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Studies on the geology of the iron ores of Lappland

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Studies on the geology of the iron ores of Lappland.

By

PER GEIJER.

The following pages will contain the results of some studies on the geological problems of the iron ores of Lappland, made during the last few years. During the years 1905—1909, the writer was engaged in examinations of the geology of the iron ores of the Kiruna district, the work forming one link in the series of scientific researches arranged by the mining company, Luossavaara-Kiirunavaara Aktiebolag. The result of the writer's work was published in 1910 as a monograph,[1] a summary of the general geology of the district being given at the same time by the organizer of the researches, Dr HJ. LUNDBOHM.[2]

My work at Kiruna resulted in the formulating of a working hypothesis regarding the origin of the apatitic ores of Lappland. This paper contains some new material for the solving of this problem, gathered during the years passed since the writing of the Kiruna monograph. Direct quotations of the latter will be given in some special cases only, as it is supposed to be at the hands of the reader.[3]

[1] Igneous rocks and iron ores of Kiirunavara, Luossavaara and Tuolluvaara (In the series »Scientific and practical researches in Lappland arranged by Luossavaara-Kiirunavaara Aktiebolag»), Stockholm 1910. This work will be here referred to as *Kiruna*, for the sake of convenience.

[2] Sketch of the geology of the Kiruna district. G. F. F. 32: 751 (Also as guide N:o 5, XI:th internat. geol. congress, Stockholm 1910).

[3] An author's abstract is published in Economic Geology, Vol. V, 1910, p. 699—718, and a shorter one in Geol. Zentralblatt, edited by K. KEILHACK, Vol. XVII, p. 290.

I.

Geology of the Ekströmsberg ore field.

Introduction.

Ekströmsberg, as to the size the third of the iron ore fields of Lappland (the larger ones are Kiirunavaara and the Gellivare group of mines) lies nearly due west of Kiirunavara, the distance from the town of Kiruna being 30 *km* as the crow flies. The ore field was known during the 18:th century, but its exact site was forgotten, and it was not refound until in 1895. Since 1907 it is the property of the Swedish Crown.

The field lies 4 *km* south of the Kalix river, on the lowest western slope of the Pidjastjåkko mountain, the summit of which attains a height of 1 013 *m* above sea level (547 *m* above the level of the river). It lies in the uppermost fringe of the birchwood, in beautiful surroundings. The nearest settlements are at two points at the river, each at a distance of about 5 *km*.[1]

The geology has been studied by SVENONIUS,[2] BÄCKSTRÖM[3] and STUTZER.[4] The numerous interesting features described by these authors made a visit desirable, so that I should be able to compare the field with the other iron ore deposits of the Lappland region, especially with those around Kiruna. In 1910, I therefore spend about ten days at Ekströmsberg.

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[1] The position of Ekströmsberg is indicated on maps in the atlases accompanying »Jukkasjärvi malmtrakt» by F. SVENONIUS and V. PETERSSON (Sveriges Geol. Unders. Ser. C, n:r 183) and »Iron ore resources of the world» (Stockholm 1910).

[2] Op. cit.

[3] G. F. F. 26: 180 (Abstract of paper read at the meeting, March 3:d, 1904). See also Rep. British Assoc. 1904, p. 560.

[4] Neues Jahrb. für Min. etc. Beil. Bd. XXIV, 1907, p. 548.

The main outlines of the geology of the field in question have been traced by the previous visitors, and STUTZER's opinion of the origin of the ores is (in the main points) shared by the writer, but my researches gave many new results which necessitate a complete new description of the field.

Professor BÄCKSTRÖM has most kindly put at my disposal his specimens from Ekströmsberg and the thin sections cut from them. This material has been of great service to me, as some prospecting works were inaccessible at the time for my visit. Further, my thanks are due to Mr G. MONTELIUS, who most friendly acted as camp-hand during my stay at Ekströmsberg.

The ore field is in most parts drift-covered, but there are also scattered outcrops, especially along its southwestern border. North of the southeastern end, the country rock is well exposed in a number of small gorges, cut by the drainage of a big ice-dammed lake which occupied the plateau country to the south during the last stages of the great glaciation.

Until 1903, prospecting and developing work was eagerly carried on. A detailed magnetic survey of the field was completed, and a true reading of the results was made possible through the digging of trenches across the strike of the ore bodies at various points. In this way, a fairly good idea of the nature and size of the deposits was obtained. The first geological description was given in 1899 by Dr SVENONIUS,[1] leader of one of the field parties of the Swedish Geological Survey which were engaged in the study of the new-found ore deposits in Lappland. SVENONIUS describes the general outlines of the geology of Ekströmsberg. There appears a number of parallel ore bodies, some of magnetite, some of hematite or locally a mixture of both, alternating with beds of a red porphyry. The occurrence of »skarn»-like

[1] Op. cit.

rocks and of interstratified quartzitic bands is also mentioned. SVENONIUS publishes an analysis of the porphyry (see p. 739). No opinion of the geological history of the field is given and most attention was paid to features of economic interest, the chief object of the expedition. The description is accompanied by a geological map in 1 : 8000 and a map of a part of the field on a larger scale (both compiled by Mr A. O. BERGMAN, M. E.).

The prospecting work at Ekströmberg was continued, and a detailed map was compiled by the late Mr C. ERICSSON, M. E. On this map, the one published by Prof. V. PETERSSON in »Iron ore resources» is based, and also the one accompanying this paper. The next geologist to visit the field was Prof. BÄCKSTRÖM, who spent a week there with Mr ERICSSON in 1903. Only a very brief account of his observations has appeared in print, an abstract of a paper read before Geologiska Föreningen in Stockholm. He regards the porphyries as extrusives, and the ores as pneumatolytical products; a granophyre occurring between the ore beds is described as probably intrusive.

Dr STUTZER, in 1906, during his series of researches on the Lappland iron ore fields also visited Ekströmsberg. In the descriptive part of his paper, the attention paid to the bands (»Ströme») of ore in the porphyries is especially to be noticed. STUTZER shares BÄCKSTRÖM's opinion of the porphyries, but regards the magnetite ores as magmatic surface flows. No definite opinion of the hematite ores is given, but they are possibly, according to this author, submarine pneumatolytical products.

Survey of the geology.

The ore bodies form a system of parallel beds, raised to a nearly vertical position, the dip being about 80° to the southwest. Intimately alternating with the ores appears a porphyry, without quartz phenocrysts but carrying quartz in the groundmass, like the quartz-porphyries of Kiirunavaara-

Luossavaara and Tuolluvaara. It is certainly an extrusive rock. Syenite-porphyries, partly rich in magnetite, occur as narrow bands which are, in most cases, also probably surface flows. The position of exposures in the neighbourhood of the ore field is indicated on the sketch, fig. 1.

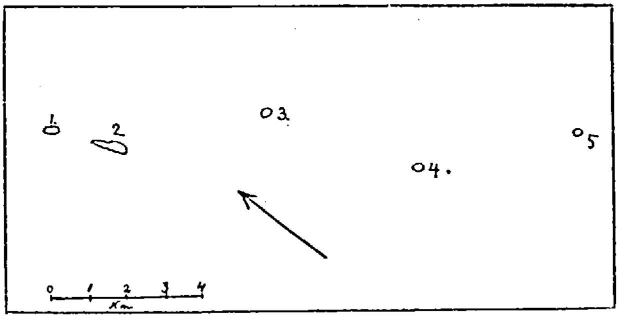

Fig. 1. Position of outcrops in the neighbourhood of Ekströmsberg.
1. Njakak, a hill consisting of magnetite-syenite-porphyry and albite porphyry. 2. Ekströmsberg. 3. Summit of Pidjastjåkko, porphyries similar to those of Ekströmsberg. 4. Skuokimjokk, a continuation of Ekströmsberg. 5. Navetåive, porphyry of the same chemical composition as that of Ekströmsberg.

The main ore body at Ekströmsberg is a magnetite ore more than 1 200 *m* in length. Further there are beds of specular hematite, and magnetite beds of a smaller size, all mainly to the southwest of the main ore. It is a matter of taste how many ore beds one will count, as the porphyry is partly very intimately banded with ore.

On the northeastern side of the main ore there is a homogeneous porhyry[1] with some bands of syenite-porphyry and, near the ore (at least in the middle of the field) containing streaks of ore and apatite. Between the ore beds, at $y = 200$ to 400, there is a similar porphyry and, within the northeastern portion of this area, a granophyric phase of intrusive origin (Bäckström, op. cit.). The porphyry southwest of the main hematite ore contains large quantities of ore and apatite, occurring as parallel bands of varying width. To the

[1] With »porphyry» is here always understood the quartz-porphyry.

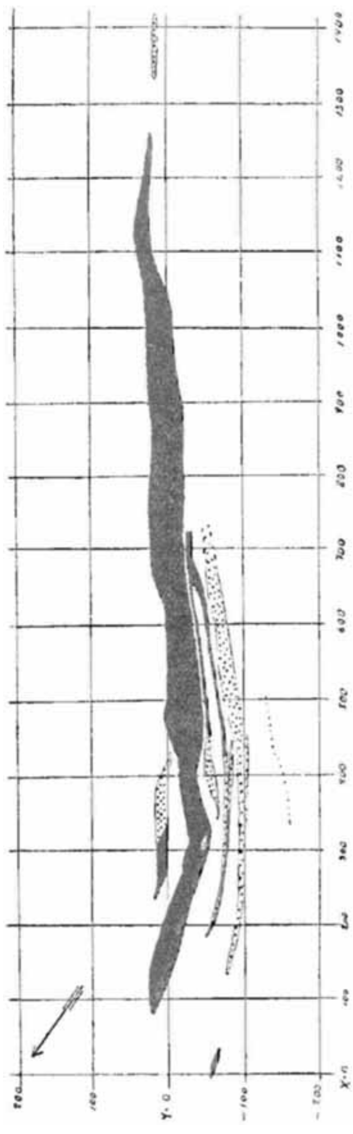

Fig. 2. The ore bodies of Ekströmsberg, from map by C. Ericsson. Scale 1 : 10,000. Magnetite is black, hematite dotted, quartz-porphyry white (the syenite-porphyry bands are too small to be indicated). (The rectangular net marks the coordinate system used at magnetometric measurements etc. at the field, and is used here to facilitate reference to the map.)

southwest, this porphyry is bordered by a new hematite zone, broader than the bands just mentioned, but not attaining the size of the main bed of this ore. Further to the southwest outcrops are very scant and do not reach more than some ten meters across the strike, the porphyry is devoid of ore bands.

Signs of pressure metamorphism are seen everywhere in an evident and sometimes pronounced schistosity.

The quartz-porphyry.

The porphyry exhibits certain variations which make it desirable to give separate descriptions of the varieties characterizing different parts of the field.

The porphyry northeast of the eastern end of the field. Red feldspar phenocrysts, usually 4—6 *mm* in diameter, lie in a dense groundmass of a reddish or reddish gray colour. The groundmass is quantitatively predominant so that the rock is perpatic in the sense of certain American authors. The similarity to the hanging wall rock of Kiirunavaara is striking. The rock seems to be rather homogeneous in composition and structure. The phenocrysts consist of microcline with subordinate perthitic intergrowths of albite, they are thickly tabular or compound, as in the corresponding rock of Kiruna. The groundmass consists of feldspar and quartz, finely distributed iron ore, scattered zircon crystals and aggregates of small titanite grains. The structure is »patchy», the quartz forming sponges about 0,2 *mm* in diameter with irregular outlines against each other. In these sponges, the heavily pigmented red feldspar appears as irregular grains or laths, sometimes partly forming a continuous structure. Nevertheless, it can in many cases be shown that the intergrowth is of a poikilitic nature, while in others a decision would be difficult, were it not for the resemblance to the plainly poikilitic cases. Here is not the place to discuss this structure in detail, it may only be pointed out that it is entirely the same structure which is so common in the similar porphyry of the Kiruna district.[1]

In the phenocrysts, new-formed muscovite and small tourmaline prisms are sometimes seen, evidently the results of a pneumatolytic after-action (»auto-pneumatolysis» of LACROIX[2]). Pressure phenomena are always visible, but vary greatly in force: sometimes the phenocrysts are intact, sometimes they are crushed and rolled out, with new-formed quartz between the fragments. The quartz sponges of the groundmass show strain shadows and become elongated, or are divided into smaller individuals.

The porphyry immediately northeast of the main ore is exposed in one small test pit only, at x = 700, y = 75. It is reddish gray, has smaller phenocrysts than the already described type, and contains numerous parallel bands of apatite and magnetite, usually only some *mm* thick, but sometimes reaching a width of one *dm*. The phenocrysts are even here perthitic microcline, they are gathered in streaks, parallel to the ore bands; some are crushed. The groundmass contains much red pigment, it is patchy with the sponges elongated in the direction of the flow structure, which is otherwise marked by the ore bands and the phenocrysts.

The rock area at x = 200—450; y = 0 to — 25. The northeastern half of the area is a granophyre (compare below), the other is a light red, slightly schistose porphyry with bands of coarsely crystalline blue magnetite. These bands follow, on the whole, the general dip of the series, they cannot be called dikes, as they are lying freely in the porphyry, with a length that is often only a few times the width. This latter reaches several *dm* in some cases. There are also smaller stripes, with much apatite, titanite and hornblende.

[1] This structure will be fully described in another paper, now in preparation.

[2] A. LACROIX: Étude minéralogique des produits silicatés de l'éruption du Vésuve (avril 1906). Nouvelles Archives du Muséum, 4. Série, T. IX, Paris 1907.

The composition of the rock is the same as at the precedent localities. The phenocrysts are often crushed, the groundmass shows stripes of new-formed quartz.

The porphyry between the main ore and the largest hematite bed. In this area, the porphyry forms several beds of moderate thickness, alternating with ore. The phenocrysts are small, the groundmass has a deep red colour. A very pronounced fluidal structure, parallel to the strike and dip of the series, is produced by innumerable streaks and bands of apatite-magnetite or pure magnetite, varying in width from a fraction of a *mm* up to 1 *cm*. This banding with white and bluish-black streaks is very conspicuous. It is undoubtedly a fluidal structure of primary origin, although somewhat accentuated through later pressure. In some places there appear bands up to 1 *m* in width, of a grayish or bluish-white quartzite.[1] The microscopic examination reveals a quartz mosaic with magnetite and some apatite. Everything suggests a silicification of apatite-magnetite bands as the origin of this quartzite.

Under the microscope, the banded porphyry is very similar to that occurring immediately northeast of the main ore. The phenocrysts are microcline with perthitic albite patches and are generally somewhat damaged, the fragments being cemented by new-formed microcline, albite, perthite and quartz. The groundmass is fluidal with an indistinct patchy structure and streaks of probably new-formed quartz. Also here, everything points at a primary flow structure, strengthened by pressure metamorphism. In one test pit, the rock has a yellowish white colour caused by much sericite, the phenocrysts are albite with suddenly terminating twin lamellæ, the type called »striped albite» in the Kiruna monograph.

The ore and apatite bands are aggregates of rather coarsely

[1] This rock is evidently the interstratified quartzite mentioned by SVENONIUS.

crystalline magnetite in the porphyry, or more sharply defined bands of apatite, magnetite (idiomorphic), muscovite in shape of crystal plates, orthite rather abundant in irregular grains, some quartz. The intimate connection between these bands and the porphyry shows beyond any doubt that they must be regarded as a kind of schlieren (or »contemporaneous veins»), and not as dikes or veins distinctly younger than their wall rock. The remnants of a patchy structure in the porphyry groundmass make it clear, that the rock must be a massive eruptive and no tuff, consequently the bands cannot be layers.

The porphyry southwest of the largest hematite bed. In a geological respect, this area is the most interesting part of the field. The porphyry itself is megascopically similar to the lastly described type and shows a fluidal alternation of bands of slightly different colour, but the banding with ore and apatite is here of infinitely more importance.

In wide areas, the bands predominate over the porphyry. The whole rock mass becomes pseudostratified through these parallel bands of ore (generally hematite) and more or less pure apatite. The peculiar phenomenon becomes even more accentuated through the fact that some of the larger bands, 3—5 *dm* in width, show a regular banding of a second order, with alternating lines of ore and apatite, like the »stratified ores» of Kiirunavaara and Tuolluvaara. Some bands, however, have a more irregular interior structure, and others do not exhibit the layer-like appearance but form more irregular schlieren.

The phenocrysts consist mostly of the usual perthitic microcline. Within considerable areas, however, the albite content is higher, and some slides show only »striped» albite. The latter do not seem to represent a separate flow but to cohere with phases richer in potash. Signs of crushing are often seen. The groundmass, always drenched with red pigment, winds around the phenocrysts. The patchy structure is common, and the sponges are often (pseudo-?) fluidally arranged. Sometimes this structure is developed only in some parts of the slide, the rest being very fine-grained, probably devitrified. In other cases the groundmass may be called microgranitic, a structure which here probably also results from devitrification. Streaks of new-formed quartz are common.

The ore and apatite bands show the same characters that are already described above. The apatite mostly forms slightly elongated grains, and the structure resembles that

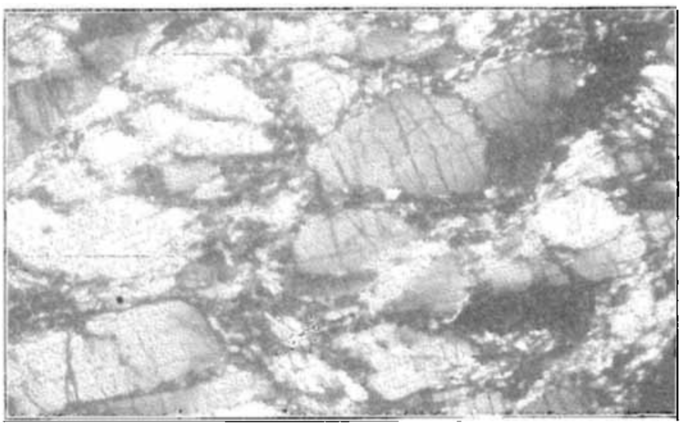

Fig. 3. Crushed apatite rock, showing strain shadows and granulation. Ekströmsberg. Nic. +, magn. 20 diam.[1]

of the apatite masses in the Kiruna ores, or the apatite dikes of that district. STUTZER (op. cit) observed a case of fluidal arrangement of apatite prisms in an apatite band in the porphyry. The present writer has found another phenomenon of considerable interest: an originally coarsely crystalline apatite band showing the effects of mechanical granulation in an uncommonly perfect development. The original size of the apatite grains was from a few to 10 *mm*. The present state is a typical »mortar structure», with

[1] I am indebted to Mr A. HJ. OLSSON for the taking of the microphotographs accompanying this paper.

grains of up to 8 *mm* in size lying in a finely granulated mass. The larger grains show irregular strain shadows and are interwoven by a network of crushing zones, producing every transition from an entirely homogeneous crystal to a finely granular aggregate. Even where the outlines of the separate grains are distinct, their nature of fragments is obvious. The structure sometimes assumes an aspect similar to the trachytoidal flow structure met with in certain apatitic ores of Lappland, but a closer examination reveals considerable and decisive differences. In the mashed apatite rock, the grains do not show the regular prismatic form and, though sometimes subparallely arranged, never form windings and eddies as is frequently seen in the other case.

Orthite is a common mineral in the ore and apatite bands. It always forms irregular grains, sometimes as much as 1 *mm* in diameter. The pleochroism is strong, with brownish red and golden green colours, the birefringence ($\gamma - \alpha$) amounts at least to 0.032, the maximum value given in text-books.

Signs of chemical alteration are frequently observed in the porphyry, evidently caused by volcanic after-action like the silicification of apatite bands already described. Most often, this metamorphism appears as a new-forming of quartz in streaks in the groundmass, together with hematite (crystal plates), feldspars, tourmaline and fluorite. Both the hematite and the green fluorite may be megascopically visible. In a loose boulder, a peculiar phenomenon was found. The rock is made up principally of quartz grains, generally about 0.10—0.15 *mm* in diameter, and with irregular outlines. Much hematite and orthite is also present, concentrated on the boundaries between the separate quartz grains. Some small patches of a fine-grained quartz-feldspar groundmass are visible. It seems highly probable, that this peculiar structure is the result of the silicification of a porphyry with a patchy groundmass, the large primary quartz fields of which determined the orientation of the later on added silica.

The chemical composition of the porphyry.

	I.	II.	III.
SiO_2	69.65	72.92	69.41
Al_2O_3	14.68	13.70	13.92
Fe_2O_3	3.01	0.93	3.33
FeO	1.01	1.10	1.52
MgO	0.32	0.25	0.64
CaO	1.02	0.29	0.89
Na_2O	0.22	0.19	5.59
K_2O	9.25	9.10	3.08
TiO_2	0.44	0.36	0.38
P_2O_5	—	—	0.05
H_2O	0.74	0.69	0.64
	100.34	99.53	99.45

I. »Porphyry from Pidjastjåkko»,[1] SVENONIUS, op. cit. (p. 15).

II. Porphyry from Suppatsch, Stora sjöfallet (*ibid.*).

III. Average of four analyses of the hanging-wall rock of Kiirunavaara-Luossavaara (*Kiruna*, p. 132).[2]

SVENONIUS emphasizes the remarkable likeness between Nos. I and II, especially as compared with the more sodic rocks of Kiruna. No. II does not belong to the iron-bearing region (Suppatsch is situated about 55 *km* southwest of Ekströmsberg) but it is probably closely related to the ore-bearing eruptives. The analyses will be discussed in the following.

The granophyre.

This rock occupies about the northeastern half of the rock area at x = 200—450. It carries phenocrysts of perthite (with a considerable albite content), some few *mm* in size, generally surrounded by a micrographic fringe. Quartz phenocrysts are wanting. The groundmass consists of perthite and quartz, in a slightly complicated intergrowth.

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[1] This name is sometimes used also for the ore field. The analyzed rock certainly comes from Ekströmsberg.

[2] See foot-note n:o 1, p. 727.

The granophyre consequently has the same composition as the predominant porphyry. On account of the great megascopical resemblance of the two rocks, the actual contact between them is difficult to trace. It is, nevertheless, quite obvious that the granophyre, as already explained by BÄCKSTRÖM, is a magma rest which contrary to the main mass has solidified as an intrusive.

The syenite-porphyries.

These rocks are confined to certain parts of the field and form narrow bands running parallel to the strike of the quartz-porphyry.

Northeast of the main ore. In the porphyry north of the eastern end of the field I found two bands of dark greenish gray, schistose rock, running in the general direction of strike about 10 *m* apart. Each band does not reach much more than 1 *m* in width. The rock in one of them consists mainly of an acid oligoclase in broad laths 0.15—0.20 *mm* in length, together with a network of probably new-formed biotite and some magnetite and apatite. The rock of the other band is of a rather different character. It carries so much magnetite as to justify the name magnetite-syenite-porphyry, with small highly corroded feldspar phenocrysts, in a groundmass of albite and magnetite. The albite shows a fine lamination. The slide shows narrow crushing zones, and streaks of new-formed quartz and micas. Between these, however, the primary structure of the rock is well preserved. It is the most common one of the magnetite-syenite-porphyry: small and narrow feldspar laths with the magnetite squeezed in between them. All the primary characters of the rock are very similar to those of the porphyry of the neighbouring hill Njakak (see fig. 1, and the next section of this paper).

At $x = 1\,300—1\,400$. The small hematite area to the east of the main ore is exposed in two small test pits only, both showing narrow hematite bands in a brownish gray, highly schistose porphyry. The microscopic examination reveals a rock differing from the just described magnetite-syenite-porphyry only in a little lower magnetite content and a higher degree of pressure metamorphism.

In the main hematite ore. At x = 525, y = — 80, there is exposed a band of syenite-porphyry in the middle of the main hematite ore, with contact approximately parallel to the strike of the ore body. Its width is about 2 *m*. The rock consists of an oligoclase-albite (about Ab_{90} An_{10}) in narrow laths 0.06—0.10 *mm* long. Between them lie small crystal aggregates of magnetite, and there is also some new-formed biotite. The rock exhibits a very beautiful trachytoidal flow structure.

The ores.

At Ekströmsberg, both magnetite and specular hematite appear as ore minerals. The main ore bed consists of magnetite locally mixed with hematite, especially at the southeastern end, where the oxide enters in a considerable quantity. The smaller magnetite beds are rather similar in this respect. The largest hematite bed is very low in magnetite.

The most important gangue mineral — practically the only primary one — is apatite, which occurs in varying, though never very great quantities.

The following analytical figures are taken from PETERSSON's report in »Iron ore resources».

Two complete analyses on magnetite ore have been made:

	I.	II.
Fe_2O_3	4.83	4.09
Fe_3O_4	82.28	80.12
MnO	0.18	0.35
CaO	3.84	4.68
MgO	0.50	0.73
Al_2O_3	0.61	0.88
SiO_2	5.33	4.21

	I.	II.
P_2O_5	2.52	3.46
TiO_2	n. d.	0.17
S	0.06	0.03
	99.56	98.62

About hundred general samples show the following figures:

	Main magnetite ore.	Main hematite ore.	Other ores.
Iron	58.43—68.68	54.60—65.94	56.71—67.85
» , average	64.10	61.07	63.15
Phosphorus	0.280—2.42	0.792—2.336	0.238—1.842
» , average	1.27	1.46	1.094

Sulphur varies from 0.03 to 0.07 per cent, TiO_2 from 0.17 to 0.56.

Magnetite ore. The qualities of this ore being somewhat different in the various larger exposed areas, each one of these requires a separate description.

In the area about x = 270—310, y = —30 to —50, the magnetite is rather much mixed with hematite. Its apatite content is high, the mineral mostly appearing as bands or streaks, usually following the general direction of strike. The largest band reaches a width of 15 *cm* and a length of 3 *m.* Ore varieties with different apatite content alternate in an irregular, schlieric manner, distinctly appearing on weathered surfaces. Skeleton forms of the magnetite are locally observed, but this interesting structure does not reach the regularity found in certain parts of Kiirunavaara, especially at Bergmästaren. Streaks of light green, fibrous hornblende also occur.

Also around x = 500, y = 0 to — 50, the finely crystalline ore carries much apatite. A variety consisting of magnetite with much apatite evenly distributed forms regular bands, or anastomosing or forking schlieren, in ore low in apatite. Some stripes consist of a fine-grained mixture of apatite and quartz. There are also more coarsely crystalline streaks with well developed apatite crystals. STUTZER (op. cit.) has already called attention to the fact that this structure is common at Ekströmsberg, but very rare at Kiruna. All parallel structures follow approximately the general direction of strike.

At x = 690, y = 0, the ore is similar to the lastly described exposure. At x = 980, y = 20 to — 20 the ore does not carry much megascopically visible apatite. Hematite occurs in narrow bands and more or less mingled with the magnetite, also as crystal plates in small fissures, as on Kiirunavaara.

Under the microscope, small crystals of zircon are sometimes observed in the ore. Quartz is common, in aggregates of small grains. There can hardly be any doubt as to its secondary nature. One finds, for instance, varieties made up of magnetite and quartz, entirely corresponding to the abovementioned silicified apatite bands in the porphyry. Like the secondary quartz in the porphyry, this one also shows strain shadows and granulation.

The contact of the main magnetite ore body with the porphyry is well exposed near x = 275, y = — 30. Towards the northeastern contact, the ore becomes rich in green fibrous hornblende in streaks and lumps, enclosing both magnetite and apatite. The hornblende felt partly carries abundant titanite. The microscopical examination shows the following mineral constituents of the »skarn»: hornblende, magnetite. apatite, titanite, biotite, quartz, calcite. The titanite forms idiomorphic crystals of widely varying size. Here and there, small patches of porphyry groundmass appear in the slides. Thus this »skarn» is entirely analogous to that of Kiirunavaara, both in its mode of occurrence and in its composition. Especially noteworthy in both cases is the abundance of titanite, and the fact that the »skarn» replaces porphyry.

At x = 515, y = — 50, in a prospecting trench, an ore variety somewhat similar to the »skarn» forms a band about 10 *m* wide, bordered by porphyry on both sides. It consists of magnetite, apatite, quartz and hornblende.

Hematite ore. The ore in the main hematite ore body can be considered as typical of the oxide ore of the field. This ore body is well exposed, forming a long, low outcrop. It shows a very pronounced jointing, the predominant system following the general directions of strike and dip. On a weathered surface, the ore has a coke-like aspect. It is often undistinctly stratified with narrow, very short layers of ore with a different content of apatite. Narrow stripes of pure apatite are sometimes seen, and similar stripes of reddish quartz. Over wide areas, however, the ore is entirely massive. A drusy structure is very common, the cavities being lined with small hematite crystals and further partly filled with reddish quartz in rounded grains. Under the microscope, this quartz sometimes shows a peculiar wavy extinction, quite distinct from the usual strain shadows and probably caused by a primary radial structure.[1] It is probably of hydrothermal origin.

Exposures in the neighbourhood of Ekströmsberg. (See fig. 1, p. 731).

The magnetite-syenite-porphyry and associated rocks of Njakak will be described in another section of this paper, in this connection only their similarity to some of the syenitic rocks of the ore field ought to be emphasized. The three other groups of outcrops shown in fig. 1, the summit of Pidjastjåkko, Skuokimjokk and Navetåive, have that in common, that their rocks are closely akin to the quartz-porphyry of Ekströmsberg. At the summit of Pidjastjåkko two or three

[1] Compare MICHEL-LÉVY and MUNIER-CHALMAS: Mémoire sur diverses formes affectées par le réseau élémentaire du quartz (Bull. Soc. Franc. de Minéralogie 1892, p. 159), and LINDGREN and RANSOME: Geology and gold deposits of the Cripple Creek district, Colorado (U. S. Geol. Survey, Prof. Paper No 54, p. 179).

knobs of solid rock, surrounded by blocks broken off by the frost, break the monotony of the drift-covered country. They are very distinctly visible even from Kiruna. These outcrops, the next ones in an easterly direction from Ekströmsberg, consist of a porphyry with numerous big feldspar phenocrysts in a dense, grayish red or sometimes nearly black groundmass. The examination of three slides has shown, that the phenocrysts consist of »striped» albite with subordinate perthitic laths of potash feldspar. Two slides contain large, strongly crushed quartz grains, which may have been phenocrysts, but more probably amygdules. Notwithstanding the high degree of crushing that has befallen these rocks, a sphærulitic structure is well preserved in some parts of the groundmass. The third slide shows no large quartz grains, its feldspar phenocrysts show a high degree of idiomorphism. The groundmass is extremely fine-grained and rather rich in magnetite. The latter is unevenly distributed, the groundmass consisting of small rounded patches without magnetite, separated from each other by a mass rich in this mineral. There can be no doubt that this groundmass originally solidified as glass. The rock is strikingly similar to one phase of the Kiruna quartz-porphyry (specimen from near the church, Kiruna).

Skuokimjokk was not visited by the present writer. According to SVENONIUS (op. cit.) there are small exposures of a schistose porphyry with narrow hematite beds. It may be called a continuation of Ekströmsberg.

In the collections of the Geological Survey of Sweden there is a slide labelled »500 *m* west of the summit, Navetâive». The rock has phenocrysts of albite surrounded by sphærulitic growths, and similar sphærulites make up a good deal of the groundmass, while the rest shows the intergrowth of quartz and feldspar characterized as »reticulating quartz».[1]

[1] This structure will be further described in another paper now in preparation.

The geological history of the district.

The first question presenting itself is this: is the quartz-porphyry an extrusive or an intrusive rock? The two authors who have hitherto uttered any opinion on that matter quite agree with one another: BÄCKSTRÖM calls the rocks effusive beds (but points out the abscence of pyroclastics), STUTZER is of the same opinion, being especially impressed by the pronounced flow structure. As the present writer also shares this opinion, no discussion is required here.[1]

The effusive origin of the Ekströmsberg porphyries is of a very great importance for the interpretation of the geology of another ore field, namely Kiirunavaara-Luossavaara. BÄCKSTRÖM and LUNDBOHM[2] considered the porphyries of this district as surface eruptives, an opinion that has been shared by DE LAUNAY,[3] while STUTZER[4] regards them as »Gangporphyre». From a consideration of all facts in the case, the present writer became pretty well convinced of the truth of the »effusive» interpretation, a detailed discussion being given in the Kiruna monograph. At Ekströmsberg, I have got unexpected proofs of the correctness of this view. As already emphasized, the structure of the Ekströmsberg quartz-porphyry is practically the same as that of the chemically similar rock of Kiruna, although there appear, of course, in the one field certain phases that do not have exact correspondance in the other. As the structure of chemically similar rocks depends only on the rate of cooling, this factor must

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[1] In the literature concerning Ekströmsberg, there are some vague remarks about the existence of transitions between the porphyries and » a granite-like rock». It is impossible to understand whence this idea has come. There are outcrops of granite to the east of Pidjastjåkko (SVENONIUS op. cit.), but this granite stands in no direct relation to the porphyries of the ore-bearing zone.

[2] G. F. F. 20: 68.

[3] L'origine et les charactères des gisements de fer scandinaves. Annales des Mines, 1903.

[4] op. cit.

have been nearly the same at Kiruna as at Ekströmsberg. As the extrusive nature of the Ekströmsberg porphyry is universally recognized, it follows as a corollary that also the quartz-porphyry of Kiirunavaara-Luossavaara must be regarded as a surface eruptive.

At the typical ore fields of Lappland one finds, closely associated with the ore, syenite-porphyry or quartz-porphyry or both these rocks. The syenite-porphyry has a silica percentage of 55—60, otherwise its composition may vary considerably, while the quartzporphyry, with about 70 per cent silica, is essentially an alkalifeldspar-quartz rock with some magnetite, carrying phenocrysts of feldspar but not of quartz. At Kiruna, the main ores lie between syenite-porpyry and quartz-porphyry beds of about the same order of magnitude. At Tuolluvaara, the country rock is quartz-porphyry, syenite-porphyry being present only as very subordinate dikes, while at Mertainen, where the mode of occurrence of the ore rather much reminds of Tuolluvaara, only syenite-porphyry occurs.

The proportion between the two rock types at Ekströmsberg is about the same as at Tuolluvaara. Unfortunately, the mode of eruption of the syenite-porphyries cannot be satisfactorily determined. It is sure, that they are older than the folding that has raised the series to a nearly vertical position, but it remains to find out whether they are interstratified surface flows or later intrusions in the series of quartz-porphyry beds. The first described syenite rock can hardly be interpreted otherwise than as an intrusive, its structure being too coarse for a surface flow of such a small thickness, also the band in the main hematite bed is probably intrusive, while the other bands perhaps are lava flows. The latter are apparently to be regarded as outliers of the syenitic rocks of Njakak, while the quartz-porphyry of the ore field forms the northwesternmost exposed part of a series of such flows extending in a southeasterly direction at least to Navetåive.

The late- or post-volcanic thermal action has been of the same nature at Ekströmsberg as at Kiruna, but of much less intensity. Its most important form is the silicification, but there is also to be noted the frequent developing of specular hematite, orthite, sericite, and locally tourmaline and fluorite. The infrequent calcite probably also belongs to this set.[1]

The origin of the ores.

This problem has been discussed by BÄCKSTRÖM and by STUTZER. The former expresses the same views as concerning Kiruna and Mertainen, namely that the ores have been formed through a pneumatolytic after-action in connection with the eruption of the surrounding volcanics, while the latter considers the magnetite to be an extrusive bed, contemporaneous with the porphyry, as to arguments for its magmatic nature he refers the read er to his detailed discussion of Kiruna. A sedimentary origin is, according to him, impossible also for the quartziferous beds) quartz-magnetiterocks) and for the analogous hornblende-bearing bed, as they show fluidal structures. He expresses no definite opinion regarding the hematite ores, but they might perhaps be pneumatolytic, if the eruptions were submarine. To the present writer, the magmatic nature of the magnetite ore seems certain, because of the analogies with Kiruna and the close connection with the porphyry. As the quartziferous beds, as stated above, most probably are nothing else than highly silicified magnetite beds, originally rich in apatite, and secondary quartz occurs also in the main ore, the whole difference lies in the degree of secondary alteration — consequently the quartziferous beds have the same origin as the main ore.

The hematite beds offer a more complicated problem. Com-

[1] STUTZER considers it an original constituent of the porphyry. »Im Schliff fand sich weiter Calcit, der neben unzersetzten Mikroperthiten auftrat. Er dürfte hier nicht als sekundäres sondern als primäres Produkt gedeutet werden, also magmatisch sein» (op. cit. p. 613). The proof referred to, the unaltered state of adjacent feldspars, seems a very weak footing for the daring idea of calcite as a primary constituent in an extrusive quartz-bearing rock.

paring the ore of the main magnetite bed and typical hematite ore, one finds distinct differences, and all attempts to find proofs of a secondary (martitic) origin of the latter have been in vain. On the other hand, there is often found a mixture of the two minerals, and the ore bands in the porphyry consist now of magnetite, now of hematite, indicating no very great difference in the conditions at their forming. When I came to Ekströmsberg, I expected to find the hematite beds to be, with regard to their origin, in broad lines analogous to the hematite ores of the Kiruna district (Hauki complex) regarded by me as products of late- or post-volcanic pneumatolytic action, as suggested with regard to the Ekströmsberg ores by BÄCKSTRÖM and also, though with reservation, for the hematites by STUTZER. However, I found it impossible to maintain this idea. The main hematite bed at its eastern end splits up into a number of ore stripes with porphyry between, and the more narrow bed further to the south shows a similar ending towards the west. Considering also, that the ore bands in the »banded porphyry» between these two beds mostly consist of hematite (while in other parts of the field generally of magnetite), one must admit that the hematite ores are quite as closely associated with the porphyry as are the magnetite beds. There are many factors at a surface eruption (perhaps even submarine!) that may cause the iron compounds to crystallize now as magnetite, now as hematite. From the technical handling of iron ores many examples in this respect can be gathered.

The very intimate association between ore and porphyry gives sufficient proofs for the igneous origin of the former. The masses of ore and apatite must have been segregated prior to extrusion, forming bodies of the most varying size, and have been rolled out through fluidal movements.

Some details deserve special attention. The *hornblende »skarn»* occurs in entirely the same way at Ekströmsberg as at Kiirunavaara and the similarity in mineralogical composition is striking, the high titanite content being especially noteworthy. This mineral's abundance in the contact rock is quite agreeing with its mode of occurrence within the ores (Luossavaara) where it chiefly is found in druses. Like the tourmaline, which is found at some points on Kiirunavaara (*Kiruna*, pp. 104 and 115), the titanite evidently avoids the ore bodies proper, its formation taking place through reactions of the kind commonly classed as pneumatolytic. For the Kiruna district, I have pointed out this fact and its accordance with the rôle of the titanite in the silicate rocks of the tract, and it is now very interesting to find it to hold true also at Ekströmsberg.

Another interesting feature is the occurrence of the orthite. It is rather common in the apatite-ore-bands in the porphyry, with all probability as a primary constituent, and further occurs in the rocks in a way that makes it highly probably that it has been formed secondarily, during the silicification. In the Kiruna district, I have found the orthite in various kinds of rocks. The microscopical examination shows a few scattered grains in the porphyries and the Kiirunavaara ore body, while it is a little more common in the apatite dikes or their immediate wall rocks. Megascopically visible, sometimes in crystals several *cm* long, the orthite is very common in the mainly of quartz and ankerite consisting veins that were formed through the thermal after-action of the quartz-porphyry, and it is also common, though only in grains of microscopical size, in the quartzitic hematite ores resulting from the same after-action (*Kiruna*, e. g. pp. 153, 183, 189). Further I have found it in microscopical quartz veinlets in porphyry from the Painirova ore field (together with tourmaline) as small scattered grains in the Svappavaara ore and abundant in the feldspar nodules of the magnetite-syenite-porphyry of Njakak (see the next section of this paper). In all these cases, crystal outlines are generally lacking, except in the quartz-ankerite-veins of Kiruna. The common twinning of the orthite is often observed, but no zonal structure. The pleochroism is always strong, in reddish brown and golden green colours, the birefringence very high, amounting to 0.032. This widespread occurrence of the orthite in the ore-bearing igneous formation is in itself an interesting fact, but its paragenetical relations are especially noteworthy. In accordance with its behaviour in other magmas, for instance in granite, it is concentrated in the last crystallizing part of the magma, being most common in the products of the after-action. Its occurrence in the apatite-ore-segregations at Ekströmsberg is therefore interesting, as it is in favour of the working hypothesis proposed by the present writer for the origin of the Lappland ores (*Kiruna*, pp. 264—273). The occurrence of the orthite is a feeble argument alone, but it is one of the many facts in advance of this hypothesis.

The chemical character of the porphyry.

Reference has already been made to the unusual chemical character of the Ekströmsberg porphyry, and its similarity to a porphyry from Suppatsch. SVENONIUS points out the striking resemblance between these two analyses, and their contrast to the sodic rocks of the Kiruna district: there exist perhaps two zones or provinces, an easterly one with prevalent sodium, and a western one with potassium, but SVENONIUS also remarks that the material is too scanty to allow any definite conclusions in this respect. Later analyses (the average of the quartz-porphyry analyses is given on p. 739) have shown that the relation between the alkalis in the Kiruna rocks is more varying than supposed, though sodium is generally predominant. Turning to the Ekströmsberg porphyry, it will be found that none of the numerous specimens collected by Prof. BÄCKSTRÖM and by myself corresponds to the analysis, as considerable quantities of albite are visible even in those cases where the potash feldspar predominates. When I examined the slide of the analyzed rock, however, I found a type with no visible albite,[1] but otherwise quite similar to my own material. It therefore seems, as if by a peculiar chance the specimen selected for analysis should represent an exceptional case, the main mass of the rock being of a composition rather similar to that of the Kiruna quartz-porphyry, though with somewhat more potash.

II.

New data on magnetite-syenite-porphyries.

The name magnetite-syenite-porphyry was introduced (*Kiruna*, pp. 58, 234—235) to comprise »rocks consisting of alkali-feldspar (with only a very small proportion of anorthite) and of magnetite in a great quantity», other minerals being present in insignificant amounts only. The scope was made wider than the qualities of the examined type rock necessitated (this being pre-eminently a sodic rock) as it was deemed convenient to wait for more knowledge concerning this peculiar magma before introducing a too narrow definition. It was shown that rocks of this kind appear as subordinate schlieren in the syenite-porphyries of Kiirunavaara, and as bodies of geological importance north of Luossavaara; in both cases the magnetite-syenite-porphyry is only a differentiation phase of the normal syenite-porphyries, connected with them by transitional forms. Further, attention was called to the occurrence of related rocks in other parts of the iron region of Lappland, especially to SUNDIUS' find of pebbles in the Kurravaara conglomerate, representing many highly interesting types, and to certain rocks from Malmberget (Gellivare) examined by HÖGBOM; finally the close resemblance to a fragmental rock from Ural was emphasized.

New data are now available, and make it possible to get a better idea of the rôle of the magnetite-syenite-porphyry in

[1] It must be remembered that only the phenocrysts, not the feldspars of the groundmass, can be determined.

the differentiation processes in the rock magmas of the iron-bearing region. The pebbles in the Kurravaara conglomerate have now been studied in detail by SUNDIUS. As his treatise appears in this journal, and probably is at the disposal of every reader of this paper, I need not give any review of it now, but reference will later be made to some of the more important of his results. During my stay at Ekströmsberg in 1910, I was lucky enough to find in the neighbourhood of this ore field a new occurrence of magnetite-syenite-porphyry, forming the Njakak hill (se fig. 1, p. 731) about 1.3 *km* distant from the northwestern end of the Ekströmsberg field. Further, as already described, small bodies of this rock appear inter-stradified in the quartz-porphyries of this ore field.

Although modelled on a larger scale, Njakak rather much resembles Hopukka near Kiruna, which also mainly consists of rocks of a magnetite-syenitic character. It forms a ridge in a W—E direction, about 1 or 1.5 *km* long, and the western end shows gentle slopes in all directions and is connected with adjacent hillocks, but at the eastern, higher one it forms a more marked ridge, rising at least 100 *m* above the surrounding more level country, with an especially bold precipice towards the south. Seen from the east, as from the trail leading from the Kalix river to Ekströmsberg, it presents a peculiar sugar-loaf-like outline, very much different from that of the mountains in this tract in general. All gentler slopes are covered with a continous drift mantle, but the steep sides show good exposures. Natural outcrops are, therefore, limited to the eastern end, but a little further westward there are some small pits dug when, in the nineties, the magnetic properties of the magnetite-rich rocks inspired prospectors with vain hopes.[1] The southern side consists of dark magnetite-syenite-porphyry and pink-coloured syenite-porphyry, the latter occupying its eastern end. The same rocks are found on the

[1] Njakak is often mentioned among the small »ore fields» without economic value, but its geological nature has never been described.

northern side, but here the limit is more to the west, indicating that the boundary plane between the two rocks has a northwesterly trend. The boundary is not sharp, having the character of a »differentiation contact» zone; it has a vertical position.

The magnetite-syenite-porphyry has a dense, very dark bluish gray groundmass and scattered small red feldspar phenocrysts, further it carries red feldspar nodules, which are compact or not seldom drusy, sometimes abundant, but in other phases rare. These nodules are generally regularly rounded, circular or elliptical in cross-section, from a few up to 10 *mm* in size, and often fluidally arranged. Besides the feldspar, magnetite, chalcopyrite and pyrite enter as constituents, sometimes also quartz (in drusy nodules); the sulphides are also often found on fissures. Narrow strings of red feldspar, apparently related to the nodules, are common.

The pink-coloured porphyry carries feldspar phenocrysts in a fine-grained groundmass, its nodules consist of feldspar and quartz. This rock, as already mentioned, occupies the eastern end of the ridge, but it also forms subordinated schlieren in the magnetite-syenite-porphyry. Rocks with an intermediate magnetite content are more rare. They usually have a grayish red colour and are connected with the magnetite-syenite-porphyry through gradual transitions. Also between the latter and the pink rock there is no real difference in age, as one never sees sharp contacts between them, but always a gradual transition, although often a very rapid one. The relation seems to be that of a basic phase (the magnetite-syenite-porphyry) to a more salic phase of the same rock. Within the border zone, one observes schlieren of magnetite-syenite-porphyry, a few *dm* long, in the pink porphyry, but within the part of the mountain occupied by the former rock, the latter is found only as »dike schlieren», often vaguely defined and usually not more than a few *cm* wide. This close connection of (subordinate) alkali-feldspar rock with the magnetite-syenite-porphyry was also noted in the Kiruna district (*Kiruna*, p. 62—63).

The microscopical examination of the typical magnetite-syenite-porphyry shows the small and rare feldspar phenocrysts to be in some cases orthoclase, in others »striped» albite. The shape is always very irregular due to corrosion. A black pigment (magnetite?) is very common, especially in the marginal portions. The chief constituents of the groundmass are feldspar and magnetite, further there is rather much titanite (in small grains) and apatite. The feldspars are always lath-shaped, usually 0.060—0.075 by 0.008—0.015 *mm*. Albite la-

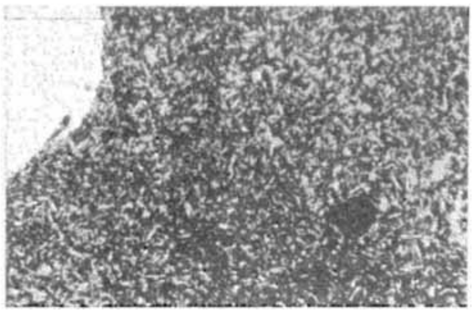

Fig. 4. Magnetite-syenite-porphyry, Njakak.
Ord. light, magn. 20 diam. Feldspar nodule (in the corner) and magnetite-feldspar groundmass.

mination is often visible. The index of refraction indicates oligoclase-albite. Irregular perthitic spots of potash feldspar can sometimes be discerned. The laths are sometimes trachytoidally arranged, or form sheaf-like groups. Between these feldspars, which in ordinary light appear as sharply defined white rectangles, lies a mass consisting mainly of magnetite but also containing some feldspar material. Similar phases occur also at Kiruna, but there the separation has often been carried on so that the rectangular feldspars lie in a mass of magnetite only. The magnetite content of the Njakak rocks is irregularly varying, it may be estimated to 25—35 per cent of weight in the magnetite-syenite-porphyry proper.

The nodules are very well defined against the surrounding groundmass and consist mainly of feldspars, 0.2—0.6 *mm* in size. The feldspar is partly »striped» albite with or without intergrown microcline, partly potash feldspar with perthitic laths of albite. Magnetite sometimes appears as crystalline aggregates. Irregular grains of orthite are common, they are not much inferior in size to the feldspars and usually occupy the outer portions of the nodule or lie in the groundmass

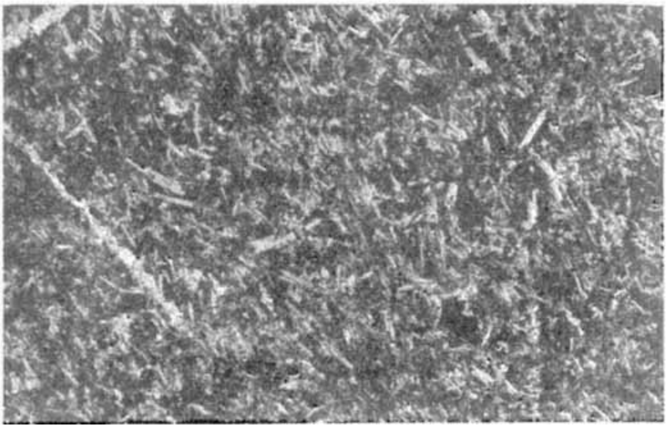

Fig. 5. Magnetite-syenite-porphyry, Njakak.
Ord. light, magn. 20 diam. Groundmass of feldspar and magnetite.

just outside of it, as does often the apatite in the nodule-bearing rocks of Kiruna. It shows the usual optical properties of the orthite in the ore-bearing rocks of Lappland (compare p. 751). Finally there is some quartz in small grains, and pale brown biotite. The red strings do not directly cohere with the nodules, contrary to the relations of similar bodies in the magnetite-syenite-porphyries of Kiruna, they seem to be a little younger. They consist of albite, microcline, quartz and some apatite; the individuals of feldspar and quartz usually stand perpendicularly to the plane of the string.

A slide of pink-coloured porphyry, from the eastern end of the ridge, shows a rock consisting of »striped» albite, in slightly elongated grains 0.10—0.20 *mm* in size, with irregular outlines. There is further rather much titanite in small grains, some apatite, a few small grains of magnetite, and finally much calcite, partly as veinlets. The nodules consist of albite and quartz and are connected with the surrounding groundmass in a way that suggests secondary enlargement of the nodule minerals. The quartz shows strong strain shadows, the structure of the groundmass is also best explained by assuming some degree of metamorphism, but through lack of material I cannot decide whether this is only a local phenomenon. A slide of a typical pink-coloured schliere in magnetite-syenite-porphyry shows a rock in all essentials similar to that just described, it carries rather much apatite (at least 3 or 4 per cent).

The transition from magnetite-syenite-porphyry to a reddish gray schliere was also examined. The transitional zone is only a few *mm* wide, but nevertheless there is a gradual transition (»differentiation contact»), and no sharp boundary. With diminishing content of magnetite, this mineral is concentrated into fewer and larger crystalline aggregates, the feldspars grow larger and especially broader, and are coloured by a red pigment. This rock is very similar to some porphyry varieties of Hopukka, which are also connected with magnetite-syenite-porphyry, though not so closely as is here the case.

In a chemical respect, the magnetite-syenite-porphyry of Njakak does not materially differ from the corresponding rocks of Kiruna. The only difference lies in the content of potash, which is high especially as compared with the analyzed specimen from Kiruna (compare below). The bulk of the potash feldspar, however, is contained in the nodules, as is also the case in some magnetite-syenitic schlieren of Kiirunavaara.

Of the magnetite-syenite-porphyries of Lappland there are two analyses, viz. of a specimen from the area south of lake Nokutusjärvi, Kiruna district (*Kiruna*, p. 67), and of one from Malmberget, Gellivare.[1] An analysis of the corresponding rock from Wyssokaja Gora, Ural, has been published by LOEWINSON-LESSING.[2]

	I.	II.	III.
SiO_2	45.32	32.83	45.05
Al_2O_3	13.09	9.24	14.30
Fe_2O_3	21.74	35.77	16.93
FeO	7.12	14.84	7.13
MnO	0.04	0.05	n. d.
MgO	0.18	0.47	1.30
CaO	2.19	0.55	2.81
Na_2O	7.51	4.92	6.14
K_2O	0.17	0.86	1.86
H_2O	0.24	0.35	3.49 (Loss at ign.)
P_2O_5	0.32	trace	n. d.
TiO_2	1.15	0.62	n. d.
S	0.02	0.03	n. d.
CO_2	1.26[3]	—	n. d.
	100.35	100.53	99.01

I, Nokutusjärvi, Kiruna; II, Malmberget, Gellivare; III, Wyssokaja, Ural.

It is apparent from the descriptions, that the magnetite-syenite-porphyry of Njakak shares the general characters of the analyzed rocks. The regularity, in the main points, of the magnetite-syenite-porphyry rock type both in chemical composition and in structure, together with its geological relations, characterizes it as a normal link in the series of the ore-bearing rocks and makes it evident, that it has not been formed through some kind of resorption of pre-existing ore bodies by the magma.

[1] A. G. HÖGBOM: The Gellivare Iron Mountain, G. F. F. 32: 561 (also as guide No 4, XI:th internat. geol. congress, Stockholm 1910).

[2] Ann. de l'Inst. Polytechn. de St. Pétersburg V, 1906.

[3] Calcite, mainly in cavities.

The pebbles studied by SUNDIUS carry a practically pure albite. The rocks are somewhat altered, however, and there are, according to SUNDIUS, reasons to suspect that this pure albite is of a secondary origin, the original plagioclase having been of a somewhat more basic character. The important question is whether the content of anorthite in the magnetite-syenite-porphyries increases or decreases with that of iron. The latter seems to be the rule, the analyzed rocks showing plagioclases (calculated from the analyses) of the composition Ab_{98} An_2, Ab_{97} An_3 and Ab_{83} An_{17} respectively. (The rock from Ural is perhaps altered, as it shows a very high loss at ignition.) The optical properties of the plagioclase in the Njakak rock point at a composition somewhere about Ab_{90} An_{10} —Ab_{92} An_8. The average titanium content in the magnetite-syenite-porphyries is not higher than in the normal syenite-porphyries, rather the contrary. The phosphorus content is generally at least as high as in the latter, but astonishingly low in No II.[1] The characteristic feature, however, is the ratio ($FeO+Fe_2O_3$): MgO. In the normal syenite-porphyries it varies from about 4 per cent to 3 up to 15 : 2, and its further variations may be illustrated by the following percentages: Phase of Kiirunavaara syenite 15.21 : 1.96, magnetite-syenite-porphyry of Wyssokaja (III) 24.06 : 1.30, d:o of Nokutusjärvi Kiruna (I) 28.86[2] : 0.18, d:o of Gellivare (II) 50.61 : 0.47.

It is true that there are certain cases (not analyzed) where the MgO content is higher, notably in some peculiar uralite-bearing pebbles described by SUNDIUS, but it is impossible to deny the fact that the differentiation has tended, from the beginning, so separate the iron from the magnesia. In this respect, as well as with regard to the relation of the titanium to the iron, the differentiation producing magnetite-syenite-

[1] It may also be pointed out, that the apatite content is at least as high in the schlieren of albite rock as in the magnetite-syenite-porphyry, with which they are associated.

[2] This figure is a little too high, as the magnetite here is evidently to some extent oxidized to hematite.

porphyry is similar to the one which has produced the apatitic iron ores of Lappland.

ROSENBUSCH, in his »Elemente der Gesteinslehre», points out that in the foyaitic magmas Mg dissappears together with Ca, but in the grano-dioritic magmas with Fe. In the latter case, Fe occurs mainly as ferrous iron, combining with Mg to form silicates, while it in the former case is trivalent and takes the place of Al in silicate molecules. Fe appearing as magnetite seems generally to follow the compounds of Mg, the only case where the differentiation tends, from the beginning, to separate these two elements being when the magnetite becomes concentrated in the pegmatitic mother-liquor, as has been imagined by the present writer regarding the Lappland ores. It seems, therefore, that the magnetite-syenite-porphyry bears the same relation to the mother magma as do these ores, that is, that it has a lower temperature range of crystallization than the normal syenite-porphyries. The composition of the plagioclase already referred to is in favour of this explanation.

The physico-chemical properties of the system albite-magnetite have been studied by LENARČIC[1] and by DAY and ALLEN[2], and it has been shown that even a small percentage of magnetite in the melt very considerably reduces the extreme viscosity of albite, in fact, LENARČIC succeded to obtain crystallized albite in this way. It is possible that this important lowering of the viscosity is caused by an exceptional lowering of the melting-points, but the laws controlling the viscosity of solutions are but little known as yet. According to DŒLTER,[3] the eutectic ratio albite: magnetite is 3:1, a relation that is rather common in the magnetite-syenite-porphyries.[4]

[1] Centralblatt für Min., XXIII, 1903, p. 705.

[2] Isomorphism and thermal properties of the feldspars. Carnegie Inst. of Washington, publ. No. 31.

[3] Physikalish-chemische Mineralogie (Leipzig 1905), p. 133.

[4] This ratio seems to have been obtained from the melting-points of glasses, a method which ought to give at least approximate figures in this respect.

We do not possess much knowledge concerning the differentiation process that leads to the forming of ore deposits from a magnetite-syenite-porphyry, consequently we cannot decide whether this rock really represents a transitional stage between the parent magma and the ore. The ores described by SUNDIUS are known only as pebbles, and their geological relations to the parent rock are therefore practically unknown.

Some cases were found during the survey of the Kiruna district, the most important one being a certain portion of the »Nokutusvaara ore field» (*Kiruna*, p. 187 and 191, and fig. 59).[1] There, the ore — magnetite with much apatite — forms dike-like schlieren of widely varying size and form. It is partly rich in albite, whose relations to the magnetite are those most common in magnetite-syenite-porphyries: the ore mineral, though bounded by its own crystal faces, is squeezed in between the feldspars (*Kiruna*, fig. 59). It is remarkable that the same structure is found in magnetite-feldspar segregations formed by the coalescence of nodules in a Kiirunavaara porphyry (*Kiruna*, p. 37). In some other porphyry varieties of the same mountain, especially rich in apatite and magnetite, we find the same tendency to give off these minerals, in the form of nodules and similar bodies (the extreme inhomogeneity of these rocks makes a short review impossible, compare *Kiruna*, p. 38—41).

The fact that the magnetite in most magnetite-syenite-porphyries has most evidently crystallized *after* the feldspar points the same way: that the differentiation of ore bodies from a magnetite-syenite magma at least generally takes place in the way suggested as the probable explanation for the genesis of the iron ores in general in the Lappland re-

[1] Additional field work on this little exposed area has shown, that the country rock for the most part deserves the name magnetite-syenite-porphyry, carrying up to 30 per cent magnetite or more.

gion, that is, as a part magma with a lower temperature of crystallization.[1]

In striking contrast to these cases of ore differentiation stands the common occurrence of alkali-feldspar — mainly albite — in the same manner, *i. e.* as nodules and as dike-like schlieren which seem to be of a little later consolidation than the magnetite-syenite-porphyry, as for instance at Njakak. While we cannot yet explain these facts, it may be remembered that albite rocks sometimes appear as part magmas with a very low crystallization temperature[2], therefore this phenomenon is not incompatible with the hypothesis that the crystallization of the magnetite-syenite-porphyry took place at a lower temperature than that of a normal syenite-porphyry.

Addendum. This paper was already in press, when the October number of the »Zeitschrift für praktische Geologie» appeared containing W. DIECKMANN's paper »Die geologischen Verhältnisse der Umgebung von Melilla unter besonderer Berücksichtigung der Eisenerzlagerstätten des Gebietes von Beni-Bu-Ifrur im marokkanischen Rif». The ore deposits in question are, according to DIECKMANN andesite varieties with an uncommonly high content of magnetite, the author calls them magnetite-andesites and compares them with the magnetite-syenite-porphyries of Kiruna described by the present writer. Unfortunately the highly altered state of the rocks makes it for the present impossible to fix the bearings of the interesting discovery on the problems discussed above. The plagioclase of the andesites is a very basic variety (bytosonite) but the magnetite-rich rocks represent, according to DIECKMANN, smaller eruptions of a later date than the main masses of the district, a fact that at least makes it possible

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[1] Some sides of the differentiation problem will be treated in a later section of this paper.

[2] Compare for instance V. M. GOLDSCHMIDT: Die Kontaktmetamorphose im Kristianiagebiet (Kristiania 1911), p. 301.

that the phenomena in question in the andesites of Melilla are analogous to those of the alkaline eruptives of Lappland.

III.

Eruptive structures in apatite-magnetite rocks.

The structures of the Lappland ores have furnished several important proofs of their magmatic origin. In the Kiirunavaara ore body, the ophitic distribution of the pyroxene, the skeleton forms often developed by the magnetite and the trachytoidal arrangement of apatite prisms are especially suggestive features. It may be true that the skeleton form of the magnetite, as pointed out by Prof. BERGEAT in a review,[1] in itself is no proof of a magmatic origin, but when there are only two processes to choose between, magmatic crystallization or pneumatolytical sedimentation, this structure seems to point at the first alternative.

I have devoted further attention to the trachytoidal flow structure, having a number of new thin sections cut from the specimen from Geologen, Kiirunavaara, which furnished the slide reproduced in *Kiruna*, p. 110. It has been of a special interest to compare this structure with the effects of mechanical granulation of apatite, which are so well illustrated by the crushed apatite rock from Ekströmsberg, described p. 737. As already pointed out, the latter partly shows characters resembling the trachytoidal rock, but a closer inspection reveals very important differences. There are no sharp boundaries between the grains, they are not so elongated as to justify a parallel arrangement from fluidal movements and, above all, they are never arranged in windings and eddies.

The typical fluidal ore from Geologen consists of variously shaped lumps of crystalline magnetite, from several *cm* in size downwards, and of thin lamellæ of the same mineral,

[1] Die genetische Deutung der nord- und mittelschwedischen Eisenerzlagerstätten in der Litteratur der letzten Jahre. Fortschr. d. Mineralogie, Kristallographie und Petrographie, I, 1912.

embedded in a finely crystalline apatite mass. The apatite prisms are of a practically uniform size, a fact that alone is enough to show that they have not been formed through the crushing of larger grains. Also the shape of smaller apatite patches shows beyond any shade of doubt that the size of these prisms must be an original one. The characteristic feature of this structure is, however, as already mentioned, the frequently whirl-like arrangement of the apatite prisms. This phenomenon is illustrated by fig. 6, showing a typical slide magnified 3 times. The apatite prisms are of too small a

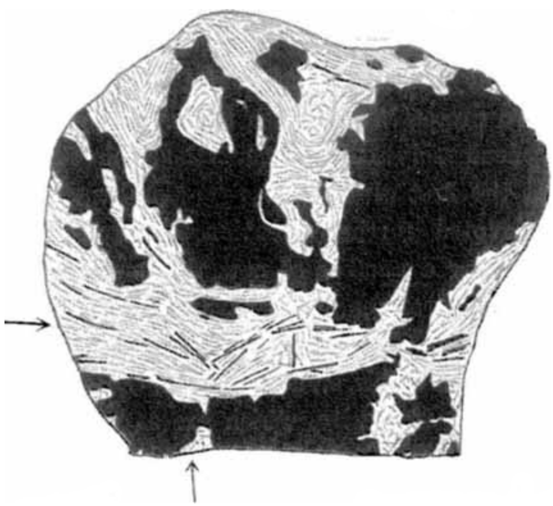

Fig. 6. Slide of *ore with flow structure*, Geologen, Kiirunavaara; magn. 3 times. Black is magnetite, the gray lines indicate the arrangement of the apatite prisms in the various parts of the slide. (See also the text!) The area reproduced in fig. 7 occupies about 14 by 18 *mm* with centre at the point indicated by the two arrows.

size to be shown in this scale but the drawing is meant to show the direction of the flow structure in the different parts of the slide, especially the larger windings. It is at once apparent, that neither granulation nor recrystallization under stress could bring forth structures that are so evidently caused by the hindering influence of the already solid magnetite lumps and lamellæ on the crystallizing apatite mass between them. Fig. 7 shows, on a larger scale, a detail of this flow structure.

A similiar flow structure was also found in an apatite concentration in the so-called Rektor magnetite ore of Luossavaara. In this case, there is no magnetite to cause so marked windings as in the Geologen ore, but the structure is nevertheless a typical trachytoidal one, and the regularity also here excludes the possibility of a secondary origin.

It would of course be of interest to compare the structures

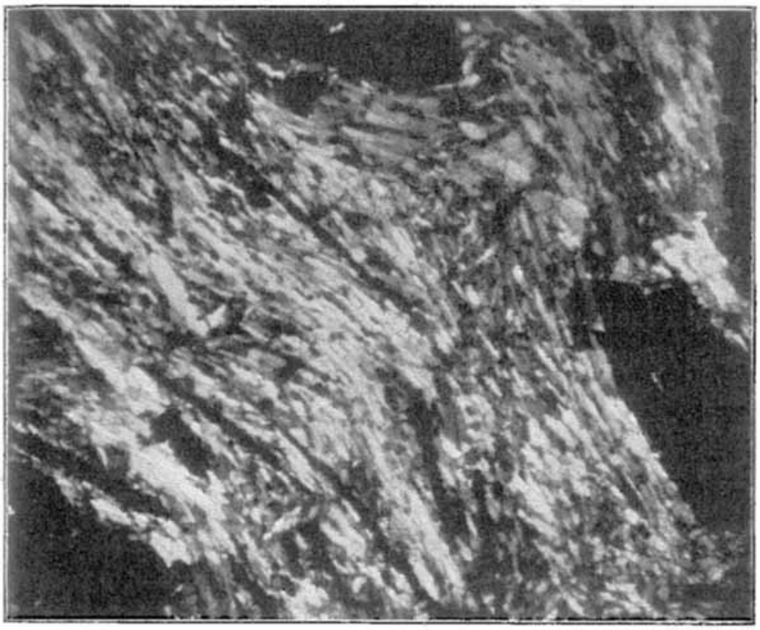

Fig. 7. *Trachytoidal flow structure (apatite)*, same slide as fig. 6. Nic. +, magn. 16 times. Black lumps (near the sides) and laths are magnetite.

of the apatitic iron ores of Lappland with those of other igneous apatite-magnetite rocks. Magmatic ores of this composition, however, are rare, and the only types I have examined are phases of the titaniferous ores in the nepheline-syenite of Alnö, described by Högbom,[1] which represent deep-seated types. Attempts to study the structures developed by

[1] G. F. F. 17: 100.

a more rapid crystallization, by melting ore rich in apatite encountered many difficulties. Lacking the experimental equipment necessary for careful work of this kind, I was only able to obtain some rather insignificant results, which, however, in view of the scarceness of published data of this kind may deserve some attention. I am indebted to Prof. PALMÆR, of the High School of Technics, Stockholm, for permission to use a cryptole resistance furnace and an arc furnace in his laboratory. The high melting-point of apatite[1] combined with the impossibility to regulate the temperature within certain limits, prohibited the use of platinum vessels, and the magnetite's faculty of resorbing many crusible materials (spinel, corundum, MgO) made the work still more difficult. The results were thus practically limited to some experience regarding the crystallization of pure apatite melts.

By very rapid cooling — removing the crucible with the still molten charge from the furnace — the apatite was obtained in a partly glassy state. The crystallization had produced skeleton individuals 0,2—0,4 *mm* in length, hollow hexagonal prisms compact only at the middle. These prisms sometimes show a tendency to trachytoidal arrangement. The forms are such as one would expect at quickly crystallizing apatite, and the strange forms described by HERRMANN[2] from Lausitz granites probably depend on other causes.

With the small arc furnace used there were obtained roughly circular melts 2—4 *cm* in diameter and only 3—4 *mm* thick, below was a sintered crust. The temperature range from somewhere near 2000° down to red glow was passed in about a minute or a little more. Nevertheless, the melts crystallized as a mass of compact apatite prisms, up to several *mm*

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[1] Although I have made only a few and very uncertain temperature measurements, I feel convinced that the fluorine apatite from Kiirunavaara, which I used, does not melt below 1550° the figure given by BRUN (Recherches sur l'exhalaison volcanic, p. 33) as the melting-point of apatite. Figures of 1300—1350° are certainly too low.

[2] Krystallskelette von Apatit, N. Jahrb. f. Min. etc. 1893 II p. 52.

in length. In the very surface of the melt, the crystals generally lie in the surface plane, but deeper down they lie at random or tend to stand at right angles to the cooling surface (compare fig. 8). These experiments thus show a great rapidity of crystallization of the apatite. In the main lines, both as regards form and arrangement of the apatite grains, the structures obtained in this way are rather closely similar to some structures of the apatite concentrations in the Kiiru-

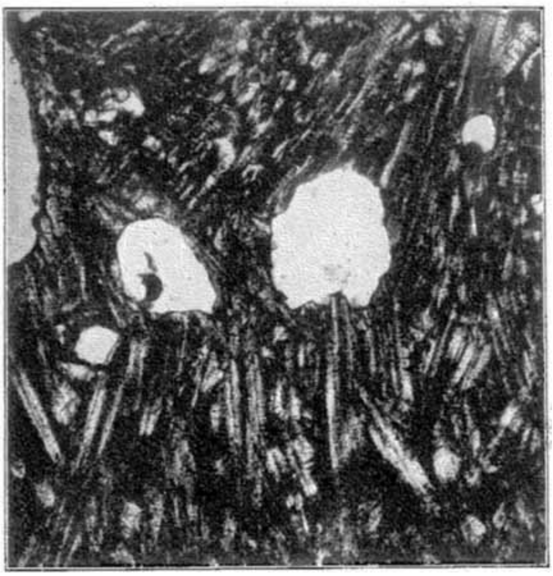

Fig. 8. Melt of *apatite and magnetite*. Ord. light, magn. 32 times. Section at right angles to the upper surface of the melt, which is 1—2 *cm* above the upper edge of the figure. The apatite prisms enclose crystal skeletons of magnetite (see the text). The white spots are steam cavities.

navaara ore, while the latter in other cases are so to say intermediate between the synthetical products and the deep-seated ores of Alnö. Radial grouping of the prisms is often seen in the melts. Magnetite crystallizes as regular skeletons, the bars being respectively parallel and perpendicular to the longer axis of the enclosing apatite prisms (fig. 8).

The typical iron ore of Alnö (Högbom's type VI) according to Högbom consists of about 49 per cent (weight) titanomagnetite, 42 per cent apatite, 5 per cent pyroxene, and some pyrites and calcite. Another type (VII) carries less magnetite, but a great quantity of olivine and some biotite instead of the pyroxene. The rocks are rather inhomogeneous.

Both types are mottled, the apatite being partly gathered in patches. In these patches, it forms isometric grains with

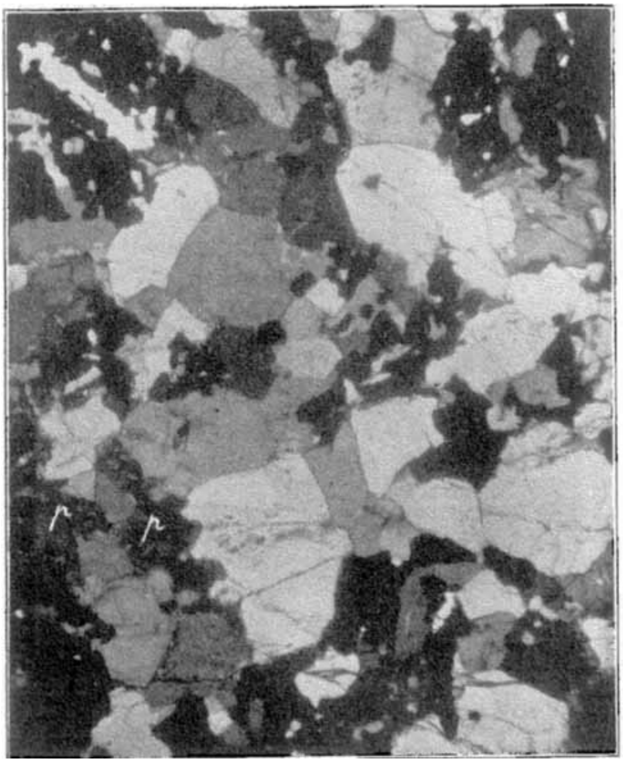

Fig. 9. *Apatite ore* in nepheline-syenite, Alnö. Nic. +, magn. 16 times. The apatite is white or gray in various shades, the magnetite black, at *p p* two pyroxene grains.

simple outlines against each other, only occasionally showing a tendency to elongation parallel to the *c* axis. As soon as there also appears magnetite, however, the size of the apatite grains decreases, and they often attain a more prismatic form. Fig. 9, a slide of Högbom's type VI, shows a typical aggregate of apatite grains and, both in the centre and near the sides, small patches showing intergrowth of apatite and magnetite. Both these structural forms are of interest for the comparison with the Lappland ores. The pavement structure of apatite shown in the figure is not actually found in the latter, evidently because of their volcanic character,[1] but there are sometimes tendencies towards it. The intergrowth of apatite and magnetite is entirely analogous to certain phases of the Kiirunavaara ore, and also the differences between the apatite in the pure patches and the one intergrown with magnetite is sometimes observed in the latter.

As a summary of the new researches may thus be said, that the further study of the trachytoidal flow structure has definitely proved its primary nature, and that the comparison of the apatitic iron ores of Lappland with other magnetite-apatite rocks of igneous origin has shown that also the other structural forms are such that could be expected in a rather quickly cooled igneous rock of this composition.

IV.

Problems in the geology of the Kiirunavaara-Luossavaara ore bodies.

Part of the new observations that are described in the previous sections of this paper, throw new light upon some of the more discussed points in the geology of the most important among the »iron mountains» of Lappland, Kiirunavaara. Since the writer finished the report on the ore fields of the Kiruna district, to which reference has been made many times in this paper, many papers have appeared, in which various sides of the geology of this district have been considered, and also my interpretation of these phenomena has been now supported, now criticized. The authors of these papers are generally members of the excursions of the international geological congress in 1910, and many important new views were also put forth in the lively verbal discus-

[1] Even when evidently intrusive, as at Tuolluvaara, the ores must have cooled so rapidly that they may be called volcanic.

sions during these excursions. It is therefore now suitable to consider the points where any more important differences of opinion exist, notably the questions of the mode of eruption of the wall rocks and the ore bodies. Before that, however, I wish to thank those who in some way or other have taken part in this discussion, for their friendly criticism and valuable help. If many of them left Kiruna with ideas that I must regard as unsupported by the facts, the fault lies mainly with me who have failed to convince them by word of print or mouth.

There are especially two points in the geology of the Kiruna ores that still form the subject of discussions: the mode of eruption of the porphyries, and that of the Kiirunavaara-Luossavaara ore bodies. Considering first the problem with regard to the rocks, those geologists who have taken part in the detailed survey of the district have always agreed in regarding the porphyries as most probably effusives, while the opposite opinion is especially represented by Dr. STUTZER. During the congress excursions this problem became much discussed, and the agglomeratic zone of Luossavaara made many before hesitant excursionists inclined to accept the effusive interpretation.[1]

The problem in question derives most of its interest from its relation to the mode of eruption of the ores. If the porphyries are intrusives, it follows as a corollary that the ores must be so too, while the proving of their effusive nature would leave it an open question whether the latter are of intrusive or effusive origin. In the Kiruna monograph, my position to the problem regarding the ores was put forth in a rather summary manner, which makes it desirable to bring out more clearly the facts speaking for and against. A discussion of this problem, however, to my mind must be footed on the basis that the ore-bearing rocks are probably effusives, or, at least, that their intrusive nature is very far from being

[1] Compare for instance the paper by Prof. TERMIER, quoted on p. 775.

proved. Thus the problem with regard to the porphyries must first be considered.

Let it at once be emphasized, that we know the exposed rock areas around Kiruna enough to be able to say, that none of the rival hypotheses can be proved with any absolute certainty to be the right one. There are no intrusions of the porphyries in question known in the supposed laccolite roof, nor are there in the porphyry beds any interstratified rocks that are undeniably surface deposits.[1]

STUTZER has pointed out, that fragments of the quartz-porphyry are lacking in the lower part of the Hauki complex. As these beds, however, generally seem to be of a tuffogeneous origin, this argument is of rather little importance. The other arguments for STUTZER's opinion were also discussed in the Kiruna monograph, and none of them was found convincing. Among later writers on the subject, the most decided position in defence of the intrusive explanation has been taken by Dr FERMOR.[2] In his paper, however, I have only found one single argument for this opinion: »The foot-wall syenite-porphyry, which is seen on Kiirunavaara to pass downwards into crystalline syenite of a plutonic aspect, must be an intrusive rock and not a surface lava flow» (p. 116). Whether the fine-grained syenite of Kiirunavaara really has a plutonic aspect may be a matter of taste, but it is certainly not sure that it *must* be an intrusive rock. It seems quite as certain, that the lower parts of a very thick lava flow of this composition ought to crystallize in this way, and I have recently seen examples that go rather far to confirm this view. During the excursions last June, to which Swedish geologists were invited by Prof. BRÖGGER of Christiania, I had occasion to see the famous rhomben-porphyry beds, which are now being mapped in detail by Prof. BRÖGGER and his assistant, Dr J.

[1] It will, however, be very difficult to explain the agglomerate of Luossavaara with its rounded pebbles as part of an intrusive rock.

[2] See p. 775.

SCHETELIG. While the thickness of these beds never actually reaches that of the supposed flow of Kiruna, it may at least be said to be of the same order of magnitude, and the mass brought forth at one single eruption probably in some cases surpasses that of the latter. Especially striking is the structure of the porphyries, which are holocrystalline practically right up to the upper surface, the quickly chilled crust being of a very insignificant thickness (some *dm* at most). Indeed, the structure through the whole thickness of a bed is that of a syenitic dike porphyry, and the feldspars of the groundmass may reach several tenths of a millimeter in diameter, the rock thus resembling the transitional stages between porphyry and fine-grained syenite in Kiirunavaara. When having formed acquaintance with these products of giant fissure-eruptions, one can hardly deny the fact that the Kiruna syenite *can be* an effusive rock.[1]

With regard to the quartz-porphyry, it has already been pointed out, that it is structurally very similar to the effusive porphyry of Ekströmsberg. Comparisons with other porphyries of similarly high geological age make me believe, that the microgranitic structure in the Kiruna quartz-porphyry, more often than I have previously maintained, is a devitrification structure. The fluidally elongated, litophysæ-like »buttonholes» also point to an effusive rather than to an intrusive rock. The only coarser phase, »type 3» (*Kiruna*, p. 131) is perhaps a small intrusive body like the granophyre of Ekströmsberg. Finally, there is the agglomerate of Luossavaara to reckon with. As already mentioned, many of our congress visitors regarded this as the deciding factor in favour of the effusive interpretation.[2] In view of all these facts it is apparent, that the effusive origin of the porphyries is still

[1] That even-grained syenite can be formed at a very moderate depth below the surface is also illustrated by LACROIX' recent researches on Réunion. (C. R. Ac. Sc., T. 154, 1912.)

[2] Dr FERMOR does not mention this rock, and it seems as if he unfortunately missed the excursion to it.

the most probable explanation, at least *we have no right to base any conclusions whatever on their supposed intrusive origin.*

As already said, if the rocks are intrusives the ores must be so too. This is the position taken by STUTZER, who also points out some observed facts favouring his hypothesis. If the porphyries, on the other hand, are effusive, as I argued in my previous report and still maintain, this fact gives no information with regard to the ores in this respect. They may be effusive, or concordant intrusions.

In the Kiruna monograph, I uttered as my belief, without discussing things for and against, that the ores are effusives. With regard to the age of the ores, compared to that of its wall rocks, this idea may be called a magmatic modification of the pneumatolytic-sedimentary hypothesis of BÄCKSTRÖM and DE LAUNAY.

The facts on which to base one's opinion are chiefly: the geological position of the ore bodies, the nature of their contacts and the occurrence of ore fragments in the hanging wall rock.

The geological position of the ore bodies, following the contact between syenite-porphyry and quartz-porphyry[1] is well in accordance with the effusive idea but does not, however, deny the possibility of their intrusive nature. The contact phenomena are characterized by a certain degree of metamorphism and some small intrusions of ore in the foot wall, while such phenomena are lacking or very feebly developed at the hanging wall contact. This difference, and the insignificance of the last-mentioned phenomena, favours the idea that only the foot wall existed at the *mise en place* of the ore, but it may be questioned, whether the pressure of the magnetite flow (amounting to 25—30 *kg.* on the sq. *cm*)

[1] Diamond drill cores from southeastern Kiirunavaara (Konsuln ores) have recently been studied by Mr ZENZÉN and the writer and show that also these ore bodies mark the contact already mentioned. There must thus be several faults in this part of the mountain.

could be enough to produce the injections of ore magma visible in the foot wall of northern Kiirunavaara, even when taking into account the high fluidity of molten magnetite.

It is the presence of ore fragments in the quartz-porphyry that forms the main footing for the hypothesis of a surface flow of ore magma. Let it only be remembered here, that these fragments generally are sharply defined, sometimes angular, and that they represent nearly all ore types of Kiirunavaara, fragments of various types often being found together. These fragments cannot be basic segregations from the surrounding rock, they must come from an ore body petrographically identical to the Kiirunavaara-Luossavaara ores and cut through by the quartz-porphyry.

The undeniably intrusive nature of the Tuolluvaara ores has certainly impressed many in favour of the intrusive idea,[1] while the acquaintance with the unfortunately distant and seldom visited Ekströmsberg ought to work the other way.

There is undeniably much fascination in the intrusive interpretation, especially if the writer's views of the differentiation process hold true, that is, if the ore magma has crystallized at a somewhat lower temperature than the associated rocks, and contained more pneumatolytic substances, which perhaps would have escaped if brought to only atmospheric pressure. This side of the problem has probably influenced Prof. BERGEAT, who regards the ores as »a pegmatitic injection».

Those who accept the intrusive origin of the ores must remember, that from their geological relations they must, in this case, have been formed as a nearly horizontal sheet, and

[1] In fact, Dr FERMOR writes (p. 117) that he was »convinced of the magmatic intrusive origin of the Lapland ores, the clinching piece of evidence being the magnetite dikes at Tuolluvaara running through the porphyries». It cannot, of course, be his opinion that this phenomenon proves the intrusive nature of the Kiirunavaara ore, for by that way of reasoning we could point at Ekströmsberg as proving that it is effusive (although it is true, that the intrusive nature of Tuollavaara is evident, but the effusive nature of Ekströmsberg only very highly probable).

not as a dike. The latter idea was especially attractive when, before and during the first stages of the mining operations, the ore back-bone of Kiirunavaara rose above the surrounding rocks in the same way that has given to dikes their Scotch name, but a closer inspection shows that this explanation, while certainly the right one for Tuolluvaara, does not hold good here.

Among papers published since the writing of the Kiruna monograph, and treating the problems discussed above, the following ones may be cited:

Arlt, H.: Geologie der Eisenerzlagerstätten von Kiruna und Gellivare. Glückauf 1911.

Bergeat, A.: Die genetische Deutung der nord- und mittel-schwedischen Eisenerze in der Literatur der letzten Jahre. Fortschr. d. Mineralogie etc. I, 1912.

Fermor, L. L.: On the origin of the iron ores of Swedish Lapland. J. Iron and Steel Inst. 1911, p. 113.

Newland, D. H.: Notes on the origin of the Swedish magnetites. New York State Museum, Bull. 149, p. 107.

Termier, P.: L'excursion A 2 du 11me Congrès géologique international. Bull. Soc. géol. de France 1910, p. 752.

For criticism of my interpretation of these problems I am further indebted to several other Congress visitors, and to Prof. R. A. Daly, of Boston, who in personal letters to Dr Lundbohm and myself has made many interesting and valuable suggestions.

V.

The differentiation process.

The last part of the precedent section was devoted to a problem in the geology of the Kiruna district that by its very nature hardly can be expected to become definitely settled in a near future. The most important riddle, however, and the one of the most universal interest seems to be rather generally regarded as partly solved. The opinion of the congress visitors at Kiruna, expressed during the excursions or in print afterwards, shows that the idea of the ores being magmatic differentiation products, and having crystallized from igneous solutions, is supported by most authors. In some previous sections of this paper new proofs for this opinion have been brought forth.

But this is only a step on the way to the solution of the problem of the origin of these ores. When the detailed work in the Kiruna region had resulted in the gathering of many new facts to support the magmatic theory, which had already been made probable by HÖGBOM and STUTZER, I proceeded to carry the investigation farther, and to trace the outlines of the differentiation process. The result was summarized as follows (*Kiruna*, p. 268): »The ores thus represent the last crystallizing parts (*i. e.* the parts having the lowest temperature of crystallization) of the series, in which the differentiation of the original parent magma has resulted ... The main ores, which are almost free from 'pneumatolytic' substances — except the apatite — must have crystallized under quite magmatic conditions, equal to those of the rocks; the apatite dikes, though having magmatic structures, have in these regards been akin to pegmatites. The hematite ores are not igneous and perhaps not eruptive in a proper sense, though their deposition may be regarded as one of the last phases of the volcanic activity.»

This hypothesis has been favourably commented by some authors, especially by Prof. BERGEAT,[1] Dr FERMOR[1] and Dr ARLT.[1] To my mind, the solution of this problem is a necessary condition if we wish to turn the establishing of the magmatic nature of the ores to further profit for the science of ore deposition, and of petrology in general. The idea was advanced as a »working hypothesis», and since the opinion

[1] In the papers quoted p. 775.

quoted above was written, I have tried to gather new facts relating to it.

The rôle of the orthite in the ore-bearing magmas of Lappland, discussed in a previous section of this paper, in itself an insignificant feature, becomes of importance when it points in the same direction as many other phenomena. The ores of Painirova have been characterized as a magnetite-apatite pegmatite (*Kiruna*, p. 270). While occurring in a porphyry, the feldspars of which do not surpass some tenths of a millimeter in size, the ore contains apatite crystals of a finger's size. The position of these crystals, at right angles to the contact with the wall rock or fragments of it also reminds one of a common structure of pegmatites. Outside of the Lappland ore region, I have examined the ore deposits in diabase at Näsberget,[1] which were briefly mentioned in the Kiruna monograph (p. 262) and found ample evidence that their origin was of the nature I had assumed from only a cursory examination. The examination of the only iron ore prospects in the wide areas of abyssal syenite rocks in northern Sweden (south of the Lappland ore-bearing region), on the other hand, showed them to be analogous to the titaniferous ores of the gabbro family.[2]

The problem in question, however, is a complicated and difficult one, and also certain foreign deposits, which I have not been able to visit, must be taken into account. Nevertheless, I think the material already gathered makes it highly probable, that the magmatic differentiation in the case of all the Lappland ores of this type has worked in the way I imagined, and a review of their relation to other iron ore types may be of interest.

[1] G. F. F. 33: 21.

[2] G. F. F. 34: 183.

To get the problem of iron ore differentiation illustrated in so many ways as possible, I also studied the quartz-banded magnetite deposits of Sydvaranger in Norway, but the results caused me to oppose the hypothesis of their magmatic nature (G. F. F. 33: 312).

The formation of an eruptive[1] iron ore deposit requires a magma containing iron compounds, and its subjection to differentiation. We can distinguish two main types of differentiation, at least in deep-seated rocks. In the one, the iron (as magnetite or ilmenite) is concentrated (how, we do not exactly know) together with compounds with a high melting-point (as Mg-olivine, rhombic pyroxene, spinel) and forms »basic segregations». This is the origin commonly attributed to the titaniferous ores of the gabbroid rocks. In the other type, the iron occurs as volatile compounds which during the crystallization of the rock are gradually squeezed out, this being the source of the iron content of contact deposits.[2]

The first type, as already mentioned, is found in abyssal (or rarely hypabyssal) forms of the gabbro family, and also in nepheline-syenites. No deposits of this kind are reported from a real diorite, and there are only insignificant examples known in syenites and quartz-syenites.[3] In granites such ores seem to be very rare, or entirely lacking. Ores formed through the action of iron vapours emanating from an intrusive rock are, on the contrary, much more common with acid rocks than with the basic ones. There is hardly more than one single contact deposit with gabbro known,[4] but there are

[1] With *eruptive* is here understood an iron ore deposit, the iron of which has been deposited there as its first solid phase. In this way, the term embraces not only all ore products of magmatic crystallization, but also all deposits from gaseous emanations from the igneous rocks, including such cases where they have mingled with underground waters and thus been brought to the surface.

[2] In at least many cases, it is evident that the iron has been carried in the form of halogene compounds, but it may be asked whether it not sometimes has occurred as watery solutions, above the critical temperature.

[3] As an example may be cited the occurrences in northern Sweden described by the present writer (see p. 777, foot-note).

[4] The Cebolla district in Colorado, recently described by SINGEWALD (Economic Geology, Vol. VII, 1912, p. 560) is the first example of a titaniferous iron ore of contact-metamorphic origin. Another form of iron ore deposit formed through emanations from a gabbro rock is the specular hematite-albite vein type (compare J. H. L. VOGT, G. F. F. 14: 214).

many following the contacts of diorites and monzonites and especially syenites and granites. Practically the same is true of the hypabyssal phases of these magmas. This difference has long been noted, and has often been referred to a higher content of mineralizers in the acid rocks.

Turning now to the effusive phases, the most striking feature is the absence of any surface forms of the titaniferous ores. Instead, basalt eruptions are often followed by the emanation of vast quantities of iron compounds in gaseous state or liquid water solutions, the iron becoming more or less immediately precipitated and giving rise to sedimentary ore deposits. This is, in short, the origin attributed to the red hematites of the German Devonian and is also the hypothesis regarding the main mass of the primary material of the Lake Superior iron-bearing formations now embraced by the leading American workers in this region.[1] The latter authors emphasize the contrast referred to between the deep-seated and the surface forms of the gabbro magma, and point to difference in pressure as being possibly the cause.[2] Volcanic rocks of a syenitic and quartz-syenitic composition are sometimes accompanied by magmatic iron ores (Kiirunavaara type), but acid rhyolites are generally barren. It may be noted, however, that there are, according to the authors quoted above, signs indicating that such rocks in part of the Lake Superior region have been at least as closely associated with the ferruginous sediments as have the basalts.[3]

Apparently, eruptive iron ores may be conveniently classed in three groups: 1. the titaniferous ore group: magmatic, without pneumatolytic minerals and standing in a basic segregation relation to the parent magma; 2. a group comprising ores that are the products of magmatic crystallization, but

[1] Compare VAN HISE, LEITH and MEAD: Geology of the Lake Superior region. U. S. Geol. Surv. Monog. LII.

[2] Op. cit. p. 561.

[3] Op. cit. p. 507.

carry pneumatolytic minerals as accessory constituents, and stand in a pegmatitic relation to the parent magma (Kiirunavaara type, and others); 3. the emanation group, differing from the others in being non-magmatic, and typically represented by contact deposits. The last two groups are comprised in BERGEAT's term *perimagmatic* deposits.[1] I shall here use the term late-magmatic for the second group, which comprises those perimagmatic ores that are really magmatic or igneous in the sense these words are used for rocks. To this group belong the deposits of the Kiirunavaara type in Lappland and certain deposits closely related to them (e. g. the apatitic ores of the Adirondacks), further magnetite masses in pegmatite dikes, which sometimes attain considerable proportions, even if they can not be called ore in a commercial sense, the magnetite ore in diabase at Näsberget and similar deposits in diorite in the Alps.[2]

In the discussion of the differentiation problem in the Kiruna monograph, it was shown that halogenes cannot have played any important rôle, the nature of the differentiation being that the crystallization of the magnetite was deferred. Indeed, it is a striking feature in the ore-bearing rocks of Lappland, notably in the magnetite-syenite-porphyries, that the magnetite has crystallized after the feldspars. Now this deviation from the usual order of crystallization must have been caused by the chemical composition of the rocks, as it is too regular and widespread a phenomenon to be accounted for only by incidentally favourable physical conditions. If, however, it depended on this composition as shown in the analyses, we

[1] Fortschritte d. Mineralogie, Kristallographie und Petrographie, herausgegeben von Dr G. LINCK. Bd II, p. 9. The difference between the two subdivisions of the perimagmatic group has also been emphasized by Prof. BERGEAT in this paper.

[2] G. F. F. 33 : 21. The pegmatitic relation of the Näsberget ores to the mother rock is evident, and it is highly probable that they crystallized from a fluid (molten) and not from a gascores solution.

could expect a similar differentiation in innumerable igneous bodies where it is now lacking, as the analyses show a rather wide range in the composition of the various rocks that occur in a very close relation to the ores. It was therefore supposed that magmatic water was an important factor in the differentiation (*Kiruna*, p. 268).[1]

The magmatic water has undeniably been called upon to explain all sorts of phenomena that prove in some way mysterious to the petrologist. This popularity, however, has suffered much through BRUN's excellent researches on volcanic emanations,[2] which in all examined cases have proved the absence of water at the paroxysmal stage. BRUN has, however, failed to explain the presence of water-containing minerals as products of magmatic crystallization, and because of that, and of certain features of pegmatites and the frequently associated quartz veins, I think most petrologists still find it necessary to reckon with a certain amount of water as dissolved in the magma, even if the astonishing results of BRUN's investigations have shown that the volcanic explosions are caused by other constituents, and that water is absent at the paroxysmal stage of the many volcanoes examined by him.[3] It may also be remembered, that because of the low molecular weight there are no great quantities of water needed to produce a considerable effect in lowering the freezing-point, a fact that has recently been emphasized by BASTIN in a paper on the pegmatites of Maine.[4]

The idea that water has been at least one of the causes of the differentiation becomes still more probable if we consider

[1] It lies near at hand to refer the lowering of the freezing-points to the characteristic pair magnetite-apatite, but the widely varying relations between these minerals in the ores makes it improbable that this association alone has been the cause of the differentiation. Some typical titaniferous ores are also rich in apatite, as at Alnö.

[2] BRUN, A.: Recherches sur l'exhalaison volcanique.

[3] Compare for instance A. N. WINCHELL: Brun's new data on volcanism (Ec. Geology, Vol. VII, 1912, p. 1).

[4] Journal of Geology. Vol. XVII, 1910, p. 297.

also the peculiar nodules in the ore-bearing rocks, which were very closely described in the Kiruna monograph. It is true that magnetite and apatite are not the only minerals that form nodules, hornblende being also common, and titanite and feldspar rather frequent, but there are so many striking parallels between the results of differentiation as they appear in the nodules and in the ores that we can hardly escape to refer both processes to similar causes, even if there have been certain differences in a physico-chemical respect.[1] The nodules are mainly confined to the syenite-porphyries[2] and are in the quartz-bearing porphyries replaced by apatite dikes, magnetite schlieren or similar bodies. In both cases, minerals that in general belong to an early period of consolidation, especially magnetite and apatite, are found in the last residuum, and rather sharply separated from the mother rock.

Nodules entirely analogous to those in question are certainly rare, and those of magnetite are, so far as the writer's knowledge goes, unknown outside the part of country now under discussion; the fact that they are, so to say, co-limital with the ores of the Kiirunavaara type, can hardly be merely an incident, it must involve some common cause.

Water must have contributed to the forming of the nodules, as is especially apparent when they have the character of only partly filled vesicles (*Kiruna*, p. 240). It may be that also other gases can give rise to vesicles, but there is hardly anything else than water we can think of as the solvent, from which the nodule minerals have been deposited.[3]

In my previous discussion of the nodules (*Kiruna*, p. 240), I thought that the water and the dissolved substances (now

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[1] BÄCKSTRÖM was the first who emphasized (G. F. F. 20: 74) that the origin of the ores must resemble that of the nodules.

[2] Their absence in the even-grained syenite is probably due to the higher pressure in this part of the eruptive body (*Kiruna*, p. 240).

[3] The analogous rôle of the water in the forming of miarolitic cavities has been pointed out by BASTIN (op. cit.).

forming the nodule minerals) had been separated from the rest of the magma in the liquid state, as a result of limited miscibility. This way was taken especially to account for the absence of any decided structural break between groundmass and nodule in many cases. Most characters of the nodules, however, can be explained by assuming that they were formed through crystallization from gaseous watery solutions. This would mark a difference from the magmatic apatite dikes and the ores, and there are also other dissimilarities, but they cannot obscure the still more important analogies.

The idea that water has contributed to the forming of iron ores through magmatic differentiation in intermediate and acid rocks has been advanced also by Prof. SJÖGREN[1] and Dr NEWLAND,[2] who finds it probable for the non-titaniferous magnetites of the Adirondacks. Prof. VOGT,[3] in a recent paper, has quoted the opinion of these authors and the present writer, and finds that the idea »deserves attention as a working hypothesis».

It thus seems, that the general chemical composition of the ore-bearing rocks together with a certain amount of water have been the causes of that separation of magnetite etc. of which we see results of the most varying magnitude, from nodules and small dikes up to some of the largest ore bodies known, but it is impossible to decide, how much is to be credited to the former factor (and to the pair magnetite-apatite) and how much depends on the later escaped water. I have already (p. 780) pointed out some facts indicating, that the differentiation may perhaps have had the character of a fractionary crystallization, but the material at hand is too incomplete to allow any conclusions in this respect — it

[1] G. F. F. 30: 115.

[2] Geology of the Adirondack magnetic iron ores. New York State Museum, Bull. 119, 1908.

[3] Über die Bildung von Erzlagerstätten durch magmatische Differentiation. Fortschr. d. Mineralogie etc. II, 1912.

is possible that diffusion processes and perhaps even limited miscibility have also influenced the results.

Even if water has influenced the differentiation, the crystallization temperature of at least the larger ores (Kiirunavaara, Luossavaara, Ekströmsberg) must have been rather near that of the porphyries. The augite in the Kiirunavaara ore is the same as in the rocks (and it cannot be xenocrysts), while in the nodules, notwithstanding their very close connection with the porphyries, hornblende instead appears, a difference that most probably depends on the temperature. It is also a characteristic feature that the titanite, which in the rocks belongs to the very last phase of magmatic crystallization, or is of even later consolidation, in the ores is confined to the borders and druses, as is also the tourmaline. The apatite dikes, however, as was pointed out in the Kiruna monograph, represent a lower crystallization temperature. The hematite ores (Hauki complex), partly accompanied by calcite and barite may most appropiately be classed as hydrothermal, the frequent occurrence of orthite — a characteristic component also of the quartz-ankerite veins of the district — together with their geological position marking their relation to the volcanic activity. They belong to the second subdivision of the perimagmatic group.[1]

It is apparent, that halogene compounds, if present in the magma, ought to be concentrated in the late-magmatic differentiation product. As already pointed out (*Kiruna*, p. 259) it is probable that the veins of specular hematite in the larger magnetite ores have originated in this way, the main mass of these ores, however, being of magmatic origin.

As a summary, it may be said that the working hypothesis discussed here seems fairly well in accordance with the known facts concerning the apatitic iron ores of Lapp-

[1] Only part of the Hauki ores were examined by the present writer. A fuller understanding of them will be possible when ZENZÉN's researches are completed.

land, even if many points require extensive further researches.

I have here only considered the ores of Lappland, with which I am myself familiar, not the various analogous deposits in other parts of the world. Some of the latter occur in deep-seated rocks, as the Solberg and Lyngrot mines in Norway, the Mineville and related deposits in the Adirondacks, or in rocks of uncertain origin, as the Grängesberg deposits in Central Sweden. There are, even apart from the characteristic apatite content, many features pointing at a similar origin of all these deposits and those of Lappland, and the mode of origin attributed by NEWLAND[1] to the Adirondack ores does not materially differ from the one proposed by the writer regarding the latter.

Among deposits connected with effusive or hypabyssal rocks, *i. e.* in a geological association similar to that of the Lappland ores, the group of deposits connected with the syenite rocks of Ural, and the solitary Cerro de Mercado in Mexico offer many resemblances. At the latter, the geology of the ore body is to a great extent veiled by superficial deposits. From the available data, however, the following general idea may be obtained.[2] The ore forms one or several dike-like bodies in Tertiary rhyolites of varying acidity, which probably are effusives. The contacts are covered, but the frequent occurrence, in the talus, of rhyolite fragments coated with iron ore in crystals to my mind suggests, that the wall rock is interwoven with ore veins, and when weathering most readily splits up along these planes of weakness. The occurrence of small veins with, among other minerals, apatite,

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[1] Op. cit.

[2] The writer's knowledge concerning the Cerro de Mercado is mainly based on the following papers:

M. F. RANGEL: Criadero de fierro del Cerro de Mercado en Durango (Bol. Inst. Geol. de Mexico N:o 16).

O. C. FARRINGTON: Observations on the geology and geography of western Mexico etc. (Field Columbian Museum, Geol. Series, Vol. II, No. 5).

hornblende and specular hematite is a feature recalling related phenomena in the Lappland districts. The ore itself has much in common with the Lappland ores. It is crystalline hematite, a type that in Lappland is best represented by some ore bodies of Ekströmsberg. It is extremely hard and shows signs of columnar jointing. The cavities with martite crystals (reproduced by FARRINGTON) recall druses in the Kiirunavaara ore. There is a characteristic apatite content of several per cent, and titanium in a quantity similar to the one in the Lappland ores. The silica seems to be a later addition, like the silica content in, for instance, the hematite ore of Ekströmsberg. It seems as if there are only two alternatives to choose between regarding the origin of the Cerro de Mercado: pneumatolysis or magmatic crystallization. The available data allow no definite conclusion, but it seems to the present writer, that the physical properties of this geologically young ore body make the latter alternative the more probable one.

The analogies between the ores of Lappland and the Blagodat-Wyssokaja type of Ural were emphasized fifteen years ago by HÖGBOM.[1] The associated rocks are very closely similar to the syenitic rocks of Lappland, the occurrence of magnetite-syenite-porphyry in both regions being an especially interesting feature, but the quartz-porphyry type of Kiruna, Tuolluvaara and Ekströmsberg seems to be lacking in Ural. The Ural ores are high in iron and low in titanium, like the Lappland deposits, and their apatite content is generally low but sometimes high (Lebjahinskoje), in the latter case the ore is strikingly similar to certain varieties of the Lappland ores — even the »stratified ore» is found here.[2] The magmatic origin of at least the majority of these deposits must be regarded as proved, but it must be admitted that they do not in all respects confirm the ideas expressed above concerning

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[1] G. F. F. 20: 115.

[2] BOGDANOVITSCH, K.: Die Eisenerze Russlands. Iron Ore Resources of the World. p. 389.

the nature of the differentiation. While some features could be cited that do so, the common occurrence of spinel and pyroxene in the Blagodat ore rather points to an origin similar to that of the titaniferous magnetites.

Sammanfattning.

I förestående uppsatser redogöres för en del af förf. under de senaste tre åren utförda undersökningar inom Lapplandsmalmernas geologi samt diskuteras några redan i Kirunamonografin 1910 behandlade problem, som i någon mån belysas af de vunna nya erfarenheterna, och rörande hvilka en del kritiska anmärkningar och nya uppslag framfördes af 1910 års kongressdeltagare.

Undersökningar af Ekströmsbergs malmfält hafva visat, att den rådande porfyren därstädes strukturellt står mycket nära Kirunas kvartsporfyr (ehuru den är mera pressad än denna senare) och att i kemiskt hänseende skillnaden mellan dessa båda bergarter är mycket mindre än förut förmodats. Liksom förut äfven Stutzer ansluter sig förf. till Bäckströms uppfattning, att porfyrens hufvudmassa är en serie lavaströmmar, men det lilla granofyrområdet en intrusivbergart. Särskildt afseende fästes vidare vid den rikliga förekomsten af band af malm och apatit i porfyren, hvilka antyda, att icke blott magnetitmalmen, såsom redan förut angifvits af Stutzer, utan äfven blodstensbäddarna äro af magmatiskt ursprung och samtidiga med porfyren. Den vulkaniska efterverkan har vid Ekströmsberg, liksom vid Kiruna, hufvudsakligen haft karaktären af en silicifiering. Här har denna varit mindre omfattande, men den är af särskildt intresse därigenom, att tydligen apatitrika malmbands förkisling ledt till uppkomsten af de kvartsitiska inlagringar i porfyren, hvilka redan beskrifvits af Svenonius.

De syenitporfyrer, som i helt underordnad mängd uppträda vid Ekströmsberg, äro delvis så magnetitrika, att de böra

betecknas som magnetitsyenitporfyrer. Vidare befanns det strax nordväst om Ekströmsberg belägna berget Njakak uppbyggas af sådana bergarter jämte en hufvudsakligen af albit bestående porfyr, en association som äfven återfinnes inom andra områden, såsom vid Nokutusjärvi nära Kiruna. Njakaks magnetitrika porfyrer likna de inom detta sistnämnda område förekommande, särskildt med afseende på strukturen; kemiskt föreligger en viss olikhet så till vida, att Njakakbergarten är kalirikare — dock uppträder kalifältspaten hufvudsakligen i mandlarna. Med stöd af hittills tillgängliga data rörande magnetitsyenitporfyrer påvisas, att dessas relationer till öfriga differentiationsprodukter af modermagman synas vara analoga med malmernas (jämför vidare nedan).

Då i Kirunamonografin stort afseende fästes vid fyndet af trakytoidal struktur uti Kiirunavaaras malm, har förf. ägnat denna strukturform fortsatt uppmärksamhet och anser dess primära natur ställd utom allt tvifvel. Vidare har jämförelsen med några omsmälta apatitprof och med den af Högbom beskrifna apatitrika malmen från Alnön visat, att de apatitrika Lapplandsmalmernas strukturer äro sådana, som man kan vänta sig hos magmatiska malmer med dessa senares sammansättning och geologiska uppträdande.

I Kirunamonografin hade förf. anslutit sig till Lundbohms och Bäckströms åsikt, att Kiirunavaara-Luossavaaras porfyrer äro ytbergarter och, ehuru öfvertygad om malmernas natur af magmatiska stelningsprodukter, också till dessa författares uppfattning af malmerna såsom ytbildningar. Såväl under geologkongressens exkursioner som senare i tryck ha dessa åsikter blifvit kritiserade och delvis mycket bestämdt utdömda. Hvad bergarterna beträffar, visas här, att denna opposition står på skäligen svaga fötter. Däremot vill förf. icke förneka, att flera omständigheter tala för att malmerna kunna vara intrusiva, dock synas alltjämt skälen för den motsatta uppfattningen mera öfvertygande.

Slutligen har här återupptagits den redan i Kirunamonografin diskuterade frågan om malmernas förhållande till modermagman. Den af förf. såsom arbetshypotes framställda tolkningen, att malmerna utgöra ett i viss mån pegmatitartadt sekret, hvars kristallisationstemperatur legat under de med dem sammanhörande bergarterna, har genom de nya erfarenheterna i hög grad vunnit i sannolikhet.

Mineralog. Inst., Stockholms Högskola, nov.—dec. 1912.