SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 624 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 61 NR 9

PER GEIJER

INTERNAL FEATURES OF THE APATITE-BEARING MAGNETITE ORES

STOCKHOLM 1967

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1. INTRODUCTION

The original incentive to the following compilation was a discussion, at Kiruna in 1965, with members of the geological staff of the Luossavaara-Kiirunavaara Aktiebolag ("LKAB"), which operates iron mines in northernmost Sweden. This discussion resulted in a text that was stencilled for use in the LKAB and among others interested in the subject. As is not unusual, the grouping of observed facts in a new way also brought out features which had earlier not received the interest they deserve. Since ore deposits of this general type are now receiving increased attention in several countries it was found desirable to make the compilation accessible also to geologists unable to use the original, Swedish text. What follows is thus mainly a translation of the latter.

As indicated by the title there will be no general presentation of the geological aspects of the ore type or of the geochemical process through which the ore substances were concentrated. These subjects were included in a survey some decades ago (Geijer 1931). Nowadays this presentation is antiquated in some respects, especially as regards occurrences in Chile and Utah, on which important new data are available and will be reviewed. Otherwise reference must be made to the earlier publication, and, especially as regards the differentiation process, to brief papers of 1935 and 1960. The chief aim of this compilation is a survey of the mutual relations of the minerals that characteristically make up the ore bodies, stressing features which may give indications about the physical and physico-chemical conditions under which the ores were formed.

This is not to be regarded as a scientific treatise in the usual meaning of the term. It is rather an inventory of detail problems, presented as a talk to those who might be interested in the study of this remarkable ore type. It points out traits which appear significant, and tells, by detailed references, where to find further data on them — a sort of "reading guide". In some cases also hitherto unpublished field notes will be quoted, a verbal translation being chosen in order to reproduce correctly the original impression. Unfortunately it is impracticable to reproduce the many earlier illustrations to which reference will be made.

The ores will be spoken of as magmatic. In view of their generally intrusive relations to the country rock, certain textural features, and the inferred temperature of formation this is, at least for most occurrences, the only available term. And the recently discovered surface flows of El Laco in Chile, of the same character as the intrusive deposits, give further support to this designation. Yet it seems clear, and has been maintained by me ever since my first works on the subject, that this does not mean that the consolidation of the ores was wholly comparable to that of a "normal" igneous rock. The difference has been ascribed to the supposed role of volatile substances. So little is, however, still known about what has been called the "pneumotectic" or "low magmatic" stage of mineral and rock formation that it is futile to attempt now any precise physico-chemical interpretation of the variations in the effects of the volatiles that appear to be indicated by different deposits belonging to this ore type, beyond a discussion of the criteria for a possible distinction in certain cases between the alternatives magmatic and gaseous (pneumatolytic). But it is clear that study of this subject will provide one way of further penetrating into this difficult scientific field in general.

As stated above, the common form of emplacement of the ore bodies is intrusive. The contacts against the country rock are sharp. The ore bodies often take the form of dikes, generally rather wide in proportion to their length, or of sills, but more irregular shapes are also encountered. Associated with the ore bodies in most occurrences, though on a greatly varying scale, is an "ore breccia": a system of, in most cases, equally sharply defined ore veins, of thicknesses generally to be measured in centimeters or decimeters, in the wall rock. In most deposits the amount of ore in units of workable size is very much greater than that occurring as veins forming ore breccia. However, at Mertainen, SE of Kiruna, the reverse is probably true, and there are in the neighbourhood very extensive areas of ore breccia in which, so far as is known, larger ore bodies do not occur.

It is important to note that commonly the field evidence unequivocally indicates forceful injection, not a filling of pre-existing open fissures. The best illustration of these relations was furnished by the stripped rock surface about the ore bodies of Tuolluvaara (Geijer 1920, 1931), where it could be seen that brecciation by magnetite veins has caused an expansion of the affected area, the porphyry splitting up along joints, or occasionally along flow planes. An exception from this pattern, and so far the only proved one, is represented by the Iron Springs district, Utah, where there is evidence that deposition took place in open contraction fissures (Mackin 1947). Characteristically, however, the pattern is there much more simple than in the ore breccias.

Associated with the massive injection of ore material there has been in many deposits an apparently gaseous transport of material into the country rock, resulting in various kinds of replacement in the latter. Among deposits in Sweden, Tuolluvaara and Gällivare (Malmberget mines) give good illustrations, on very different scales (compare Geijer 1931). The chief products in both cases are amphibole and albite, showing that Mg, Fe, Ca and Na were introduced. At Gällivare some magnetite and apatite were also formed. At the contacts of the Kiirunavaara ore body there is often evidence of the metasomatic development of amphibole and magnetite within a narrow zone in the adjacent porphyry. The nature of the process is particularly clear where it has affected only the groundmass, leaving the feldspar phenocrysts intact. Other deposits show analogous phenomena. There is, however, always a clear distinction between the emplacement of the ores (including, at least for the most part, the veins of the ore breccia), which occurred by displacement, and this associated replacement process. Further, there are known districts where ores of this type, and pyrometasomatic iron ores in limestone, are associated with the same igneous body. This applies to certain groups in the Urals (Derwies 1924) and to Iron Springs, Utah (Leith & Harder 1908, Mackin 1947).

2. FINE-GRAINED AND COARSE-GRAINED APATITE

As a rule, apatite in the ores is developed in one of two forms which may be characterized as fine-grained and coarse-grained. Occurrences that are not easily referred to either category are rare. On the other hand, both types may be found in the same ore body, but then with one of them decidedly predominating.

In one type — "fine-grained apatite" — the mineral occurs as grains generally from a few tenths of a millimeter up to about 1.5 mm in length. The shape is usually short prismatic where free development has been possible, but slender prism shapes are sometimes found in purer apatite concentrations, not rarely with a trachytoidal fluidal arrangement. Fine-grained apatite occurs in any proportion with magnetite, from sporadic grains in the purer ore to bodies of apatite rock. This is the most common type found in Swedish deposits, but in most other countries it appears to occur only subordinately in the same ore bodies as coarse-grained apatite.

In the coarse-grained type the apatite grains generally reach at least a couple of centimeters in length. In some deposits they are thickset, but more often the shape is long prismatic, with a length about 5 times the thickness. The dimensions of the crystals are, of course, dependent on the conditions of growth: thus at Iron Mountain (Missouri) apatite prisms may not reach one centimeter in length in narrow ore veins of the ore breccia, but in larger units about 10 cm, the shape being the same in both cases. The distribution of coarse-grained apatite within an ore body is generally another than in the preceding type. It is rarely evenly distributed in the ore, nor does it often occur as units of pure apatite rock in the latter. Instead the normal mode of occurrence is in more or less local, very apatite-rich portions of an ore body which otherwise hardly contains any visible apatite. Oriented textures are common, as will be described below.

There is no absolute rule with regard to the relative grain size of magnetite and apatite. At Kiirunavaara, for example, both are fine-grained, and at Algarrobo both are generally coarse-grained. At Painirova, however, fine-grained magnetite is associated with apatite in both developments.

Broadly speaking, there appears to be a prevalence of fine-grained apatite in those deposits that are intimately — both genetically and spatially — associated with volcanic rocks, and of coarse-grained apatite in those formed under more deep-seated conditions. The most striking exceptions are represented by the occasional occurrence of coarse-grained apatite in ore bodies of the former group.

In the extrusive ore bodies of El Laco apatite is reported to occur as sporadic needles (Park 1961). The crystallization of apatite as slender prisms on rapid cooling is *a priori* to be expected, a fact confirmed by my own very primitive experiments (Geijer 1912, p. 766).

3. ORE WITH FINE-GRAINED APATITE

Variations in the proportion magnetite : apatite and the mutual relations of the different phases were studied, under unusually favourable conditions, in the outcrops on the ore ridge of Kiirunavaara, lightly etched by post-Glacial weathering. Observations were recorded by Stutzer (1907) and in my own more detailed description (Geijer 1910). For a general survey reference must be made to these works. Here only certain features will be treated: local differentiation (3.1), apatite-banded ore (3.2), and intrusions of apatite rock within the ore body (5).

3.1. Local differentiation

A remarkable aspect of the extremely varying proportions between magnetite and apatite that could be observed, was that locally a separation into pure apatite rock and pure magnetite ore was indicated. In these areas small lumps of apatite rock were found to be surrounded by a shell of pure magnetite, equally sharply bounded inwards against the apatite rock and outwards against the rather apatite-rich ore in which these zonal bodies are found. Common dimensions were, for the apatite core a couple of centimeters and for the magnetite shell a thickness of some millimeters. The shape of the zonal unit in the ore surface varied somewhat, the shell being generally circular or elliptical, or with a slight constriction that gives it a lemniscate form; occasionally the shell is broken at one point.

This phenomenon appears to illustrate a local differentiation, as already stated, but it is impossible to explain how these numerous centers of differentiation started, or why the growth appears to have stopped at approximately the same stage in all units, which appears to make the average composition of each zonal unit comparable to that of the undifferentiated ore between them.

3.2. Apatite-banded ore

3.2.1. *General characteristics.* The above term appears more suitable than "stratified ore", as was used in the first description of the phenomenon (Geijer 1910). "Stratified" implies a genetic interpretation which is clearly not applicable; besides, there are transitions to a more streaky distribution of the two components, magnetite and apatite. Banding occurs only in ore with fine-grained apatite, as defined above. This explains why it has so far been observed only in Swedish deposits, and in that of Lebiajaja in the Urals (Högbom 1898). The banding is a most remarkable feature in these ores, and must be taken into account in attempting to reconstruct the way in which they were formed. All relevant observations will, therefore, be reviewed in detail.

The phenomenon is an alternation of units with different proportions of magnetite and apatite, imitating a stratification. The apatite bands are, as a rule, pure or with only a little magnetite. In the magnetite bands the proportion may vary, from very apatite-rich ore to almost pure magnetite. The former case has been noted at Tuolluvaara and in the extension of the Rektor ore body which is exposed in the street Lärargatan at Kiruna. A moderate or high content of apatite appears to be most common. It must be noted that the variations referred to represent different occurrences of apatite-banded ore; within each sequence of ore bands, on the other hand, the proportion is fairly constant.

3.2.2. *Kiirunavaara.* The following description is based not only on already published data (Geijer 1910) but also on some not hitherto quoted field notes from the years 1906—1908. With the later disappearance of the ore outcrop due to mining, opportunities to study the phenomenon have become greatly restricted. Localities are here indicated by reference to the names of the hillocks on the original ore ridge. (Compare map, Geijer 1910.)

Typical banded ore occurred rather extensively near the foot wall in the northern part of Statsrådet and northwards from there on Geologen, and also in the spur of ore projecting obliquely into the foot wall in the lower area between Geologen and the next hillock, Gruvingenjören. Since the ore body undoubtedly was emplaced as an approximately horizontal sill, this distribution means that the banding was here restricted to its bottom parts. Higher up in the ore body on the stretch Statsrådet—Geologen the average content of apatite in the ore appeared to be lower, banding was absent, and the apatite, where megascopically visible, was largely in the form of irregular bodies of pure apatite rock.

The most conspicuous development of the banded ore may be designated as finely laminated. It is built up of lamellae of apatite, with absolutely plane surfaces and an even thickness of some tenths of a millimeter, alternating with lamellae of magnetite with rather much apatite, the latter units reaching somewhat greater thickness but hardly ever surpassing 1.5 mm. Such fine lamination has been observed through a thickness of 2 dm. (The best illustration of it is found in Geijer 1910, p. 98, Fig. 34.) On a fresh-cut surface the banding is difficult to discern, while on weathering the banded ore may take on a most deceptive resemblance to charcoal.

Sometimes, however, it occurs that a single lamella, or a few in succession, are moderately plicated, without this deformation having visibly affected those above and below. In one case I have observed that a band of apatite sent out one thin vein upwards and one downwards at the same point.

Unfortunately I never noted how far a laminated zone could be followed, but the general impression from my notes is that length was at least 10 times the thickness. The termination of the banding in the strike direction did not take place by wedging out, but in such a way that "the bands disappear in the purer ore, such as often occurs as thicker bands in the finely laminated one" (field note, 1908).

Banding, even if not of the finely laminated type, has also been observed in the outcrop in other parts of the ore body. Especially noteworthy is the observation that on the hillock Landshövdingen apatite-banded ore occurred "for a considerable stretch in the neighbourhood of the hanging wall", according to my notes. In another occurrence in the same part of the ore body the banding, in contrast to the rule, was found not to run exactly parallel to the ore boundary.

Microscopical study has given the impression that in the laminated ore the apatite has crystallized before the bulk of the magnetite. It was further found that the apatite grains lie with their longer axes in the plane of the banding, but otherwise without any marked parallel arrangement (Geijer 1910, p. 112). It is, however, desirable that these textural relations be further studied on samples of banded ore from various deposits.

In addition to the fine lamination found in the same parts of the ore body, there is also an alternation between different proportions of magnetite and apatite in a streaky manner. This may grade into a pattern of irregular schlieren (Geijer 1910, p. 101, Fig. 38). In the same parts one also encountered a banding in much thicker units, in which the smooth and shining weathered surface of the ore bands indicated almost pure magnetite. (For illustrations of this type, with common thicknesses, see Geijer 1910, p. 99, Fig. 36.)

The banding in relation to the country rock is illustrated by the following examples.

The large slabs of dike porphyry (older than the ore) which were enclosed in the ore body on Geologen, close to the foot wall (Geijer 1910, map, 1960, Fig. 11) were partly replaced by an actinolitic amphibole and for the rest interwoven by veins of varying composition: amphibole, amphibole and magnetite, only magnetite, "magnetite and apatite (often banded)" (field note 1906), or only apatite. The occurrence of banding in these veins is particularly noteworthy.

The spur of ore, mentioned above, which at the northern end of the hillock Geologen projected into the foot wall, in its lower part (thus next to the foot wall contact) contained a considerable amount of amphibole in the form of straight, parallel band a few centimeters wide, and also apatite in a finer banding, wholly similar to that observed on Geologen (field note 1907). Northwards this ore spur begins to carry sporadic inclusions of porphyry, and then grades into an ore breccia in the western (bottom) part of the sill-like body of dike porphyry that here forms the foot wall of the ore body. (Compare the maps quoted above.)

3.2.3. *Rektor ore body, Kiruna.* In this ore body, banding of apatite and ore minerals (magnetite and hematite) is common (see for example, Geijer 1950, Fig. p. 13), but no exact counterparts are found to the most finely laminated ore at Kiirunavaara. It may be noted that the ore differs in composition from that of Kiirunavaara, not only by a higher average content of apatite and the presence of primary hematite in addition to the magnetite, but also in wholly lacking amphibole but instead containing a small but constant amount of quartz. Since some curious interpretations of this ore body have been published, it is pertinent to point out that its emplacement by intrusion is as clear as in any geological unit, from the fact that it encloses large blocks of the adjacent rocks, both from the foot wall and the hanging wall (Geijer 1950, Pl. 1). Discussion of this avowedly in other respects enigmatic deposit falls outside the scope of this paper. The continuation of the Rektor ore body which is exposed in the street Lärargatan shows throughout its width (about 1 m) a rather coarse banding of alternating units of almost pure apatite and of apatite together with magnetite and hematite. Both here and in the Rektor ore proper a trachyt~~oidal~~ flow texure is common in the apatite.

3.2.4. *Apatite dikes in the Abel area, Kiruna.* These dikes occur NE of Mount Luossavaara (Geijer 1910, map), in the uppermost parts of the body of quartz-bearing porphyry which forms the hanging wall of the huge Kiirunavaara and Luossavaara ore bodies and the foot wall of the Rektor ore, the best exposures being in the Abel claim and vicinity. They often carry magnetite and then show banding (Geijer 1908, Fig. 3, repr. 1910, Fig. 48). "A parallel structure marked by magnetite and apatite, parallel to the walls, appears to be the rule rather than exception. When struck with the hammer the different bands separate easily, but the boundary between them is never quite sharp" (field note 1907).

3.2.5. *Tuolluvaara.* This deposit, situated 4 km E of Kiirunavaara, is not sill-shaped like the latter but made up of several wide and comparatively short ore dikes. The wall rock is in part intensely brecciated by ore veins. (Compare Geijer 1910, and, with more details, 1920.) The content of apatite varies but is on the average rather low. The mineral occurs in two different forms (apart from a wholly local third type, Geijer 1920, p. 22). One type is rather similar to the apatite of Kiirunavaara, white in colour and occurring in grains generally 0.5 to 1 mm in length. The other form is reddish or sometimes greenish, with a grain size generally about 1 cm, without any pronounced prismatic shape. The former type is the only one occurring in most of the apatite-rich parts of the ore bodies. The latter appears to occur sporadically in ore with a low average content of apatite, in the form of single grains or quite small aggregates; it has also been observed in the veins of the ore breccia. Further, it forms the rare occurrences of pure apatite rock brecciating pure magnetite ore. (See below, under 5.)

It is clear from these data that banding can occur only with the first-mentioned, fine-grained type of apatite. With this, however, it is the rule. As at Kiirunavaara, banding occurs near the boundaries of the ore bodies. Thus in the largest ore body, Choulalongkorn, where there was a belt of apatite-rich ore next to the hanging wall, banding was marked; it did not, however, begin immediately at the contact but was separated from it by a narrow zone without distinct banding. Similarly, in the Ararat ore body banding has been developed along the hanging wall. In the Västra Siam ore, again, regular banding has been observed at the foot wall. (Compare below.)

Banding in the Tuolluvaara ores is hardly ever fully comparable to the most regular fine lamination at Kiirunavaara, but otherwise there is no essential difference. Often, at least, the magnetite bands contain rather much apatite. A section parallel to the banding does not show any general orientation of the grains in an apatite-band. It is not certain, however, that this is an original texture: there are in the deposit signs not only of the preservation of primary textures, (as in the form of apatite parenthetically alluded to above) but also of recrystallization — certainly in the groundmass of the porphyry, probably in the magnetite.

An especially instructive example of banding is the one that could once be studied at the foot wall of the Västra Siam ore body. (Compare Geijer 1920, p. 18, Fig. 2.) This is best described by quotation from my field notes: "The ore is rich in apatite, partly with a schlieric alternation of ordinary C^1 [commercial quality with 0.2—0.6 per cent P] and very P-rich, but further out in the narrowing ore wedge it is well banded, on both a large and a small scale" (field diary 1918, SGU archives).

3.2.6. *Gällivare (Malmberget)*. In the chain of sill-like ore bodies which form the "Main Ore" of this field, banding of apatite is very common. Generally it takes the form that apatite grains lie in parallel rows, with many short gaps. It is not rare, however, to find also bands of pure apatite rock, reaching several centimeters in thickness. The present aspect of the banding is probably a result of the general recrystallization that has affected both the ores and the country rock, in contrast to the deposits previously described. Thus one may suspect that the rows of apatite grains have originally formed thin bands which, however, became discontinuous because of the increase of grain size at recrystallization. A comparable phenomenon is found in quartz-banded hematite ore changed by metamorphism into magnetite. Here, thin ore bands are often turned into chains of magnetite grains, because this mineral is apt to attain under such conditions a greater grain size than the hematite which it replaces. The possibility remains, however, that the distribution of the apatite in the Gällivare ores is essentially unchanged — compare below, on rows of apatite grains locally in the ore of Algarrobo, in which no metamorphism has operated.

3.2.7. *Origin of the banding*. No definite explanation of the banding appears possible at present, but the following alternatives appear to be the only ones to reckon with: a fluidal phenomenon in the crystallizing ore magma, or rhythmic crystallization.

The banding shows a distinct association with the boundaries of the ore bodies. It is important to note, too, that banding occurs also in wedges of ore, as in the above examples from the spur from the Kiirunavaara ore body that grades into ore breccia, and in the Västra Siam ore body at Tuolluvaara. In the latter case it is also of interest that a more irregular and streaky mixture of the two minerals changes into a regular banding as the ore gradually becomes narrower.

These facts appear to indicate that one is concerned with a fluidal phenomenon. If so, there are two different interpretations open. One is that fractions with different proportions of magnetite and apatite, such as are common for instance in the Kiirunavaara ore, have been rolled out into parallel sheets before complete consolidation. Against this interpretation may, however, be cited the constant proportion, broadly speaking, between the two minerals in a sequence of ore bands. The other possibility is that separation of the apatite bands occurred during, and as a result of, such rolling out. The crystallization sequence that is indicated by the admittedly meagre observational material may be cited in support of this view.

Rhythmic crystallization, proceeding from the walls inwards, is another possibility. This, however, appears less likely so long as only the above observations are taken into account, yet it deserves attention because of the possibility that it may have operated in certain occurrences with coarse-grained apatite (4.7).

4. ORE WITH COARSE-GRAINED APATITE

4.1. General characteristics

In addition to the features already mentioned (under 2) as distinguishing this mode of occurrence from the fine-grained form, certain oriented textures are commonly found in ores with coarse-grained apatite, viz., radial and parallel arrangement of apatite prisms. The former texture is found around inclusions, either of country rock or of ore, from which the prisms radiate. Very often they increase in thickness outwards, becoming club-shaped, which fact proves that the direction of growth was from the inclusion outwards. The parallel growth of apatite prisms, again, is found where growth has started perpendicularly from a plane surface, the wall of an ore body or of a vein in ore breccia. It also occurs, however, and by no means infrequently, that such a pattern begins at one not otherwise discernible surface within the ore unit. This surface appears to be on the whole parallel to the boundary surfaces of the latter. Parallel apatite prisms often grow close to each other, but generally there is some magnetite between them, at least in the form of thin septa, sometimes producing a kind of "honeycomb texture".

4.2. Painirova

This little known deposit, situated 16 km SE of Kiruna, can be described as an irregular ore breccia which includes larger concentrations. Among Swedish deposits it is the only typical example of coarse-grained apatite.

As mentioned above, the magnetite is fine-grained. Also a large part of the content of apatite occurs as small grains. Quite different is the development of the apatite in portions of the ore, in which it occurs in abundance, even making up almost half the volume. It is then found as prisms up to finger size, and typically illustrating both parallel growth, perpendicularly to the walls, and radial arrangement around inclusions of porphyry. The latter feature is illustrated by a detailed drawing published by Sveriges Geologiska Undersökning (1900) and still better by a photograph by Stutzer (1907). A significant detail, noted by myself on a visit to Painirova, deserves to be quoted. "The apatite prisms perpendicular to the contact are the rule, but often there occurs along the contact a narrow, fluidally streaky apatite-rich ore; only inside it do the larger apatite crystals come" (field note 1909). No similar development has been noted around the enclosed porphyry fragments.

4.3. Leveäniemi

In the large ore body of Leveäniemi (situated E of Painirova), apatite occurs in the fine-grained form (R. Frietsch, pers. comm.). But a distinctly later phase of ore formation is represented by apatite-bearing magnetite veins, 0.1—0.5 m wide, in which the apatite occurs as stubby crystals, arranged perpendicularly to the walls of the vein (quoted from Frietsch, 1966). To judge from the description and a specimen, the length of the apatite grains is about 2 cm. It is to be noted that they are not attached to the wall, but begin some centimeters inside the vein, exactly in the same way as in an ore vein at Cachiyuyito in Chile, as reproduced in the following (under 4.4.).

4.4. Occurrences in Chile

From a visit to three Chilean deposits — Algarrobo, Ojos de Agua and Tofo — in 1928, observations were included in my survey of 1931. This article is now out of date on important points, systematic investigations of many deposits by a number of Chilean geologists having led to a much better knowledge of the subject. The features treated here have, however, not so far been subjected to further study; therefore my observations will be reported in full. Before turning to this subject, however, it is appropriate to relate on what points my conclusions have to be corrected, and on which they, in my opinion, are still valid.

My impression was that the ores were genetically related to the (Mesozoic) volcanics in which most of them occur. New data make it evident that instead the parent rock is to be sought in the (likewise Mesozoic) batholithic complex in which the volcanics occur as roof pendants. This means, of course, that the genetic problem takes on a very different aspect. On the other hand I cannot agree with the conclusion of Ruiz (1964) that the ores were formed by contact metasomatism, and I maintain that they are to be interpreted as magmatic products — within the meaning of "magmatic" as outlined above. The reasons for this view can be summarized as follows. There are remarkable analogies, amounting to identity in all relevant aspects, with deposits elsewhere for which an origin by replacement is clearly excluded. The ore bodies — where I have seen them — are sharply bounded against the country rock, without transitions. Typical ore breccia is found associated with the larger units (although seldom on any important scale), and the ore bodies proper are sometimes dike-shaped, as at Ojos de Agua. The arguments for an origin by contact metasomatism are largely derived from the recently discovered deposit of Boquerón-Chañar, in which, to judge from the description (Ruiz 1964), metasomatic formation of magnetite may have taken place, at least to some extent. The widespread occurrence of scapolite in this deposit would also appear to furnish a weighty argument for an interpretation by such high-temperature replacement, since scapolite as a magmatic product is hardly consistent with our more or less conventional ideas of magmatic crystallization. Nor is one justified to use, as argument for a magmatic origin, the fact that in some occurrences, both in Chile and in Sweden, scapolite is found in magnetite veins of ore breccias, for it seems quite possible that such veins are deposited from gaseous solutions. A decisive fact is, however, that some scapolite, together with the usual non-metallic constituents amphibole and apatite, also enters into the undoubtedly magmatic flows of El Laco (Ruiz 1964). Thus the presence of scapolite cannot be regarded as an argument against a magmatic origin, and the complete analogy in mineral composition between the Quaternary El Laco flows and the Mesozoic deposits of Chile furnishes a most weighty reason for interpreting the latter, too, as magmatic products, although their mode of emplacement has been different.

At *Algarrobo* the more or less martitized magnetite ore is for the most part coarsely crystalline, with reflecting surfaces reaching 6 to 8 cm. The content of apatite is unevenly distributed and on an average not high. In part it occurs in the fine-grained form, mostly gathered in small streaks and then similar to the apatite concentrations of Kiirunavaara; the immediately associated magnetite has been noted to be fine-grained too. By far the greater part of the apatite, however, is of the coarse-grained type, and displays all the features cited above as characteristic for this type. It occurs in considerable amounts in portions of an ore body, without any marked limits against apatite-poor ore. The crystals may reach finger size. Illustrative are these notes from the examination of a certain ore body: "Apatite occurs, where present at all, abundantly in large prisms, generally approximately parallel but, also where the mineral predominates, separated from each other by martite. Often the apatite prisms are seen to grow out from certain, not otherwise marked planes, and stand at approximately right angles to them" (field note 1928). In one remarkable case the apatite prisms were found to radiate from rounded inclusions of ore (Geijer 1931, p. 23, Fig. 5). Within a certain restricted outcrop there was observed at several places a most peculiar grouping. The units are portions of the ore, approximately rotational ellipsoids in form, with their main dimensions about 15 and 30 cm, respectively, from whose periphery the apatite prisms have grown *inward;* between them there is, as usual, magnetite. The most probable explanation of these units seems to be that they were formed as "gas pockets", filled by the material last to crystallize. At one point at Algarrobo, near the boundary of an ore body, apatite was observed to occur as relatively small grains, arranged in rows. This may perhaps be something comparable to the apatite-banded ore of Swedish deposits, as described above.

At the much smaller deposit of *Ojos de Agua,* near Algarrobo, the ore bodies are dike-shaped. The average amount of apatite is higher than at Algarrobo. The ore is coarse-grained, the martitized magnetite grains reaching 2—3 cm and the apatite prisms often one decimeter in length and centimeters in thickness. As to the distribution of apatite in the ore bodies, "it forms 50 per cent, or more, of the ore within vein-like although not sharply bounded bands, in which the apatite prisms stand perpendicularly to the sides of the band, either (most often) from *one* central zone, but sometimes in several parallel rows" (field note 1928). The latter case is schematically illustrated by Fig. 1. A noteworthy detail is that a narrow magnetite seam, wholly similar and parallel to the one from which the left double row of apatite prisms grows out, as a clearly later element cuts one side

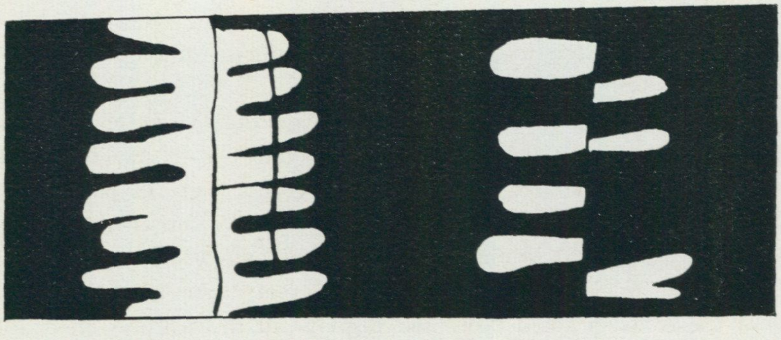

Fig. 1. Sketch of texture in ore, Ojos de Agua: apatite crystals in magnetite (martitized). Horizontal outcrop surface. Approximately 1/4 nat. size.

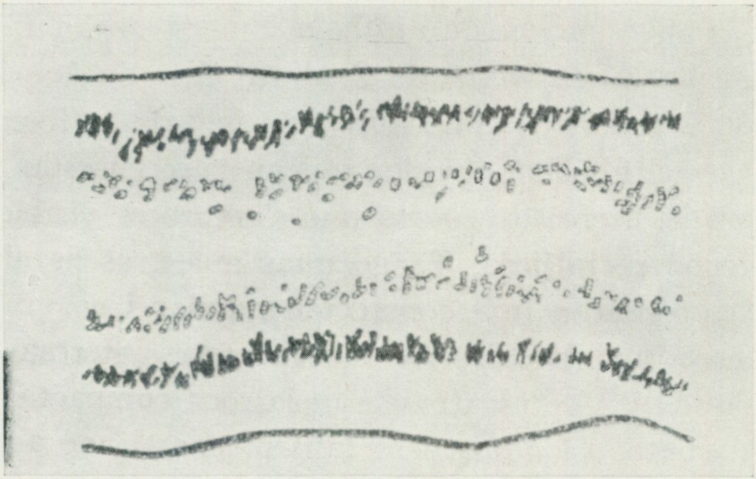

Fig. 2. Distribution of apatite and hornblende in magnetite vein, Cachiyuyito. After Linnemann (1921). Scale not given in original.

of this row. The apatite-rich bands run parallel, at least approximately, to the sides of the ore bodies. Also at Ojos de Agua apatite prisms were observed to grow out radially from an inclusion of ore.

From *Cachiyuyito*, an occurrence in the same province, Linnemann (1921) published a sketch of the distribution of apatite and hornblende in a magnetite vein, here reproduced as Fig. 2. With its comparatively thickset apatite grains and the distribution pattern, this occurrence shows a remarkable similarity to the apatite-bearing magnetite veins of Leveäniemi.

The *Tofo* deposit differs somewhat from those now described. The martitized ore is more finely crystalline. My observations on the apatite are fragmentary. It forms thickset prisms ("very much as at Algarrobo"); also a concentration of coarse-grained apatite was noted. According to information received at the mine the large apatite grains occurred scattered in the ore body, partly in a parallel arrangement; also streaks of fine-grained apatite were said to occur. (Compare Algarrobo.)

4.5. Occurrences in North America

At *Iron Mountain* in Missouri the mode of occurrence of the ore is similar to that of Tuolluvaara. The ore is much more coarse-grained than there, however. Apatite was observed by me chiefly in the veins of the ore breccia, in which it is very common as prisms, up to about one decimeter in length, growing out from the walls of the vein or radially from an inclusion of the porphyry that forms the country rock.

The *Barth* ore body at Palisade in Nevada according to Jones (1913) shows similar radial grouping of apatite crystals in the ore breccia. Of the apatite in the ore body Jones reports that it occurs as small crystals, scattered or in concentrations.

At *Iron Springs,* Utah, the main deposits are of pyrometasomatic origin, in limestone, but in the intrusive parental rock there occur veins of magnetite and apatite in which the apatite prisms have grown from the walls, forming a comb texture (Leith & Harder 1908, Mackin 1947). According to the analyses, the average amount of apatite in the pyrometasomatic ore bodies should be about 1.1 per cent, while single samples may surpass 15 per cent. For the veins no analytical figures are available, but the descriptions indicate that the average proportion of apatite in them is much higher.

In the *Kamloops* district, British Columbia (Young & Uglow 1926), there occur in two areas groups of magnetite dikes, in some cases reaching several hundred meters in length and some meters in thickness. The country rock is a large plutonic body, varying in composition from gabbro to monzonite. The ore appears to be, for the most part, low in phosphorus, but in places apatite, mostly in large grains, occurs abundantly, these portions appearing as bands several feet in width and following the boundaries of an ore dike or forming a central zone in it. The similarity to Ojos de Agua is striking, but oriented textures are not reported from Kamloops.

4.6. Occurrences in India

The occurrences of apatite rock in Singhbhum contain magnetite; one of them is even reported to have been worked as an iron ore deposit. Apparently they may be regarded as an extremely apatite-rich variety of the apatite-bearing magnetite ores. Very little detailed information about their nature is available, but a recent paper (Bohla et al. 1966) incidentally mentions that both apatite and magnetite occur as "large euhedral crystals". Though this does not give any clear picture of the mutual textural relations of the two minerals, it is evident that the deposits must be referred to the group with coarse-grained apatite.

4.7. Origin of the texture

The phenomenon with prismatic apatite crystals grown perpendicularly from the walls of an ore body is a typical example of what is called comb texture. This texture is hardly ever reported from ordinary igneous rocks. It is found in pegmatites, although less commonly than in the ore deposits considered here, and rarely with the regularity often found in the latter. On the other hand, this texture is common in fissure-filling veins in which mineral deposition has occurred from liquid or gaseous solutions. An important difference from these kinds of deposits is, however, not uncommon in the apatite-bearing magnetite ores, namely, the occurrence also of a radial arrangement of the apatite crystals around "unsupported" fragments, of country rock or of ore, enclosed in the ore body. Evidently such cases indicate a medium in which the isolated fragment could remain in position sufficiently long for an undisturbed crystallization of the apatite, and also of the magnetite — since else the apatite prisms would hardly have remained intact. And the conclusion must apply also to the whole ore body, including those parts where the apatite prisms instead grew out from the walls. Obviously, neither a gas nor a liquid of low density fulfills this requirement, and the condition at the time of injection of the material which was to crystallize as magnetite and apatite can only be designated magmatic.

In one case, however, where comb texture of apatite occurs in magnetite veins (but apparently no radial grouping has been noted), weighty arguments have been presented in support of the interpretation that deposition occurred successively from gases which passed through the fissure. I refer to the report by Mackin (1947) on the Iron Springs district in Utah, briefly quoted above. According to Mackin the veins fill contraction fissures in the intrusive parental rock of the deposits, and the vein fillings were derived from the rock adjacent to the fissures by magmatic gases escaping through them. The extraction of iron is indicated by zones along the fissures in which iron-bearing silicates have been altered.

For the occurrences at Iron Springs this interpretation appears plausible. Some points remain obscure. Is the apatite also assumed to derive from the wall rock, and if so, what is the quantitative aspect of that interpretation? And it is also clear that the interpretation cannot be applied to the other cases reviewed above which have in common with those of Iron Springs an orientation of apatite prisms in magnetite. Already the unsupported fragments, known to occur at least at Painirova, Algarrobo and Ojos de Agua, alone eliminate the hypothesis as a *general* explanation. In several deposits with the texture in question, as at Algarrobo, the shape of the ore bodies is inconsistent with the idea that they should represent once open spaces where gases passed through and gradually filled the void with a compact mineral aggregate. Also where the ores are fissure fillings conditions have not been comparable to those described from Iron Springs, where convincing arguments have been produced for relating the fissuring to the contraction of the cooling rock. In other deposits and, as mentioned above, most clearly seen at Tuolluvaara, the fissure pattern is a result of expansion caused by the forceful injection of the ore material.

Parenthetically it may be noted that the zones of extraction of iron which are reported from Iron Springs do not have any counterparts in the Swedish deposits. Instead there is often noted a replacement of the rock by new-formed iron-bearing minerals. (Compare above under 1.)

A mode of formation similar to that ascribed to the Iron Springs veins is indicated also for a number of mineral deposits that show great similarity, in both composition and texture, to those now discussed, but which occur under different geological conditions, without any close spatial association with an igneous mother rock. A good example of what I have in mind is presented by the Nautanen district near Gällivare (Geijer 1918). There, a mineralization of chalcopyrite in supracrustal feldspar-quartz rocks shows great variation in the associated new-formed minerals: magnetite, hornblende, apatite, scapolite, tourmaline, garnet and quartz, in varying combinations and proportions. What is of interest for a comparison with the magnetite-apatite veins now discussed is the fact that there occur, in addition to a disseminated replacement, also veins which are fissure fillings and which consist chiefly of actinolitic hornblende, apatite and magnetite. Such veins may reach several decimeters in width and show the characteristic comb arrangement of the apatite crystals, growing out from the walls (Geijer 1918, Fig. 15). From the general geology of the region it can be concluded that this mineralization is genetically connected with a granite which occupies wide areas although not, in the present surface of erosion, in any close proximity to the mineralized area.

It appears that magnetite-apatite ores with comb texture can be formed both magmatically, as illustrated by the occurrences with unsupported inclusions, and pneumatolytically. In many occurrences, features distinctly indicating either alternative are absent. In a discussion of the apatite-bearing iron ores of northern Sweden I have once written that their formation "belongs to the borderland between magmatic and pneumatolytical phenomena, so that they in one case ought to be designated by one of these terms and in other cases by the other, and that by too strongly emphasizing the contrast between them one is apt to overlook the fact that in treating this problem understanding of the close relationship between the processes is a prime requirement for a correct solution" (Geijer 1920, p. 31, transl.). No essential modifications in this statement appear called for today.

In most of the deposits of the type with which I am familiar, there is evidence that "magmatic" is the correct designation for the ore bodies, but it is not to be denied that ore breccias may instead have been formed, to some extent, by a gaseous phase. In this connection it is worthy of note that the ore breccias often are richer in apatite than the ore bodies with which they are associated, indicating a certain fractionation. Always, however, it is necessary to remember the evidence of forceful injection, even where a pneumatolytical origin may appear probable.

As to those magnetite ores that are characterized by coarse-grained apatite, neither the comb texture as such nor the radial grouping appears to present any difficulties of interpretation. There is, however, one frequently encountered aspect of the comb texture that deserves special attention; it has also been repeatedly accentuated in the foregoing. It is that the comb pattern may occur well *within* the ore body, instead of being based on its walls. The phenomenon is clearly seen when occurring in narrow ore dikes, as exemplified by the figure from Cachiyuyito (Fig. 2), but most observations refer to the interior of larger ore bodies. It differs from the ordinary comb texture by the fact that crystallization did not start with apatite, but with magnetite, the apatite beginning to form only when some magnetite had already crystallized next to the walls. An exceptional variation is represented at Painirova, where, as described above, the comb texture also begins a short distance inside the ore boundary, but is separated from the latter by a fine-grained, fluidally streaky zone of apatite-rich ore. These relations seem to indicate a more marked break in the consolidation of the ore magma, perhaps even separate intrusions.

A most puzzling example of comb texture is represented by the sketch from Ojos de Agua, Fig. 1 above. The pattern in itself might suggest that apatite crystals, growing out from a thin fissure, had replaced magnetite. This interpretation would, however, be contrary to all other experience from ores of the type, even if a slight corroding effect of apatite on magnetite may be traced locally at Tuolluvaara (5, and Fig. 4).

5. DIFFERENT INTRUSIONS IN THE SAME ORE BODY

At several deposits there have been observed intrusive relations between different parts of the ore body. The occurrence, at Algarrobo and Ojos de Agua, of small inclusions of pure ore in an apatite-rich variety has already been mentioned. The phenomenon is encountered only locally in these deposits, however, and the amount of ore that can be proved to belong to the earlier phase is insignificant. Further study may perhaps shed more light on the quantitative relations. Among other deposits with coarse-grained apatite the veins at Leveäniemi may be mentioned, although their emplacement appears to have been structurally independent of the earlier formed huge ore body, and the occurrence therefore, strictly speaking, does not fall under the heading as formulated above.

Reasons for devoting a separate section of this paper to the subject are, however, presented by some occurrences in Sweden (with fine-grained apatite). For one of them, Tuolluvaara, it is clear that certain ore bodies are composed of two separate intrusions, which have followed the same fissure system and were not radically different in magnitude. The other kind of relationship to be treated here is the occurrence of bodies of apatite rock which show intrusive relations to more or less pure magnetite ore varieties, although apparently forming part of the same original ore intrusion; the best examples are from Kiirunavaara.

The dike-shaped ore bodies of Tuolluvaara are, apart from local portions rich in apatite, composed of ore very low in phosphorus (< 0.015 per cent P) and a somewhat greater amount of ore with a moderate phosphorus percentage (in commercial quantities < 0.60 per cent P). In the latter often no apatite is discernible, and distinguishing it from the lowphosphorus variety requires chemical analysis. On the other hand there are also parts in which the amount of apatite is much higher than the average; these parts generally show banding, as described above (under 3.2.5). The geological relations between the two types are imperfectly known. They could be studied with advantage in the stripped outcrops, but when my studies began — in 1907 — the parts most interesting in this respect were already largely eliminated through open cut mining. From what remained, and from data recorded during mining, the following picture is obtained of what apparently the most instructive part of the deposit, the largest or Choulalongkorn ore body.

This ore body, striking WSW-ENE, had a surface length of about 300 m and a width generally about 15—20 m, the dip was moderately steep SSE. The original surface was, in 1907, still preserved at the western end, and showed ore without visible apatite, in which were enclosed several fragments of ore comparatively rich in apatite and having a somewhat irregular banding. A drawing published by Stutzer (1907, Fig. 7) is probably from here. A less clear picture of the banding but a better one of the contact relations between the two ore varieties is presented by a photograph (Geijer 1910, Fig. 67, and 1920, Fig. 4). It is here reproduced as a partly schematical drawing (Fig. 3), in order to bring out the essential features. I have noted explicitly that the banding in the inclusions ran approximately parallel to the near-by hanging wall, although they were wholly surrounded by ore of the later intrusion. It may be observed from the figure, however, that the intrusion did not follow the banding but cuts obliquely across it, with a characteristic contact pattern.

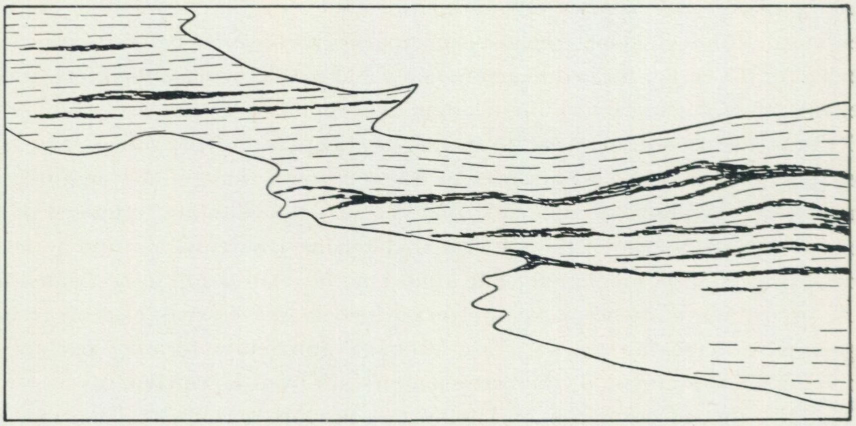

Fig. 3. Inclusion of apatite-rich ore in pure ore, Tuolluvaara. Horizontal outcrop surface. Approximately 1/5 nat. size. Drawn from a photograph (Geijer 1910, p. 216). In the inclusion the distribution of apatite is shown in black, the more conspicuous bands and streaks being reproduced individually, and the finer pattern schematically.

From the open cut, which already at the time of this field work extended for most of the length of the ore body, I have noted that (comparatively) phosphorus-rich ore, in part with regular apatite banding, occurred all the way along the hanging wall. These observations are confirmed and supplemented by data published by Fagerberg (1913). According to this description, low-phosphorus ore ("A" quality, < 0.015 per cent P) formed the part of the ore body next to the foot wall, and ore of "C" quality (max. 0.60 per cent P) the part near the hanging wall. The figure for the latter quality shows that the apatite-banded ore can only have made up a subordinate portion; it was observed by me close to the hanging wall. Fagerberg also remarks that the boundary between "A" and "C" ore was not discernible to the naked eye, and could only be determined by sampling and analysis. Of special interest is his statement that portions of "C" quality were "suddenly" encountered when mining in the zone of "A" ore. If these portions had belonged to the later intrusion, they would more likely have had a marked extension in the direction of the ore body, and they would not have turned up so abruptly as the description implies. The most likely explanation is, therefore, that they were large fragments of the earlier ore intrusion, but not directly discernible as such because they were so much lower in apatite than the zone nearest to the hanging wall.

From the outcrop of the much smaller ore body in the Snorre claim, about 170 m distant from that of Choulalongkorn, I have noted that "a few small fragments of very P-rich, indistinctly banded ore are enclosed in the pure ore in the usual way" (field diary 1918, SGU archives). Thus there, too, the later intrusion has followed the same fissure as the earlier one. However, one would not be justified in concluding from the evidence reviewed here that the other ore bodies at Tuolluvaara, with both low-phosphorus and "C" quality ore, are also built up in the same way. Without direct proof, one must allow for the possibility that an intrusion may have had an inhomogeneous distribution of apatite, as has been noted at so many other deposits of this type.

When thus larger units of ore at Tuolluvaara have been found to be made up of two separate intrusions, the question presents itself — what are the relations of the ore breccia to each of them? No definite answer is possible, but the existence of the problem makes it desirable that relevant facts be made known. First it must be stated that nowhere has a pattern been observed in the breccia, such that it can be interpreted as evidence of its formation in several generations. Ore breccia occurs in association with ore bodies, both when the latter are low and when they are high in apatite. The northernmost and partly very apatite-rich ore body, that of Bråk, is accompanied by an ore breccia remarkably rich in apatite. For the rest, however, the amount of apatite in the breccia appears to be low, and the mineral where observed is always in the form of isolated, rather large grains, or groups of such; the type of apatite characteristic of the banded ore is not seen. Since, as already pointed out, ore breccias are often richer in apatite than the larger ore units with which they are associated, this might perhaps be an indication that the breccia was mainly associated with the later, low-phosphorus ore intrusion.

The other phenomenon to be considered under this heading, the occurrence of apatite rock with distinctly intrusive relations to earlier consolidated ore, is fundamentally different from what has just been described from Tuolluvaara. The latter case is wholly analogous to what may be encountered in any kind of intrusive igneous rock. The relations exhibited by the apatite rock are instead virtually without a parallel among such rocks. It is the most conspicuous example of distinct age differences between phases of what is evidently one intrusive body, not — as at Tuolluvaara — of several different injections. Therefore the intrusive units of apatite rock are particularly important as illustrating the ways in which these ores differ from a "normal" magma.

The most instructive observations could be made on the original ore ridge of Kiirunavaara. Although for the most part varieties with different proportions of magnetite and apatite grade into each other without distinct boundaries, intrusive relations on a small scale are frequently observed. In such cases the phase richer in apatite is, as a rule, the later one.[1] A good example is represented in a photograph (Geijer 1910, p. 94, Fig. 30) which shows irregular lumps of ore enclosed in a mass of apatite with a little, streakily concentrated amount of magnetite. The bodies of apatite rock may therefore be regarded as the end member of a series, and in their case the difference in age is especially marked. Details of the intrusive relations have been figured by Stutzer (1907) and by myself (Geijer 1910, p. 93, Figs. 28 and 29). The ore that is split up by the apatite rock is low in phosphorus; in my Fig. 28 it is iron black and apparently pure magnetite.[2] The bodies of apatite rock in the Kiirunavaara ore body are irregular and branched, or dike-like, even with such dimensions as a length of more than 20 m combined with a thickness of only 10—20 cm. On the whole, the extension of such bodies is parallel to that of the ore body. Most of them may not reach more than a few tons, but the largest contiguous units probably exceed 100 tons.

Similar relations have been observed also at Tuolluvaara, in the upper parts of the Bråk ore body (the only ones I have studied). The pointed ends of this lenticular ore body contained much apatite in the form of flat, anastomosing lenses of apatite rock, parallel to the dip of the ore body; in detail, the relations were clearly intrusive, the apatite rock also containing small splinters of ore. The latter did not carry any visible apatite. The apatite rock is reddish gray and

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[1] The exceptions that occur are mostly on a quite small scale. Thus, at one locality on the hillock Landshövdingen, veins of pure ore, "of a finger's width", have been noted cutting ore with the dull blackish surface characteristic of weathered ore with much evenly distributed apatite.

[2] Stutzer (1907, p. 585) has figured a similar specimen which he, however, has interpreted as showing that the magnetite ore was the later element. In my example the opposite relation is evident, as the pure ore forms sharply angular fragments surrounded by apatite rock, and Stutzer's figure leaves room for the same interpretation.

Fig. 4. Apatite rock (white) and pure magnetite ore (black); specimen from Tuolluvaara. Slightly reduced from natural size.

comparatively coarse-grained, quite different from the apatite of the banded ore at Tuolluvaara. The relations are illustrated by the drawing, Fig. 4[1].

A noteworthy fact is that the boundaries are often wavy, in a way suggesting that the magnetite was somewhat corroded by the apatite — a unique feature.

In the apatite-rich Rektor ore body at Kiruna intrusive breccias of apatite rock in ore are frequently observed. In this deposit, however, the ore fragments probably always contain a good deal of apatite.

Similar phenomena are also known from the large ore bodies of Grängesberg, in Central Sweden. Especially along the hanging wall in the open cut called Skärningen they could be studied in the beginning of the century. The zone is reported to have in part averaged 8 per cent phosphorus, or more than 40 per cent apatite. There was an alternation of slabs of apparently pure magnetite ore and pure apatite rock, but in details the relations clearly showed the latter to be the younger element. The tabular pattern is reminiscent of the dike-like apatite rock bodies of Kiirunavaara, but may at Grängesberg have become accentuated through some later deformation. A typical specimen has been figured by Johans-

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[1] It is not definitely known that the specimen, which belongs to the collections of the Royal Technological Institute, Stockholm, comes from the Bråk ore body. This one, however, is the only one at Tuolluvaara from which the characteristic feature has been recorded.

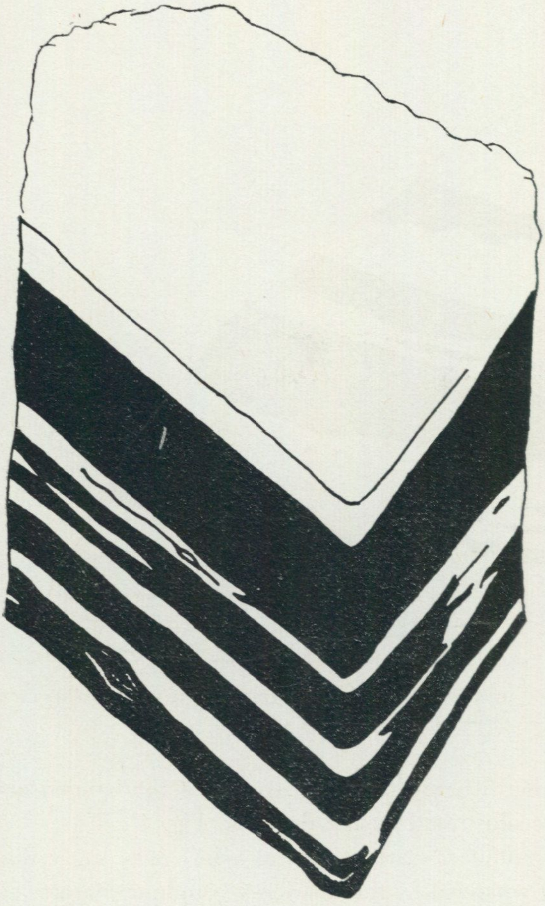

Fig. 5. Apatite rock (white) and pure magnetite ore (black); specimen from Grängesberg. 3/4 nat. size.

son (1910, p. 342). Another sample, almost certainly from the same zone, is shown in Fig. 5. It is remarkable by having a thin lamella of magnetite which can hardly be interpreted as an enclosed fragment, although it is otherwise evident that the apatite rock forms the later element.

Intrusive breccias with fragments of ore enclosed in apatite rock are also reported from the Lebiajaja deposit in the Urals (Högbom 1898). The apatite bodies, which reach dimensions to be reckoned only in decimeters, extend in the strike direction of the ore body. Their apatite is very coarse-grained. In the same ore body, as already quoted, a streaky banding of apatite is a conspicuous feature. As Högbom compares the latter phenomenon to the banding in the Gällivare ores it is probable that the apatite in this case is to be referred to the fine-grained type; at least it must be in much smaller grains than in the intrusive apatite rock.

There are thus remarkable similarities between Lebiajaja and several Swedish occurrences with fine-grained apatite: apatite banding and intrusive apatite concentrations ocurring in the same ore body. Evidently both phenomena must be regarded as normal though not always developed features in apatite-rich ore bodies characterized by fine-grained apatite (in the sense used here).

The intrusive apatite bodies indicate that, when the content of apatite is high, differentiation within the ore intrusion has produced, as the fraction last to crystallize, a residual melt of pure apatite. By some kind of pressure this was then injected into the already consolidated portion of the ore body. This transcription of the relations observed in the field is all that can be presented by way of interpretation.

6. AMPHIBOLE

Amphibole occurs in many — probably in most — deposits of this ore type. It is, however, characteristically absent from the apatite-rich Rektor deposit, which instead always contains some quartz. The apatite dikes of the Abel area at Kiruna represent an intermediate type, with but little quartz and only exceptionally containing amphibole. A diopsidic pyroxene has also been noted in some ores, for examples at Kiirunavaara, but is, on the whole, much rarer.

The amphibole in the ores is normally an actinolite, or an actinolitic hornblende, green in colour and often fibrous. The Grängesberg ore bodies show a greater variation, however; in addition to actinolite there occur tremolite, anthophyllite and cummingtonite (Magnusson in Geijer & Magnusson 1944, p. 326), and in the Norra Hammar deposit hornblende. It is not clear if the purely magnesian amphiboles are of primary origin, but there are no indications to the contrary.

The actinolite occurring in the ore is wholly similar to the one that has formed through replacement of the wall rock or of inclusions in the ore body, as at Kiirunavaara, but it is clear that it is normally a primary constituent of the ore. At Kiirunavaara part of the amphibole which occurs disseminated in the ore within certain areas is uralitic, replacing diopside (Geijer 1910). Generally, however, there is no reason to doubt its primary nature.

The amphibole is hardly ever so widespread in an ore body as the apatite frequently is, but otherwise there are noteworthy similarities in the relations of these two minerals to the predominant magnetite. Illustrative examples are the occurrence of apatite and amphibole as separate bands in the same part of the Kiirunavaara ore body, as described above (under 3.2.2), and the similar grouping of apatite and amphibole prisms in certain Chilean deposits with coarse-grained apatite, as at Algarrobo (own observations) and Cachiyuyito (Fig. 2, above).

Regarding the quantitative relations between amphibole and apatite no exact data are available. My impression is that, in most deposits, there is decidedly less amphibole than apatite, but in ore bodies very low in phosphorus the amphibole may predominate over apatite.

7. TOURMALINE, SCAPOLITE AND CALCITE

None of these three minerals is characteristic of the ore type as such. They are found only in a few deposits and then mostly in small amounts. Their occurrence is of interest, however, as indicating the conditions under which the ores were formed.

7.1. *Tourmaline*. In the Kiruna district the following relevant occurrences of tourmaline have been observed. At some points on the Kiirunavaara ore ridge the mineral has formed small lenses in the ore, rather near the foot wall (Geijer 1910, p. 104, 115). Of the apatite dikes in the Abel area, some contain much tourmaline as a distinctly primary constituent (Geijer 1908, 1910). The apatite-rich Rektor ore body nearby shows great similarities to these dikes, including such details that the quartz, which forms a subordinate component of both, characteristically contains numerous enclosed grains of apatite, smaller than those of the surrounding apatite aggregate. But in the Rektor ore no tourmaline has ever been observed. This is the more remarkable because its silicified wall rock contains lenticular concentrations of sericite which regularly carry radiating aggregates of tourmaline. In the siliceous "Hauki" ores, of hydrothermal origin, tourmaline has also been observed, but only sporadically and as microscopical grains.

Similar conditions are found in some other provinces. Thus the Algarrobo ore bodies occasionally contain tourmaline, in the form of rounded balls of black tourmaline rock; the surrounding ore consists of finely crystalline hematite and is thus different from the ordinary Algarrobo ore. East of the ore bodies there is a zone of highly siliceous ore, with abundant tourmaline in the form of very small grains (Geijer 1931). And in Missouri there is no tourmaline reported from the intrusive Iron Mountain deposit, but the mineral occurs abundantly in the hydrothermally formed Pilot Knob deposit (Singewald & Milton 1929).

Thus in the "typical" ores, which in this connection means those consisting of magnetite, apatite and amphibole, tourmaline is only of sporadic occurrence, but it is common as a product of the hydrothermal activity which has formed another aspect of the same mineralization.

7.2. *Scapolite* is reported from only a few ore deposits of this type, but its presence in them is a feature of considerable importance for the genetical interpretation. At the large deposit of Boqueron-Chañar in Chile scapolite occurs as a common mineral in the ore (Ruiz 1964). At Algarrobo no scapolite has been observed in the ore bodies, but locally the country rock is interwoven by veins of magnetite, scapolite and actinolite, which occasionally show a middle zone of scapolite, bounded by magnetite on both sides. At others among the Mesozoic deposits of Chile scapolite appears to be wholly lacking, but is found in the extrusive ore bodies at El Laco, of Quaternary age (Ruiz 1964).

Outside Chile, Mertainen in Sweden is the only example of scapolite so directly associated with the ore, although it is found in the skarn breccias of Gällivare (Malmberget; Geijer 1930). At Mertainen, as at Algarrobo, the mineral appears to be lacking in the larger ore units but is found in many of the magnetite veins that brecciate the country rock. In these veins the spatial relations of scapolite and magnetite are sometimes the same as were just described from Algarrobo, but in other cases they are reversed, the scapolite occupying both sides of the vein, and the magnetite the middle (Geijer 1919 b). Scapolite has also formed, by replacement, in the porphyry between the veins.

The scapolite is always marialitic, and thus contains considerable amounts of chlorine. The complete absence of scapolite at Kiirunavaara, where the foot wall porphyry is, in composition, closely similar to the country rock of Mertainen, indicates that chlorine was probably not present for the formation of scapolite when that ore body was intruded. The rôle of the two common halogens, fluorine and chlorine, in the formation of ores of this type is a problem of great interest, both because of the assumed decisive role of volatiles in their formation, and because regional variations in the proportions are indicated. However, analytical material of the two characteristic ore components which may contain them — apatite and actinolite — is regrettably scarce. Of the actinolite no determination is available at all. On apatite from the Swedish deposits only a few partial determinations have been carried out. Two of them — from Kiirunavaara and the Abel dikes — indicate a fluorine apatite, the determinations of chlorine giving about 0.15—0.20 per cent. Similar proportions appear to characterize the apatite in the Gällivare (Malmberget) ores (Geijer 1930, p. 30). Strikingly different are two determinations on apatite from the apatite-rich magnetite veins at Leveäniemi, which show 0.86 and 1.37 per cent chlorine and 1.90 and 0.86 per cent fluorine, respectively (Parak, quoted by Frietsch 1966), a remarkable variability. It is pertinent to ask whether this occurrence of chlorine apatite indicates a regional or a local variation within the province; there are no data available on apatite from the ore body of Leveäniemi, nor from the Gruvberget (Svappavaara) deposit nearby or on the apatite that occurs sporadically in the scapolite-bearing ore breccia of the distinctively low-phosphorus deposit of Mertainen. The problem is accentuated by the fact that the apatite of the Mesozoic deposits in Chile, which, as already related, are in part associated with scapolite, is reported to represent the chlorine variety (Ruiz 1964).

7.3. *Calcite* occurs as a primary constituent in several deposits, as at Gruvberget (Svappavaara), where it forms fine-grained aggregates in the ore, largely similar in development to those of apatite. Because of the comparison above between fine-grained and coarse-grained apatite, this example may be supplemented with the following observation. In the largest of the dike-shaped ore bodies at Ojos de Agua I noted a single crystal of calcite, in the form of a rhombohedron more than 10 cm in size with sharply euhedral contours against the surrounding ore. This euhedral development appears to mark the crystal as a primary mineral in the ore, an origin by replacement of the magnetite being improbable, and the size fits well into the general textural pattern of Ojos de Agua.

8. COLUMNAR MAGNETITE

A peculiar form of magnetite which has been observed as a local phenomenon in the Kiirunavaara ore body was originally described as "columnar ore" (Geijer 1910, p. 86). This choice of term was misleading, however, as it was clearly not any form of jointing, in otherwise ordinary ore, but instead a special textural development of magnetite. "Columnar magnetite" is therefore more appropriate.

No new observations on the subject have been made. But it is now clear that the phenomenon presents more interest than was realized at the time of the original description. Therefore the latter will here be supplemented with some not previously published details, before the possible interpretations are discussed.

On the ore ridge of Kiirunavaara, bodies of columnar magnetite were observed at several points, especially on the northeastern slope of the hillock Landshövdingen, well above the foot wall contact. The characteristic feature of these units, which never contain anything but magnetite, is that they consist of parallel "columns" or stalks of the mineral, with a length generally about 5 to 10 times the thickness; the size is practically constant within each band of parallel stalks. The dimensions in the different bands vary from a thickness of a few millimeters and a length of a couple of centimeters to about 1.5 cm and 12 cm, respectively. The stalks often show reflecting surfaces; the angle against the length axis I estimated to be about 30°.

At the time of study (Sept. 1908) conditions in the area on Landshövdingen were not wholly favourable, partly because the surface was dotted with piles of frost-broken ore blocks that had been collected in preparation for mining the area. As far as I could ascertain, however, the columnar magnetite formed several dike-like bodies, about one meter in width and a couple of meters in length. Their extension was parallel to the boundaries of the ore body, with the exception of one exposure which showed a distinct deviation from this direction. The columns were always perpendicular to the boundaries of the band or dike. The contact with ordinary ore below was straight and even; the upper contact may have shown irregularity on a quite small scale. The units were composed of several sets of columns or stalks. Dimensions were virtually constant within each such set, but varied between the sets. A partial section which was noted provides an imperfect illustration. From the upper surface, the contact with ordinary ore, downwards, the following thicknesses were exposed: 16 cm "medium coarse", 6 cm "fine", 2 cm "medium", 1.5 cm "fine", 3 cm "medium", 5 cm "finer". These data are regrettably incomplete. As is apparent from the normal dimensions reported above, at least the topmost set must be double.

The phenomenon is clearly a growth form of magnetite. The angle of parting, mentioned above, is puzzling but cannot justify any other conclusion. A similar development of pyrite has been described (Geijer 1928), the sample (from the dumps of a small sulfide mine) showing a parallel growth of stalks a few millimeters in thickness and about as many centimeters in length, with an even base but ending with octahedral faces. Growths exactly similar in pattern, but reaching very much larger dimensions, are known to be common in the industrial crystallization of alum.

As to the origin of the columnar units at Kiirunavaara, it is clear that they have crystallized later than the surrounding ordinary ore. It is equally clear that they are not "secondary", for the physical character of the ore body excludes the possibility that structural forces acting upon the consolidated ore body should have produced the large gashes that were subsequently filled by magnetite. It is certainly improbable that a crystallization of this nature took place in a magma. The most likely explanation is that the columnar growths started from the bottom of open spaces, in the form of very flat lenses, mostly extending parallel to the position of the ore body, i.e. horizontally or nearly so. There is, in several respects, a suggestive similarity to the "gas tubes" coated with magnetite crystals that Park (1961) has decribed as occurring in the magnetite flows of El Laco. It may be noted that Holmquist (1925) described an analogous growth — apart from the dimensions of the crystals — of magnetite on the walls of an iron tube in a refrigerator, the iron having been dissolved by an ammoniacal watery solution and redeposited as magnetite. In none of these two cases is there any evidence of columnar growth, but this is only to be expected from the shape of the cavity in which crystallization took place.

The most probable interpretation of the columnar magnetite is thus that it was successively deposited from a gaseous or liquid solution in flat "pockets" that developed in the ore body during its consolidation.

9. COMMENTS ON EL LACO

The group of deposits known as El Laco, of Quaternary age and recently discovered in the Andes of northern Chile, is certainly the most scientifically interesting representative of the type. This was evident already from the first, brief description by Park (1961), and has been amply confirmed through more detailed later work (Sánchez, reviewed by Ruiz 1964). For the understanding of the ore type in general these data reported from El Laco are of fundamental importance. They will therefore be briefly discussed here, although this means that the treatment is extended over the boundaries of the subject that is defined by the title of this paper.

Of the various occurrences of iron ore at El Laco most are reported to represent surface flows that have issued from adventitious (or "parasitic") craters situated around the andesite volcano of Pico Laco — a position that appears significant — but one (Rodados Negros) is interpreted as a wide fissure filling. The thick flows have extended only a few hundred meters from their points of issue. The ore is always rich in iron, consisting of magnetite and hematite, among which, to judge from the descriptions, magnetite greatly predominates. Other mineral constituents are actinolite (partly in some quantity), apatite in needles, scapolite, and quartz (in the form of "eyes", and therefore possibly secondary).

It is striking that the three minerals characteristic of this ore type — magnetite, apatite and actinolitic amphibole — are found also to make up these ore bodies, whose evidently extrusive nature otherwise makes them unique. Scapolite is, as mentioned above, much rarer in ores of the same type, but its presence connects El Laco in an interesting way with the Mesozoic deposits of Chile, thus in the same greater metallogenetic province.

El Laco suggests the following reflections.

The obvious magmatic nature of the deposits confirms the interpretation of the ore type in general as magmatically formed. This applies also to the similar Mesozoic deposits in Chile. The scapolite is especially important, as already indicated, as its occurrence in some of the Mesozoic deposits would otherwise have presented a seemingly strong argument for ascribing to them an origin by pneumatolytic replacement. This remark, however, does not imply that processes of the latter nature may not also have been active in the formation of some of the Mesozoic deposits.

The occurrence of so closely analogous deposits in the Andean belt of Chile, but under wholly different geological conditions and separated in time by a magnitude of about 100 million years, together with the occurrences in the Cordilleran zone of North America (compare above) and in Mexico (Cerro Mercado, in the State of Durango), emphasizes the permanency of the ore-forming factors in the Cordilleran zone of the Americas.

The extrusive nature of the El Laco ore bodies is understandably regarded as something out of the geological ordinary. The fact ought not be surprising, however, but certain features of the ores are. The Kiirunavaara ore body was once interpreted as a surface flow (Geijer 1910) because of the field evidence accessible at the time; more complete exposures due to mining operations later proved that this interpretation was untenable (Geijer 1919a). The idea had been criticized by several geologists of great authority. I had also myself admitted that there were some weak point in my interpretation. Thus my view on the importance of volatiles in the development of the ores appeared difficult to reconcile with the idea of a flow under only atmospheric pressure, where such substances presumably would be rapidly lost (Geijer 1912, p. 774). However, since it was clear that many deposits have formed at quite shallow depth, the intriguing question remained: how would the product look, if the ore magma somewhere happened to break through to the surface? Now, however, El Laco has given the answer: clear evidence of a magmatic nature, and, what is admittedly unexpected, no difference in mineral composition. Especially remarkable is the fact that such minerals as actinolite and scapolite are present, apparently in quite the same way as in the intrusive ore bodies. The shape and extension of the El Laco ore flows may, however, possibly be an indication that loss of volatiles caused a rapid increase in viscosity after the ore magma flowed out on the surface, as these features strongly contrast against the remarkable mobility shown at intrusive emplacement, particularly by the ore breccias.

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