the origin is more diffuse as the magnetite is very low in trace elements and thus differs from the magnetite in the apatite iron ores, to which this part of the deposit is similar in general appearance. It cannot be excluded that the northwestern part has the same mode of formation as the southeastern part and that the pooriness in trace elements is due to the same metasomatic activity.

From the trace element distribution in the hematite occurring both as pebbles and in the matrix in the *conglomerates at Doktors kulle* and *Saurusvaara* (p. 39) the following conclusions about the possible source of the hematite can be drawn. At *Doktors kulle*, east of Luossavaara, the hematite material in the conglomerate at the bottom of the Upper Hauki series can either be derived from the apatite iron ore at Luossavaara or from a hematite ore of the Hauki type in the Lower Hauki series. The geochemical features of the

hematite material justify the first assumption as the trace elements in the hematite, except for a lower content of nickel and somewhat higher contents of chromium and titanium (table 10), are equal to those in the magnetite in the apatite iron ores (fig. 2). The similarity is still closer with hematite in the apatite iron ores (fig. 3), the hematite in the conglomerate having only a somewhat higher content of chromium. If the hematite in the conglomerate is compared with the hematite in the ores of the Hauki type (fig. 3), obvious differences are found. The hematite in the conglomerate is richer in chromium, titanium, nickel, cobalt, zinc, and vanadium than the hematite in the Hauki ores, but the contents of magnesium, copper, molybdenum, and manganese are equal in both.

Even the hematite in the conglomerate at Saurusvaara is possibly derived from an apatite iron ore as its trace element distribution is similar to that for iron oxides in such ore. The hematite at Saurusvaara contains, however, only a small amount of nickel (less than 20 p. p. m.), in which respects it differs from the magnetite in the apatite iron ores. The manganese content is somewhat higher than is the case in the magnetite and hematite in the apatite iron ores. As regards the other trace elements, the hematite at Saurusvaara is similar to the iron oxides in the apatite iron ores.

The trace elements in two samples of magnetite in granite-pegmatites veining *gneisses* of unknown origin SE of Karesuando near the Finnish border have been investigated (p. 39). In the *gneisses* sillimanite-bearing or quartzitic intercalations are occasionally found, showing that the *gneisses*, at least in part, are of sedimentary origin. On the other hand, they contain layers of metamorphosed basic rock, presumably of volcanic origin. Whether the magnetites are formed by the granite-pegmatites in which they are sited or are derived by a mobilization of the surrounding *gneisses* is unknown. Nor do the geochemical features of the magnetites give any hint as to the mode of formation. However, the trace element distribution in the magnetites is rather similar to that in the magnetites in the skarn iron ores and stratified iron ores, but no conclusions will be drawn from this fact.

8. GEOCHEMICAL CONSIDERATIONS

8.1. Apatite iron ores in Northern Sweden

In the opinion of Geijer (1931b, 1935) the apatite iron ores in Northern Sweden are formed by the same magmatic activity that gave rise to the host rock of these ores. To a later phase of the main ore formation belong the hematite ores of the Hauki type, the formation of which occurred at a lower temperature and with a greater amount of volatiles than that of the apatite ores. This later metasomatic, hydrothermal activity affected some of the deposits of the Kiruna type resulting in an alteration of the wall rock and the ore. This al-

teration is held responsible by the present author (Frietsch 1967a) for the formation of hematite from magnetite in the apatite iron ores, magnetite always being primary.

The distribution of trace elements in iron oxides formed in the different units of this magmatic activity, namely the syenite-porphyrific wall rock, the apatite iron ores, and the iron ores of the Hauki type, shows changes. On p. 44 it has been demonstrated that the formation of the magnetite in the syenite-porphyrifics is in principle rather similar to the formation of the magnetite in the apatite iron ores.

The contents of the ferrides and of magnesium, copper, and zinc in the magnetite and hematite in the different units of this differentiation are shown in fig. 8. For the iron ores of the Hauki type only the hematite is considered in the following discussion. Of the magnetite one single analysis (from Ainasjärvi) exists, and therefore no comparisons are made with the magnetite in the syenite-porphyrifics and with the magnetite and hematite in the apatite iron ores, for which several analyses are available.

From the diagram in fig. 8 it is seen that when going from the first formed syenite-porphyrifics to the later developed apatite iron ores there is, in the iron oxides, a marked decrease in the content of chromium and a less pronounced decrease for magnesium and titanium, but an increase for zinc and manganese. For the other elements the changes are more ambiguous. As regards nickel and cobalt there is an increase in magnetite but a decrease in hematite, which shows that the latter mineral has been less apt to take up these elements than magnetite. For copper and vanadium there is no change. Furthermore, the molybdenum content in both magnetite and hematite has increased to some extent.

Turning from the apatite iron ores to the later formed hematite ores of the Hauki type there is a rather sharp drop in the contents of most elements. Thus titanium, nickel, cobalt, zinc, vanadium, and manganese have decreased, but for copper there is a slight increase and for molybdenum there is no change.

Summarizing the above it seems that when going from the iron oxides in the first formed syenite-porphyrifics to the iron oxides in the later formed apatite iron ores a depletion in chromium and to a lesser degree in magnesium and titanium took place. At the same time an enrichment in molybdenum, zinc, and manganese occurred. In the final stage of the differentiation, when the iron ores of the Hauki type formed, the ore solutions were depleted in titanium, nickel, cobalt, zinc, vanadium, and manganese but somewhat enriched in copper. Molybdenum remained unchanged.

The decrease of chromium, magnesium, nickel, cobalt, and vanadium and the increase of molybdenum and copper in the iron oxides in the differentiation described is in accordance with what is known about the behaviour of these elements in the magnetite formed during a fractional crystallization as

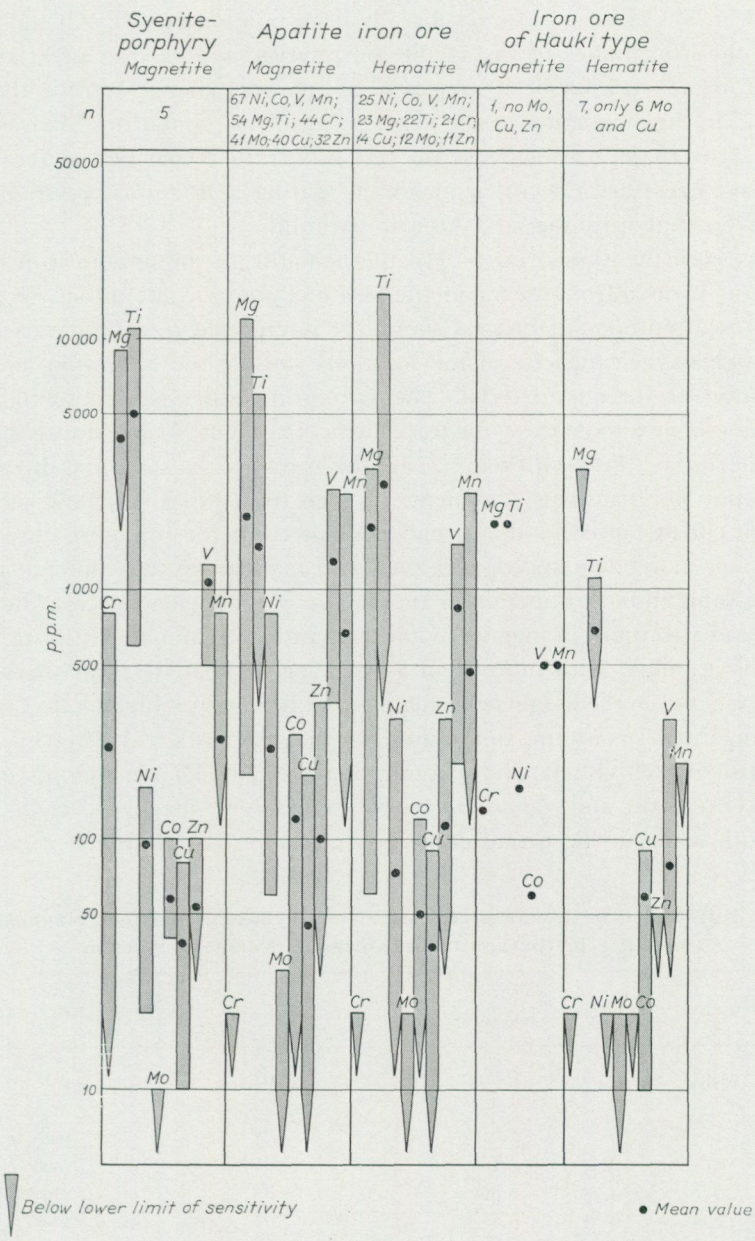


Fig. 8. Contents of some trace elements in magnetite and hematite in the syenite-porphyrics, apatite iron ores and the iron ores of the Hauki type, all in Northern Sweden.

shown by Wager & Mitchell (1951) from the Skaergaard intrusion, by Howie (1955) from the Madras charnockite series, and by Sen et al. (1959) from the batholith in S. California. As has already been pointed out (p. 97) the Co/Ni ratio in the iron oxides of the syenite-porphyrines, apatite iron ores, and the Hauki iron ores has not been subject to appreciable changes during the fractionation. In the magnetites of the Skaergaard intrusion and the Madras charnockite series there is an increase in the Co/Ni ratio. That this increase does not always necessarily occur in magnetite during a fractional crystallization is, however, shown by the S. California batholith.

As has been mentioned on p. 113 the hematite in the apatite iron ores is secondarily formed from the magnetite by a metasomatic alteration. According to the present author this process should be interpreted as a simple oxidation due to high oxygen fugacity of the solutions causing the alteration and with no addition of foreign material. The two iron oxides should therefore be expected to have almost the same trace element content. As previously pointed out by the author (Frietsch 1966, p. 272) this is in fact the case, and the present investigation confirms this statement. As seen from fig. 8 magnetite is richer in nickel, cobalt, and vanadium than hematite, but for titanium, chromium, magnesium, molybdenum, copper, zinc, and manganese the contents are almost the same in both minerals. If the means of these elements together with barium and strontium in magnetite and hematite are compared statistically, it is possible to show with more than 95 per cent probability that there is no difference between the contents of magnesium, titanium, molybdenum, copper, zinc, manganese, strontium, and barium but that there is a real difference in the contents of nickel, cobalt, and vanadium (table 33). That hematite contains less nickel, cobalt, and vanadium as compared with magnetite is in accordance with what has been said earlier about the restricted ability of hematite

Table 33. Differences in the mean of trace element contents between magnetite and hematite in the apatite iron ores in Northern Sweden

Element	$t_{\text{calculated}}$	$t_{0.975}$	Difference
Mg	0.00	2.02	no
Ti	1.26	2.03	no
Ni	5.05	1.99	yes
Mo	2.17	2.01	(no)
Co	6.86	1.99	yes
Cu	0.70	2.01	no
V	4.01	1.99	yes
Zn	1.50	2.02	no
Mn	1.46	1.99	no
Sr	2.18	2.02	(no)
Ba	0.71	2.11	no

to take up these trace elements in comparison with magnetite. When the magnetite in the apatite iron ores was secondarily altered to hematite, the concentration of the elements did not change, except for a slight decrease in nickel, cobalt, and vanadium. However, the contents of these elements in some of the hematites is as high as in the magnetites (see figs 4 and 7).

The apatite iron ores include a group of hematite-(magnetite)-deposits characterized by a high content of phosphorus (up to about 5 per cent) and sometimes by a rather high content of quartz and calcite. These ores have, in the opinion of Geijer, been formed at a lower temperature than the main mass of apatite iron ores but are still magmatic in character compared to the late, metasomatic, hydrothermal iron ores of the Hauki type. As seen from table 6, p. 19 these deposits, which comprise Haukivaara, Henry, Nukutus, Pattovare, and Rektorn, do not differ regarding their trace element distributions from most of apatite iron ores. The Hauki iron ores have, on the whole, a low content of trace elements as compared with the apatite iron ores, but this is not the case with the apatite-rich ores. The only feature which denotes similarity with the Hauki iron ores is that some of the analyzed samples from the apatite-rich deposits are rather high in barium. This, however, only means that barite is associated with hematite in both types of ore and accompanies the hematite in the analyzed samples.

A magmatic origin for the Swedish apatite iron ores has been challenged on geochemical grounds by Landergren (1943, 1948) who, in his work on the geochemistry of the iron ores of Sweden, considered the apatite iron ores to be originally sedimentary though later modified by paligenetic processes. In the ores in the Grängesberg area he found a deficiency of the ferrides which should exclude the apatite iron ores from the category of normal primary differentiation products. Furthermore the distribution of the lithophile elements should make the possibility that the intrusion of the apatite iron ores has arisen from a residual magma very unlikely. ". . . 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" (Landergren 1948, p. 109). ". . . the apatite iron ores of the Grängesberg area show such a large deficiency of ferrides (with the exception of V, which in this case follows P), that the ore cannot be the result of any *primary* magmatic differentiation process in the upper lithosphere" (Landergren 1943, p. 69). "The lithophile elements Li, Rb, Sr, and Ba show no absolute enrichment in the iron ores of the Grängesberg area in comparison to their content in the upper lithosphere." ". . . the iron ores of the Grängesberg area cannot have been injected as any pneumotectic

residual magma . . ." "Under such conditions an enrichment of these elements typical for residual solutions from a magma is to be expected . . ." (ibid., pp. 69–70). ". . . 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 by endogene processes" (Landergren 1948, p. 163). "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" (ibid., p. 137). "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" (ibid., p. 168). "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" (ibid., p. 172).

The premises on which Landergren based his opinion for the origin of the apatite iron ores may now be discussed. Firstly, if the ferride deficiency in these ores is considered it is questionable if this feature really is proof of a non-magmatic origin for the apatite iron ores. The assumption of the ferride deficiency was based on the following fact. Landergren compared the ratio between the iron content in the Grängesberg ore and the upper lithosphere (which means a concentration of about twelve times) with the ratios between the other ferrides in the Grängesberg ore and the upper lithosphere. From these ratios he found in the ore a deficiency of the ferrides (except for vanadium which together with phosphorus is enriched in the ore) which should exclude the apatite iron ores from the category of normal differentiation products. One may ask why the apatite iron ores, if they were magmatic, should originate from a parental magma with just the bulk composition of the upper lithosphere, i. e. why is a concentration of the ferrides of just twelve times necessary to prove that an iron ore is of magmatic origin. To the present author it seems more reasonable to explain the ferride deficiency by supposing that the apatite iron ores were formed by a magmatic differentiation and that the magma supplying these was already depleted in some elements when split up into ore-bearing and silicate fractions. On p. 114 it has been demonstrated that the changes shown by certain elements (decrease of chromium, magnesium, nickel, cobalt and vanadium; increase of molybdenum and copper) in the iron oxides formed in the different stages of the process giving the apatite iron ores and the iron ores of the Hauki type, is in accordance with what is known about the behaviour of these elements in magnetite formed during a fractional crystallization. Further, it must be emphasized that the iron oxides in the apatite iron ores have only limited possibilities to

take up trace elements. The ferride deficiency of the apatite iron ores compared to the composition of the upper lithosphere could therefore easily be explained by the restricted substitution possibilities for the ferrides in the iron oxides.

If the concentration-coefficients (i. e. the ratio between the content of an element in mineral or rock and the content of this element in the upper lithosphere) in table 30 are reviewed, it is obvious that Landergren's concept that the ferrides (except vanadium) are not enriched in the iron oxides in the apatite iron ores is correct if a concentration of twelve times is required. If only the content of the upper lithosphere and not twelve-fold multiplication is taken into consideration nickel, cobalt, and zinc are enriched in the magnetite but only the last two elements in the hematite of the apatite iron ores. As seen from table 30 the concentration-coefficients for the ferrides as well as for magnesium, copper, zinc, strontium, and barium are rather similar in the iron oxides in the different types of iron ores and rocks, and there is no readily apparent relationship between the different values of the coefficients and the origin of the iron oxides. Higher values than unity are, however, found for most elements in the iron oxides in the basic magmatic rocks. The iron oxides in the other ores and rocks classified as magmatic show also a deficiency of most elements (even the ferrides) if a concentration of twelve times is required. Therefore, as has been stated before, the coefficients of concentration for the ferrides do not reveal much about the origin of an ore and cannot be used to distinguish between magmatic and non-magmatic iron ores.

Summarizing, the above remarks mean that the ferride deficiency found by Landergren does not prove that the apatite iron ores are non-magmatic because the same deficiency is found in other magmatic iron ores. The accumulation-coefficients of the ferrides (table 31) show that the iron oxides in the apatite iron ores have values similar to the other, magmatically formed iron oxides.

According to Landergren (1943, 1948) the lithophile elements lithium, rubidium, strontium, and barium show no absolute enrichment in the apatite iron ores in Sweden (only strontium and barium were investigated in the Grängesberg area). They could not, therefore, be considered to have formed from a residual magma. The present investigation shows that this statement does not hold for the apatite iron ores in Northern Sweden, at least as far as barium and strontium are concerned; rubidium and lithium have not been determined. It has formerly been stated by the present author (Frietsch 1967a) that barium in the form of barite belongs to the last stage in the differentiation giving the iron ores of the Kiruna type, namely, the formation of the iron ores of the Hauki type. The high contents of barium in this type of ore as shown in table 25 confirm this statement. Table 25 also shows an increase of the strontium content in the iron oxides in the differentiation, as the Hauki

ores have higher strontium values than the syenite-porphyrries and the apatite iron ores. Strontium occurs in the Hauki ores, most likely in barite.

Furthermore, the high degree of oxidation in the iron ores of the Kiruna type as compared with a low degree of oxidation in the host rock was used by Landergren (1948, p. 176) as an argument against the magmatic formation of these ores: "The relatively high value for og (degree of oxidation) 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 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." If Geijer's assumption that the iron ores of the Kiruna type were formed by solutions rich in volatiles (mainly water) is taken into account, the statement of Landergren is not valid. If volatiles were active in the differentiation, several indications of which exist, the oxygen fugacity in the magma must have been high enough to allow the iron present to form magnetite.

The apatite iron ores in the Precambrian of Southeast Missouri are clearly very similar to the iron ores of the Kiruna type in Northern Sweden (Kisvarsanyi 1966, Kisvarsanyi & Proctor 1967). Kisvarsanyi considered them to be of magmatic origin. The similarities extend as much to the general appearance of the ores as to their mineralogical features. The host rocks for the ores in Missouri are unmetamorphosed volcanics of acid composition with occasional intermediate types. The volcanics have been intruded by granitic rocks, more rarely by intermediate rocks. Metamorphic rocks are very rare but, in the Boss area biotite schists of local extent occur. According to the present author, when visiting the area, these biotite schist seem to be derivatives of dikes of dioritic composition which cut the volcanics. Sedimentary rocks are thus missing in the Precambrian of the Southeast Missouri iron province.

In the opinion of Landergren the apatite iron ores in Sweden have been formed by sedimentary processes and secondarily reworked by paligenetic ones. In Southeast Missouri a sedimentary mode of formation for the apatite iron ores is, however, not possible as sedimentary processes are totally absent. The apatite iron ores in Missouri and in Sweden are not only similar to each other in general appearance and mineralogical composition but also geochemically. As seen from table 34 the distribution of trace elements in magnetite in the apatite ores and in hematite in the ores of the Hauki type in Northern Sweden is roughly the same as in their equivalents in Missouri. The trace element content for the Missouri deposits is taken from the work of Kisvarsanyi & Proctor (1967, table IV). The values for magnetite are the mean of the samples from the Pea Ridge, Iron Mountain, and the Bourbon apatite iron ore deposits. For hematite the values comprise the mean of the samples from the Pilot Knob and Cedar Hills deposits, which are of the same type as the

Table 34. The mean of the trace element contents in magnetite in the apatite iron ores and in hematite in the ores of the Hauki type from Southeastern Missouri (according to Kisvarsanyi & Proctor 1967) and Northern Sweden

District	p. p. m. of										
	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	Mo	Mg	Al
	Magnetite, apatite iron ore										
S. E. Missouri	3560	1060	20	1700	41	49	4	119	3	930	710
N. Sweden	1500	1300	10	70	120	220	<40	100	7	1900	1590
	Hematite, iron ore of the Hauki type										
S. E. Missouri	480	3	1	22	11	6	1	150	30	42	4570
N. Sweden	700	80	<20	<200	<20	<20	60	<50	<30	<3000	>3700

iron ores of the Hauki type in Northern Sweden. Table 34 shows that in the apatite iron ores the magnetite in Northern Sweden is higher in cobalt and nickel than the magnetite in Missouri. The other elements in this mineral are of the same magnitude in both provinces. For the hematite in the iron ores of the Hauki type there are some differences, the hematite from Missouri contains less vanadium and copper and more zinc than the hematite in Northern Sweden. Otherwise the trace element distribution in the ores of the Hauki type in these two areas is rather similar, being characterized by a poverty in trace elements. As the iron ores in Missouri are most likely of magmatic origin, a sedimentary origin being clearly excluded, and as these ores in the trace element distribution are similar to the apatite iron ores in Northern Sweden, there is no geochemical support for a sedimentary mode of formation for the apatite iron ores in Northern Sweden.

According to Hegemann & Albrecht (1954, p. 101) the Lahn-Dill ores in Western Germany and the apatite iron ores in Northern Sweden are geochemically similar to each other and should thus be of the same origin: "Nach unseren geochemischen Befunden können die Lagerstätten von Kiirunavaara, wie schon St. Landergren erkannt und hervorgehoben hat, nicht als liquid-magmatische Differentiationsprodukte und endogene Intrusionen aufgefasst werden, aber auch nicht als primär rein exogene Anreicherungen des Verwitterungsbereiches. Vermutlich dürfte es sich bei ihnen ursprünglich um Bildungen im Gefolge extrusiv-submariner Vorgänge handeln, die durch nachfolgende Metamorphosen weitgehend umgeändert wurden." The authors base their opinion on the following facts. The distribution of the trace elements in the Kiruna type does not fit any other type of iron ore investigated. The maximum contents of the trace elements are mostly astonishingly low. The Ti/V ratio

in the unseparated ore does not show any similarity with the same ratio in intramagmatic iron ores to which Hegemann & Albrecht assigned the titaniferous ores as well as all high-temperature ores in magmatic rocks of intrusive and extrusive origin. In comparison with the contents of the upper lithosphere only manganese, vanadium, and cobalt are enriched in the apatite iron ores. The concentration-coefficient for titanium, chromium, and nickel is below unity, and in this respect the apatite ores are similar to the Lahn-Dill ores. Hegemann & Albrecht pointed out that there are, however, geochemical differences between the two types of ore. Thus the magnetites in the Kiruna type contain somewhat higher amounts of magnesium, manganese, and vanadium. Even cobalt and chromium should be included as the diagrams presented in the paper of Hegemann & Albrecht show higher contents of these elements in the apatite iron ores than in the Lahn-Dill ores. As both types are considered by the authors to be akin to each other the difference in trace element content is explained partly by the metamorphism of the Swedish ores, partly by differences in temperature during the formation of the ores.

In summary, the views of Hegemann & Albrecht indicate that the ores of the Kiruna type do not show any similarities with the intramagmatic iron ores from a geochemical point of view but are similar to the ores of the Lahn-Dill type.

The number of samples of the iron ores from the Lahn-Dill area investigated in the present work is small compared to the number of samples from the apatite iron ores in Northern Sweden, and a fair comparison of the geochemistry in the two types of ores is thus not quite feasible. In spite of this, even the few analyses of the Lahn-Dill ores show that there are important geochemical differences between the two types. Fig. 2 shows that the magnetite in the apatite iron ores has much higher contents of titanium, cobalt, and vanadium and somewhat higher contents of nickel, copper, and zinc but a somewhat lower content of molybdenum (table 22) than the magnetite in the Lahn-Dill ores. The contents of chromium, magnesium, and manganese are equal in both types of ore. The hematite in the apatite iron ores has a much higher content of titanium and a somewhat higher content of vanadium but lower contents of nickel, copper, and molybdenum than the hematite in the Lahn-Dill ores (fig. 3). The contents of chromium, (magnesium), cobalt, zinc, and manganese are equal in both types of ore.

If the accumulation-coefficient for the ferrides in the iron oxides are compared, it is found that the Lahn-Dill ores have a much lower value than the apatite iron ores (table 31). The Lahn-Dill ores have a coefficient lower than any of the other iron oxides investigated, indicating a marked deficiency of ferrides.

In summary, the iron oxides in the apatite iron ores (in Northern Sweden) have higher contents of trace elements, especially titanium and vanadium,

than the iron oxides in the Lahn-Dill ores, the magmatic activity responsible for the latter being relatively depleted in trace elements. The lack of geochemical similarity between the two types of ores is, however, not surprising when considering the great difference in their general appearance and mineralogical composition. The geochemistry of the iron oxides in the Lahn-Dill ores will be further reviewed in a later section.

From the geological point of view it is quite clear that Geijer's opinion that the apatite iron ores were formed by the same magmatic activity that gave rise to the volcanic rocks enclosing the ores is correct. From what has been said above there is no reason to believe, on geochemical evidence, that these ores have not been formed by magmatic processes. The geochemical features of the iron oxides in these ores merely point to a formation of the apatite iron ores by a fractional crystallization.

8.2. Iron ores in the Misi area, Northern Finland

The magnetites in basic intrusives are characterized by high contents of titanium and in most cases of chromium and vanadium, too (cf. table 17). In this respect they differ from the magnetites in all other types of rock and iron ore. The iron ores in the Misi area are, as has been mentioned earlier (p. 49), considered to be magmatic and to have formed in connection with the intrusion of gabbros and albitites. As seen from table 14 the magnetite in these ores does not contain appreciable amounts of titanium, chromium, and vanadium in comparison with the magnetite in basic intrusives. The magnetite in the Misi ores is found to be lower in chromium, titanium, molybdenum, cobalt, copper, zinc, and vanadium but higher in nickel than the magnetite in the basic magmatic rocks (fig. 2). Magnesium and manganese are about equal in both.

The relative poorness in the elements titanium, chromium, and vanadium in the magnetite in the Misi ores shows that these do not represent normal segregation deposits. The ores are thus not geochemically directly related to the enclosing gabbro as is the case with the titaniferous iron ores, this also being indicated by the fact that the Misi ores cut the enclosing gabbro and albitite. This supports the opinion expressed by Nuutilainen (1968) that the Misi ores have been formed as a late phase in the same magmatic activity giving the gabbro and the albitite, thus explaining the poverty in trace elements. The fact that the Misi ores are associated with albitites would, however, in the opinion of the present author, suggest that metasomatic processes have been operative, too. The albitites in the Misi area are, in general appearance and in mineralogical composition, similar to the leucodiabases in the Norrbotten county, which are most possibly metasomatic alteration products of basic magmatic rocks (p. 46). The albitites in the Misi area occur like the leucodiabases in the vicinity of tectonic disturbances.

In summary, the Misi ores differ both in general appearance and in trace element distribution from other iron ores found in basic magmatic rocks, these features being explained by the formation of the ores in a late stage of magmatic activity.

8.3. Volcanic-sedimentary iron ores in Northern Sweden, Northern Finland and Western Germany

Four groups of volcanic-sedimentary iron ores have been investigated geochemically in the present work, namely the Lahn-Dill ores in Western Germany (p. 52), the Kittilä ores in Northern Finland (p. 52) and the skarn ores (p. 26) and stratified ores (p. 33) in Northern Sweden. In many respects similarities are found between these ores. They are all more or less intimately connected with basic volcanic rocks. Layering of the ore is found in the stratified ores of Northern Sweden, the Kittilä ores, partly in the Lahn-Dill ores and only to a lesser degree in the skarn ores of Northern Sweden. The main ore mineral in the Kittilä ores, the stratified ores, and the skarn ores is magnetite. It is subordinate to hematite in the Lahn-Dill ores. Hematite is found occasionally in the skarn ores. The Kittilä ores, the stratified ores, and the Lahn-Dill ores are predominantly quartz-rich. Carbonates are always associated with the ore: in the Kittilä ores siderite and mangano-siderite, in the Lahn-Dill ores calcite, dolomite, and siderite, in the skarn ores and the stratified ores calcite and dolomite. Iron sulphides are common in the skarn ores and the stratified ores. They are occasionally found in the Lahn-Dill ores but are missing in the Kittilä ores. The dark silicates accompanying the ore minerals show some differences, however. Those in the Lahn-Dill ores and in the Kittilä ores are magnesium-rich. Those in the skarn ores are calcium- and magnesium-rich and in the stratified ores iron-rich. Calcium-magnesium-rich silicates also occur subordinately in the stratified ores.

Different opinions about the origin of the Lahn-Dill ores have been presented by different authors (p. 52), but most commonly these are considered to be exhalative sedimentogeneous products formed in connection with the enclosing basic volcanics.

The Kittilä ores and the associated jasper quartzites were regarded as normal (clastic) sediments by Hackman (1924). Geochemical investigations by Sahama (1945) show the jasper quartzites to lack appreciable amounts of zirconium and titanium, thus distinguishing them from the clastic quartzites. E. Mikkola (1941) and Kaitaro (1949) considered the ores and the jasper quartzites to have been formed in connection with the basic volcanism which gave rise to the host rock of these formations. According to Mikkola they are chemical precipitations on the surface of the basic volcanics. Kaitaro considered the ores and quartzites to be of exhalative sedimentogeneous origin. A similar

opinion regarding the origin of the ores is expressed by Paakkola (1968). It should further be pointed out that the occurrence of minnesotaite (p. 52) indicates a similarity with the other Precambrian iron formations where this mineral is in many cases found.

The stratified iron ores in Northern Sweden connected with sediments and basic volcanics are considered as metamorphic chemical sediments (cf. p. 33).

The origin of the skarn iron ores in Northern Sweden is less clear than that of the iron ores discussed above. Geijer (1918b, 1929, 1931a, 1935, and Geijer & Magnusson 1952) regarded the skarn ores as replacement deposits formed by emanations from intrusive rocks. T. Eriksson (1954), Ödman (1957), and Frietsch (1966, 1967b), however, considered these ores to be metamorphosed sedimentary formations. In the opinion of the present author the main reason for a sedimentary mode of formation of the skarn ores is that these and the stratified ores, of which the last mentioned have a clear sedimentary origin, are both related to basic volcanics and sediments and are in most cases found in about the same stratigraphic position. In some deposits the two types of ore pass into each other. In the skarn ores is sometimes encountered a skarn-layering or more rarely a carbonate-layering which can be interpreted as a relict sedimentary feature. The skarn ores and the stratified ores thus seem to have the same origin, being formed simultaneously with the enclosing sediments and basic volcanics. Through a later regional metamorphism connected with the intrusion of plutonic rocks the sedimentary features of the skarn ores were in many cases almost totally obliterated.

When comparing the geochemical features of the different volcanic-sedimentary iron ores discussed above it is found that the skarn ores and the stratified ores in Northern Sweden are similar to each other, but different from the Lahn-Dill ores and the Kittilä ores, which in turn are different from each other.

If the skarn ores and the stratified ores in Northern Sweden have a different origin, the former being pyrometasomatic and the latter sedimentary according to the opinion of Geijer, it is to be expected that they will show different geochemical characteristics. As seen from fig. 2 the trace element distribution in magnetite in these types of ore is rather uniform. If the means of the trace element contents in magnetite in the two types of ore are compared statistically, it is possible to show with more than 95 per cent probability that there is a real similarity in composition for most trace elements (table 35). Real differences are only found for zinc and manganese, both of which occur in greater amounts in the stratified ores than in the skarn ores. The similar distribution of cobalt, nickel, and vanadium in the magnetite of the skarn ores and the stratified ores is obvious when studying the diagrams in figs 4, 5, and 7.

As seen from fig. 2 the range of the contents of certain trace elements in magnetite in the skarn iron ores and the stratified iron ores is rather great,

Table 35. Differences in the mean of trace element contents between magnetite in the skarn iron ores and magnetite in the stratified iron ores, both in Northern Sweden

Element	$t_{\text{calculated}}$	$t_{0.975}$	Difference
Cr	1.16	2.05	no
Mg	0.93	1.98	no
Ti	2.16	2.00	(no)
Ni	1.35	1.99	no
Mo	0.33	1.99	no
Co	1.23	1.99	no
Cu	0.89	1.99	no
V	1.09	1.99	no
Zn	3.92	2.04	yes
Mn	3.86	2.01	yes
Sr	2.12	1.99	(no)
Ba	0.21	2.01	no

especially for chromium, copper, and vanadium. The great range for vanadium is specially noteworthy. Fig. 5 shows that about half the magnetites in the skarn iron ores have contents higher than 640 p. p. m. V (the mean), with values up to 2900 p. p. m., and that about one fifth of the magnetites in the stratified ores have a value greater than 440 p. p. m. V (the mean), with values up to 3800 p. p. m. The chromium values in both types of ores are mostly low, the mean in the skarn ores being 40 p. p. m. and in the stratified ores 90 p. p. m. In both types, however, high contents are encountered, up to 420 p. p. m. in the skarn ores and 1200 p. p. m. in the stratified ores. No relationship between the high contents of vanadium and chromium in the two types can be observed. Tables 8 and 9 show that the high contents of these elements are mostly confined to certain deposits within the skarn ores and the stratified ores. To a lesser degree this seems to be the case with titanium, nickel, cobalt, copper, and zinc. All these differences are certainly primary features and possibly due to variations in the depositional environment.

The above remarks indicate that the magnetites in the skarn iron ores and the stratified iron ores are similar to each other from a geochemical point of view. This supports the opinion that they have a similar origin, but that there are rather great variations in the contents of some trace elements in the different deposits.

The magnetite in the skarn iron ore at Rautuvaara in Northern Finland (table 14) is rather similar to the magnetite in the skarn iron ores in Northern Sweden regarding the trace elements (fig. 2). Thus the Rautuvaara ore, from a geochemical point of view, is related to the skarn iron ores in Northern Sweden and possibly has the same origin.

If the trace element contents in the magnetite in the Kittilä jasper quartzites and mangano-siderites (table 14) are compared to those in the magnetite in the skarn iron ores and the stratified iron ores in Northern Sweden (fig. 2), it is found that the Kittilä ores are the lowest in magnesium, titanium, nickel, cobalt, zinc, and vanadium; the contents of chromium, molybdenum, copper, and manganese being equal in the three types of ore. There thus seems to be a tendency for the magnetite in Kittilä ores to be lower in trace elements than the skarn iron ores and the stratified iron ores in Northern Sweden.

In the Lahn-Dill ores hematite has lower contents of chromium, magnesium, titanium, nickel, and molybdenum but higher contents of cobalt, copper, zinc, and vanadium than magnetite, the content of manganese being equal in both minerals (table 15). The iron oxides in the Lahn-Dill ores differ geochemically from those in the other volcanic-sedimentary iron ores investigated in the present work, especially if compared with the skarn ores and the stratified ores in Northern Sweden. These two types of ore have in common much higher contents of trace elements than the Lahn-Dill ores. The magnetite in the skarn and stratified ores has higher contents of chromium, magnesium, titanium, cobalt, copper, zinc, and vanadium but a lower content of molybdenum than the magnetite in the Lahn-Dill ores, the contents of nickel and manganese being similar in the three types of ore. The magnetite in the skarn ores and the stratified ores is more similar to the hematite in the Lahn-Dill ores regarding the contents of cobalt, copper, zinc, and vanadium, but for the other elements the same differences are found as between magnetite in the skarn ores – stratified ores and magnetite in the Lahn-Dill ores. If the trace elements of the hematite in the skarn ores and the hematite in the Lahn-Dill ores are compared (fig. 3), it is found that the hematite in the skarn ores contains more magnesium, titanium, and cobalt but less nickel than the hematite in the Lahn-Dill ores, the contents of chromium, copper, zinc, vanadium, and manganese being equal in both types of ore.

Between the iron oxides in the Kittilä ores and in the Lahn-Dill ores there also exist geochemical differences. These are, however, less pronounced for magnetite than for hematite in the Lahn-Dill ores. The magnetite in the Kittilä ores contains more chromium, copper, and manganese but less nickel, molybdenum, and zinc than the magnetite in the Lahn-Dill ores (fig. 2). The contents of magnesium, titanium, cobalt, and vanadium are similar in both types of ore. If the magnetite in the Kittilä ores is compared with the hematite in the Lahn-Dill ores regarding the trace elements (fig. 3), it is found that the Kittilä ores are higher in chromium and manganese but lower in nickel, molybdenum, cobalt, copper, zinc, and vanadium than the Lahn-Dill ores, only magnesium and titanium being equal in both types of ore.

Summarizing, the above remarks indicate that within the volcanic-sedimentary iron ores investigated in the present work similar geochemical features

are only found between the skarn ores and the stratified ores in Northern Sweden. The iron oxides in these types of ore are higher in trace elements than those in the Kittilä ores and the Lahn-Dill ores. This is, however, not very pronounced for the hematite in the Lahn-Dill ores. If compared to the iron oxides in the magmatic iron ores and rocks investigated the iron oxides in the Lahn-Dill ores and the Kittilä ores show a marked deficiency of trace elements. The geochemical differences found between some of the volcanic-sedimentary ores indicate, in spite of the fact that these ores have a similar mode of formation, that there have been differences in the depositional environment.

For Precambrian iron formations there are no geochemical data available except for those in Central Sweden investigated by Landergren (1948). The non-apatitic iron ores in Central Sweden comprise quartz-banded ores, skarn ores and limestone ores. The quartz-banded ores were, in the opinion of Geijer & Magnusson (1952), originally deposited as chemical sediments as is evident from the bedded character, the very regular stratification and similarity to other banded iron formations in the Precambrian. The source of the iron and silica has to be sought from volcanic emanations. The origin of the skarn ores and the limestone ores is still much debated. According to Geijer & Magnusson these might be partly mobilized ores of sedimentary origin, partly true pyrometasomatic deposits. A clear division into those of primarily, sedimentary origin and those of pyrometasomatic origin is not always possible. Due to this uncertainty regarding the mode of formation of the non-apatitic iron ores in Central Sweden, a comparison of the geochemical features in these and in the volcanic-sedimentary iron ores investigated in the present work is not fully justified. This will, nevertheless, be attempted as the data given by Landergren show that the different types of ore in Central Sweden are rather similar to each other regarding their trace element contents. From table 59 in the work of Landergren it can be seen that the mean contents of cobalt and nickel in the limestone ores, skarn ores, banded quartz ores, and unbanded quartz ores show small variations (between 25 and 50 p. p. m.). From the comparison made below, however, no genetical conclusions will be drawn as to the origin of the ores in Central Sweden. The contents of titanium, vanadium, manganese, cobalt, and nickel in the magnetic fraction in the different types of the non-apatitic iron ores in Central Sweden taken from the work of Landergren (table 15) are shown in table 36. The contents of chromium and magnesium given by Landergren could not be used in this connection as the analyses comprise the whole ore (or the gangue). Table 36 shows that the magnetite in the skarn iron ores and stratified iron ores in Northern Sweden has much higher contents of titanium, vanadium, cobalt, and nickel than the magnetite in the non-apatitic iron ores in Central Sweden. The manganese content is almost the same in the stratified iron ores in Nor-

Table 36. The content of some ferrides in the iron oxides in the non-apatitic iron ores, Central Sweden (taken from Landergren 1948); the skarn iron ores and the stratified iron ores, Northern Sweden; the iron ores in the Kittilä area, Northern Finland and the iron ores in the Lahn-Dill area, Western Germany

Ore deposit	Ore mineral	p. p. m. of									
		Ti		V		Mn		Co		Ni	
		range	mean	range	mean	range	mean	range	mean	range	mean
Non-apatitic iron ore, Central Sweden	Magnetite	<100-1000	270	<10- 30	10	<100->10000	3500	<10-300	10	<10-100	10
Skarn iron ore, N. Sweden	Magnetite	<600-4800	900	<50-2900	600	<200- 5000	900	<20-200	80	<20-360	100
Stratified iron ore, N. Sweden	Magnetite	<600-9600	1840	<50-3800	440	<200- 7200	2500	20-260	100	<20-260	70
Iron ore, Kittilä, N. Finland	Magnetite	<600- 600	400	<50- 400	160	<200- 27000	9100	<20- 20	15	20- 80	40
Iron ore, Lahn-Dill, W. Germany	Magnetite	-	<600	<50- 300	120	<200- 1800	700	-	<20	40-200	100
Iron ore, Lahn-Dill, W. Germany	Hematite	-	<600	300- 500	400	<200- 1000	500	20- 40	30	80-200	130

thern Sweden and in the non-apatitic iron ores in Central Sweden, both of which are higher in this element than the skarn iron ores in Northern Sweden. The iron oxides in the Kittilä ores and in the Lahn-Dill ores are higher in vanadium and nickel as compared with the magnetite in the non-apatitic ores in Central Sweden though the contents of titanium and cobalt are similar in all these ores. The manganese content is higher in the Kittilä ores than in the ores in Central Sweden and in Lahn-Dill.

The magnetites in the non-apatitic ores in Central Sweden thus differ decidedly from magnetites in all the volcanic-sedimentary iron ores investigated in the present work by having low contents of vanadium and nickel, the contents of the other elements being either lower or higher.

It is interesting to note that Landergren (1948, table 59) found, for the non-apatitic ores in Central Sweden, a Co/Ni ratio between 1.2 and 1.6, the values thus occurring within a rather narrow range. These values comprise, however, the whole ore and are not quite comparable to the Co/Ni ratio presented in table 28 in the present work. From this table it is seen that among the volcanic-sedimentary iron ores only the iron oxides in stratified ores in Northern Sweden have a value (1.4) similar to that of the ores in Central Sweden. In the skarn ores in Northern Sweden the ratio is 0.8, in the Kittilä ores 0.4, and in the Lahn-Dill ores ≤ 0.2 . This means that the Co/Ni ratio in these ores shows a much greater variation than in the non-apatitic ores in Central Sweden.

9. SUMMARY

The trace elements in magnetite and hematite of the different iron ore types and of some rocks types in the Norrbotten county, Northern Sweden, have been determined spectrochemically. Furthermore the iron ores in Northern Finland and in the Lahn-Dill area, Western Germany, have been investigated in the same manner. In the paper 220 analyses of magnetite, 44 analyses of hematite, and 25 analyses of iron ore or rock have been recorded. The analyses comprise the elements Si, Al, Ca, Mg, Mn, Ti, Ba, Sr, Ni, Co, Cr, V, Cu, Zn, and Mo. In a small number of samples B, Be, Ga, Sn, Sb, Zr, Cd, Pb, and Ag have also been analyzed. As a rule hematite takes up smaller amounts of Cr, Ni, Co, V, Mn, and partly Ti but higher amounts of Mo than magnetite. This relationship is due to differences in the crystal-chemical properties and in the mode of formation of these minerals.

The iron ores and rocks investigated belong in the main to three genetical groups: magmatic, volcanic-sedimentary, and metasomatic. In many cases the absolute values of the trace elements, the ratios of certain element pairs, and the concentration-coefficients in the magnetite and hematite do not show

any marked differences within these groups. It is thus not always possible to make a definite division between the different types of iron ore and rock by means of the trace element distribution in the iron oxides. In some types of iron ore and rock the iron oxides do show characteristic geochemical features. In general the magmatic iron oxides are higher in trace elements, especially the ferrides, than the volcanic-sedimentary and metasomatic iron oxides. The highest contents are without doubt found in the iron oxides in the basic magmatic rocks. In some of the volcanic-sedimentary and metasomatic iron oxides a ferride deficiency compared with the content of these elements in the upper lithosphere is found, indicating that the processes giving these iron oxides have been depleted in ferrides.

In Northern Sweden two types of volcanic-sedimentary iron ores are encountered, namely the stratified, usually siliceous ores and the skarn ores. For the latter a pyrometasomatic origin has also been postulated. The trace element distributions in the magnetite in both types of ore are, however, similar, which indicates that they are genetically related to each other. To the same genetical group belong the iron ores in the Kittilä area in Northern Finland and the iron ores in the Lahn-Dill area in Western Germany. The iron oxides in these ores are poorer in trace elements than the iron oxides in the skarn ores and stratified ores in Northern Sweden, a feature which is not very pronounced in the hematite of the Lahn-Dill ores. Within the volcanic-sedimentary iron ores there are thus some geochemical differences which possibly are due to differences in the depositional environment.

The apatite iron ores in Northern Sweden have, in the opinion of Geijer (1931b), been formed by a magmatic differentiation during which the silicate rocks have been largely developed as volcanics of acid or intermediate composition. To a later stage of this magmatic activity belong the metasomatic Hauki hematite ores. The present investigation shows that the trace element distribution in the iron oxides formed during the various stages of the differentiation: syenite-porphyrific wall rock – apatite iron ore – Hauki ore, has been subjected to changes. Cr, Mg, Ni, Co, and V have decreased, Mo and Cu have increased. This relationship is in accordance with what is known about the behaviour of these elements in the magnetite formed during fractional crystallization. The late-formed Hauki ores are on the whole depleted in trace elements, except for Ba and Sr, which indicates that they were formed by residual solutions in the magmatic activity.

A magmatic origin for the apatite iron ores has been rejected on geochemical grounds by Landergren (1943, 1948), mainly due to the fact that these ores show a large deficiency in ferrides and cannot consequently have been developed by any primary differentiation process in the upper lithosphere. The primary formation of the iron in the apatite ores is, according to Landergren, connected with exogenic, sedimentary processes, the iron having been later,

secondarily, reworked by paligenetic processes giving the intrusive appearance of the ore. The present investigation shows, however, that the same ferride deficiency is found in the other magmatic iron oxides (even in those in magmatic segregations) and this deficiency cannot thus be used as an index for a non-magmatic origin of an iron ore.

According to Hegemann & Albrecht (1954) the apatite iron ores in Northern Sweden are geochemically similar to the volcanic-sedimentary (exhalative sedimentogeneous) iron ores in the Lahn-Dill area and should consequently have the same origin as these. In the present investigation it is, however, found that the iron oxides in the apatite iron ores and in the Lahn-Dill ores show a different trace element distribution. The Lahn-Dill ores are low in most trace elements, especially Ti, Co, and V, as compared with the apatite iron ores. The trace element distribution in the iron oxides in the Lahn-Dill ores merely points to a similarity with the Kittilä ores in Northern Finland, these also being of volcanic-sedimentary origin.

The magnetite ores in the Misi area in Northern Finland are considered to be magmatic and formed in connection with the intrusion of gabbro and albite-extreme rocks. The trace element distribution in the magnetite shows that these ores are not closely connected with the enclosing gabbro, the content of Cr, Ti, and V being much lower than in other magmatic segregation deposits. The Misi ores were possibly formed as a late phase in the magmatic activity giving the gabbro, the ore-forming solutions being relatively depleted in trace elements.

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