SVERIGES GEOLOGISKA UNDERSÖKNING

SER. C. Avhandlingar och uppsatser. N:o 367.

ÅRSBOK 24 (1930) N:o 4.

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GEOGRAPHICAL DISTRIBUTION, GEOLOGICAL CHARACTERS, AND ORIGIN

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PER GEIJER

STOCKHOLM 1931

KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER

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Introduction.

The name of the »Kiruna type», derived from the chief mining town in Lappland in northernmost Sweden, has been employed (65, 50) for the iron ore deposits that are being worked in that neighbourhood. It is somewhat more convenient than the term »Kiirunavaara type», taken from the chief ore body of the district, which has also been used. The »Kiruna type» will here be used in a more extensive sense, to embrace, regardless of geographical position and age, all those deposits that are, in their geological features, closely comparable to those at Kiruna. The characteristics of the type, as here understood, are as follows: Ores of magnetite (or rarely hematite), with a moderate to low amount of gangue minerals; fluorine apatite is generally conspicuous, and amphibole or pyroxene often appear, but other minerals are, on the whole, to be regarded as occasional accessories; the titanium content is low, TiO_2 rarely surpassing 1 per cent, sulphur is generally very low. The deposits are closely connected with igneous rocks that are mostly of an intermediate or moderately siliceous character and that have, with few exceptions, solidified as surface flows or as intrusions at small depths. Along with these typical representatives will be treated certain deposits, geographically associated with them but of different character, yet clearly recognized as being the products of the same general geological processes. The age of occurrences of the Kiruna type ranges from Archean to Upper Tertiary.

With regard to the amount of iron contained in the present ore production, the Kiruna type probably comes third after the enriched sedimentary deposits of Lake Superior and the bedded oölitic ironstones of Mesozoic or Paleozoic age, although the Bilbao type — replacement carbonate ores, generally oxidized — probably is not far behind it.

About twenty years ago, the author completed a geological study of the iron ore deposits around Kiruna (16) which has, in later years, been followed by a number of papers relating to the same deposits, and to others within the same metallogenetic province (18, 21—26). With the recent publication of a monograph on the Gällivare ore field (26), and a survey of the general Pre-Cambrian geology of the region in question (27), a certain plan of study has been carried out, and the time seems appropriate for a discussion of the evidence thus accumulated with regard to the Kiruna type. This discussion has not been included in the summary just quoted, because it is necessary to devote much space also to related deposits in other parts of the world. Having previously had some field experience of certain North American ore deposits of this character (19, 20), the writer has recently also had an opportunity to study the most important iron ores of Chile which, thanks to various factors, and particularly their comparatively young age, furnish important material for the interpretation of the Kiruna type. Of deposits not visited by the writer, several, and particularly the Cerro Mercado in Mexico, have in recent years been the subject of important new studies which are here abstracted.

With the central position occupied by the deposits in northern Sweden among the material that forms the basis of the following discussion, it has been thought necessary to summarize at some length the geological conditions in this region. A comparatively detailed description has also been devoted to the Chilean representatives of the type, as their geological relations have so far been very imperfectly known.

Metallogenetic provinces and epochs with iron ores of the Kiruna type.

In Sweden there are two regions with ores of this character: the Archean (or in any case Pre-Cambrian) of northernmost Sweden, with Kiirunavaara, Gällivare, etc., and a portion of the Archean ore-bearing region of Central Sweden, with Grängesberg and some other deposits.

The Pre-Cambrian of southern Norway contains two groups of deposits that are more or less typical: Lyngrot, and Nissedal.

On the eastern side of the Ural Mountains, in Russia, there is a belt with a number of deposits of Devonian age.

In the United States are several groups. One, differing in certain features from the typical development, is at Mineville, in the southeastern Adirondacks, in Pre-Cambrian rocks. Another group, likewise of Pre-Cambrian age and strikingly similar to parts of the North Swedish region, is in southeastern Missouri (S:t François Co.). Younger deposits, of Tertiary age, are known from the Cordilleran region, with Palisade (Nev.), Twin Peaks and Iron Springs (Utah). The last-mentioned group, however, is mainly of another although distinctly related type.

Mexico possesses, in the Cerro Mercado, a quite typical representative. Its age is Tertiary, probably early Pliocene (Ordoñez, 48).

In Chile there is a great number of ore deposits of this type — in fact, all the more important iron ores of the country appear to belong to it. The age is very late Mesozoic or early Tertiary.

Sweden.

In the iron-bearing region of *northernmost Sweden*, the actually producing fields are at Kiruna (Kiirunavaara, Luossavaara, Tuolluvaara) and Gällivare (Gällivare field, operated as two units, viz. Malmberget and Koskullskulle).

There is also a number of other deposits, some of them quite large, that are not yet opened up.

Four main subdivisions have been recognized in the Pre-Cambrian of this region, two supracrustal series and two groups of plutonic rocks (27). The oldest unit appears to be the supracrustal porphyry-leptite series. Next comes a group of plutonic rocks, ranging from gabbros to granites but with a particularly important development of various syenitic and quartz-syenitic members. There exist evident analogies between this set of plutonic rocks and the volcanic phases of the supracrustal series. The third member is the Vakko sedimentary series, and the fourth a group of large granite bodies (Lina granite group). The relative age of these two latter units is, however, not established with absolute certainty (27).

The iron ores of the Kiruna type are associated with the volcanic rocks that, within a large part of the region, almost alone build up the porphyry-leptite series. The two plutonic groups have also given rise to mineralization. Associated with various phases of the older group, from diorites to granites, there occur in the limestones and dolomites of the porphyry-leptite series replacement deposits of the contact type, with magnetite ore, low in phosphorus but accompanied by much pyrite, in a silicate gangue (skarn) of actinolite, diopside, chondrodite, etc. With the Lina granite, small copper deposits in the leptites are genetically connected (Nautanen type). These ores will not be further considered here, only it may be pointed out that in spite of the undoubted existence of a comparatively close relation between the volcanics and the plutonic group that comes next after them in age, there is no other similarity in the kinds of mineralization accompanying them than the fact that in both cases iron is the only metal of importance.

Among the volcanic rocks of the region, the following petrographical types have been distinguished (27): basalts (or diabases), spilites, porphyrites and albite porphyrites, albitophyres, basic syenite-porphyries, ordinary syenite-porphyries, and quartz-bearing porphyries. As spilites are classed rocks characterized by the combination of albite feldspar with a great amount of femic molecules, mainly in the form of uralitic amphibole. Albite porphyrites are similar to normal porphyrites, only that their feldspar is albite, presumably of secondary origin. Albitophyres are rocks made up almost entirely of albite; the now rather ambiguous term keratophyre has been dropped. Of the syenite-porphyries, those that show a deficiency in silica, giving rise to normative olivine and nepheline, are classed as basic, and the others, with a low percentage of normative (generally also modal) quartz, as ordinary syenite-porphyries. The »quartz-bearing porphyries» mostly carry about 20 per cent quartz, entirely contained in the groundmass; more siliceous varieties, with quartz also as phenocrysts, are rare. In certain areas, as near Kiruna, the microtextures are well preserved, in other cases the groundmass is completely recrystallized (the rock then being classed as leptitic), and more seldom also the feldspar phenocrysts have been destroyed. Agglomerates and tuffs occur with the greenstones, but only very rarely with the more alkaline rock types.

Remarkable is the occurrence of varieties rich in magnetite (magnetite-syenite-porphyries). The best examples may be designed as iron-rich albitophyres, consisting only of the ore mineral and albite, but there are also such phases of syenite-porphyries containing some potash feldspar. A similar development in the spilites can be traced from certain conglomerate pebbles (59), but has not been encountered *in situ*. A striking feature in the magnetite-syenite-porphyries is the late crystallization of the magnetite, which is shut in between the feldspar laths of the groundmass.

The ore deposits are mainly associated with the porphyries. In connection with spilites and albitophyres there occur iron-rich rock varieties, as just mentioned, possibly even small segregations of ore, but no real ore bodies.

Since Kiirunavaara is by far the largest and most important among these deposits, it forms the best starting-point for a description. The bed-like ore body, with a moderate dip, is underlain by syenite-porphyry and overlain by quartz-bearing porphyries. The foot-wall porphyry downwards grades into a fine-grained syenite. The igneous body has an exposed thickness of more than 700 meters. Since all the overlying rocks are younger, and there are no signs of any erosion interval, it has been concluded that this body was extruded at the surface (16, 18, 22). Its very great thickness, however, appears to exclude that it ever formed a flow in the ordinary sense. One would rather think of it as a viscous magma mass piled up above a wide opening. The upper porphyritic parts of this syenitic body frequently exhibit a remarkable amygdaloid texture with nodules of hornblende, magnetite, titanite, and apatite. These mineral aggregates were regarded by Bäckström (7, 8) as deposited by gases as a result of volcanic after-action. The present writer (16, 18) instead concluded that they were formed by a late-magmatic concentration under the influence of the water content of the magma, as they are surrounded by zones free from such minerals. When the nodules are numerous, these zones coalesce, and the rock mass apart from the nodules thus consists wholly of feldspar.

As to the quartz-bearing porphyries overlying the ore body, they probably form a series of flows, although it has not been possible to indicate any boundaries between separate flows. It has been maintained by several geological visitors to Kiruna (58, 10, 65) that the porphyries are intrusions. The syenite has already been discussed. With regard to the quartz-bearing porphyry, this view is not supported by any observed facts. Instead, the groundmass textures — mainly finely poikilitic, and sometimes spherulitic ones — are well consistent with an extrusive origin, but could not be expected if the rocks in question formed one intrusive body. Moreover, there are found in adjacent districts (as near Ekströmsberg) porphyries with an identical textural development, and in part plainly devitrified, which form a distinct bed series and are indubitably extrusions (27).

The ore body sends out vein systems in the foot-wall (»ore breccia»), particularly along the contact between the ordinary foot-wall porphyry and a sill of dike-porphyry, connected with a set of dikes that cut the syenite and also the porphyritic phases into which the latter grades. There are similar contact phenomena along the hanging-wall boundary, but on a smaller scale. With the appearance of ore veins there is generally a great quantity of an actinolitic amphibole developed by replacement of the porphyry. The ore is cut by a couple of dikes of the same character as the dike-porphyry just mentioned, and also by several dikes of granophyre.

These relations are interpreted as follows (22). The sequence is: syenite and syenite-porphyry, quartz-bearing porphyry, dike porphyry, ore, dike porphyry once more, and finally granophyre[1]. The ore body thus reached its place during the time when a »Nachschub» of porphyry magma was being intruded. As to the occurrence of ore inclusions in the quartz-bearing porphyry, which once led the author to believe that this porphyry was later than the ore body (16), and to other details in the relations between ore and country rock, reference is made to several reports by the author (16, 18, 22), and to literature discussed in them.

The ore body itself has a simple composition. Magnetite is the only primary iron mineral of importance. Secondarily, however, it is in places oxidized to martite (compare 24, or 27). Apatite is the most common non-metallic mineral. Large portions of the ore body, particularly in greater depths, are of Bessemer grade, but otherwise the apatite content is high, most of the ore produced containing at least 2 per cent phosphorus, equivalent to 10.8 per cent apatite.[2] The relations between magnetite and apatite have been studied by Lundbohm (42), Stutzer (58), and the present writer (16) in whose work also the results of previous students are incorporated. Certain features of genetic significance may be mentioned. In general, the apatite has crystallized later than the magnetite. Thus there are often seen irregular streaks and veins of pure apatite, or of apatite mixed with some magnetite, which brecciate the richer magnetite ore. A very striking texture is represented by arborescent skeleton crystal growths of magnetite in a mass of apatite (16). There are also various mixtures of ore varieties with different proportions of apatite. In such cases, there is sometimes noted an impoverishment in apatite around concentrations of this mineral (58, 16). A most peculiar variety is the »stratified ore» (16), in which the apatite has crystallized before the bulk of the magnetite. Another feature, found very rarely and visible only under the microscope, is a distinct fluidal arrangement of the apatite grain. In general this mineral, when forming comparatively pure segregations, is developed as thick prisms some tenths of a millimeter in length, and arranged at random. The fluidal texture appears only when the apatite forms smaller

[1] It is an open question whether the granophyre belongs to the same differentiation series.

[2] The interestingly high percentage of cerium oxides in apatite from the Ural iron ores, recently published by Boldyrev (4), has raised the question whether also the Kiirunavaara apatite has a similar composition. According to an investigation by Dr. A. Bygdén, this appears to be the case. Thus, apatite from Kiirunavaara (with 40.79 per cent P_2O_5, corresponding to 96.67 per cent fluorine apatite in the sample) was found to contain 0.88 per cent cerium earths and an impure sample from the Rektor ore body on Luossavaara (87.86 per cent apatite) 0.99 per cent of the same group and 0.05 yttria earths. It is of interest to compare this result with the appearance of orthite in certain related deposits, as in apatite bands at Ekströmsberg (18), at Algarrobo (epidote-orthite, compare p. 24), and in the Hauki hematite ores.

and thinner prisms, which can be arranged in typical »trachytoidal» whirls (fig. 1).

Of the other non-metallic minerals occurring in the ore, diopsidic pyroxene (and uralite) is the only one of any quantitative importance, but it is restricted to certain belts (compare 16). Stripes of tourmaline have been noted in the ore at one place near the hanging-wall contact.

The much smaller Luossavaara ore body is similar to Kiirunavaara in its geological relations and general character but is, on the average, lower in apatite. The local presence of titanite in druses is worthy of note (16).

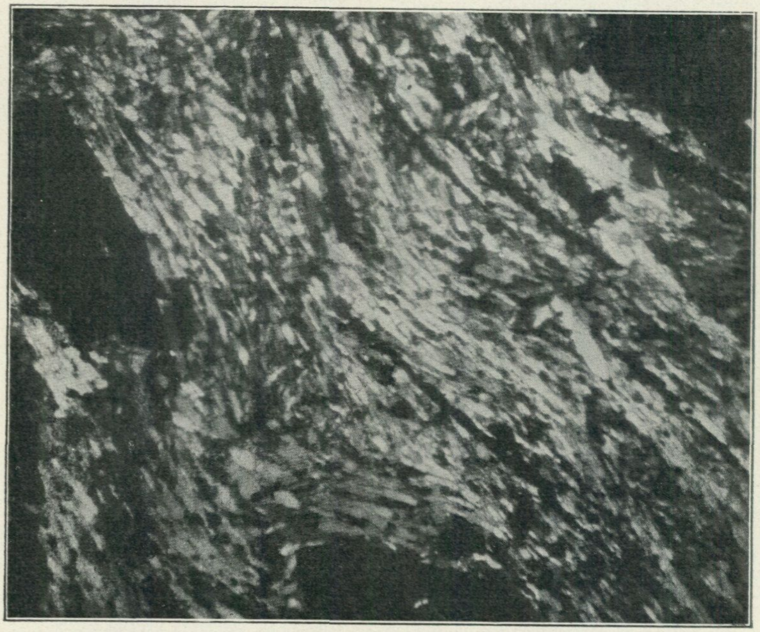

Fig. 1. Trachytoidal flow texture in apatite, Kiirunavaara. Microphoto., nic. crossed, × 16. Black lumps and laths are magnetite. (From 18).

The upper parts of the quartz-bearing porphyry contain a number of apatite dikes, texturally similar to the purer apatite masses in the ores, and sometimes with a certain content of magnetite and hematite, or locally with much tourmaline in small prisms (15, 16). Between the quartz-bearing porphyry and the overlying complex of tuffogeneous rocks, and flows, there occurs the Rektor ore body of highly phosphoric magnetite-hematite ore, with a little quartz and carbonates. The tuffogeneous rocks and associated flows (originally syenite-porphyries or related types, and quartz-bearing porphyries) have been subjected to a strong hydrothermal alteration which has resulted in silicification, sericitization, and deposition of hematite (Hauki hematite ores) by replacement. With the hematite, barite and orthite are often associated, and occasionally tourmaline.

A few kilometers E. of Kiirunavaara, the Tuolluvaara deposit (16, 23) occurs in a quartz-bearing porphyry (with secondarily recrystallized groundmass). The ore forms dike-like bodies, partly branching out into »ore breccia» of a most striking character (fig. 2). The porphyry fragments are evidently bounded by joint fissures; one gets the impression that the rock has been broken up along the joint planes, and the interstices between the blocks thus formed have become filled with ore. The peripheral parts of the rock fragments show a greenish or whitish tinge instead of the normal reddish colour, because of a metasomatic development of hornblende and albite. Sometimes,

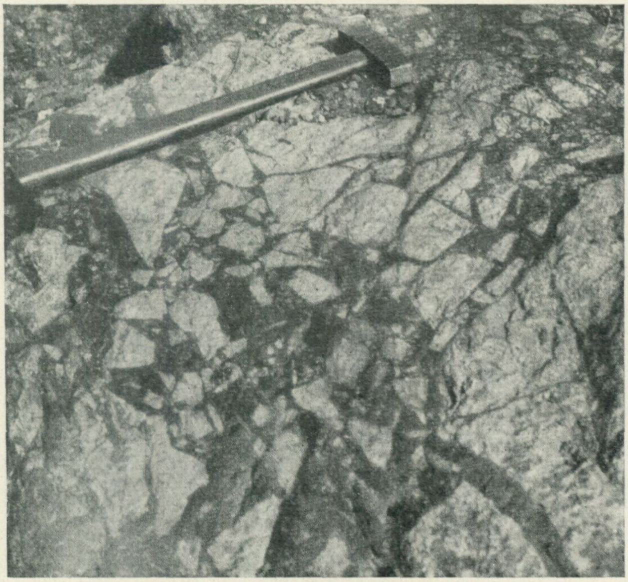

Fig. 2. »Ore breccia», Tuolluvaara: veins of magnetite in leptitic porphyry; stripped glaciated surface. (From 23).

particularly when the veins are thin and contain much hornblende, they have the character of replacement veins rather than fissure fillings.

The ore is to a great extent of Bessemer grade; the rest has a moderate phosphorus content and partly shows pseudo-stratification with apatite. Slabs of such stratified ore are enclosed in the purer magnetite.

The Ekströmsberg ore bodies, about 30 kilometers W. of Kiruna, occur in a quartz-bearing porphyry which is somewhat more potassic than the hanging-wall rock of Kiirunavaara and Luossavaara, but otherwise entirely similar to it. The apatite content is moderate. The main ore body is magnetite, forming a fairly regular bed. There are also beds of crystalline hematite, and a very peculiar banding of ore and apatite bands in the porphyry. On the whole, the hematite ore — which is almost certainly primary (non-martitic) — appears to occur in very much the same way as the magnetite. At the insignificant Skuokimjokk deposit, on the other hand, not far from Ekströmsberg, hematite with stripes and lumps of red jasper occurs in a partly silicified porphyry.

Mertainen is a deposit low in apatite, largely similar to Tuolluvaara in the shape of its ore bodies, and with »ore breccia» developed on a very great scale. The country rock is a syenite-porphyry, often with much new-formed biotite and scapolite. Scapolite of a later age, resulting from emanations produced by plutonic rocks, is of very frequent occurrence in this region, but the Mertainen scapolite must be connected with the mineralization, as it also forms a constituent of magnetite veins belonging to the »ore breccia». An amygdaloid development is very common in the porphyry, with compact magnetite fillings. There is a distinct hiatus between these magnetite nodules and the veins of the same mineral as indicated by the fact that the veins cut across the direction into which the nodules are sometimes elongated.

Painirova, a much smaller deposit, is in part rich in apatite, developed as large prismatic crystals that occasionally grow out from enclosed fragments of porphyry, or from the walls of the ore body (61, 58).

The Gällivare field (30, 26), next to Kiirunavaara-Luossavaara the largest ore concentration of this region, shows us the ore-bearing porphyries in a stage of strong metamorphism, only the phenocrysts and the occasionally occurring amygdules (of hornblende, diopside, titanite, and magnetite) being preserved; sometimes even these features, at least the phenocrysts, are obliterated. There are represented quartz-bearing types, basic syenite-porphyries, and albitophyres. On the whole, the apatite content of the ore is moderate. Pseudostratification is very often seen. Magnetite is the predominant ore mineral, but crystalline hematite also occurs. The development of hematite may possibly be a secondary phenomenon. The ore bodies are tabular. »Ore breccia» occurs, but more frequently there is a vein system and impregnations of hornblende (»skarn breccia»), often with magnetite, apatite, biotite, and a number of other minerals. When skarn brecciation has been carried to a finish, the result is a mass consisting mainly of albite feldspar, with lumps of hornblende skarn that are reduced remnants of what were once rock fragments. Fig. 3 illustrates the stages in this process. Skarn breccia, and ore breccia as well, are generally associated with ore bodies, but may also occur without any apparent such connection.

The Svappavaara and Leveäniemi deposits are too imperfectly known to furnish any facts of importance for the genetical interpretation of the type, except that they partly carry calcite, occurring in very much the same way as the apatite. The country rocks are recrystallized, leptitic, and their original character cannot be definitely ascertained; probably they have been basic syenite-porphyries.

Nakerivaara, largely developed as ore breccia, occurs in an oligoclase-amphibolite, probably a metamorphic diorite-porphyrite. The same is the case with the small Dundret deposit near Gällivare.

It has long been clear that the ore deposits here described must have originated through some kind of differentiation in the same magma that produced the associated porphyries. Two different lines of explanation were at first discussed, one of which may be briefly classed as the pneumatolytic hypothesis, and the other the hypothesis of magmatic differentiation. The former was presented in a discussion of the Kiirunavaara—Luossavaara deposits, by Bäckström in 1898 (7). Starting from the vesicle-filling aggregates of hornblende, magnetite, titanite, and apatite, Bäckström emphasized the peculiar fact that »minerals which in normal igneous rocks crystallize first and before the feldspars, here occur as the very last products», and referred the deposition of the main ore bodies to similar gas reactions. A modification of this view was presented

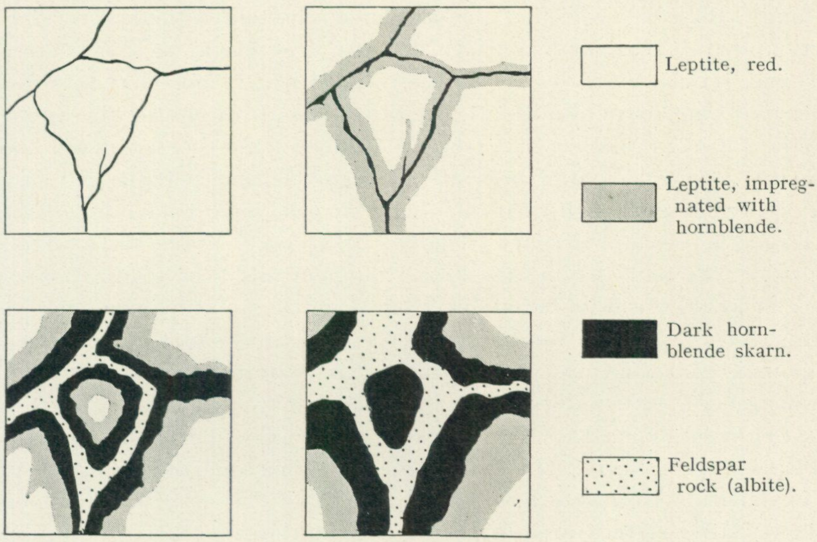

Fig. 3. Schematical picture of the stages in the development of »skarn breccia», Gällivare field. (Adapted from 26).

by De Launay (34), who thought that emanations of iron chloride had reacted with sea water, resulting in a pneumatolytical-sedimentary deposition of hematite, later changed to magnetite. Bäckström, in 1904 (8), when discussing also the ores of Ekströmsberg and Mertainen, formulated his views as follows: »The iron ores occurring in association with effusive rocks should accordingly have obtained their material from below, during the last stage of the volcanic activity, in the shape of compounds of iron, phosphorus and titanium (chiefly chlorides and fluorides), emanating as gas or as super-heated solutions. In the surface regions these have been decomposed by the water and the silicates they have been in contact with».

The hypothesis of magmatic differentiation is due to Högbom, also in 1898 (29), who when discussing the Ural group of similar deposits considered also those of Kiirunavaara—Luossavaara. Högbom regarded the ore bodies as products of differentiation *in situ,* in analogy with many deposits of titaniferous iron ore. Stutzer (58) took up this hypothesis, and greatly strengthened it by his observations, especially with regard to the relations between ore varieties of different apatite content. As before him De Launay, however, Stutzer points out that the contact relations of the ore bodies exclude an origin by differentiation *in situ*. His conclusion is, therefore, that the ores formed magmatic segregations that were erupted as separate bodies, comparatively contemporaneous with the associated porphyries.

The author (16, 18) also arrived at the conclusion that the ores must be characterized as magmatic. However, the existence of a fairly continuous series connecting the main ore bodies with distinctly hydrothermal deposits, and the often late crystallization of the magnetite in the associated rocks, led him to the conclusion that the ores have represented the last crystallizing fraction of the porphyry magma. »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. 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. In this rest, the bulk of the water and the mineralizers in a proper sense (e. g. compounds of boron) must have gathered, as is always the case» (16, p. 268).

Among later contributors to the discussion, R. A. Daly and J. H. L. Vogt are to be mentioned. Daly (10) thinks that the ores of Kiirunavaara-Luossavaara have been segregated out of the overlying quartz-bearing porphyry; his explanation is thus a form of the magmatic hypothesis. However, the contact relations later traced by the writer, and the fact that a set of porphyry dikes seems to be intermediate in age between the quartz-bearing porphyry and the ores (22), would appear to rule out this explanation.

Vogt's opinion (65) is that the ores were formed by the accumulation of sinking crystals, later re-melted and erupted as separate igneous bodies. This view faces the difficulty of explaining the transitions to fractions with very high contents of volatile components, and all other signs of late crystallization of magnetite and apatite in this petrographic province.

The apatite iron ores of *Central Sweden*, with Grängesberg as the most important unit, occur in a tract, the geology of which is much more difficult to decipher than is the case in the northern region, because of the always considerable degree of metamorphism. The chemical and mineralogical character of the ores, however, is very much the same. The containing rocks are of several chemical types, but can all of them be interpreted as porphyritic igneous rocks, or possibly as tuffs. In chemical character they are not quite comparable to those of the region just described. The type most directly associated with the apatitic ore of Grängesberg consists chiefly of albite-oligoclase (Ab_{87} An_{13}), quartz (about 24 per cent), and biotite (compare 31). Generally the contacts of the ore bodies are but little complicated, and »ore breccia» is rare, although some good examples have been identified (compare 41).

Beyond Johansson's hypothesis (31) of magmatic differentiation (by liquation), and a general opinion that the geological history of these deposits has been comparable to that of the deposits in northern Sweden, discussion of the origin of these ores has not yet proceeded.

Norway.

According to J. H. L. Vogt (64, 2), the Söftestad deposits in Nissedal, Telemarken, are of the same general character as those of Grängesberg, although much smaller. Apatite is the chief non-metallic mineral, averaging about 9.5 per cent (1.75 % P). No data about the geological environment are available.

At Lyngrot near Arendal (Vogt, 64, 2), magnetite ore with apatite, hornblende, etc., occurs in a granite, partly in the form of an »ore breccia» enclosing fragments of granite. It is not quite clear, how completely this deposit corresponds to the Kiruna type. There are analogies to the copper deposits of La Higuera (Prov. Coquimbo) in Chile, where chalcopyrite with magnetite and specularite occurs in gangue of actinolite and apatite, forming veins in gabbro. Also the Näsberget deposits in Sweden (17) belong to a similar type, evidently related to the Kiruna type but probably not entirely comparable to it.

Russia (Ural).

To summarise satisfactorily the geological relations of this group of iron ores belonging to the Kiruna type presents great difficulties. The author has no personal experience of the district, and the literature published in Russian has only in small part been accessible to him. Moreover it seems clear that strong weathering has constituted a serious handicap in the field studies. The published maps and sections are never carried into details. The following presentation is based on the available literature (62, 29, 39, 40, 3, 12, 67), and on a study of specimens collected in 1897 by A. G. Högbom and F. Svenonius.

The ore-bearing district in question, elongated in the general S.—N. trend of the Urals, is largely built up of volcanic rocks, alternating with limestones of Devonian age. Among the volcanics there are greenstones of varying character, and keratophyres, with their tuffs. There are also intrusive syenite bodies, probably closely related to the extrusive series.

At Vyssokaja Gora, the ore forms thick banks in a fine-grained syenite, rapidly varying in texture and changing into syenite-porphyries, partly with so fine a groundmass as to appear like hälleflintas. The syenite mainly consists of a sodic perthite, and has a striking general resemblance to the complex of syenite and syenite-porphyries that forms the foot-wall of Kiirunavaara. One remarkable difference, however, is the presence at Vyssokaja of great quantities of altered rock, now consisting mainly of garnet and epidote. The ore is of a high grade and contains but little apatite.

The Lebiajaja deposit, about 6 kilometers from Vyssokaja, on the other hand, is in part rich in apatite which forms either irregular segregations or fairly regular thin bands, both features recalling well-known characters of the Kiirunavaara ore.

Gora Blagodat would appear, from the description by Tschernyschew, Högbom, and Bogdanowitch, to be built on essentially the same lines as Vyssokaja. It seems, however, from the data supplied by Miss Derwies (12), as if the ore-bearing complex of syenite and syenite-porphyries formed an intrusion in the supracrustal series of flows, tuffs, and limestones.

The ore of Blagodat presents several peculiar features. Feldspar is reported to be frequent in some varieties, and to have crystallized before the magnetite. More unusual, and unique among deposits referable to the Kiruna type, is the common occurrence of phases with high percentages of augite and green spinel, first reported by Högbom. This variety in thin sections has the same general appearance as many titaniferous iron ores. The augite has a distinctly pink colour in thin sections, and is not comparable to the light green diopsidic pyroxene associated with so many other deposits of the Kiruna type.

The origin of these deposits has generally been ascribed to processes of magmatic differentiation (Tschernyschew, Högbom, and others). On the other hand the association with limestones, although generally not a close one, and the appearance of garnet-epidote rocks as alteration products of syenites and porphyries, have brought into the discussion the possibility of an origin by contact metasomatism (Bergeat, and others). Recently, Miss Derwies has distinguished, at Blagodat, between contact deposits apparently interstratified in the series of volcanic rocks and limestone, and magmatic ore bodies in the syenite itself and its porphyritic phases. The ore magma is regarded as the last crystallization product of the syenitic magma, saturated with volatile constituents, in »conditions intermediate between the state of solutions and the gaseous state», and in physical respects approaching residual pegmatite solutions[1].

United States.

Of the iron ore occurrences in the Pre-Cambrian of the *Adirondack* region, only a group around Mineville exhibits characteristic features of the Kiruna type, the ore being high-grade magnetite with a moderate admixture of apatite. The associated rocks are mainly foliated syenites of a decidedly plutonic character. Much has been written on the geology of the Adirondack ores, but the problem they present is a very difficult one, involving as

[1] It may be added here that, to judge from published descriptions, the Magnitnaja deposits in the southern part of the Ural belt are rather typical contact deposits.

it does the detailed interpretation of a complex of plutonics and intruded and perhaps partly assimilated sediments, all of which have received their present characters under deep-seated conditions. From available descriptions, and from observations made during an interesting excursion in 1913 under the able guidance of Dr. D. H. Newland, the writer has got the impression that the ore deposits in question are probably genetically related to the Kiruna type. For the general problem here considered, the chief interest lies in the deep-seated character of the igneous rocks associated with the ores.

The iron ores of the Pre-Cambrian of *southeastern Missouri* are characteristic representatives of the Kiruna type. The rocks containing them are syenitic or quartz-bearing porphyries, mostly with a pronouncedly effusive textural development. In its general character, this porphyry series has much in common with the ore-bearing porphyries of northern Sweden. The most important ore deposits are at Iron Mountain, Shepherd Mountain, and Pilot Knob. Iron Mountain is strikingly similar to Tuolluvaara in the dike shape of the workable ore bodies, and the abundant development of »ore breccia». The ore is a comparatively coarse hematite which is in part clearly martitic. Apatite is especially conspicuous in the ore veins that form the breccia, its crystals often reaching up to a finger's size, and often radiating from enclosed porphyry fragments or growing out from the walls. In textural features, therefore, the North Swedish deposit which forms the most exact counterpart of Iron Mountain is Painirova. There is also some amphibole (tremolite or actinolite), and quartz. More locally, a garnet rock with hematite and calcite has been found in association with the ore (54)[1].

The Shepherd Mountain occurrence has not been visited by the writer. According to descriptions by Crane (9), and Singewald and Milton (54), it is on the whole similar to Iron Mountain, but apatite and amphibole are not reported and there is instead rather much quartz, and also pyrite. Pilot Knob, on the other hand, represents a different form. It is the Missourian counterpart of the Hauki hematite ores near Kiruna. It is a bedded deposit, composed of two hematite layers separated by a bed of sericite schist. The upper ore bed contains layers of breccia that increase in frequency upwards, and a thick bed of which forms the top member. The ore is a dense, finely bedded hematite, containing feldspar and quartz and also, mainly in vugs and fissures, some barite. The breccia consists of angular or rounded fragments of more or less silicified porphyry, in a mass of quartzy hematite. It appears to grade into the porphyry. Recently, Singewald and Milton have described the common occurrence of tourmaline in association with the hematite in the breccia. While the ore itself does not present any particularly striking similarities to the Hauki ores, the breccia is practically identical with a common development of the latter.

As a result of detailed studies of this group, Crane (9, p. 132) formulated his views on their origin as follows: »The ores, in general, are regarded as having been deposited from hot, iron-bearing solutions as an after effect of the

[1] The writer is indebted to Mr. John Edwin for some specimens of this interesting rock.

porphyry extrusion, the solutions coming from the porphyry itself or from a source common to that of the porphyry. That at Shepherd Mountain is very largely a filling of stretch fissures due to the cooling and consolidation of the porphyry; that at Iron Mountain is in part fissure filling, but more largely a replacement of the porphyry, while that interstratified with porphyry breccia, as at Pilot Knob, Cedar Hill, and Russell Mountain, represents the more or less complete replacement and infiltration of stratified tufaceous beds of iron oxide.»

The present author (19, 20) got the impression that, in the case of Iron Mountain, replacement has been a subsidiary process and fissure-filling the most important way of deposition. Otherwise his conclusions were, in principle, the same as Mr. Crane's, the only difference being that Crane only speaks of the ore-forming solutions as hot, while the author would class them (except Pilot Knob and analogous occurrences) as magmatic, or at least very near the temperature of granite pegmatites.

Also Spurr (55) emphasizes the »clean-cut intrusive» nature of the Iron Mountain deposit, described by him as veindikes, in analogy with the view formulated by the author. Pilot Knob, on the other hand, is regarded by Spurr as a »black-sand» beach deposit. More recently, Singewald and Milton have discussed this group (54), adding also a number of important new observations. They uphold Crane's views, but stress his conclusions in a direction away from the side taken by the present writer, by stating in the final sentence: »If Iron Mountain alone were involved, one might be inclined to consider the mineralization pneumotectic, but since the Pilot Knob mineralization is so nearly like it, a more remote magmatic affiliation is indicated; a mineralization for which the term hypothermal would seem more correct». As to Pilot Knob, the clear cases of replacement and the frequent occurrence of tourmaline, as reported by Singewald and Milton, appear to form decisive grounds for an accepting of Crane's views in this deposit, and of the author's comparison with Haukivaara[1]. Some of the questions relating to Iron Mountain will be taken up in the following. It may be pointed out already, however, that while the presence of the garnet rock probably must be regarded as a new sign of replacement, the interpretation of Pilot Knob cannot be applied without modifications to Iron Mountain, any more than an explanation of Haukivaara can be directly applied also to Kiirunavaara.

In the Cordilleran region, a most typical representative of the Kiruna type appears to be the *Barth* ore body, near Palisade, Nevada. A detailed description by J. Claude Jones (32) gives a good picture of this deposit. The surrounding rock is a flow of hypersthene andesite, so basic as to carry, in its lower portions, phenocrysts even of olivine. The potash content is remarkably high (2.48 % K_2O against 2.94 Na_2O), indicating latitic affinities. The age is not mentioned, but from the geographical position a Tertiary age may

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[1] It is of interest to note, however, that the author, in the case of the largely similar Kuosatjvare deposit in Sweden (27), has been forced to a conclusion identical with that advanced by Spurr for Pilot Knob.

be inferred. The ore body forms a thick lens of high-grade hematite. Some magnetite also occurs, and Jones indicates the possibility that the hematite is, on the whole, secondary after magnetite (martite). The only impurities are small apatite crystals, scattered throughout the ore mass or segregated in patches. The outlines of the ore body are distinct, but there is a considerable amount of ore veins in the wall rock, apparently forming an »ore breccia». The andesite fragments in this breccia are green-coloured from an abundant development of secondary mica (phlogopite). Apatite crystals radiate from their corners, in the way that has already been described from Painirova and Iron Mountain.

Jones is of the opinion that the ore body was formed by replacement, but he also points out that »the replacement of the andesite has been remarkably complete. It is only in favorable situations that any evidence of the stages in the process can be detected. — — — — The striking feature is the extremely narrow zone of partial replacement.» As to the source of the ore solutions he says that they »came either as an after effect of the flow of andesite or as a basic splitting up of the magma that gave origin to the following rhyolites that cap the andesite».

The martite deposit of *Twin Peaks*, Utah, described by Patton (49)[1], also seems to belong to this type. The martite forms a system of dikes and veins in a siliceous rhyolite, and contains both apatite and augite.

The *Iron Springs* district in Utah, described by Leith and Harder (35), mainly harbours contact replacement deposits, but there are also some smaller bodies that apparently may be referred to the Kiruna type. The igneous mother rock, which forms laccolites in a series of Carboniferous, Cretaceous, and Eocene strata, is described as an andesite, but the high silica and potash rather suggest the term quartz-syenite-porphyry, as pointed out by Lindgren (36). The age is regarded as Lower Miocene. Ore deposition has mainly taken place through high-temperature replacement of the limestone at the contact. The ore mineral is magnetite and hematite. The phosphorus content, averaging 0.2 per cent, is higher than the normal value in contact deposits. Addition of soda, fixed in the form of albite, is a noteworthy feature of this mineralization. It may be remembered that a similar process has been noted at Tuolluvaara and Gällivare (in skarn breccia), as mentioned above, and to some extent at Kiirunavaara (25). A more subordinated type of occurrence at Iron Springs is in the form of fissure veins in the igneous rock. These, when of little width, sometimes show a comb structure, with apatite prisms arranged at right angles to the walls. Leith and Harder are of the opinion that the iron has been transported in the form of gaseous ferrous solutions, possibly as chloride, carbonate, or sulphate, as an after-action of the igneous intrusion.

[1] The author unfortunately has not had access to this paper. It is here quoted from a summary by Foshag (14).

Mexico.

It appears that only one of the iron ore deposits of Mexico can be referred to the Kiruna type — the Cerro Mercado, at Durango. This one, however, is of a considerable magnitude, and also presents characters of a great geological interest. Thanks to recent descriptions by the Instituto Geológico de Mexico (Salazar Salinas, and others, 52), and by Foshag (14), an entirely satisfactory basis for a comparison with the Kiruna type localities is available. The information previously supplied by Rangel (51) and Farrington (13) had already permitted certain conclusions with regard to the general similarity between Cerro Mercado and the North Swedish ores, but it is now possible to go much further.

The Cerro Mercado, according to the descriptions cited, is a mountain of Tertiary volcanics: latite, tuffs, and potassic rhyolite. Their age, according to Ordoñez (48), is Lower Pliocene. The characters of the massive rocks indicate surface flows. The ore consists of martite, sometimes very coarse-grained, up to 5 or 7.5 cm (14). Locally, skeleton growths occur (14). Apatite appears to be a constant component, generally to the amount of 2 or 3 per cent and with a fairly even distribution; phases particularly rich in this mineral are not reported. Silica, in the form of quartz, chalcedony, and opal, is widespread but mostly without any quantitative importance; it appears to represent a later phase of the mineralization. The ore forms flat-lying bodies. Foshag is of the opinion that several of them can be interpreted as sections of one single bed, broken up by faults.

The contact relations of the ore bodies are characterized by good examples of »ore breccia», and by considerable alteration of the wall rock. One of the most important products of this alteration is the development of a diopsidic pyroxene. Sometimes this mineral forms veins and gives rise to a »skarn breccia» that apparently is, in its essentials, similar to those of the Gällivare field. This impression, obtained from the descriptions, is corroborated by the examination of specimens kindly sent to the author by Dr. Foshag. There is some magnetite and apatite associated with the pyroxene. The pyroxene aggregates constitute the »pyroxenite» that has been reported from Cerro Mercado (52). An alteration of the latite to a clayey mass, largely consisting of a hydrous aluminium silicate (montmorillonite) also often has taken place at the same points as the introduction of pyroxene. There is also a development of magnetite, calcite, pyroxene, and apatite, in a way comparable to the occurrence of the purer pyroxene skarn.

Salazar Salinas and his co-workers regard the ores as basic magmatic differentiates, a view apparently largely influenced by their interpretation of the pyroxene rock. Foshag points out that the composition of the ore, and the apparently intrusive relations towards the country rock, indicate a magmatic origin. However, difficulties to explain the evolution of a magma of this character make him prefer the hypothesis of replacement by iron-bearing solutions.

Chile.

All important iron ore deposits in Chile belong to one well-defined belt that occupies, roughly speaking, the western third of the provinces of Coquimbo and Atacama, and extends northwards into Antofagasta. The deposits are most numerous in southern Atacama and northern Coquimbo. Most of them occur at some distance from the coast.

The region in question is referred to the Coast Cordillera, but this orographic element is not, in these parts of Chile, so distinctly separated from the High Andes as is the case further south, where the Longitudinal Valley is well developed, or in the north, where the wide nitrate pampas intervene between the mountain chains. The Coast Cordillera is generally regarded as a core of old rocks — Pre-Cambrian or Paleozoic — overlain by late Mesozoic and Tertiary deposits. From what the writer has seen of the ore-bearing belt in southern Atacama and northern Coquimbo, and from the available geological literature — which is very meagre, as far as this particular portion of the Coast Cordillera is concerned — it appears that the iron ore belt entirely falls within the younger, in a geological sense Andean part, and has nothing to do with any old, pre-Andean block along the Pacific. The main geological units in the belt between El Tofo and the town of Vallenar are the same that are familiar to any geologically interested traveller on the »Longitudinal» from Santiago northwards: the »porphyrite formation», and large granodioritic intrusions. The porphyrite formation (56, 45, 66) is a series of basaltic and related lavas, generally porphyritic and often amygdaloid, with intercalated coarse tuff agglomerates and beds of sediments, generally limestone. In age it ranges from Jurassic to Upper Cretaceous[1]. This bedded series is often faulted and tilted, but does not, within the zone in question, display any signs of close folding. It is intruded by enormous masses of light gray granodiorite (the »Inclusion granite» of Little, 38). There are also shallow (hypabyssal) intrusions of rocks that generally can be referred to andesites and trachytes, or to their more coarse-grained dioritic or syenitic equivalents. With this group the iron ores are connected. At Tofo, the ore-bearing rock, although itself free from quartz, appears to be closely connected with a typical »Andine granite», or granodiorite. At Algarrobo, on the other hand, there is a very marked difference, not only in composition but also in age, between the granodiorite and the ore-bearing complex, the latter representing a later and much more superficial igneous manifestation. Thus, the iron-bearing rocks should not be older than the late Cretaceous, and more probably of Tertiary age (compare also 6).

Among the published descriptions of Chilean iron ores, Vattier's reports (63, and others) give a wealth of data on the shape and the size of the ore bodies, but very little information concerning the country rock. The Tofo

[1] The »Cerro Negro Series» of Lindgren and Bastin (Econ. Geology, 17, 1922, p. 77), wide-spread in the country surrounding the Braden mine, is closely similar in general characters to the »porphyrite formation» of the region now considered, and also to its development along the Trans-Andine railway. It seems highly probable that it is of the same age.

deposits have been described by several visitors (compare 44), and for the numerous occurrences in the south of Atacama, Linnemann's report furnishes many important data. Also Daniels's brief paper ought to be mentioned.

The ore mineral is magnetite, often secondarily oxidized to hematite (martite), and sometimes mixed with primary hematite. The chief impurities are an actinolitic amphibole, and apatite. In general, none of these minerals appears in any quantity, thus the iron content is high. The apatite is mostly quite subordinated, but in some deposits, as at Ojos de Agua, it is locally abundant.

It is the opinion of all recent students that the ores are of magmatic origin, although probably not without connection with »after-action» processes. This is the position taken by Miller and Singewald (44, 53), Harder (quoted by Miller and Singewald), Daniels, and Linnemann. Harder and Daniels both point out the fissure-filling, dike-like appearance of ore bodies.

The writer's own field experience is limited to the ore fields of Algarrobo, Ojos de Agua, and Tofo.

The stock-like ore bodies of the Tofo deposit[1] consist of finely crystalline magnetite, more or less altered to martite, and contain occasional prisms of altered amphibole. In places some apatite is also visible. The country rock at some distance from the ore bodies has been found to be a fine-grained granodiorite or »Andine granite». It has tabular plagioclases, about one millimeter in length, zonally built, probably averaging about $Ab_{70}An_{30}$, further quartz, in part irregularly intergrown with the plagioclase, very little potash feldspar, some uralite (occasionally with lamellar twinning), and magnetite. In the area affected by the mineralization, the character is different. The rock is there a diorite porphyry, free from quartz and made up almost entirely of oligoclase. The texture is porphyritic, with a development of numerous phenocrysts of varying sizes and a fine-grained groundmass, sometimes quite subordinated. In general, the rock in the neighbourhood of the ore bodies has become strongly altered, obviously in connection with the introduction of the ore. It is penetrated by a network of magnetite veins, mostly not more than one or a few centimeters in width — often much less — and frequently with apatite along the middle. Veins of actinolitic amphibole are also very numerous. The rock between the distinct veins (whether of magnetite or amphibole) is, to a smaller or larger extent, sometimes even completely, replaced by amphibole with some epidote. An exception is represented by a band, about one meter wide, in which the network of magnetite veins takes on another appearance, and replacement by amphibole is lacking. This rock, otherwise similar to the diorite porphyry just described, differs from it by a rather high percentage of pyroxene, in two generations. The pyroxene is an enstatite-augite with a small angle of the optical axes and low birefringence, and with a striking lamellar twinning parallel to 100.

[1] The writer wishes to express his sincere thanks to the local representatives of the Betlehem Steel Co. for facilities extended during a rapid geological examination of the open cut workings at Tofo.

Several dikes of diorite porphyry are later than the mineralization. A specimen from one of these dikes proved upon microscopical examination to be practically identical with the pyroxene-bearing rock that was just mentioned. The latter is unquestionably older than the ore, but since it differs in composition and also has reacted, during the mineralization, in a way different from that of the country rock in general, it is reasonable to suspect that it represents a dike injected into this rock. If this be the case, then we have at Tofo a set of diorite-porphyry dikes that are in part older and in part younger than the ore, in analogy with the relations found at Kiirunavaara. This, however, in the case of Tofo can only be presented as a possibility that may deserve further study.

Algarrobo[1], probably the largest of Chilean iron ore fields, is situated in the province of Atacama, about 30 kilometers S.W. of the town of Vallenar. It is surrounded by granodiorite hills. The ore-bearing belt forms a series of dark hills, strongly contrasting against the light grayish yellow surface colour of the granodiorite. This belt is about 1 or 1.5 kilometer wide, running nearly due south—north and tapering towards the south. The northern end is covered by alluvial deposits, but the exposed length surpasses ten kilometers. It is made up of volcanic rocks — of the character of sodic andesites, and trachytes — in part rather strongly altered, of ore bodies, and of a number of trachytic and andesitic dikes that cut the older rocks and also the ore bodies. The belt has a steep position, and seems to have rather regular and straight boundaries against the granodiorite. Unfortunately, the actual contact is generally masked by float. In some cases, dikes similar to the main ore-bearing rock are observed in the granodiorite, and some of the dikes that cut the ore-bearing complex can be followed into the latter rock. From these facts, as well as from a consideration of the general geology of the region, there seems to be no doubt that the ore-bearing rock is younger than the granodiorite and forms a dike-like intrusion in the latter.

The granodiorite is generally fine-grained, with thickly tabular feldspars, about one millimeter in length. Part of it is really a sodic granite, poor in dark minerals, but there are also seen, on a smaller scale, dioritic phases with zonal plagioclases (about Ab_{70} An_{30}), a considerable percentage of uralite and but little quartz. The uralite shows the same kind of lamellar twinning as the enstatite-augite of the Tofo rocks. Seams of tourmaline are often noted in this rock complex, particularly in the most quartzy varieties. The rocks are much fissured, and cut by narrow crush zones.

In the central part of the ore field, where a deep »quebrada» gives good exposures of undecomposed rock, the main mass of the ore-bearing igneous body is found to be an agglomerate. In a grayish green groundmass, with small white phenocrysts of plagioclase, there lie rounded or sinuous, but rarely angular inclusions, from a few tenths of a millimeter to 8 or 10 centimeters in diameter, perhaps even a good deal more. These inclusions are mostly

[1] The writer is indebted to the Compañia Chilena-Alemana-Holandesa de Minas de Algarrobo for permission to publish these observations from a geological study of the property.

darker than the containing rock, which they often surpass in quantity, with a dark, bluish purple or blackish gray groundmass and white phenocrysts of plagioclase, generally not over 2 mm in size. Under the microscope, the cementing rock is found to consist of an albitic plagioclase (refractive indices $< 1{,}538$) as phenocrysts and as groundmass laths, 0.025—0.030 mm in length, and of subordinated chlorite between the latter. The fragments generally show a very high proportion of magnetite in the groundmass. Their plagioclase phenocrysts are like those in the cementing rocks, thickly tabular,

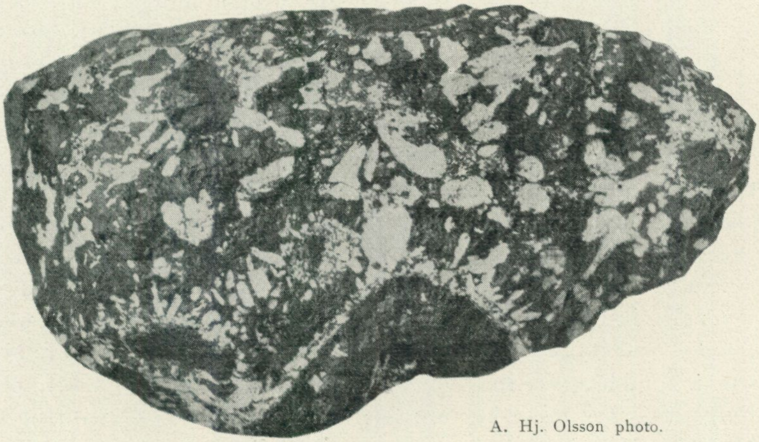
A. Hj. Olsson photo.

Fig. 4. Agglomerate, Algarrobo. Microphoto., ord. light, $\times$ 16. Shows sinuous fragments of rock extremely rich in magnetite and with well-developed feldspars.

and show good crystal faces against the groundmass. In one case the composition was optically determined to Ab_{85} An_{15}, with areas of Ab_{95} An_{5}. The magnetite is probably largely oxidized to hematite. It is developed in extremely small grains, aggregated between the narrow plagioclase laths of the groundmass. In certain fragments, almost no feldspar can be discerned in the groundmass, the feldspar phenocrysts thus lie in a mass of nearly pure iron ore (fig. 4). Although the plagioclase is not so pronouncedly sodic as in the magnetite-syenite-porphyries of northern Sweden, the analogy in composition is very striking, and in texture it is practically complete.

Agglomeratic rocks of this character can be traced over a large portion of the ore field. In one place, a related form was encountered, consisting entirely of sinuous or rounded fragments, fitting well together and varying but little in size, about 0.15—0.30 mm. They consist of the same sodic andesite-like rocks as the coarse agglomerate, including varieties very rich in iron ore.

Massive rocks of an andesitic habitus have been identified in several parts of the field. Their feldspars are often destroyed, being altered to sericite, chlorite, and opal. When preserved, they are mostly found to have optical properties similar to those mentioned above, but there has also been found a variety with more basic oligoclase (more than 20 per cent An). The magnetite content of the groundmass is often rather high. There is also much chlorite, presumably replacing dark silicates and interstitial glass.



A. Hj. Olsson photo.

Fig. 5. Boulder of unusually apatitic ore (martite), Algarrobo. About $^1/_2$ nat. size.

Near both ends of the ore field, and occasionally also in its central parts, a potassic trachyte appears instead of the andesitic rocks.

The ore of Algarrobo is a very rich martite, forming bold outcrops. There is more or less magnetite left in it, and purer magnetite is encountered underground. There is, therefore, no doubt that the martitization is a result of superficial weathering. The size of grain is remarkable. Ordinarily, it is measured in millimeters or one or a few centimeters, but in some varieties one may see reflecting surfaces that reach up to seven or eight centimeters. A little amphibole is often noted. Apatite is not observed in most outcrops, but is rather conspicuous in places. As is generally the case in ore deposits of this type, it appears to be more common in dikes of smaller dimensions than in the larger ore bodies. Sometimes the apatite forms finely crystalline segregations, aggregates of thick prisms that are about 0.30 mm long by 0.08 mm wide. The similarity to the apatite aggregates in the Kiirunavaara ore is complete. Generally, however, the apatite forms larger prisms, up to a finger's size. These prisms frequently grow out parallelly from a certain plane, with very thin partitions of ore between them, forming a striking honey-comb texture. In other cases, the surface from which they start is that of a lump of purer ore (fig. 5). These characteristics apply also to the Ojos de Agua ore, and, according to Linnemann's description, also to that of Cachiyuyito. Sometimes a little epidote-orthite is associated with the apatite. Quite locally, the Algarrobo ore shows another character, being made up of small specular hematite plates that enclose rounded lumps of a fairly coarse-grained tourmaline rock.

The ore forms stock- or dike-like bodies, generally very sharply defined against the wall rock. »Ore breccia» in the form of magnetite dikes and veins in the country rock does not appear on any large scale, although dikes high in apatite are remarkably frequent within certain restricted areas.

Sometimes the country rock has been strongly altered, clearly in connection with the introduction of the ore. Actinolitic amphibole has formed, or, more commonly, biotite in fine flakes. The frequently occurring chlorite may also in part belong to this stage, or replace earlier minerals belonging to it. Some magnetite and apatite are also introduced along with the silicates. In certain parts of the field, the alteration has led to the formation of scapolite rocks, with some actinolite.[1]

Another type of alteration has resulted in aggregates of tourmaline, quartz, and hematite. The tourmaline is very fine-grained, down to 0.003 mm in size. In general these three minerals appear in comparable quantities, but locally one of them predominates. Quite exceptionally, bodies of martitized magnetite appear also in this association. This type of alteration has followed well-defined zones, and its products outcrop as marked ledges. There are also places where a complete silicification of the igneous rocks has taken place — generally so that the micro-texture can still be discerned — without any introduction of iron or boron.

The dikes that cut the ores and the enclosing rocks belong to several petrographic types, all of them porphyritic. The majority are trachytes, generally with both orthoclase and an albitic plagioclase (sometimes, in the phenocrysts, forming very coarse and irregular perthitic intergrowths), but in some specimens one or the other of these kinds of feldspar predominates almost to the exclusion of the other. Quartz is almost invariably present in moderate quantities, filling miarolitic pores, or poikilitically enclosing the feldspar laths of the groundmass. Magnetite in small crystals is also a constant component of these dikes, but the quantity is always small. Chlorite may develop abundantly in the groundmass, and gives to the rock a greenish tinge, which caused many trachyte outcrops to be, in the mapping, mistaken for andesitic rocks. There are also some dikes of andesitic composition, with basic plagioclase (andesine to labradorite), pyroxene of the enstatite-augite variety, ore minerals, etc.

The geological interpretation of the ore-bearing belt of Algarrobo presents a somewhat complicated problem. So much is obvious, in any case, that it represents an igneous body which has solidified at a very shallow depth. It is built up of agglomerates, formed by lava rocks of somewhat varying com-

[1] The occurrence of scapolite in specimens from Algarrobo has already been noted by Dr. Cissarz (private report).

position, mixed and welded together while at least part of them were still in a fluid state, and also by massive volcanic rocks, both andesites and trachytes. It must be left an open question whether any material has been brought down from above, from the surface, by falling back into a deep opening. The only rock that suggests such a possibility is the well »classified» fragmental tuff mentioned above. Otherwise, the agglomeratic phases show no features that preclude their having been formed in the sub-structure of a volcano rather than at the surface. Bedding is entirely absent. Apart from the occurrence of the ores, and the metasomatic actions related to them, as scapolitization, the sequence of events is a normal one for a volcanic sub-structure: intense alterations, particularly a replacement by silica, have taken place, and the final stage has been marked by a number of dikes, almost limited to this belt, and more or less closely related to the types represented in the main mass. The whole picture is just what one would expect in the sub-structure of a volcanic edifice of andesitic and trachytic character, when its nature has been that of a line or fissure eruption rather than a »central» volcano.

The ore bodies of Ojos de Agua, north of Algarrobo, probably belong to a more or less direct continuation of the Algarrobo zone. The ore outcrops, particularly the main ore body on the top of a conical hill known as the Cerro Pyramide, illustrate, probably better than most iron ore outcrops in Chile, the control that the resistant iron ore masses have exercized on erosion. The wall rock, cut by a network of ore veins, belongs to types similar to those encountered at Algarrobo. One specimen that has been studied microscopically is a sodic trachyte, almost entirely made up of albite feldspar, ranging in size from tabular phenocrysts 2 mm in length down to more isometric groundmass grains only 0.04 mm in diameter. There is also some magnetite and quartz, and secondary chlorite, which is especially abundant near magnetite veins. Another specimen is a feldspatic andesite, very rich in phenocrysts of strongly altered oligoclase. The ore forms a number of steep, dike-like bodies, everywhere accompanied by a network of magnetite veins, mostly not more than about one centimeter wide, and often with quartz along the middle. This network is elongated in the same direction as the ore bodies. The ore is a coarsely crystalline martite, with grains 2 or 3 cm across. Actinolite is sometimes present in quantity, but mostly quite subordinated. Apatite is rare in some parts of the deposits, but abundant in others. It occurs in thick prisms, often club-like in shape, increasing in thickness from the starting-point. It is not rare to find crystals a decimeter in length and several centimeters in width. The apatite sometimes forms more than 50 per cent of the volume of the ore. These apatite-rich portions generally form elongated bands, dike-like but vaguely defined, in which the apatite prisms are arranged at right angles to the axis of the band, growing out in both directions from the axial plane, in analogy with the texture described above from Algarrobo. More rarely, the prisms start from a lump of ore, in the same way as in the specimen shown above in fig. 5.

Origin of the Kiruna type of iron ores.

As once formulated by Stutzer, »all earnest geologists» have regarded the Kiirunavaara-Luossavaara ores as genetically closely connected with the porphyries. This conclusion may well be extended to apply to all other representatives of the Kiruna type proper. For everywhere do these ores occur in igneous rocks, and quite frequently there are found facts indicating that they were, also in time, most intimately associated with the containing rocks. The best examples of such features are the occurrences of dikes belonging to the same igneous series as the wall rocks of the ore bodies, yet later than the ores, as at Kiirunavaara, Tofo, and Algarrobo.

The igneous rocks associated with ores of the Kiruna type present a moderate variation in chemical characters. Generally they belong to rather alkaline types that carry no quartz or at least not more than about 20 per cent. This is the case in the North Swedish region, in the Urals, in Missouri, and at Iron Springs, Utah, and such rocks also occur, although not alone, with the deposits in Mexico and in Chile. More siliceous rocks — true rhyolites or quartz-porphyries — are rarely encountered with these ores, but the Mexican »ore mountain» of this type, the Cerro Mercado, is largely built up of such a rhyolite. Rocks that may be classed as diorite porphyries and andesites have been encountered in many Chilean fields, and it is probable that they predominate decidedly over the trachytes in this metallogenetic province. Quite locally, similar rock types appear with ores in the North Swedish region, as at Nakerivaara. The most pronounced character in the way of low silica is perhaps represented by the andesite associated with the Barth ore body, in Nevada. Yet both there, and in the case of the bodies of the Gällivare field that are bounded by basic syenite-porphyries, there are also more siliceous rocks in the neighbourhood. Basalts and diabases have never been found to carry ores of this character.

With regard to the geological appearance of the containing rocks, a volcanic character is the rule; shallow (hypabyssic) intrusions are also frequently represented, however, but truly deep-seated rocks have been met with only in two cases that are, perhaps, not quite comparable to the rest. Surface flows carry the deposits in Mexico, Nevada, Missouri, and at least at some of the Swedish fields. Tuffs are not common, but are reported both from Mexico and Missouri and also, though in less immediate an association with the ore, from Kiruna. The problem of Algarrobo has been outlined above. Clearly hypabyssic intrusions, on the other hand, contain the most important ores of the Ural group, at Iron Springs in Utah, and at Tofo and presumably other fields in Chile. The only cases of deep-seated conditions are Lyngrot in Norway and Mineville in the Adirondacks. Particularly as these latter deposits may be to some extent different from the Kiruna type, it is clear that this type characteristically is associated with rocks that have solidified at the surface or at least at comparatively moderate depths. It follows, from the close association in time, that the ore bodies themselves also must have formed at quite moderate depths.

Of the different views that have been advanced to explain the origin of ores of this type, three only can be said to have any actual interest: the magmatic, the pneumatolytic, and the hydrothermal one. When speaking of magmatic in this connection, two processes, different in principle, may be meant. Either the ore substance has been segregated from the parent magma through a separation of early-formed magnetite crystals, resulting in an »accumulative» or »proto-enriched» deposit. This is the view taken by J. H. L. Vogt (65). As already pointed out above, the fact that the ores are always later than the bulk of the associated rocks has forced Vogt to add the hypothesis of re-fusion before the definite *mise-en-place*. The circumstance that the same intrusive relations return in every deposit of this world-wide type makes it extremely improbable that such a combination of events has been responsible for its production. It is also significant that no proto-enriched but not re-fused ore of this general character has been encountered anywhere, except possibly the augite- and spinel-bearing ore variety of Blagodat. This variety is unique among the ores of the Kiruna type, and also lacks the characteristic apatite. If one accepts the explanation that it is a product of proto-enrichment in a syenite magma, then the very fact of its striking difference (in composition) from all other ores of the Kiruna type certainly strengthens the view that the latter cannot be re-fused products of the same origin.

The other possible form of magmatic origin is that the ore substance formed a rest magma, remaining in the liquid state after the bulk of the parent magma had solidified as rocks. This explanation, advanced by the author about 20 years ago when considering the ores around Kiruna, appears to be the only form of the magmatic hypothesis that can explain the regularly late position of the ores in the magmatic sequence, and also the chain of transitional forms leading all the way to clearly hydrothermal deposits.

The pneumatolytic and hydrothermal hypothesis have that in common that they picture the ore deposition as a pronouncedly gradual process, the substance being successively transported to the place of deposition.

More or less interdependent of the problem magmatic against pneumatolytic or hydrothermal is the question of the *mise-en-place* of the ore substance, by intrusion (or fissure filling in other ways) or by replacement. If a magmatic origin is proved, replacement can only have been a subordinated, accessory process, and, *vice versa*, an ore body formed wholly or mainly by replacement can never be classed as magmatic. In the case of a pneumatolytic or hydrothermal origin, both fissure filling and replacement may have taken place.

It must be remembered that a decision can sometimes be difficult. If replacement can be proved to have occurred on a small scale, as in the case of offshoots containing unreplaced remnants of country rocks, or passing, by »dilution» with rock material, into impregnations, one is left in doubt whether the conclusion can be extended to cover also pure ore masses of a magnitude far surpassing that of the portions showing evidence of replacement. The author is well aware that there are cases when such an extension is fully justified, having also himself, in a discussion of the Huelva and related pyrite deposits, pointed out that »the absence of any proofs of replacement in the solid sulphide mass can hardly be quoted as speaking against replacement, for when the metasomatic process goes on until the rock is completely replaced, the textural proofs of replacement are generally destroyed»[1]. But the situation is certainly changed when positive evidence can be presented that replacement has not occurred. And this, in the author's opinion, in most cases holds true of the bulk of the ore bodies of the Kiruna type, and it may reasonably be extended to also such otherwise analogous cases from which direct evidence cannot be produced. No experienced geologist would now ascribe the ore body of Kiirunavaara to replacement. Yet there is no doubt that replacement (mainly by amphibole) has occurred to some slight extent at the contacts, and it is practically impossible to draw up, in the mine, a line separating these extremely subordinated portions from the main mass of the ore body. Again at Tuolluvaara, certain veins in the ore breccia — rich in amphibole, it is true, but also containing much magnetite — are not fissure fillings but imperfect replacements. But the majority of the veins, and the wider dikes of the breccia, as well as the workable ore bodies, show such clean-cut boundaries that replacement can hardly be thought of. The sharply angular rock fragments fit together, and the ore fills voids, not volumes once occupied by now disappeared rock material. At Tuolluvaara, then, replacement has been a quite subordinated process, but perhaps not to the same degree as at Kiirunavaara. Even at Gällivare, where replacement to a certain extent can be proved to have occurred in ore breccia and in ore banding, most of the ore, including the workable bodies, exhibits distinct boundaries without any signs of replacement. The amphibole skarn and associated minerals, on the other hand, is largely in the form of replacement veins, as already described.

In the iron ore fields in Chile that have been visited by the author, evidence of replacement was also found, but generally of silicates, as amphibole or mica, much less of magnetite (we are not for the moment considering the hematite-tourmaline-quartz type of Algarrobo, which is clearly a product of replacement).

In the case of Iron Mountain, Missouri, the author's impression also was that fissure filling has been the main process, and replacement of but little quantitative importance, except with regard to the amphibole (19, 20). In this, the author is at variance with Crane, and still more decidedly with Singewald and Milton[2]. It may be that the occurrence of garnet rock with hematite

[1] Congr. Géol. Internat., Espagne 1926, Comptes Rendus, p. 1233.

[2] It is, perhaps, rather characteristic of the difficulties encountered in this problem, that, on the other hand, Prof. Singewald does not reckon with replacement at Tofo, in Chile (44, 53), while the author, although sharing Singewald's view that the ore bodies are magmatic products, is absolutely convinced that the amphibole veinlets occurring there have been formed largely by replacement, like the impregnations of the same mineral.

and calcite, as mentioned above, strengthens the case for replacement, or, rather, makes it probable that replacement has been of a somewhat greater quantitative importance than once supposed by the author. But there is found very frequently in the Iron Mountain deposit the clearest evidence against replacement. Consider the texture, known also from other deposits of the Kiruna type, of apatite crystals growing out from an inclusion of country rock (or, as in fig. 5 above, one of another ore variety), and thickening in the direction away from the inclusion. Even if it must be admitted that the mechanics of replacement may sometimes yield very peculiar results, it can hardly be maintained that a texture of this kind can ever result from replacement. For, if the inclusion be an unreplaced remnant of the rock, how could the apatite crystals have started from a certain surface and grown towards the centre, tapering as they grew?

To judge from Jones's clear description, the Barth ore body (Palisade) also exhibits this feature to such an extent that the clear evidence of replacement also presented by the same author must be given only a limited application. In Foshag's description of the Cerro Mercado, it is pointed out that the evidence of replacement concerns chiefly the pyroxene; when the conclusion is extended to cover also the ore, this is done mainly because other explanations are held to be unsatisfactory. At Iron Springs, Utah, those ore bodies that occur within the igneous rock itself, are held by Leith and Harder to represent the filling of contraction fissures.

It seems clear, then, that while replacement by ore minerals has taken place to some extent in most fields of this type, and replacement by amphibole, pyroxene, or mica is still more important, the main ore bodies cannot essentially be referred to this kind of origin.

If thus intrusion or gradual fissure filling has been the chief way of deposition, the next step becomes to ascertain what conclusions can be drawn regarding the temperature, and the state of aggregation.

The temperature is indicated by the mineral association present. The critical minerals are magnetite, apatite, diopsidic pyroxene, and actinolitic amphibole (the peculiar augite- and spinel-bearing ore of Blagodat is not now considered, for reasons already indicated). Other constituents do not occur in such relations that any essential positive conclusions may be drawn from them. The association mentioned decidedly suggests an elevated temperature, but does not necessarily exclude the upper portions of the hydrothermal range, which may be extended up to 365° C. It is not so much these minerals themselves that indicate a truly magmatic temperature — which may be said to begin about 550° or 600° C — as the absence of certain other minerals. For if we compare such an ore body as Kiirunavaara with some other, smaller, deposits in the same region, there are not only very marked analogies, but also some characteristic differences. Thus the tourmaline found in the apatite dikes, and the quartz that is rather wide-spread as an evidently original constituent in the Rektor ore, indicate conditions somewhat different from those reigning in the case of Kiirunavaara, where very little tourmaline has been noted, and that only in a rather peripheral position[1], while the little amount of quartz appears to be wholly secondary. On the other hand, pyroxene and amphibole are lacking in the apatite dikes. In a way, similar evidence can be found at Algarrobo, where the very great quantities of tourmaline produced by hydrothermal replacement, and also in certain local ore varieties characterized by specular hematite, contrast against the absence of this mineral in the main type of ore bodies.

Although no reliable »geological thermometer» is present, one thus has very strong reasons to suppose that the crystallization of the typical ore bodies has taken place within a temperature range comparable to that of granite pegmatites, and perhaps even higher.

There has already been pointed out a common textural feature that cannot be explained by replacement. Also a number of other textures are incompatible with this explanation, as will be seen from the detailed descriptions of the Kiirunavaara ore (16, 58). But the textures in the ores of the Kiruna type are of interest also in other respects, indicating, as they do, that the inhomogeneities in the ore body are due to differentiation within a solution — to use a neutral word — that occupied the space now filled with ore, and not to a successive crystallization from material gradually transported to the place of deposition. The segregations of phases with different proportions of magnetite and apatite which have, along with other characters of the Kiirunavaara ore, been described by Stutzer and the author, indicate that the solution containing the substances which later crystallized as magnetite and apatite was of a magmatic nature in that it, in accordance with Brögger's definition of a magmatic dike[2], filled the fissure completely when in the liquid state, and later because of cooling solidified as a rock during a continuous time interval. There are also signs of several stages, however, inasmuch as purer apatite masses brecciate an already solidified, more or less pure magnetite ore, while more rarely the contrary relations are found, as at Tuolluvaara, where slabs of apatite-banded ore are enclosed in pure magnetite. All these textures, and still more clearly the occasional development of a trachytoidal flow texture (fig. 1, above), exclude a successive deposition from dilute solutions of liquid or of gaseous character.

On the other hand there are signs of a very high mobility of the magmatic solutions. Even when most clearly fissure-filling, as in certain phases of the Tuolluvaara ore breccia, the magnetite must have had a very low viscosity. It is also apparent that crystallization proceeded more easily, with fewer crystallization points and a greater freedom of movements for the molecules, than in the associated rocks. For although many of the deposits, as Kiirunavaara, have a size of grain not very strikingly surpassing that of the surrounding porphyries, others exhibit a remarkable difference, as Painirova, Iron

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[1] Vogt (65) has pointed out that the tourmaline found by the author is only an insignificant quantity. This has, in fact, been quite clear to the author, who has himself emphasized this situation (16).

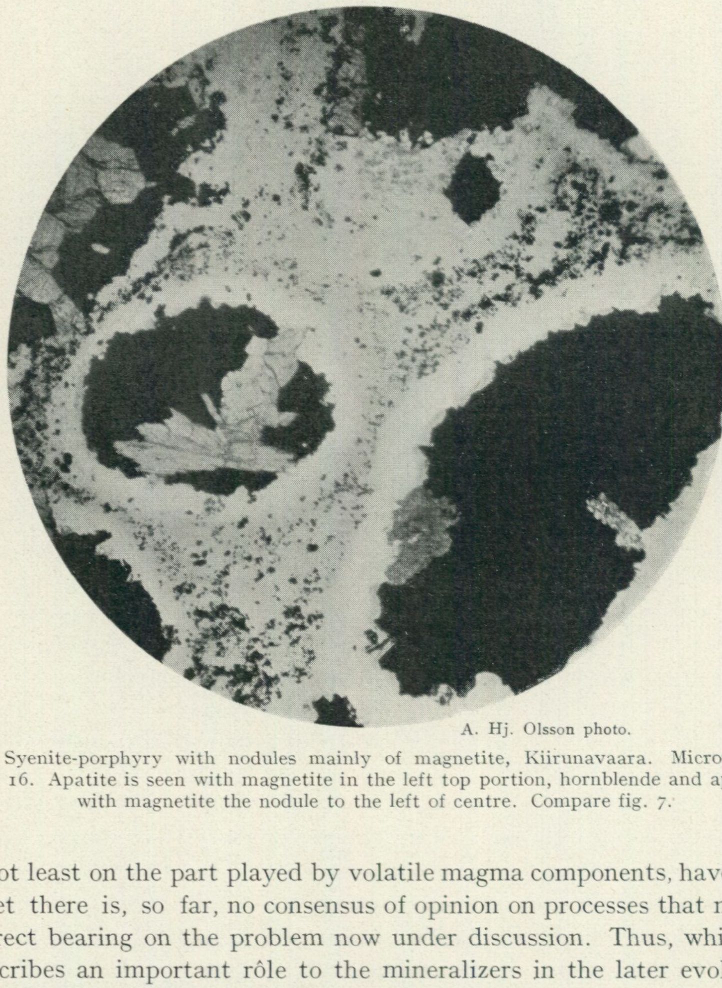
[2] Quoted by Barth, Die Pegmatitgänge der kaledonischen Intrusivgesteine im Seiland-Gebiete, Norske Videnskaps-Akad. i Oslo, Skrifter, 1927: II, no. 8 (p. 112).

Mountain (Missouri), Cerro Mercado, Algarrobo, and Ojos de Agua. It is also worth noticing that most of just these deposits display the radial grouping of apatite crystals, or their peculiar arrangement transversally in bands (as described especially from Ojos de Agua). Like the size of grain, these textures form an analogy with ordinary pegmatites. Entirely apart from the many other facts pointing in the same direction, therefore, these traits indicate crystallization in a magma with a high content of volatile constituents. The question has also been raised by the author (23) whether the state may not have been that of a supercritical solution rather than liquid magma. While this possibility must be kept in mind, a distinction between these two states can hardly be made for the present.

Above, the mineral composition of the ordinary ores of the Kiruna type was contrasted with that of certain associated deposits of less magnitude, as proving that the former ought to be referred to the magmatic temperature range. The presence of the last-mentioned group, however, with its distinct evidence of a more pronounced »pneumatolytic» or »pneumotectic» character, and the fact that no sharp distinction can be drawn between it and the ores regarded as truly magmatic deposits, furnish an additional and most important reason for regarding these latter as *late*-magmatic differentiation products. It is of a great interest, in several respects, that the chief ore bodies can, from their mineral composition and their textures, be interpreted as magmatic bodies, but the applying of the label »magmatic» must not be allowed to obscure the fact that mineralizers have played a most important part in the origin of these ores, not as modifying accessories, but as factors fundamentally necessary for its development. The term pneumotectic may perhaps be applied to all these magmatic products. It is also clear that gaseous phases have operated in a rather close connection with the magmatic stage. To such phases are ascribed the contact deposits of the Ural group, and of Iron Springs. The drusy martite veins reported from Twin Peaks (49) suggest deposition from wholly gaseous reactions, and similar phenomena can be traced also in other fields. Whether the replacement by skarn silicates and some magnetite, encountered in a number of fields and perhaps most conspicuous at Gällivare, is to be referred to gaseous or liquid watery solutions is an open question. The end of the series is represented by the hematite deposits that are evidently formed through hydrothermal processes and chiefly, at least, by replacement. Here belong Haukivaara and probably Skuokimjokk in Sweden (and, in a detrital form, Kuosatjvare), Pilot Knob and others in Missouri, and the tourmaline-rich, siliceous hematite bodies that occur in close proximity to the high-grade ores of magmatic character at Algarrobo.

The conclusions as regards the genetic character of the ores of the Kiruna type are thus essentially the same when considering all the representatives of this world-wide type as when the author once had little more than the Kiruna district to consider (16), in the late-magmatic character of the main ore bodies and the transitions, by increasing percentages of volatiles and decreasing temperature, down to typical hydrothermal deposits.

While these conclusions have a strong foundation in the geological observations, it has proved difficult to fit the differentiation process thus indicated into our so far established system of physico-chemical petrology. The author, in his earlier contributions on the subject (16, 18), did not get further than to the general and admittedly vague impression that an unusually high content of volatiles, especially water, in the parent magma was the decisive factor, and he had to leave open the question in what way this factor brought about the differentiation. Since that time, important works on physico-chemical petro-

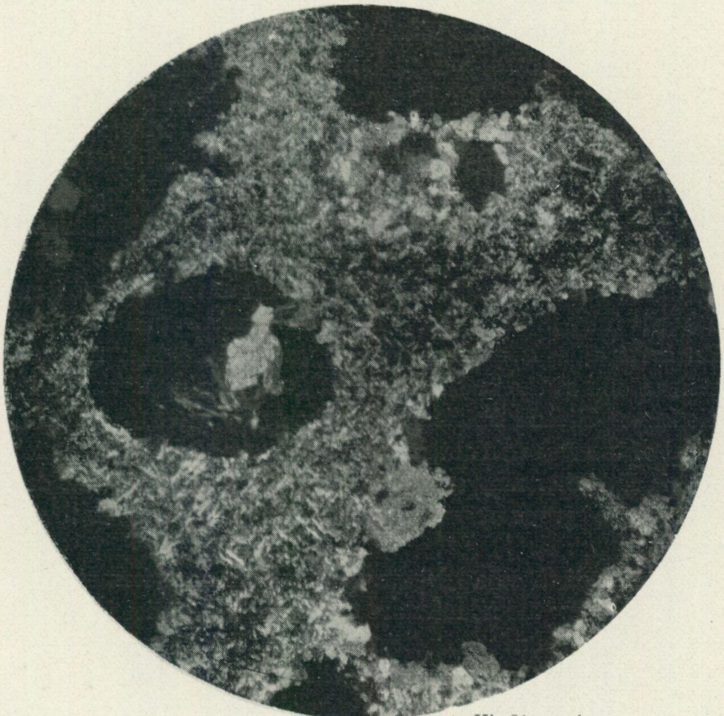


A. Hj. Olsson photo.

Fig. 6. Syenite-porphyry with nodules mainly of magnetite, Kiirunavaara. Microphoto, ord. light, × 16. Apatite is seen with magnetite in the left top portion, hornblende and apatite form with magnetite the nodule to the left of centre. Compare fig. 7.

logy, not least on the part played by volatile magma components, have appeared. Yet there is, so far, no consensus of opinion on processes that may have any direct bearing on the problem now under discussion. Thus, while Niggli (47) ascribes an important rôle to the mineralizers in the later evolutionary stages of a magma, Bowen (5) is rather conservative, and like Vogt (65) emphatically denies the possibility of a rest magma of the character in question. In the opinion of the present writer, the late-magmatic (pegmatitic or pneumotectic) character of the ore is proved by the observed facts; if this interpretation cannot be explained by reference to known physico-chemical laws, the conclusion must be, not that the geological evidence is misleading, but that our knowledge of the physical chemistry of magmas and the volatile substances contained in them has still to be improved upon.

We have, in the rocks associated with the ores, two lines of evidence pointing in the same direction as the characters of the ores themselves, that is, the production of a very late differentiation phase rich in magnetite. One is the rock group classed as magnetite-syenite-porphyries, the other the nodules (vesicle fillings) in certain porphyries. We shall now see whether a comparison with these features gives any more information on the origin of the ores.



A. Hj. Olsson photo.

Fig. 7. Syenite-porphyry with nodules mainly of magnetite, Kiirunavaara. Microphoto of same area as in fig. 6, but with crossed nicols. The white zones of feldspar are seen to be partly normal groundmass, and partly larger grains belonging to the nodules.

The characteristic features of the magnetite-syenite-porphyries are, chemically, their composition of alkaline feldspar (generally very decidedly sodic) and magnetite, and texturally, the late crystallization of the magnetite. These rocks have been encountered in the North Swedish ore-bearing region, in Ural (more locally), and at Algarrobo in Chile, and they have also been identified, without any associated ores, in New South Wales (1). They have never been found to be later than the ore bodies in the neighbourhood, therefore any attempt to explain them as due to resorption is excluded. Their repeated appearance in districts containing ores of the Kiruna type cannot be due to a coincidence.

The nodules, or vesicle fillings, are best developed in the syenite-porphyries of Kiirunavaara and Mertainen, and in certain varieties in the Gällivare field. There is a considerable variation in the mineral association, but generally hornblende and magnetite are most common, with titanite and apatite next. Biotite is found in some varieties, and feldspar is more often noted. Diopsidic pyroxene has been observed in the Gällivare field. The behaviour of the feldspar is rather remarkable. In the magnetite-syenite-porphyries, the nodules consist mainly of feldspar (16, 18). When there is feldspar present in the nodules chiefly containing ferromagnesian minerals, on the other hand, it is apt to form the outermost zone, next to the wall of the vesicle, and thus shows itself to have been deposited earlier than the ferromagnesian minerals and the apatite (figs. 6 and 7). It is worthy of note that in the specimen reproduced in figs. 6 and 7 the groundmass magnetite is in the form of crystals scattered through the feldspar mass, and not in an interstitial position. Like the fact just referred to concerning the magnetite-syenite-porphyries, this constitutes a marked lack of conformity in the order of crystallization in the rock and its vesicles, which is rather surprising in view of the very close relation between the ordinary rock and the minerals of the vesicles (compare 16).

The author is fully in accord with Bäckström in regarding the peculiar crystallization order that is marked by the vesicle-fillings of magnetite, hornblende, etc., as one of the most important facts bearing upon the problem of ore genesis in the Kiruna district. From the study of the Gällivare field (26) new material of interest was obtained when it turned out that typical vesicle-fillings of this character may sometimes occur also in rocks that carry a considerable amount of groundmass quartz. The reversed order is thus still more emphasized.

As to the origin of these aggregates, the author once formulated his views as follows (16, p. 241): the nodules are concretionary bodies in the porphyries; they have crystallized under conditions passing from igneous (magmatic) to aqueo-igneous and show a transition to the normal groundmass of the rocks on one hand and to true vesicles on the other hand. It was also indicated that the concentrated solutions had probably separated from the rock magma in a liquid state, forming immiscible drops. In a somewhat later treatment of the subject, however, the author admitted that this conclusion is not necessary, and that the hypothesis of a gaseous solution will just as well explain the observed facts (18).

While both the features now considered mean a late crystallization of the magnetite, there is the difference between them that in the magnetite-syenite-porphyries a gradual delaying has taken place, but in the case of the vesicle-fillings the segregation of a distinctly separate phase. Undeniably the latter case forms the best parallel to the differentiation of the ores, as these never grade into the rocks and only very rarely contain a little feldspar. A derivation — by squeezing, for instance — from a magnetite-syenite-porphyry might be expected to have contributed some feldspar along with the magnetite, but less ferromagnesian silicates than are found in the ores.

If we consider only the Kiruna district, there is a chemical difference also between the nodules and the ore bodies, in that the former contain a much higher proportion of ferromagnesian silicates and also much titanite, a mineral that in the ore is found only rarely, in vugs or at the contacts with the wall rock (16). That proportion is more favourable in the case of Mertainen, however. Also the separation of the material contained in the nodules is a decidedly low-pressure phenomenon, as is evident by their restriction to the porphyry phase of Kiirunavaara and their absence in the lower part of the igneous body, where only the titanite shows a comparable late crystallization. The separation of the ore substance, on the other hand, while quite clearly related in some way to only a moderate pressure, cannot have occurred so close at the surface, or the concentration into bodies containing tens and even thousands of millions of tons would never have taken place.

Disregarding the difficulties of a physico-chemical interpretation, and confining ourselves to the evidence of the geological studies, we can sum up the case as follows, with regard to the fractionating of the ore substance from the parent magma common to it and the associated rocks. The ore substance was held in solution while the bulk of the magma crystallized, and was separated, together with the volatile compounds contained in the magma, as a distinct phase in which the feldspar substance was not soluble to any considerable extent; the fraction thus formed, originally at a magmatic temperature and in a liquid or possibly a super-critical gaseous stage, was later differentiated into a series with gradually increasing percentages of water and other mineralizers, and with decreasing temperature.

The nature of the volatile substances involved in this process cannot be positively ascertained, but the lack of evidence of the presence of halogenes (apart from the fluorine contained in the apatite) at most deposits — the abundant scapolite at Mertainen and in a portion of the Algarrobo field are the only exceptions of importance — and also the clearly hydrothermal nature of the closing stages have led to the conclusion that water was the main agent (16, 18). Vogt (65) has mentioned also carbonic acid, which appears quite possible.

The question then presents itself why these rather ordinary and wide-spread mineralizers have operated in this particular way. It may have depended upon their presence, for some reason or other, in quite abnormal quantities, or on certain special factors. The first possibility has once been pointed out by the author as a probable explanation (16). But the question then arises how the magma ever came to receive such a quantity of mineralizers. To explain the appearance of much mica in certain granites, Goldschmidt (28) assumes that the magma had been intruded into sediments with a high water content. Another way is brought up by Zavaritsky's hypothesis (67) that the ore magmas of Vyssokaja, Blagodat, Kiirunavaara, etc., were segregated as the result of reaction between syenitic magma and limestone. If this view be modified by stressing the absorption of carbonic acid by the magma that might be a result of such a reaction, a way is indicated to account for an otherwise abnormal gas content. But there is, apart from the Ural deposits, and Iron Springs, no association with limestone in the districts carrying ores of the Kiruna type, therefore the explanation offered by this hypothesis, although possible, cannot be regarded as a probable one. On the whole, there is so much regularity in the occurrences of the Kiruna type that no such accidental geological event can be included as a condition *sine qua non* for its appearance. It seems more reasonable to seek the explanation in conditions more or less normally recurring in shallow-seated magma masses of a certain chemical range, under special exterior conditions, particularly as regards pressure.

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