

PER GEIJER AND OLOF H. ÖDMAN †

THE EMPLACEMENT OF THE KIRUNA
IRON ORES AND RELATED DEPOSITS



STOCKHOLM 1974

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ABSTRACT

The paper is a commentary on Parák's work "Kirunamalmernas bildning" (Parák 1973). According to Parák the iron ores of the Kiruna district should be the products of an exhalative-sedimentary process, the iron being derived from volcanic emanations and the phosphorus from organic remains. The chief arguments for this view are obtained from the group of apatite-rich deposits called the Per Geijer ores, which differ from the ordinary type of apatite-bearing ores in certain respects, such as the complete absence of amphibole. In the not outcropping Lappmalmen part of the greatly faulted deposit, exploratory drilling has disclosed

a transition upwards, by interstratification, between apatite-banded ore and a quartzose, stratified ore. The authors fully agree with Parák in regarding this phenomenon as a proof of an origin by chemical sedimentation, but reject the idea of an organic source of the apatite as wholly without foundation. The outcropping (and worked) Per Geijer ore bodies, however, present certain features that are not consistent with Parák's interpretation. A tentative hypothesis of an extrusive-sedimentary process is presented as a possible explanation of the contrasting evidence.

Parák, however, extends his interpretation to apply also to the other deposits of the district, such as Kiirunavaara, and to the apatite-bearing magnetite ores in general ("Kiruna type"). A conspicuous feature of these ores, and one of the chief reasons for interpreting them as magmatic (pneumotectic) intrusions, is that they are generally accompanied by ore breccia, *i. e.*, systems of dikes and veins of the ore-forming minerals (magnetite, apatite, amphibole) intersecting the country rock. This feature is by Parák explained by assuming that the supposedly sedimentary ore has been partly "mobilized", the factors producing this mobilization being indicated as structural disturbances, and solutions.

This has caused the authors to give a detailed account of the contact relations, with ore breccias connected with the solid ore bodies, of Kiirunavaara and certain other deposits in the same metallogenic province, as well as a general review of conditions in this respect in the analogous provinces of Missouri, Mexico and Chile-Peru. This survey shows that the immediate association with ore breccias is a characteristic feature met with in the great majority of apatite-bearing iron ores. On the other hand, the many times more numerous iron ore deposits of other nature, representing all conceivable variations in original character and structural and metamorphic history, never, so far as known, display contact relations of this kind. It is therefore concluded that the hypothesis of an extrusive-sedimentary origin, as indicated above, cannot be extended beyond the Per Geijer ores. For the ordinary type of apatite-bearing magnetite ores an origin as a magmatic differentiate rich in volatiles (pneumotectic) is indicated.

The fractionation leading to this product is briefly discussed.

1. INTRODUCTION

T. Parák's doctoral dissertation "Kirunamalmernas bildning" (Parák 1973) presents a great number of new and very valuable observations on the geology of the Kiruna district, mainly derived from the progress of mining and exploratory drilling. It is only to be regretted that Parák has not found it possible to give any details about the rocks of the ore-bearing volcanic series. It is true that there exist already petrographic descriptions of all the units concerned, but it would have been very welcome to have the new additions to our knowledge presented also in their petrographic aspects. It is, for instance, tantalizing to read Parák's new and highly interesting observations on the syenitic complex of Kiirunavaara without receiving any information about such important details as the distribution of vesicle-fillings of the ore-forming minerals.

Parák also reports a wealth of chemical data, especially on the distribution of diagnostically important trace elements in the ore minerals, and largely bases his theoretical conclusions on them.

On these data, and particularly on those derived from the special type of ore that constitutes what is known as the Per Geijer ores, Parák bases a hypothesis of ore formation through an exhalative-sedimentary process. While the arguments are mainly derived from the said units, the conclusions are extended by Parák to apply also, not only to the Kiirunavaara and Luossavaara ore bodies of the same district, but to the apatite-bearing magnetite ores in general. It may be added that this interpretation was applied to the Kiirunavaara ore body already by the first geologists who presented an opinion on the matter after personal visits to the deposit: Bäckström (1898) and De Launay (1903). In both cases, however, the hypothesis was presented without any such detailed argumentation as now put forward by Parák.

In his thesis, Parák understandably emphasizes those facts — and particularly the new ones — which have caused him to turn to the exhalative-sedimentary process as an interpretation, instead of the process of "low-magmatic" or "pneumotetic" intrusion which long has dominated geological opinion. While this is done in an objective way, the leaving out of most of the evidence on which this earlier view is based, unavoidably results in a decidedly one-sided picture.

Experience from the geology of the Kiruna district, and from many other occurrences of apatite-bearing iron ores, makes it impossible for us to accept Parák's interpretation as valid for such ores in general. Briefly stated, our opinion is that Parák's arguments appear convincing when the Per Geijer ores are concerned, although his hypothesis has to be considerably modified to fit the observed facts. This, however, applies to these ores which are characterized by magnetite and hematite in comparable amounts and often by an appreciable content of quartz and/or carbonate, and by the complete absence of amphibole. This type, as far as we know, is not found elsewhere, although certain smaller deposits of hematite in the same region (but outside the Kiruna district) may be genetically comparable. What we would call the ordinary type of apatite-bearing iron ores generally contain magnetite as the only, or at least predominant iron mineral, and in addition apatite and, mostly, an actinolitic amphibole. This is the type represented by Kiirunavaara and by almost all the other deposits in the metallogenic province to which Kiruna belongs, and likewise by the apatite-bearing ores of other countries. For these, we maintain that a pneumotectic magmatic origin is the only process that fits the observed facts.

In our commentary on Parák's work we have found it appropriate to

give detailed references whenever earlier published observations or views are quoted, so as to make it easy for a critical reader to study them in their context.

Work on this commentary had to start on the basis of Parák's dissertation (1973), without awaiting the publication of the English edition, which will appear in the same series as our article. The manuscript was fully completed at the time of Prof. Ödman's death (Dec. 3, 1973), only this sentence having to be added.

The authors are in full agreement on the views expressed, with one exception: the hypothesis presented to explain the emplacement of the Rektorn-Nukutus ore zone, and its relations to the apatite dikes. On this subject Ödman, because of too restricted personal experience of the phenomena referred to, does not wish to express any opinion. Thus for this part, the end of section 3.3., Geijer is alone responsible. This has been indicated by inserting (P. G.) at the beginning and the end of that particular part.

2. GEOLOGICAL SETTING OF THE KIRUNA ORE BODIES

For the present purpose it will be sufficient to give a very brief review of the rock units in the volcanic sequence — with few, but noteworthy sedimentary intercalations — in which the iron ore bodies occur. This sequence has a monoclinial build, with a moderate to very steep easterly dip. Three units can be discerned, here presented in order of their relative ages, and using the local designations:

- 1) Syenite-porphyry and syenite
- 2) Quartz-bearing porphyry
- 3) The Hauki complex

Petrographic descriptions can be found in Geijer 1910, and, for the "Rektor porphyry" of the Hauki complex also in Geijer 1950.

The oldest unit was originally, as exposed in outcrops on Kiirunavaara, described as a syenite-porphyry that graded downwards into an even-grained syenite of the same mineral composition (Geijer 1910). These relations have been interpreted as indicating that the whole unit forms a caldera filling, but with overflows at least in the northeastern part of the district (Geijer 1931 a, and especially 1968). Parák's new observations confirm this picture, but with the very important modifications that there can be discerned several porphyry flows above the one that shows a transition into syenite, and that the latter rock also grades downwards into a porphyritic phase — thus strengthening the caldera hypothesis.

From the upper surface of this unit Parák describes pockets filled with a conglomerate of entirely local material, cemented by magnetite ore as a very subordinate matrix. This remarkable discovery clearly shows a former erosion surface, but it cannot be decided whether the conglomerates are remnants of a once more extensive bed, or deposits in local stream channels. Because of the homogeneously local material the latter alternative may appear most probable.

The next rock unit, the quartz-bearing porphyry, carries phenocrysts of alkali feldspar in a groundmass of rhyolitic composition and with a texture, often micropoikilitic, that is clearly the product of devitrification. There enter also into the sequence beds of agglomerate, largely with angular inclusions of apatite-bearing magnetite ore, and interpreted as pyroclastic avalanches or flows (Geijer 1968).

Among Parák's contributions to the knowledge of this unit are the discoveries of an intercalated bed of anhydrite (about 5 m thick), and of a conglomerate at Luossavaara, which will be discussed in the following (under 4.3.3.).

The Hauki complex begins locally with a clastic deposit, called by Parák "porphyry detritus". This rock has earlier (Geijer 1950) been regarded as a phase of the "Rektor porphyry", of somewhat greater extension and carrying feldspar as spherulites or spherulite-fringed phenocrysts in a groundmass consisting wholly of secondary quartz; it has been interpreted as probably a silicified obsidian. Above follows an extensive flow of syenitic composition which Parák, wisely avoiding the difficulties of petrographic nomenclature, has called "Hauki porphyry". The rest — and the larger part — of the Hauki complex is mostly made up of thoroughly silicified volcanics, with intercalations of sericite rock. The wide-spread occurrence of quartz phenocrysts shows that one is concerned here with an originally more quartz-rich volcanic product than is to be found among the older units. At least part of it has formed as a tuff breccia (Geijer 1910, p. 168).

In addition to these more extensive units there is one group of rocks that is also of importance, because of its relationships to the Kiirunavaara ore body, viz., the set of porphyry dikes on northern Kiirunavaara. Parák states (1973, p. 22) that these dikes show the same composition and texture as the other Kiruna porphyries. This statement is confusing, since "the other porphyries", those associated with the syenite, and the quartz-bearing porphyry, differ widely both in composition and, as a consequence, also in texture. Actually, the composition of the dike porphyries can be said to be somewhere intermediate between the two groups mentioned; they contain some quartz in the groundmass, but much less than the quartz-bearing porphyry. Texturally, they are rather similar to the latter, with

phenocrysts of the same kind, while the groundmass is much more fine-grained than that of the syenite-porphyrries, yet never showing the micro-poikilitic development that is so common in the quartz-bearing unit.¹⁾

The bodies of iron ore occur on the contact surfaces between the three main rock units. On the contact between the syenitic complex and the quartz-bearing porphyry are the "main" ore bodies, that of Kiirunavaara in the south and the very much smaller Luossavaara ore in the north. There are positive reasons to assume that these "twin" deposits have never been connected in any section. In the present situation there is a gap of at least several hundred meters on the contact in the earth surface. A fault in the gap has caused a horizontal displacement of the contact, of about the same magnitude. These ore bodies have the mineral composition characteristic of the great majority of apatite-bearing iron ores, consisting chiefly of magnetite with subordinate amounts of apatite and actinolitic amphibole.

On the upper contact — that between the quartz-bearing porphyry and the Hauki complex — is situated the group of ore bodies known collectively as the Per Geijer ores. At the surface these ores form a very extensive, almost certainly continuous chain with, at three separate localities, thickness enough to constitute workable deposits. It has been demonstrated (Parák 1969) that the deep-lying, very large Lappmalmen ore body originally was connected with these ore bodies at the surface, the connection having been broken through a complicated set of faults. The Per Geijer ores represent a special type. In addition to magnetite, hematite enters as a constituent in comparable amounts, or may even predominate. The average content of apatite is remarkably high. Quartz and/or carbonate are present in appreciable amounts in part of the ores worked at the surface. On the other hand, amphibole has never been observed.

In the whole rock sequence there are no traces of textural metamorphism. The only change from the original characters that can be discerned is the devitrification of the groundmass of the quartz-bearing porphyry. The textures exhibited by the latter, among which a micro-poikilitic development is especially characteristic, have long been regarded as due to devitrification. This view has recently received confirmation through experiments by Lofgren (1971), who reports that by heating natural rhyolitic glasses in the presence of alkaline solutions ("to increase the devitrification rate") he has reproduced "micropoikilitic intergrowths of quartz and alkali feldspar, such as those described by Geijer (1913)", the paper referred to being a review of micropoikilitic textures, undertaken

¹⁾ When these porphyries were first described (Geijer 1910) there was used for them the totally inappropriate name "syenite-porphyry"; in later publications the prefix has been dropped.

just because of the common occurrence of this texture in the quartz-bearing porphyry of Kiruna and in other parts of the same metallogenic province.

Folding is rarely observed, and then only on a small scale and little intensity. Faulting, on the other hand, is wide-spread and has especially affected the Hauki complex, as already mentioned. In the lower units there is the fault already referred to as cutting the gap between the Kiirunavaara and Luossavaara ore bodies, and a set of steeply dipping faults across Kiirunavaara.

3. THE PER GEIJER ORES

3.1. GENERAL REVIEW

We begin with this group, because it is the one from which Parák derives the geological arguments for his general interpretation of the apatite-bearing iron ores. It is also that part of his thesis with which we agree on really essential points, although we are going to show that locally there are features in these ore bodies which are not compatible with his interpretation and thus indicate a more complicated build-up of the deposit.

The mineral composition which distinguishes this unit from what must be regarded as the ordinary type of apatite-bearing iron ores has already been indicated.

The ore is always, where exposed (whether at the surface or by drilling), found to mark the contact between the quartz-bearing porphyry and the overlying Hauki complex; conversely, wherever this contact has been exposed, the ore (or apatite rock) is found on it, although the thickness is subject to great variations. The total length at the surface amounts to about 5 km. For the southernmost 1.2 km there is apatite rock rather than ore, increasing in thickness from about 1 m to 3.5 m; about 200 m further north it swells out as the Rektorn ore body, with a length of about 700 m. After a long stretch apparently without any ore of workable dimensions there follows the Henry ore, intensely displaced by faulting, and then, as the last link in the chain, the Nukutus ore body.

The faulted Lappmalmen part does not outcrop. It has been encountered by drilling at a depth of about 700 m and is the largest unit by far of the originally continuous ore body.

3.2. THE LAPPMALMEN ORE BODY

The scientifically most remarkable feature of this ore body is that it shows a transition upwards from apatite-banded ore to quartz-banded ore (Pa-

rák 1973)¹⁾ Parák's description of the transition, by interstratification, between these two kinds of ore is clear and decisive, so far as the evidence from the few drill holes goes. In the surface exposures — the Rektorn-Henry-Nukutus zone — the siliceous stratified ore is also encountered, but there is no interstratification with the apatite-rich ore. Thus in the Hilaris claim, about 200 m south of the Rektorn workings, a prospecting trench showed, in a steeply dipping sequence above the quartz-bearing porphyry, a 3.5 m width of massive apatite rock with a little hematite, and on top of it about 17 m of quartz-rich, roughly stratified ore (Geijer 1910, p. 167–168). In the Rektorn workings and for almost 1 km northwards, there intervenes between the two types of ore the complex of rocks that has originally been designated "Rektor porphyry" (Geijer 1910). Part of this, which has been described as the homogeneous type (Geijer 1950), has now been described by Parák as a cross-bedded and thus distinctly clastic sedimentary deposit, a "porphyry detritus", — unfortunately without any petrographical data being given. The rest, Geijer's "porphyritic type", is mentioned by Parák only in passing, and this in a way showing that there cannot have been anything of it left visible at the time of Parák's studies. For this unique rock, with its striking aspect of feldspar spherulites and/or spherulite-fringed feldspar phenocrysts in a white groundmass, generally made up wholly of secondary quartz, could not have escaped his observation. Evidently this rock has, in the course of the years, been completely removed by mining, the resultant waste dumps have become covered by other material, and the published descriptions have failed to convey an adequate idea of its remarkable characters. The term "Rektor porphyry" must now be restricted to this type, which has been interpreted as an obsidian whose glassy groundmass has become entirely replaced by silicification (Geijer 1950). The relations between the two kinds of rock are now beyond the reach of study. Only so much is clear from earlier observations that they must have been very closely connected. There is thus here, in contrast to the conditions in Lappmalmen, a very distinct time gap between the two ore types.

3.3. THE REKTORN—NUKUTUS ORE ZONE

The Rektorn ore body, on the other hand, has been characterized as intrusive, but "avowedly in other respects enigmatic" (Geijer 1967). The interpretation intrusive is based mainly on the presence within this ore body of several very large inclusions derived from the adjacent rock units, both

¹⁾ The siliceous ore does not exactly correspond to what is generally in Sweden meant by the term "quartz-banded", but the difference is wholly irrelevant in the present connection.

from the foot-wall and the hanging-wall side, as mapped by Geijer and P. Ljunggren in 1947 and 1948 (Geijer 1950, Plate). The section then studied has been obliterated by later mining, as is evident from the fact that Parák has not encountered the "Rektor porphyry" (as defined above) which was well exposed at the time. Parák maintains (orally) that the inclusions referred to were brought into their present relations to the ore through faulting. No such faults were, however, noted in the mapping, although especially the very large inclusion of quartz-bearing porphyry was then very well exposed in the floor of the open cut. However, it is now obvious from Parák's data from other parts of the Per Geijer ores that the intrusive interpretation in any case cannot be applied to the whole group.¹⁾

The microtexture of the ore, both at Rektorn and at Nukutus in the north, is often such that it may well be compatible with an origin through chemical precipitation, either colloidal or microcrystalline, as assumed by Parák (compare figures in Geijer 1919 b). Such textures, however, are not the only ones that are encountered in these ores. There also occurs, and apparently not rarely, a textural development in which the apatite grains have the shape of slender prisms, one or several tenths of a millimeter in length, and sometimes showing a striking sub-parallel or "trachytoidal" arrangement. This texture is known not only from the Rektorn ore body but also from the southernmost exposure of the ore zone (Geijer 1910, p. 166). It cannot have arisen through crystallization of a chemical precipitate — and that, according to the general geological situation at Kiruna, spontaneously, without any recognizable external cause.

The texture in question, which rather suggests movement in a mush of apatite crystals, must also be considered in connection with Parák's description and figure of cross-bedding in apatite rock within the Rektorn ore body. This phenomenon has previously been observed there on a much smaller scale, and was then interpreted as the crossing of different apatite injections (Geijer 1950). Obviously, this interpretation cannot be applied to the exposure figured by Parák. But neither can the latter, as believed by Parák, be presented as a *chemical* sediment. It is instead a product of mechanical sedimentation — a deposit made up of discrete apatite grains.

We do not maintain that these facts from the surface exposures of the Per Geijer ores should invalidate the evidence of sedimentary origin presented by the transition between the different phases of the Lappmalmen ore body. But we claim that the development of the Per Geijer ores must

¹⁾ The alteration observable in the porphyry immediately below the Rektorn ore is interpreted by Parák as due to weathering before the emplacement of the ore. The products of this alteration, however, include new-formed tourmaline, sometimes intergrown with new-formed quartz (Geijer 1950). This points instead to a post-volcanic process.

have been much more complicated than suggested by Parák. We are here concerned with a mineralization to which no exact counterpart is known anywhere, and we must reckon with the possibility of elements of wholly unexpected nature.¹⁾

The contradictory evidence reviewed above appears to be restricted to Rektorn; from Henry and Nukutus nothing corresponding is known to us.

(P. G.:) There is in the district one remarkable phenomenon, not so far considered here, on which a plausible explanation of the conflicting kinds of evidence can be based, namely the dikes and veins of apatite in the porphyry immediately below the ore horizon. For details about these we must refer to an earlier description (Geijer 1910). Since, however, this work cannot be counted upon to be at hand for a reader, and Parák's extremely brief account (p. 103) is apt to be misleading, it is necessary to recount here some of the most important facts.

Veins of apatite are found in the upper portion of the sequence of quartz-bearing porphyry, at least on many points all the way from the tarn Matojärvi (now drained) to the Henry ore body, a stretch of about 3.3 km, but are not reported from Nukutus. Their greatest development, however, is south of Henry. Geijer (1910) reported them very common within a belt 600 m long (in the general strike direction) and about 100 m wide, which means a slightly lesser depth in the porphyry. Parák (p. 17), apparently on the basis of new strippings, gives an estimate of about 10 000 m². In this area the porphyry is thoroughly brecciated by apatite veins, generally from some cm to a few dm wide. In addition to these there is a number of larger dikes, running roughly at right angles to the upper surface of the porphyry. The largest dike studied measures 40 m in length and has a width varying from 0.5 to (locally) 2 m. Much of the dike area is, however, occupied by the numerous, angular fragments of porphyry which occur as unsupported inclusions in the apatite rock.

Apatite is, as a rule, the wholly predominant mineral in these dikes and veins, generally in the fine-grained development common in the ores of the district. A textural feature sometimes observed is a porphyritic development, with phenocrysts several cm in length while the grain size of the groundmass is less than 1 mm (this texture has been noted also in the Kiirunavaara ore body, but very rarely). Magnetite and hematite are lacking in many cases, but in some dikes occur even in considerable quantity. A regular banding with apatite is then not uncommon; there have also been observed fragments of such banded ore enclosed in apatite rock,

¹⁾ Rather as a curiosity we note that Parák reports, as indication of a sedimentary origin, an observation from the Nukutus ore body, in which the bedding is said to be proved by the size distribution of magnetite grains. This, if accepted as a sedimentary feature, also would indicate a mechanical deposit, not a chemical precipitate.

indicating several periods of intrusion. Of other minerals, tourmaline is common in some dikes as well as in narrower veins, but appears to be lacking in most occurrences. Microscopically there is noted some quartz, and also occasional grains of albite, which are clearly distinguishable from feldspar inclusions derived from the phenocrysts of the surrounding porphyry. A noteworthy feature is that the porphyry immediately at its contact with the apatite rock contains apatite grains and an abnormally high content of zircon. Veins of quartz and specular hematite are often associated with those of apatite, and even occur as direct continuations of such.

The intrusive nature of these dikes is evident — they did not fill open fissures. And all the features reported above indicate that the injected material in its properties corresponded to the concept pneumotectic. According to Parák, however, they should be the products of mobilization and recrystallization. The occurrence of apatite-banded ore as fragments enclosed in apatite rock is mentioned by Parák, but not that of such an ore as an integral part of an apatite dike. The only argument for "mobilization and recrystallization" that is mentioned is the grain size of the apatite. Since this, apart from the occasional prophyritic development, is common in the ores, the argument is difficult to understand. Parák's account is a statement of opinion rather than a review of pertinent facts. And one must ask how the apatite could be mobilized, how it could be injected into the porphyry, and how such great quantities of it could be detracted from the ores above without noticeably disturbing the sedimentary structures of the latter.

The reason for taking up the problem of the dikes is not, however, primarily for its illustrating what must be regarded as an unfounded hypothesis of secondary effects in the ores. It appears, instead, that from the earlier interpretation that has been reviewed here, there may be a possibility of explaining, wholly from Parák's general idea of the nature of the deposition of the Per Geijer ores, the puzzling contradictory evidence that is encountered in the Rektorn ore body.

From the way the apatite dikes occur it is practically certain that they reached the upper surface of the porphyry; this is also indicated by Parák's account of them. The question then presents itself: what happened when material such as that forming the dikes reached the surface? Parák's observations make it clear that this extrusion took place under water. In any case a totally new environment was encountered. Assuming as a highly probable situation that a partly crystallized melt was thus extruded under water, the following processes may be expected to have taken place. The still fluid portion would mix with the water (perhaps vapourized), and its content of non-volatile constituents would, sooner or later, be precipitated.

If crystallization was far advanced, the material might be extruded as a crystal mush, as indicated by the occasional trachytoidal flow texture. More isolated crystals, again, would be dispersed in the certainly greatly agitated water, to sink gradually to the bottom as a mechanical sediment, as indicated by the cross-bedded portions of the ore. Finally, of course, during later stages of the process, there would be intrusions in the earlier formed bottom deposits, if these had already reached some degree of consolidation.

An obvious objection to this hypothesis is that there is proportionately more iron minerals in the surface deposits — the ore horizon — than in the apatite dikes. However, long stretches of this ore horizon is actually just an apatite rock with quite subordinate iron minerals. And "feeders" other than the known system of apatite dikes may have contributed more iron. There is also the possibility that earlier stages of the process produced a higher proportion of iron than the final one, whose products now are to be seen as the apatite dikes.

This hypothesis would thus explain most of the otherwise enigmatic features of the ore zone. It would also explain certain similarities between the latter and Kiirunavaara, without necessitating the assumption of an identical mode of emplacement. (P. G.)

4. THE ORDINARY TYPE OF APATITE-BEARING IRON ORES

4.1. GENERAL CHARACTERISTICS

As already stated, the mineral composition of the Per Geijer ores marks them as a type apart.¹⁾ The overwhelming majority of apatite-bearing iron ores, both in Sweden and in other metallogenic provinces, are characterized by magnetite, combined with apatite and actinolitic amphibole. Some other minerals may also be found, but they are sporadic and none of them can be regarded as diagnostic. It is especially to be noted that the three minerals mentioned (together with scapolite, which is irrelevant in this connection) characterize also the extruded ore bodies of Laco (Ruiz 1965).

Parák, whose arguments for his views are largely derived from geochemical data, virtually leaves the *mineralogical* composition of the ores out of the discussion. Taking also this factor into account, one finds that all the minerals of the Per Geijer ores are such as might be products of an exhalative-sedimentary process. But it is different with the ordinary

¹⁾ This, however, does not imply that we exclude the possibility that certain other ore bodies, of less size, geologically associated with what we call the "ordinary" type, might be of exhalative-sedimentary origin. Such cases are the main *hematite* bed at Ekströmsberg, and a smaller similar body at Luopovare, to the SW of Ekströmsberg.

type of apatite-bearing iron ores. The stalks of amphibole, scattered in the magnetite mass, which are a rather common feature in the latter, cannot be the direct product of chemical precipitation. Certainly, such may be found in ore deposits which originally were formed as sediments — but only if affected by metamorphism of an intensity that has never befallen the Kiruna district.

The "magmatic" interpretation of this type of ore has been based chiefly on their properties in three respects: the mineral composition, certain internal traits of the ore bodies, and the contact relations of the latter with their country rocks. The mineral composition has already been discussed, it remains to consider the two other aspects.

4.2. INTERNAL FEATURES OF THE KIIRUNAVAARA ORE BODY

The prominent role that this deposit has played in the scientific development is due not only to its dimensions but also to two other factors: the absence of metamorphism, and the exceptionally favourable conditions of study before mining operations consumed the natural outcrop. It is hardly possible for those who never saw the ore ridge in its natural state, as an almost continuous outcrop in which a slight weathering had brought out even the finest details in the distribution of the apatite, to understand how instructive these exposures were. Stutzer (1907) and Geijer (1910, 1967) have reported a number of observations that led them to reject the exhalatory process, as indicated by Bäckström (1898) and De Launay (1903), and to seek the explanation of the observed relations in magmatic processes instead. Parák now presents another hypothesis: that the intrusive relations between different phases should be due to later, tectonic disturbances. This view must be applied also to cases where apatite bodies many meters in length brecciate various forms of ore (compare Geijer 1967). Analogous phenomena have also been observed in the underground workings. Thus Ödman found, on the 500 m level, in several consecutive cross-cuts a belt with fragments of pure magnetite ore enclosed in a brecciating matrix of gray, very apatite-rich ore. It is of interest to note that both in this occurrence and in such in the outcrop the iron-black colour of the fragments is conspicuous. Yet the excellent exposures already referred to showed no traces of any tectonic influences whatever. It is also to observe that the associated rocks do not exhibit any corresponding phenomena. There is no spatial relationship at all between the apatite bodies in question (or other features interpreted as magmatic) and the faults that at a number of places cut across the ore body. In fact, these faults were then eroded and drift-covered, and far from the phenomena in question. Besides, the mineralization that has been noted in these faults is quartz and pyrite.

We maintain, therefore, that these internal traits or the ore body must be primary features.

Among other deposits in the same metallogenic province as Kiirunavaara we wish in this connection to call attention to Painirova, with its "unsupported" rock inclusion from which apatite crystals radiate (Stutzer 1907, Geijer 1967).

4.3. THE CONTACT RELATIONS BETWEEN THE ORE BODIES AND THEIR COUNTRY ROCK

The inescapable fact that the great majority of the ordinary apatite-bearing iron ores exhibit distinctly intrusive relations to the surrounding rocks is explained by Parák as the result of "mobilization" of the ores that, according to him, were originally deposited as sediments. The factors that should have caused this mobilization are summarily indicated as tectonic disturbances and "solutions". To illustrate how this hypothesis looks when confronted with actual cases, we are going to describe the relevant conditions of the ordinary type of ore at Kiruna and the neighbouring Tuolluvaara reposit, and to give a brief review of other deposits of the same type, both in the same metallogenic province of North Sweden and in other countries. Such a review is a necessary complement, as the subject is strictly avoided by Parák.

4.3.1. ORE BRECCIAS

This term has long been used in the North Swedish province to designate systems of ore veins intersecting the country rock. The minerals are the same as in the workable ore bodies, although not always in the same proportion as in the latter: thus there is very often more apatite in the breccias (compare Geijer 1967). The width of each vein is fairly constant, and this mostly applies also to the whole system. Only in a few occurrences of ore breccia does the average width exceed some centimeters. Ore breccias are immediately associated with workable ore bodies, but they also occur — even with considerable extension — without any such connection.

Parák (p. 43) extends the term to embrace also impregnations of magnetite in the country rock. This is presumably done on technical grounds, such impregnation constituting on Luossavaara, together with breccia, a workable unit of concentrating ore. Geologically, however, it is necessary to preserve the original meaning of the term. And when Parák also includes the magnetite-syenite-porphry with such secondary impregnations we hold that petrographic facts are ignored.

Parák lists several types of ore breccia (*sensu stricto*). With slight modification of his classification we distinguish the following three types — each distinct in its "typical" development but with connecting forms of intermediate character, and even direct transitions between the types. These types are:

1. Schliere-like veins, often uniting.
2. A network of straight veins, cutting up the rock into angular fragments of varying size.
3. A network of sinuous veins with strikingly little variation in the size of the "meshes", which are generally of the magnitude of 1 or 2 dm.

The first type seems to be most common in breccia occurrences that are not connected with any larger ore concentration. The second type is well exemplified by Tuolluvaara, and the third by the foot-wall breccias of Kiirunavaara. Finally it may be remarked that there is found in the biotite-rich "gray leptites" of Malmberget (Gällivare) a more irregular, streaky pattern (Geijer 1930). The influence of the country rock on the development of the breccia is obvious in such cases, but at Kiirunavaara the pattern is the same in the syenite-porphry of the foot-wall and the petrographically different dike porphyry.

As might be expected, gradual transitions from compact ore to breccia are more often found at the end of an ore body — thus in the plane of intrusion — than at its sides.

Metasomatic effects are often associated with the fissure-filling breccia veins. A clear and simple example is found at Tuolluvaara, where the porphyry fragments — originally of a rhyolitic composition — show transformation into an albite rock with some amphibole, the alteration being peripheral in the larger fragments and complete in small ones. Development of amphibole and magnetite by replacement is very frequently encountered at the contacts of ore bodies of this type, accompanied by an outer zone of ore breccia.

4.3.2. CONTACT RELATIONS OF THE KIIRUNAVAARA ORE BODY

Because of the way in which the discussion of the emplacement of this ore body developed, the reasons for an interpretation by intrusion have never been systematically presented. We therefore find it necessary to give a full account, so as to make it possible to consider Parák's interpretation in the light of these facts.

4.3.2.1. The foot-wall contact

There is some development of ore breccia at various points along this boundary, but mostly not on any extensive scale. Often the contact is

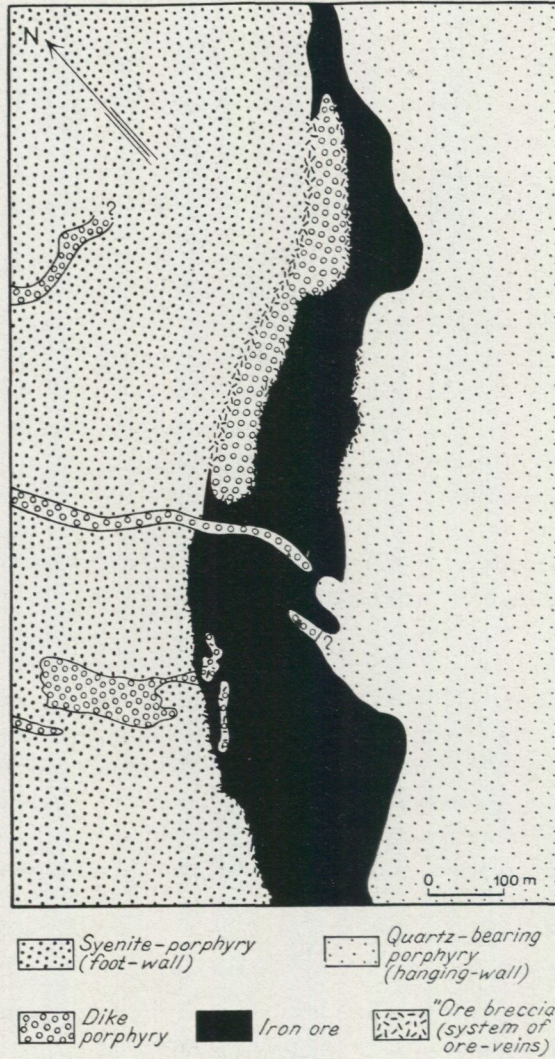


Fig. 1. Northern end of Kiirunavaara (after Geijer 1960).

marked by a felt of amphibole, 0.2 to 0.4 m thick, which outwards begins to enclose fragments of the adjacent syenite-porphyry and then gives way to such porphyry, often with magnetite veins (Geijer 1924, p. 248). In the amphibole skarn there is often also seen titanite, a mineral that appears to be entirely lacking in the ore.

The most interesting part of the foot-wall contact is — or rather was, before mining destroyed almost all the evidence — in the north, near where the ore outcrop left the ridge and sloped downwards to the foot of the mountain, a drop of about 100 m. Geijer's interpretation (e. g. 1960) of this once excellently exposed area (Fig. 1) is as follows. After the eruption of the syenitic foot-wall complex (and the probably brief interval marked by the conglomerate now described by Parák (compare the following under 4.3.2.2.) there followed the eruptions of the quartz-bearing porphyry. Next (or possibly already during this epoch) came the intrusion of the porphyry dikes. These form a set of roughly parallel intrusions, all consisting, as already stated, of the same characteristic type of rock. In part these intrusions spread out as a sill on the boundary surface between the two earlier sets of volcanics. The next stage was the intrusion of the ore body, and the last event the intrusion of at least two porphyry dikes, in every way to be regarded as members of the same set as those pre-dating the ore intrusion. According to Parák, again, the spurs projecting from the ore body into the foot-wall are the result of the ore's being cut up by porphyry dikes, and the ore breccias which occur as continuations of these spurs do not indicate that the affected areas of dike porphyry (Fig. 1) are older than the ore — they are believed by Parák to have arisen later through the influence of tectonic forces and solutions (of unspecified source or nature).

Referring for the main features to Fig. 1, we are going to supplement it with the following details. The inclusions of dike porphyry in the ore, south of the cross-cutting dike, are shown only schematically in the figure, because the very complicated relations cannot be reproduced on the scale used. These inclusions are slabs, cut by large ore dikes, most of which roughly conform to the dip of the ore body while others are almost horizontal. The rock between these ore dikes is interwoven with veins of magnetite, apatite and amphibole, in varying proportions, and is partly replaced by an amphibole felt. Going north from this area one encounters the cross-cutting porphyry dike. Here the indications of relative age are reversed: not only does the dike cut across the ore, it also contains, at several places, inclusions of ore. In the surface exposure such inclusions were noted that measured several meters (Geijer 1910, p. 44). At another point there was a cluster of angular ore fragments, measuring up to 0.5 m. Their shapes showed clearly that the joint system characteristic of the ore

body had developed already at the time of the porphyry intrusion. The dike's contacts with the ore on both sides, which have been studied in a number of exposures, are always sharply defined. In the original outcrop there was noted a border zone, "only some cm wide", with a considerable content of magnetite and amphibole (Geijer 1910, p. 117).

North of this dike the ore body follows the upper contact of the largest dike porphyry unit shown in Fig. 1. But it also inserts, from its foot-wall side, a spur along the lower contact of this body of dike porphyry, its boundary against the syenite-porphry of the foot-wall complex. This is not a result of folding or any other secondary influence: the banding of amphibole and apatite is a continuation of a structural trait noted south of the cross-cutting dike. As the ore spur tapers northwards, banding disappears and the now massive ore carries rounded inclusions of dike porphyry, and so passes into a markedly regular zone of ore breccia, always restricted to the dike porphyry. The pattern of this ore breccia is the one that has above been described as characteristic of the third type. The breccia finally connects with another, narrower offshot from the foot-wall side of the ore body.

We once (in 1952) had occasion to study together these relations as then exposed in the open cut. It was especially striking to observe the petrographical identity between the porphyry of the dike seen (to its whole width) cutting the ore body, and the rock in the meshes of the net-work of magnetite veins which form the ore breccia connected with the ore body.

It may be added that the very extensive sections of the large dike porphyry unit that have been accessible during the progress of mining operations, have never been found to contain a single inclusion of ore, as one should expect if, as assumed by Parák, the porphyry formed an intrusion in the ore body. On the other hand, bands of ore breccia, about one meter wide, have been observed in the interior of the dike porphyry area at the 150 m level (Geijer, field diary 1917, SGU archives).

The cross-cutting porphyry dike and those bodies of the same rock that are brecciated by the ore must, on both geological and petrographical grounds, be referred to an intrusion period of brief duration. During this period the ore body was emplaced. This leaves no time for tectonic influences or other factors to mobilize ore material — the relationships we have described must be primary ones.

4.3.2.2. The foot-wall conglomerate

One of the most interesting of the new observations related by Parák is the discovery of pockets in the upper surface of the syenitic complex, filled with a conglomerate of wholly local material with a most subordinate

matrix of magnetite ore. A period of erosion must thus have intervened between the eruption of the syenitic complex and that of the quartz-bearing porphyry. For the problem of the emplacement of the ore body, however, no decisive information can be obtained from the conglomerate. According to Parák's general interpretation the conglomerate should be a product of ore precipitation contemporaneous with the rolling of the pebbles. Assuming instead an intrusive nature of the ore body the conglomerate is to be regarded as a kind of ore breccia, the highly mobile ore magma having penetrated among the loose-lying pebbles — even more easily than in the solid porphyry. Under this assumption, however, the quartz-bearing porphyry should first have covered the pebble-filled pockets. That it did not penetrate into the latter is not surprising, since neither a coherent lava flow of this composition, with its high viscosity, nor an ignimbrite can be assumed to produce much in the way of intrusion in its substratum.

4.3.2.3. Inclusions of albitized rock in the ore body

The occurrence of these inclusions has hardly figured at all in discussions on the emplacement of the ore body, although they were known already from the outcrop. The various inclusions are not all petrographically quite similar, but they all have these features in common: there is a matrix of albite feldspar, evidently a product of alteration, and in this an impregnation (or locally veining) of the minerals that constitute the ore body, viz., magnetite, apatite and amphibole.

The northernmost known example was exposed in the steep southern slope of Statsrådet, the highest hillock on the ore ridge, where it formed a band with an eastern dip conformable with that of the ore body. The rock, white in colour, contained large amphibole crystals and some streaks of magnetite; it appeared to grade into the surrounding ore. Microscopic examination shows it to consist of albite grains, varying in size from 0.1 to more than 1 mm, and with very irregular boundaries (Geijer 1910, p. 119). This inclusion was also encountered in the railway tunnel, about 180 m lower down. In a drill hole a little further south (Oscar I, compare Geijer 1924, p. 251) a thickness of 10 m of albite rock was found within the ore body. The rock is impregnated with magnetite, apatite and amphibole, and is cut by veins of ore. About 30 m higher up, but still within the ore body, the same hole showed a narrower band of albite rock, which is remarkable by showing, in microscopic examination, remnants of a ground-mass texture that indicates either the dike porphyry or the quartz-bearing porphyry.

In the outcropping ore ridge, about one km S of the first-mentioned occurrence of albite rock, there was enclosed in the ore body, not far

from the hanging-wall boundary, a lenticular body of rock, some ten meters in length, which also largely consisted of albite but in which magnetite and apatite predominated, partly concentrated in bands (Geijer 1910, p. 118). Also this inclusion lacked distinct boundaries against the surrounding ore.

These inclusions must be regarded as indications of the intrusive nature of the ore body. The absence of distinct boundaries against the latter is ascribed to local replacement of the same kind that produced the impregnations of minerals belonging to the ore paragenesis in the inclusions. Replacement by secondary albite, with or without the accompaniment of amphibole, has, as already mentioned, been proved at several of the iron ore deposits of this metallogenic province. It may also be noted that 4 drill holes on Kiirunavaara, spaced along most of the length of the ore body, proved the immediate foot-wall to consist of such albitized porphyry (Geijer 1924).

The source of the inclusions may, of course, have been far from their present positions. There is a noteworthy contrast to the inclusions of dike porphyry near the foot-wall on northern Kiirunavaara, as described above (4.3.2.1), which have been affected by the ore in a different way.

4.3.2.4. The hanging-wall contact

Mining on Kiirunavaara, which began in 1903, had progressed more than a decade before the hanging-wall contact, originally drift-covered everywhere, became sufficiently exposed to permit reliable observations on the relationships between the ore body and the adjacent quartz-bearing porphyry. In 1917, however, Mr. P. A. Anderson, mine surveyor, realizing the scientific importance of his observation, noted and photographed an area of typical ore breccia in the immediate wall rock, the locality being situated in the southern part of the mountain. When long stretches of the contact became stripped and swept clean, excellent opportunities for study were provided. On such parts of the southern half of the mountain the following relations could be observed. In part the contact was straight and clean-cut, but in others "when going from the relatively pure ore towards the contact, one encounters first a zone, a couple of meters wide, of ore richly mixed with green hornblende, appearing as regularly distributed platy crystals but also as irregular masses . . . Proceeding outwards, porphyry fragments are encountered in the hornblendic ore, at first only as pieces less than an inch across, or isolated phenocrysts, but gradually becoming larger and more numerous, until the mixture of ore and rock must be described as porphyry with dikes and veins of a more or less hornblendic ore. This "ore breccia" . . . passes into porphyry without any foreign matter. The width of the zone, from the first porphyry fragments

to the disappearance of ore veins, generally amounts to 2 or 3 meters" (Geijer 1919 a, p. 9).

From the following years of open-cut mining no observations on the hanging-wall contact are recorded. Exposures of such were, of course, soon removed by continued mining, and no were observed at occasional visits. However, about 30 years after the surface observations just recorded, Ödman encountered wholly analogous phenomena in six cross-cuts on the 500 m level. Nearing the hanging-wall the ore there began to contain fragments of the quartz-bearing porphyry, while the porphyry outside was veined by magnetite ore. As at the surface, the ore near the boundary was rich in green amphibole. Kaolinization of the porphyry was observed, both in the inclusions in the ore and in the rock outside the boundary. This alteration, of course, indicates conditions different from those regulating the formation of magnetite and amphibole. A possible explanation may be found in the fact that locally in Kiirunavaara amphibole skarn has proved to contain a weak impregnation of pyrite.

According to Parák, the phenomena described should be caused by tectonic disturbances. But there were no traces of such to be seen in the very favourable exposures. It may also be pointed out that the widely spaced faults which cut across the ore body, are not known to have been accompanied by any other mineralization than a filling of quartz and pyrite, and occasionally hematite.

Particularly instructive are the relationships in the narrow continuation of the ore body, north of the mountain and mainly below the water of Lake Luossajärvi, a stretch of about one km. The following data are from Geijer 1924. The southernmost known section on this stretch is the shallow drill hole "Fyndigheten no. 20", at the foot of the mountain. Beginning in normal porphyry, the hole nearing the ore body encountered 12 m width of ore breccia in which sections of pure ore, up to 1.3 m, alternate with ore much mixed with porphyry and also with some portions of unaffected porphyry (up to 1.2 m). The breccia thus represents all stages of transition from porphyry with ore veins to ore with only sparse inclusions of porphyry — on the whole, however, the ore predominates. The porphyry is sometimes silicified. Finally, before reaching the foot-wall, the hole passed through 7.8 m width of ore, mixed only with some apparently secondary quartz.

About 400 m N of this section, the drill hole "Luossajärvi no. 1" encountered similar conditions (except the secondary quartz). In this section the solid ore resting on the foot-wall has a thickness of only 2.25 m. Above it follows, for a width of 3.0 m, an ore breccia in which now the ore, now the porphyry predominates, and this is upwards followed by a zone of 6.2 m in which the porphyry is interwoven with narrow apatite veins. In this

section the amount of magnetite in the breccia must at least approach that contained in the solid ore.

It is probable that also the rest of the ore zone below the lake, which zone, to judge from the magnetic map has an almost constant width, consists essentially of ore-rich breccia. This opinion has also been expressed by Parák (1973). The true ore body of Kiirunavaara, with a surface length of about 4 km and an average thickness of 90 m, thus has in this direction a kilometer-wide border of the nature assumed by Parák to be due to mobilization of material from the earlier formed deposit — an interpretation that to us appears utterly improbable, especially in view of the absence of other signs of such momentous changes in the rocks of the area.

4.3.2.5. The southern end

The tapering southern end of the Kiirunavaara ore body, from a claim name called the Sofia ore, exhibits features that are particularly enlightening as to the manner of emplacement of the deposit.¹⁾ This portion has been the subject of a detailed study by Ödman (1955). The investigation, underground on the 275 m level, was undertaken because of the abnormally high silica content of the Sofia ore. The observations made are so instructive that we quote here the unpublished report in translation:

"An examination was undertaken of the southern part of the ore on the 3rd level, samples were taken, and of these 15 thin sections were made".

"Breccias with often sharply bounded fragments of both syenite-porphry and quartz-bearing porphyry occur within the ore body in cross-cut 301 and further to no. 303. Breccia was also noted (in an inaccessible position) in a chute between nos. 305 and 306. The larger fragments in the breccia are, as a rule, quite fresh but show often a red-coloured margin against the surrounding ore. The smaller fragments are generally altered into a fine-grained red rock without porphyritic texture. They are vaguely bounded against the ore and are veined and impregnated by the latter (Fig. 2 here). The nature of fragments has entirely disappeared, and the schlieren sometimes give the impression of being younger than the ore, and cutting it."

"Schlieren and schlieric fragments of the red rock are encountered in the ore also outside the breccia areas. The occurrence of schlieren ends, on the whole, already in cross-cut 302, but they are found at the hanging-

¹⁾ A little further south, a fault across the strike has shifted the ore horizon — the contact between the syenitic complex and the quartz-bearing porphyry — eastwards about 500 m, the vertical component being unknown. Also south of this fault, ore (the Konsuln group) occurs on the contact (and in the adjacent porphyries). It has been believed (c. g., Geijer 1931 a) that one is dealing here with the original southernmost part of the Kiirunavaara ore body, but later observations indicate that the Konsuln ores may never have been connected with the latter.

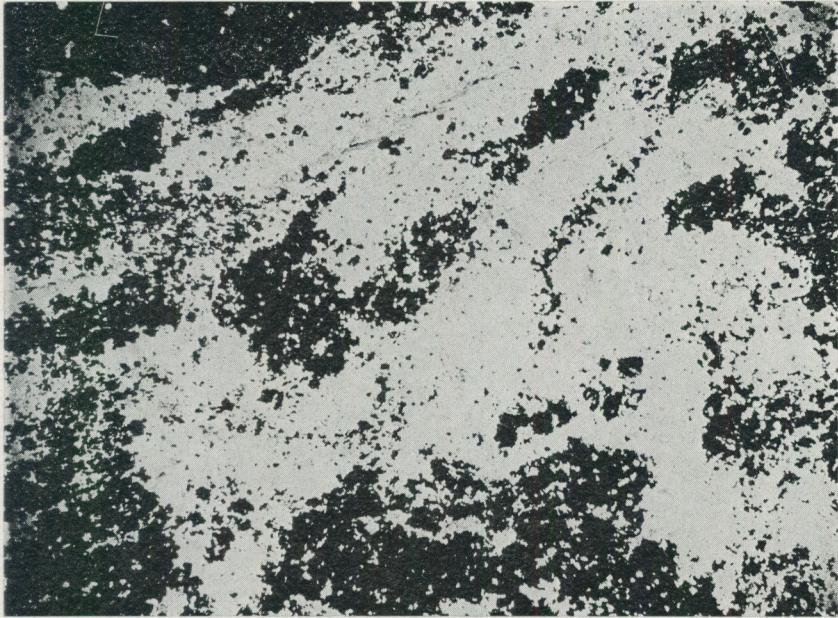


Fig. 2. Thin section from "Sofia" ore, Kiirunavaara. Ord. light, x 3. See text (after Ödman 1955).

wall in nos. 304 and 306. Some such schlieren were observed at the middle of cross-cut 307."

"Under the microscope there were identified among the fragments in the breccia both syenite-porphyry and quartz-bearing porphyry in a well-preserved state."

"The schlieren of red rock show under the microscope various stages of alteration. In some cases one can still discern that the original material has been porphyry. Many times, however, the original feldspar has disappeared and the schlieren consist of fine-grained quartz, with greater or smaller amounts of biotite, muscovite and chlorite. Apatite and magnetite are always present. Sometimes there is much calcite; as a rule it appears to have been secondarily introduced."

"The schlieren are sometimes very diffuse, and only weakly apparent in a hand specimen. The microscopic picture then shows a rather even distribution of magnetite and gangue minerals (Fig. 3 here)." "From the transitions between distinct fragments and schlieren, and from the way the latter occur in the ore, one gets the impression that the iron ore melt has

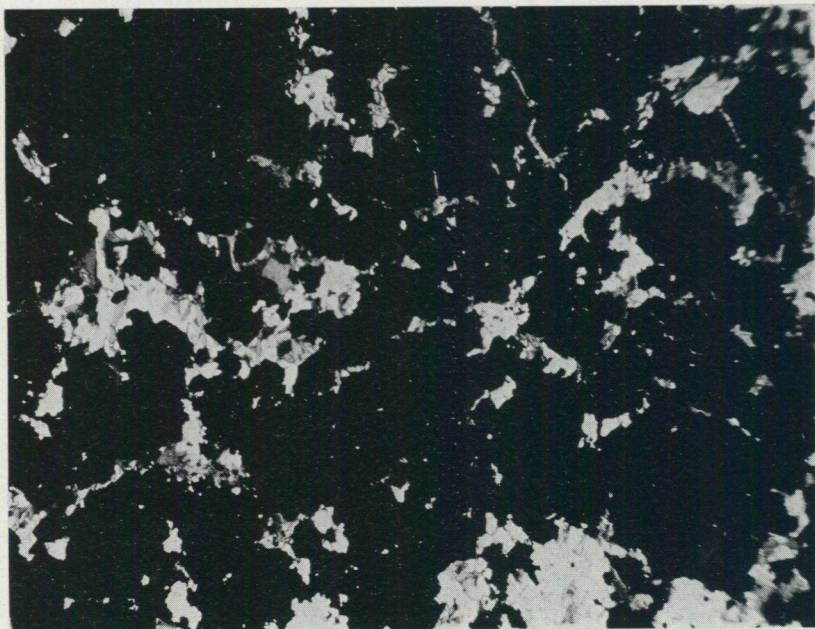


Fig. 3. Thin section of "Sofia" ore Kiirunavaara. Ord. light, x 15. See text (after Ödman 1955).

to a large extent assimilated and dissolved the fragments that it broke off and caught up from the wall rock. Clearly, great quantities of wall rock have been involved. Assimilation and digestion have taken place on a relatively large scale."

"The abnormally high silica content is thus explained by:

1. The occurrence of breccias with enclosed porphyry fragments,
2. 'dilution' of the ore through assimilation of porphyry fragments,
3. It may be added that the occurrence of breccia within the ore body in this part of Sofia, and the abundant hornblende — common in Kiirunavaara at ore boundaries and in ore veins — leads to the idea that we are here near the original, not faulted end of the ore body."

4.3.2.6. The feldspars of the quartz-bearing porphyry

It is appropriate to consider here a recent paper by Ekström (1973) which refers to the problem treated in the last preceding sections. Ekström has

studied the antiperthitic feldspars of the hanging-wall porphyry,¹⁾ and found the distribution of Na and K on the components of the antiperthite to be constant and independent of the distance from the ore body. As this property is determined by the temperature, Ekström concludes that the ore body has not had any thermal effects on the porphyry and thus cannot be magmatic (intrusive).

In this deduction, however, there is one term missing — it requires also that the antiperthite, as now studied, could not have formed after the emplacement of the ore. And Ekström himself, in fact, presents very strong reasons for assuming that this has been the case. He shows that most probably the antiperthite was developed by replacement, and points to the younger granite northwest of the district as a probable source of this alkali metasomatism. Now all students of Kiruna geology, regardless of their opinion as to the relative age of the ore body and the quartz-bearing porphyry, agree in regarding these two units as, geologically speaking, very closely connected in time. As to the granite, on the other hand, this particular intrusion is not dated, but consideration of the general geology of the province indicates that it is at least some tens of million years younger than the ore-bearing volcanic suite. If this had been the only possible, or at least, as assumed by Ekström, the most probable source of the metasomatic action that has produced the present antiperthite, it would therefore be evident that Ekström's conclusion as to the ore body lacks ground.

There is, however, one other possible source to consider, and one that to us appears much more probable than the distant granite. What we think of are alterations due to volcanic after-action, in the form of gases and liquid solutions. In the Kiruna volcanics, such effects are most conspicuous in the Hauki complex. For the markedly high potassium figure in that part of the basal Hauki unit which Parák calls "porphyry detritus", potassium metasomatism has already been mentioned as a possible explanation (Geijer 1950). And the most common rock in the Hauki next to the completely silicified volcanics is a sericite rock, which occurs as lenticular or

¹⁾ It is not our intent to make in this paper any digression into the problems of nomenclature for the pre-Tertiary volcanics of intermediate or siliceous composition, but we must raise a most serious protest against Ekström's use of the term *keratophyre* for this rock, not least because it is used in contrast to the *syenite-porphyr*ies of the foot-wall. In the first petrographic description of the Kiruna porphyries (Bäckström 1898) the foot-wall rock was called *keratophyre*, and the quartz-bearing porphyry *quartz-keratophyre*. At that time the terms still gave a fairly good idea of the nature of the rocks. Later development, however, has led to a situation that is aptly described by Schermerhorn's (1973) statement that "the rock names *keratophyre* and *quartz-keratophyre* are beset by confusion and ambiguity". Schermerhorn's clarifying discussion also shows that there can be no justification for Ekström's use of the term. And since this rock type, with varying alkali proportions, is the most wide-spread one in the ore-bearing volcanic series of the province, it would be impossible to present an intelligible account of the geology of the province if one followed Ekström on this point.

bed-shaped bodies. There is thus ample evidence of potassium metasomatism, and its distribution strongly suggests a connection with the volcanism, not with any much later geological factor. A remarkable detail in this alteration pattern of the Hauki is the fact that the intercalated flow of "Hauki porphyry" has been but little affected, and this in another way: a homogeneous development of sericite in its feldspars.

The quartz-bearing porphyry does not exhibit any such spectacular effects of alteration. Considerable parts, however, show a development of secondary quartz and biotite, accompanied by a very weak but widespread impregnation of pyrite. What speaks for alkali metasomatism — in addition to the evidence presented by Ekström — is the variable Na:K proportion in the porphyry. Of the first 4 analyses (Geijer 1910) three proved decidedly sodic, but the fourth came near an intermediate alkali proportion. And new data presented by Ekström show that the variability is still greater. This idea of alkali metasomatism appears to present a plausible answer to a question that has long intrigued geologists working in the region — the variable alkali proportions in this geologically homogeneous rock group, whose common role as the wall rock of iron ore bodies gives it a particular interest. There may also be geographical variations, however, as suggested by Geijer (1931 a, diagram p. 161). But such deviations as the extremely potassic sample from Ekströmsberg, with Na_2O 2.22, K_2O 9.28 weight per cent (Geijer 1931 a), decidedly indicates potassium metasomatism. It may also be recalled that Lofgren's (1971) reproduction of the typical textures was made in the presence solutions such as may be expected to be active in post-volcanic alteration.

Processes of the nature indicated are not episodic, they must have been going on for a long time. It is therefore impossible to say whether the feldspar of the porphyry obtained its present nature before or after the emplacement of the ore. There is known, however, a fact which shows that potassium metasomatism has been locally active after the emplacement of the ore. The porphyry dike that cuts across the ore body of Kiirunavaara (Fig. 1) showed in the outcrop an irregular variation of portions with the normal, greenish colour, and a reddish variety (Geijer 1910). The phenomenon was so striking that one of the 4 analyses made on the dike porphyries was devoted to this variety. The following figures give the alkali percentages of these analyses (using the numbers in the original, Geijer 1910):

| | No. 7 | No. 8 | No. 9 | No. 10 |
|-------------------|-------|-------|-------|--------|
| Na ₂ O | 6.89 | 6.45 | 4.48 | 6.37 |
| K ₂ O | 2.79 | 3.01 | 5.83 | 2.78 |

No. 7: dike in syenite-porphiry.

No. 8: dike cutting the ore body — ordinary phase.

No. 9: dike cutting the ore body — reddish phase.

No. 10: dike porphyry from the area enclosed by the ore body and ore breccia (Fig. 1).

Alkali metasomatism was hardly reckoned with at the time this description was written, and the variations were tacitly assumed to be due to magmatic differentiation. The only comment was that it was a "strange" phenomenon. Nowadays metasomatism seems the only possible explanation, and it is evident that this process was here active after the emplacement of the ore body.

Of sodium metasomatism there is ample evidence in the more basic volcanics of the province, in the form of albitization of plagioclase. The almost regional extension of this process in the older ("Karelian") basic volcanics was first studied by Sundius (1915). It is also, however, evident in porphyrites, originally of an intermediate (andesitic) nature, which appear to belong to the same volcanic series as the ore-bearing porphyries. In them, there are also found examples of a great development of secondary biotite, indicating that potassium, too, has been added (compare Geijer 1931 a, p. 61).

While these facts do not permit any conclusions as to the development of the antiperthites studied by Ekström, they show that great caution must be exercised in basing geological conclusions on the present properties of the feldspars.

4.3.3. LUOSSAVAARA

This ore body, once popularly regarded as a "twin" to Kiirunavaara, is — at least what remains after erosion — incomparably much smaller than the latter, its much lesser extension in depth being especially noteworthy. It, however, occupies the same level in the volcanic pile as does Kiirunavaara: the interface between the syenitic complex and the quartz-bearing porphyry.

As to conditions at the *foot-wall*, observations are available from two different stages, viz. Geijer's (1910) examination of the natural outcrops at the top of the mountain and some prospecting excavations, and Parák's (1973) from the present state of mining. Geijer noted the presence of numerous ore veins in the syenite-porphiry, and suspected that these should represent two different sets, one being segregations in the syenite-por-

phyry while "only very few large dikes are connected with the ore body, those are evidently apophyses from it and not segregations relatively in situ as the veins of the other group" (p. 120).¹⁾ The largest among the dikes connected with the ore body was one meter wide and branched off into the foot-wall just at the summit; it then ran for about 10 m nearly parallel to the ore body so that they together almost enclosed a slab of the porphyry.

Mining has later revealed that the veins of this older group are developed on a much greater scale than could be expected from the surface showings. Parák (1973) has described this, and has also discerned the other set mentioned by Geijer, with the additional valuable observation that it cuts the vein of the older group.

Parák, however, maintains that the later set is not connected with the ore body, since the latter all along the foot-wall is bounded by a seam of chlorite rock. This seam had already been noted by Geijer (1910), who described it as some dm wide and containing lumps of quartz, and, sparingly, needles of tourmaline. At the top it continued along the large ore dike. Farther north, quartz became predominant, and the chlorite "sköl" (to use this old Swedish mining term) changed into a quartz vein (with some patches of chlorite) which reached a maximum width of more than 2 meters and sent out branches that brecciated the adjacent part of the ore body.

From these facts it is clear that there has occurred some movement along the foot-wall contact after the emplacement of the ore body, and that the later set of dikes and narrower veins of ore in the foot-wall are really offshoots from the ore body.

There are indications, however, that the mineralization connected with this disturbance may have begun already shortly after the emplacement of the ore. For there has been found locally at Kiirunavaara, on the foot-wall contact and in the ore close to it, irregular aggregates of sericite and chlorite, with much tourmaline (Geijer 1910, p. 115). In these cases there are no signs of movement, but the paragenesis distinctly indicates conditions of mineralization different from those of the ore body.

Conditions at the *hanging-wall* contact are different from those described above from Kiirunavaara. There have not been noted any distinct ore veins in the porphyry, nor is there any development of amphibole skarn. The latter fact may possibly be correlated with the feature that, so far as we know, amphibole is less frequently observed in the Luossavaara ore than in that of Kiirunavaara.

¹⁾ This distinction was unfortunately forgotten when Geijer (1968) adduced also this latter group of veins as argument for an intrusive nature of the ore body.

The only change observed in the immediate hanging-wall rock is a very strong impregnation with magnetite, which we have noted in a section at the southern foot of the mountain, and a similar phenomenon described by Geijer (1910, p. 121) from same general locality. In this latter case the boundary of the ore body was marked by a mass, some dm wide, of vuggy quartz, chlorite and tourmaline — thus an analogue to the product already described from the foot-wall boundary. Outside this, the porphyry was found to be finely brecciated by irregular and vaguely bounded, microscopically distinguishable veins of magnetite, with albite and quartz. The albite grains are larger than the ordinary groundmass feldspars of the porphyry, and the latter is poorer in quartz than normally; the alteration, which extends only some dm from the contact, thus seems to be a small-scale example of the albitization sometimes associated with the intrusion of ores of this character, as has been mentioned above.

These inconspicuous contact effects in the quartz-bearing porphyry, combined with the fact that the latter, even at the very contact with the ore, is studded with angular inclusions of iron ore of the same type, have formed the main foundation for those who reject the idea that the Luossavaara ore should be a product of intrusion. But it appears unacceptable to geological common sense to attribute to it another kind of emplacement than that accepted for Kiirunavaara. Geijer (1968), in discussing the ore inclusions in the quartz-bearing porphyry, has pointed out that the inclusions must be derived from an ore body, now removed by erosion, which appears to have been situated (above the present surface) north or north-east of the Luossavaara summit. Concerning this ore body there are two alternatives to reckon with: either it formed part of the Luossavaara ore body, or it was an otherwise unknown, older one. Because of the assumed intrusive nature of Luossavaara, the latter alternative was regarded as the most probable one or, rather, "the least improbable".

It is not our intention to take up here this really intricate problem for a complete discussion, but Parák presents several new and important observations from the unit of quartz-bearing porphyry forming the hanging-wall, which it is desirable to comment upon, especially as Parák does not himself indicate any conclusions that can be judged without a very intimate knowledge of earlier observations.

The quartz-bearing porphyry is here, throughout its whole thickness except the uppermost part, developed as pyroclastic flows recognizable as such. Referring for details to Geijer's (1968) description, we give here only the main features. The porphyry shows always its normal development. Inclusions are scattered in some zones, but are to a large extent accumulated to form a kind of agglomerate. The rock inclusions are generally more or less rounded, and represent syenite-porphyrines of various

types known from the foot-wall complex at Luossavaara and northeastwards, and also the quartz-bearing porphyry, probably not quite so common. Inclusions of iron ore of types common in the Luossavaara and Kiirunavaara ore bodies are very numerous; they are always angular.

From this sequence of pyroclastic flows, Parák reports two especially important new discoveries: the presence of an intercalation of true conglomerate, and of inclusions of siliceous hematite ore in the upper part of the porphyry.

The conglomerate is reported to contain boulders of syenite-porphry, quartz-bearing porphyry, and iron ore of the ordinary type. Particularly noteworthy is the presence of a rounded boulder of such ore, whose longer axis measures 0.7 m. The exact position of the conglomerate is not clear, but apparently it is interstratified between the pyroclastic flows, presumably not far from the ore body. This conglomerate does not reach the present rock surface, nor was it encountered with anyone of the drill holes that pass through the whole sequence of pyroclastics. It must therefore be of limited extension, which may indicate a stream bed rather than a beach as the environment of deposition. In any case it proves that the series of pyroclastic eruptions was interrupted by a period of erosion.

Geijer (1968) has thought it most probable that the pyroclastic porphyry represents a series of separate eruptions, but knew no indications of any intervening pause. From the vulcanological point of view the pause in activity indicated by the conglomerate is not in any way remarkable — one may compare the period of repose of Mt Pelé between its series of glowing avalanches 1902—1903 and 1929—1932. But in the case of the Luossavaara conglomerate there is a feature of great local interest to note. Although the exact position of the conglomerate in the sequence is not clear, it is evident that there are flows with numerous iron ore inclusions both below and above it. This appears to indicate that the eruptions all the time came from approximately the same point, where there existed solid ore of the nature in question.

It appears from the context that Parák is inclined to regard the ore boulders in the conglomerate as a proof against the intrusive nature of the Luossavaara ore body. The problem is not so simple, however. Already the presence of quartz-bearing porphyry in the conglomerate, as reported by Parák, shows that a cover of this rock must have existed at the time of erosion. And the lowest part of this pyroclastic sequence is known to be studded with large inclusions of ore. True, none of these angular inclusions has been found to exceed 0.5 m in size, while the abovementioned rounded ore boulder in the conglomerate indicates a case of considerably larger original dimensions. However, what has been open to observation of this zone with large ore inclusions represents such a very small portion of it

that fragments larger than those noted may well occur there. It is also to be noted that large angular inclusions have been observed so close together as to suggest that they might be pieces of a larger one, just broken up. Therefore the conglomerate cannot be cited as a proof against the intrusive nature of the Luossavaara ore body. But neither is it to be neglected in this connection — it may turn out to be a piece of circumstantial evidence whose importance becomes apparent through further discoveries.

The other notable new discovery is less spectacular than the conglomerate, but certainly also deserves attention in the present discussion. It is the occurrence of inclusions of quartz-rich hematite ore in the upper portion of the sequence of quartz-bearing porphyry on Luossavaara (Parák 1973, p. 16). These inclusions are clearly of the same general nature as the hematite-rich parts of the silicified Hauki rocks. No inclusions entirely similar to those now described by Parák were previously known from the sequence of quartz-bearing porphyry. But there was a related one, in the typical agglomerate and thus at a lower level. This fragment, some dm in length, was by Stutzer (1907) regarded as derived from the Hauki complex, and therefore by him adduced as an argument for interpreting the porphyry as intrusive. As was pointed out by Geijer (1910, p. 249), however, the fragment is different from the siliceous Hauki ores; it consists of magnetite and quartz in about equal amounts, pyrite, and some biotite. The considerable percentage of pyrite is especially noteworthy, since it distinctly belongs to the primary mineralization. Although the inclusion thus shows features that distinguish it from the Hauki ores, it is clear that it represents a product of hydrothermal replacement, closely similar in nature to the one that gave rise to the Hauki ores. And the inclusions now described by Parák appear wholly comparable to the latter.

It is evident, then, that the pyroclastic flows of Luossavaara contain material from an otherwise unknown mineralization, similar to that of the Hauki complex but clearly older than the latter. This fact may, perhaps, somewhat strengthen the probability that the inclusions of ordinary apatite-bearing ore likewise came from an otherwise unknown deposit.

4.3.4. TUOLLUVAARA

This deposit is situated 4 km E of Kiirunavaara but in another tectonic block, being separated from the Kiruna district by at least one fault of very great throw. The reason for devoting a special section to Tuolluvaara is that it shows, clearer than any other Swedish deposit, the intrusive nature of the ordinary type of apatite-bearing iron ore.

Before mining started at Tuolluvaara, most of the low hillock where the ore bodies occur was stripped of its drift cover and swept clean, thus providing ideal conditions for study.

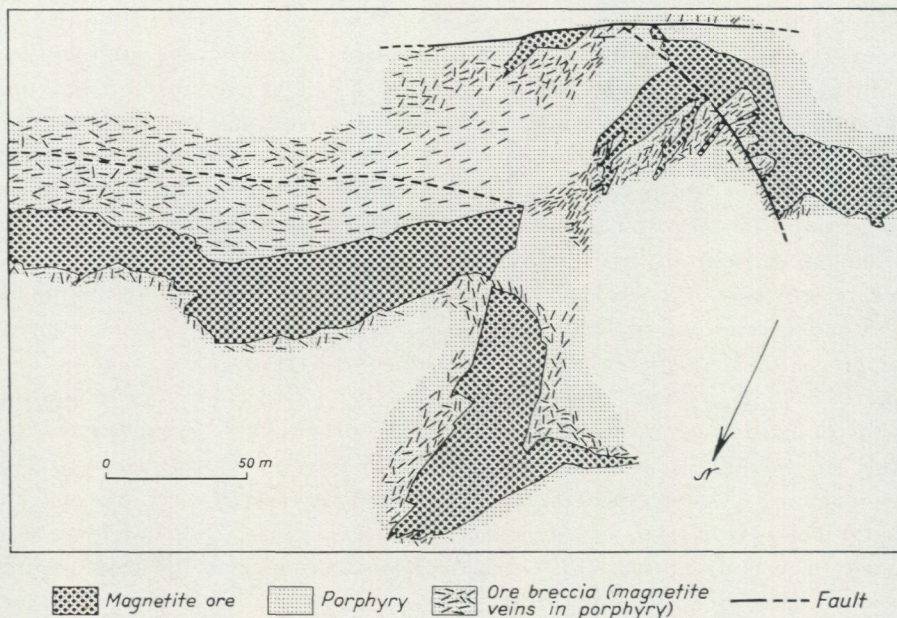


Fig. 4. Tuolluvaara, surface map of central part (adapted from Geijer 1920).

There are only two geological units to consider: the ore, and the porphyry that everywhere surrounds the ore bodies. This porphyry was, in its original development, identical with the quartz-bearing porphyry of the Kiruna district, except in the size of the feldspar phenocrysts, which are smaller at Tuolluvaara. The groundmass is now recrystallized, with a grain size generally about 0.015 to 0.030 mm, though it may rise locally even to 0.08 mm. Yet traces of the micropoikilitic devitrification texture so common in the Kiruna porphyry are still discernible (Geijer 1920).

According to Parák (p. 31) the ore bodies were probably once continuous.¹⁾ No reasons for this view are given, and it can only be understood as implying that the present spatial relationships should be due to later displacement. As seen from the surface map (Geijer 1920, Pl. 1, reproduced for the most part here as Fig. 4) this interpretation is untenable; it seems to be based on a confusion of the fissure system that guided the emplacement of the ore, with the series of very much later faults. These faults, however, are always straight and clean-cut, never grading into a system

¹⁾ Unfortunately, Parák's formulation gives the impression that this opinion has been expressed by Geijer (1920), which is wholly wrong.

similar to the pattern of the extensive ore breccia which accompanies the ore bodies, and never contain any ore minerals.

A feature of the Tuolluvaara deposit that must not be let out of sight is the proved existence of two distinct intrusions of ore in the same fissure (Geijer 1967).¹⁾

What especially distinguishes Tuolluvaara is, however, that it has been possible there — thanks to the continuous surface exposures — to study directly the transition from an ore body of workable size, through branching ore dikes of gradually diminishing thickness, into a typical ore breccia. The expansion of the affected area is evident and proves that the ore was emplaced by forceful injection, not by any filling of pre-existing fissures.

Fig. 4 is based essentially on the official mine map, the surveyor having plotted the individual ore dikes so long as their dimensions permitted them to be so indicated in the scale employed (originally 1:800), while the net of ore breccia had to be shown schematically in Fig. 4. The fault shown as crossing the dikes is an overthrust with a moderate dip and small movement.

4.3.5. OTHER DEPOSITS IN THE METALLOGENIC PROVINCE OF NORTH SWEDEN

With very few exceptions, the deposits of ordinary apatite-bearing iron ore in this province exhibit towards their wall rock relationships analogous to those described above from Kiirunavaara and Tuolluvaara, varying from the development of sparse magnetite veins to extensive breccias. A remarkable case is Painirova, not because of its irregular and little known breccia structure, but as being the only known example in Sweden of ore with "coarse-grained" apatite and the texture often found in related ores in other countries.

More typical breccia patterns are known from Mertainen, Leveäniemi, Tansari, and a number of ore bodies in the extensive MalMBERGET (Gällivare) field. In the last-mentioned group, the contiguous Ridderstolpe and Vitåfors ore bodies furnish the most instructive examples. These are among the smaller units worked at MalMBERGET. They are roughly, and in the case of Vitåfors irregularly, tabular in shape, striking approximately W—E, with Ridderstolpe, the smaller unit, to the west; dip is southerly.

The Ridderstolpe ore body at several places near its hanging-wall contact encloses numerous fragments of the wall rock, and through a very

¹⁾ To the description quoted it may be added that the fragments of apatite-rich ore observed enclosed in pure ore in the Snorre ore body were roughly rectangular in shape and of a size, according to visual memory, of 1 or 2 dm (P. G.).

ore-rich ore breccia — whose ore veins have a high content of apatite — passes into a more sparse and gradually ceasing system of ore veins; some veining of green amphibole (skarn, in local usage) extends beyond the ore veins. On the foot-wall side conditions are similar, but with a more distinct boundary between solid ore and breccia, and with less of magnetite veins but more of amphibole.

The Vitåfors ore body is, in its foot-wall, accompanied by a skarn breccia with much apatite, while the immediate hanging-wall shows much brecciation by ore veins. On this side (or possibly from the eastern end of the Ridderstolpe ore) there branches off a narrow ore body, eastwards more and more diverging from the Vitåfors ore. This narrow ore is very irregular and is largely more to be regarded as an unusually ore-rich breccia zone.

Since Malmberget, in contrast to almost all the other occurrences of this province, has been subjected to a strong metamorphism, it is important to point out that the phenomena just described clearly antedate this metamorphism. One of the proofs of this may be mentioned. There occur in the ore-bearing rocks some small intrusions of a porphyritic quartz-syenite, which has undergone the same textural metamorphism as the older rocks but, like them, is in turn intruded by dikes belonging to a set of granite and pegmatites, associated with the Lina granite, the youngest element in the Precambrian of this part of the region. Now one of these bodies of syenite has been observed to cut the skarn striping in the ore-bearing rocks, thus indicating that the skarn was developed before any appreciable metamorphism set in (Geijer 1930).

4.3.6. DEPOSITS IN MISSOURI

In the United States, the iron metallogenic province in the Precambrian terrain of southerneastern Missouri forms a remarkable counterpart to the North Swedish province. At the same time, however, it exhibits certain subordinate features not encountered in the latter, and illustrates in an instructive way variations within the type.

On a visit in 1913 to the outcropping, and therefore long known deposits of Iron Mountain and Pilot Knob, Geijer (1915, 1931 b) noted the similarities to the Swedish deposits. Iron Mountain, whose intrusive ore bodies are accompanied by an apatite-rich ore breccia, was found to combine features known from Tuolluvaara and Painirova, while Pilot Knob (apart from the regular hematite beds) in a striking way recalled the siliceous hematite ores of the Hauki complex, which are clearly formed by hydrothermal replacement.

Discoveries in later years, which include deposits of much greater magnitude than those previously known, have furnished a wealth of geological information. According to available descriptions these deposits must be referred to the ordinary type of apatite-bearing ores, although there are no truly high-phosphorus occurrences. Normally the ore bodies form intrusions in the more or less siliceous volcanics. Their accessory minerals mark a distinct difference from the otherwise comparable Swedish deposits, quartz, pyrite, fluorite and barite being reported. Of these, quartz and barite are found in the Hauki hematite ores, but pyrite is very low in all ores of the Swedish province, while fluorite, so far as our knowledge goes, has never been observed as a member of the original mineral assemblage there. From Iron Mountain, Murphy and Ohle (1968) report andradite garnet and calcite as among the most important gangue minerals. This association has, in Sweden, its counterpart in Gruvberget (Svappavaara).

Of particular interest for the subject treated in this paper is the large Pea Ridge deposit. The following characteristic is based on the clear description of Emery (1968). The ore body forms a dike-like mass in nearly vertical position, intersecting the dip and strike of the associated porphyries at an extremely sharp angle. There can be distinguished in the deposit five zones of different composition. The magnetite zone makes up the bulk of the workable ore. It may be noted that it is described as sometimes being very fine-grained, porcelain-like — a development often encountered also in the Kiirunavaara ore. The zone of specular hematite ore has a more restricted extension, chiefly along the foot-wall. Its contact with the magnetite ore is gradational. Apatite is said to be consistent in quantity throughout the ore. The "porphyry breccia" zone, of considerable width, is on the hanging-wall side, associated with the magnetite ore. It is evidently an exact counterpart to the ore breccias of the deposits in Sweden. The contact between the ore and this breccia is described as gradational, and, "in many areas, is merely a matter of definition". There is further, on the foot-wall side, a zone of hematite and quartz; a reported content of tourmaline implies a genesis comparable with that of Pilot Knob (Singerwald and Milton, 1929) and with the tourmaline-rich siliceous hematite zone at Algarrobo, Chile (Geijer 1931 b). On the other hand, there follows on the hanging-wall side, outside the breccia, a mass of quartz and amphibole, locally with concentrations of apatite.

Pea Ridge is by Emery interpreted as having been formed essentially by a single injection of magmatic differentiate, with hydrothermal end phases forming the quartz-amphibole and quartz-hematite portions of the deposit.

Ore veins brecciating the country rock are reported also to be associated with the ore body known under the unwieldy name of Pilot Knob (sub-

surface) (Snyder 1969). Also Snyder regards the deposits in question as probably derived by magmatic differentiation.

Recently Kisvarsanyi (1973), in a brief abstract, mentions "injection of ore magmas and hydrothermal fluids" as the factors that gave rise to the iron metallogenic province.

4.3.7. DEPOSITS IN MEXICO

The best known occurrence of the kind concerned in Mexico is the large one of Cerro Mercado, in the State of Durango. The following data about it are based mainly on the description by Foshag (1928) and on a set of specimens kindly sent by him (compare Geijer 1931). The ore forms flat-lying beds (possibly originally coherent) in a volcanic sequence of Lower Pliocene age. The very coarse texture of the ore is noteworthy. For the subject now under discussion the data about the relations between the ore and its wall rock are of special interest. These are characterized by the development of ore breccia, and by considerable alteration of the wall rock. An important product of this alteration is a skarn of pyroxene (to judge from the colour, a hedenbergitic diopside), apparently the "pyroxenite" of certain earlier reports. This skarn sometimes forms veins, and thus gives rise to a "skarn breccia" analogous to that of MalMBERGET (Gällivare). As in the latter case, some magnetite and apatite are associated with the silicate. It is worthy of note that no amphibole is reported from this deposit.

Cerro Mercado, however, is not the only iron ore deposit in Mexico that illustrates the contact relations that we are here concerned with. For, according to Park (1972, p. 346), "many of the iron ore deposits of Mexico are locally bordered by inconspicuous dikes and other bodies of magnetite and apatite".

4.3.8. DEPOSITS IN CHILE AND PERU

A metallogenic sub-province in the South American Cordillera, in northern Chile and in Peru, probably contains a greater number of deposits of the type now concerned than any other region. With the exception of the extrusive Laco ore bodies, which are of Recent age, all deposits on which data are available appear to occur in rocks of Mesozoic age. Presumably most of them are in the volcanics, especially where these occur as roof pendants in the Cretaceous "Andean batholith", but some are directly in intrusives belonging to that set. These ores have mostly been interpreted as intrusive but of late metasomatic replacement has come to the fore as an explanation (Ruiz 1965). This development seems to be due mainly to the evidence of replacement reported from the large deposit of Boquerón-

Chañar, but the contact relations of a number of other deposits indicate that this interpretation cannot apply to them (Geijer 1967). Park's statement (Park 1972, p. 347) that "no single type of emplacement will explain the diversity of the magnetite bodies" appears well-founded. It certainly applies also to some other provinces where apatite-bearing iron ores occur, but we believe that the ordinary type of such ore, as here defined, represents only comparatively small variations in this respect.

As to the contact relations of the Chilean deposits, Geijer (1931) has described the occurrence of magnetite veins in the wall rocks at Algarrobo (where they locally are very rich in apatite), Ojos de Agua and Tofo. Conditions at Tofo are particularly instructive. The cluster of stock-like ore bodies of this deposit (now mined out) occurs in a diorite porphyry of hypabyssic habit, consisting essentially of oligoclase.¹⁾ To illustrate the similarity to conditions in deposits of the same type of ore in Sweden, we quote in translation from Geijer's field notes (1928). "Nearer to the ore bodies, as everywhere in the open cut, the rock becomes distinctly affected by the mineralization, fissured, replaced by finely distributed amphibole and epidote, veined by amphibole and by narrow (mostly a couple of cm wide) veins of coarsely crystalline magnetite, in part with coarse apatite in groups. In connection with the ore body there occur some larger dikes of ore and, in their interstices, a fine felt of amphibole. The amphibole is always actinolitic". One thus encounters here a feature well known from Swedish deposits: the fissure-filling veins are largely magnetite, but the product of the accompanying replacement is amphibole. The only difference is that at Tofo there is a considerable amount of epidote together with the amphibole, clearly to be explained by the content of anorthite in the replaced rock as contrasted with the pronouncedly alkaline character of the feldspar in virtually all the ore-bearing rocks of the Swedish province. At Tofo, as at Tuolluvaara, there is also to note the evidence of strong disruption of the country rock by pressure emanating from the emplacement of the ore bodies.

Other deposits in this South American province exhibit relations of the same nature, but apparently the tendency of the veins to be rich in apatite is here particularly pronounced. Thus Park (1972, p. 346) writes that "the apatite-rich dikes are common around the edges of larger massive magnetite deposits that contain much smaller amounts of phosphorus and that are being mined locally for iron ore. In places in Chile so many of these dikes are present that they have been mapped and used as possible guides to the location of the larger bodies." Park further mentions the occurrence

¹⁾ At greater distance from the deposit there is a fine-grained quartz diorite, but the relations between the two kinds of rock were not established.

of apatite-magnetite-amphibole dikes associated with iron ore in Peru, at Marcona and Acari.

4.3.9. SUMMARY OF CONTACT RELATIONS

The above review demonstrates that breccias in the wall rock, formed by dikes and veins of the minerals characteristic of the ordinary type of apatite-bearing iron ore, are a feature normally accompanying ore bodies of this type. Known exceptions are very few — the "Old Bed" ore body at Mineville, in the Adirondacks is, however, a case in point. The phenomenon cannot be dependent on the presence of apatite, as two of the most instructive examples, Mertainen and Tuolluvaara, are notably low in phosphorus.

Among the world's geologically known iron ore deposits, those of the type now concerned form only a very small portion. From all the others, representing every possible variation in chemical composition, original geological setting, structural deformation and kind of metamorphism (including the influence of intrusives), there is, to our knowledge, not reported even a single case of analogous nature.

In view of these facts we regard it as an amply justified conclusion that the association with ore breccias is a primary feature of the ordinary type of apatite-bearing iron ore, and that, in consequence, Parák's hypothesis, according to which the ore bodies should originally have been sedimentary products, and the ore breccias the result of secondary process, is untenable.

5. GEOCHEMISTRY AND THE FRACTIONATION PROCESS

A truly sensational geochemical novelty in Parák's work is the author's belief that the iron, and the phosphorus associated with it in the ores, were derived from radically different sources, the iron from volcanic exhalations, the phosphorus from organic remains. The association should thus, according to Parák, be wholly accidental, and no "Kiruna type" of iron ore should exist. Previously no one has doubted that these substances stem basically from the same igneous source, however the views of the observers may have varied on other points. And the survey that we have given here, although not intended for that purpose, provides much additional evidence, confirming the view that these deposits represent a well-defined type, among whose characteristics the association of magnetite and apatite is the most important one.

Parák does not give any reason for his disagreement with this view, and only indicates the possibility of phosphate deposition from organic

sources at the time in question — about 1600 m.y.B.P. The impossibility of Parák's interpretation can be illustrated from his own observations: the cross-bedding in the apatite rock at Rektorn that has been discussed above. We may also point out some of the consequences of his hypothesis as applied to the Kiruna ores. According to this view, life at that time should have flourished, particularly in waters where a very strong volcanic after-action was going on, which introduces wholly new biological concepts. And in the case of Lappmalmen this accumulation of biologically derived phosphorus should have been going on continuously, interrupted only by chemical precipitation of iron but not by any mechanical sedimentation, so that the total thickness of apatite (leaving out the iron minerals) should amount to about 30 m. This is almost certainly without a parallel, even taking all known Phanerozoic deposits of phosphate rock into account. And this extraordinary abundance of life should not have left the slightest trace of carbonaceous residue.

On the other hand, Parák also presents a highly valuable contribution to the knowledge of the ores (and associated rocks) in the form of a very great number of chemical analyses of the ore minerals — magnetite and hematite — including data on diagnostically interesting trace elements. On this material, which is the result of systematic and very extensive sampling, Parák largely bases his conclusions as to the genesis of the ores. Even in this comprehensive material, however, some data of great importance for the understanding of the ore-forming processes are missing. Foremost among these are figures on the magnetite and the (non-martitic) hematite of the apatite dikes. If these should turn out to fall within the pattern shown by the Per Geijer ores and by Kiirunavaara, it would mean a very strong support for the hypothesis for the former that has been outlined above (p. 12), and, conversely, a clear deviation from the pattern would support Parák's hypothesis of mobilization, and thus leave the questions raised by the contradictory phenomena at Rektorn unanswered.¹⁾ Further one would like to have analyses of the magnetite that has crystallized in the groundmass of a Kiirunavaara syenite-porphyrity and of that occurring as vesicle-fillings in the same rock sample. Notwithstanding their close association, these magnetites have crystallized under different physico-chemical conditions.

Earlier, data published by Frietsch (1970) had indicated an essential similarity in the properties concerned between all the apatite-bearing ores of the province, including, for example, Kiirunavaara, Rektorn-Nukutus

¹⁾ No corresponding information can be obtained from the ore breccias of Kiirunavaara, since the ore breccias generally by their higher content of apatite indicate that they represent a certain degree of fractionation compared with the ore bodies with which they are associated (Geijer 1967).

and Tuolluvaara, while the siliceous hematite ores in the Hauki rocks, clearly formed by hydrothermal replacement, exhibit figures quite different from those of the apatite-bearing group.

The conclusions that Parák draws from the geochemical data may be summarized as follows. The Per Geijer ores and Kiirunavaara are comparable with each other and with the Devonian ores of the Lahn and Dill districts in West Germany, which are generally interpreted as results of an exhalative-sedimentary process, therefore this interpretation must apply also to the Kiruna ores.

We have no reason to disagree with this interpretation of the Lahn—Dill ores. One of us (P. G.) has, in fact, once visited the district just in order to get more light on the Precambrian quartz-banded ores of Central Sweden, which, for at least half a century, have been interpreted in this way. It is important, however, to remember the following facts. The sedimentary origin of the Lahn—Dill ores is evident — it can be considered a geological fact. The source of the iron, again, is not proved in a similar way, it is inferred from the general geological environment in which these ores occur.

We also wish to point out the following. If certain geochemical similarities between, for instance, Tuolluvaara and the Lahn—Dill ores should prove an identity in the form of emplacement, then one would be justified in interpreting the Lahn—Dill ores as products of intrusion — which would be absurd — since the intrusive nature of Tuolluvaara is as clear as is the sedimentary origin of Lahn—Dill. The difference is simply that the latter have been much publicized, and have thus come to be regarded as a standard type in a genetical classification of iron ores, while Tuolluvaara, less widely known, has remained in the background.

The first to compare Kiirunavaara to Lahn—Dill were Hegemann and Albrecht (1954). These authors also discuss the various possible ways in which the iron of the latter may have been contributed to the waters of the basin of deposition, a discussion that leads them to prefer the term "extrusive-sedimentary", as better than "exhalative-sedimentary".

Hegemann and Albrecht arrived at the conclusion that Kiirunavaara, because of geochemical similarities to the Lahn—Dill ores, but also certain differences from them, should be a product of an extrusive-sedimentary process whose geochemical characters have been considerably ("weitgehend") changed by later metamorphism. Because of the Precambrian age of Kiirunavaara it is perhaps understandable that the authors quoted found this explanation natural. Actually, however, there are no recognizable traces of metamorphism, whether in the ore or in the associated rocks. And if chemical changes such as are assumed to have occurred in this case could take place without leaving any such traces, then the very

foundations for the use of trace elements in problems of this nature would collapse.

The conclusion, therefore, ought to be that the Kiruna type is something apart, and cannot be placed into anyone of the pigeon-holes of the conventional genetical classification of iron ores which is used also by Hegemann and Albrecht.

If, instead of regarding exclusively the mode of emplacement, one considers the ways in which the ore-forming substances may have become separated from their parent magma, a better result may be achieved on this point, and the close geological relations between the ordinary type of apatite-bearing magnetite ore — i. e., the Kiruna type — and certain other forms of iron ore deposition might be understood. This brings us over to the problem of the fractionation process which led to the separation of the ore-forming material from the magma of which it once formed part.

Högbom (1898) was the first to mention magmatic differentiation to explain the origin of the Kiruna ores, but his idea of a syngenetic segregation has only historical interest. Stutzer's (1907) characterization of Kiirunavaara as a migrated magmatic segregation was based on field studies not only on this deposit but also on others in the same province. His work was practically restricted to the ore bodies, however, and he did not enter upon any discussion of the way in which the differentiation from the parent magma might have taken place. Actually, in discussions at that time, by magmatic was meant an origin similar to that of the titaniferous iron ores associated with more basic igneous rocks, the low content of titanium being explained by reference to the different character of the associated igneous rocks.

Geijer (1910, pp. 266—270) took up the nature of the differentiation for discussion. The problem was to reconcile the magmatic nature of the main ore bodies (Kiirunavaara and Luossavaara) with phenomena such as the apatite dikes, with their primary tourmaline, and the occurrence of the ore-forming minerals as vesicle-fillings in the syenite-porphyrity of Kiirunavaara, which latter fact formed the basis for Bäckström's (1898) hypothesis of what would now be called an exhalative origin of the ores. Geijer believed to have traced "a rather continuous" series from the normally magmatic main ores through the apatite dikes and the Rektorn and Nukutus ore bodies (both then exposed only in some prospecting diggings and believed to be comparable to the apatite dikes) to the clearly hydrothermal replacement deposits of siliceous hematite ore in the Hauki rocks. "The lower the crystallization temperature of the ores, the higher the content of 'pneumatolytic' minerals and the more distinct appears their character as the last crystallizing part of the common parent magma of the rocks

and the ores of the district. ".". The ore thus represents the last crystallizing part 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 "(p. 268) The group of magmatic differentiation products "may perhaps be divided into two sub-sections, one comprehending segregations of the first crystallizing minerals (iron ores of the Taberg type, chromite ores, and others), the other the 'pegmatite type'¹⁾, ores as the last crystallizing part magmas (iron ores of the Kiruna type, pyrrhotite)" (p. 269).

We have given such a long quotation from this old work because, while the designation "magmatic" was widely accepted on the grounds of the evidence presented, the views proposed about the character of the differentiation apparently did not arouse much interest, the only published sign of such being a paper by Bergeat (1912), who called Kiirunavaara a pegmatitic injection. Yet this side of the hypothesis is not less important than the other. It is, for instance, the facts behind it that make it natural for us to agree with Parák's interpretation of the Per Geijer ores (except for the source of the phosphorus, and certain details) and at the same time reject this hypothesis when Kiirunavaara and other representatives of the ordinary type of apatite-bearing iron ore are concerned, although the two types are genetically connected with the same igneous activity.

A differentiation process of the same kind as the one quoted above was by Graton and McLaughlin (1918) proposed to account for the origin of the copper ores at Engels, California. For such magmatic products, results of crystallization under the modifying influence of volatiles, these authors proposed the term "pneumotectic", as contrasted to "orthotectic" for "the normal crystallization of normal igneous rocks". These terms have not been much used, however.²⁾

On the other hand Bowen (1928), in his classic work on the igneous rocks, emphatically denied the possibility of an iron-rich rest magma. It might perhaps seem that the Laco ore bodies prove Bowen to have been wrong on this point, since they bear evidence both as to the high content of volatiles in the ore magma and the change produced by losing them when the magma came under only atmospheric pressure. This may, however, be an unjustified conclusion. For there are features in the apatite-bearing ores, not previously mentioned here, which indicate that the hypo-

¹⁾ Leith (1908, p. 277): "Ores that are carried to or near the surface in magmas and extruded from them, in the manner of pegmatite dikes, after the remainder of the magma has been partially cooled and crystallized."

²⁾ Through an inexplicable lapse Geijer (1950) called the main Kiruna ores orthotectic, when emphasizing differences from the supposedly more clearly pneumotectic Rektorn ore.

thesis of 1910 may perhaps have to be modified as to the way in which the volatiles have operated, assigning to them a more distinctly causative role.

Geijer (1910) mentioned briefly that there were not known any transitional stages between ore and silicate rock, but did not particularly dwell upon this fact. When a greater number became known of deposits of what we call the ordinary type of apatite-bearing ore, the fact stood out conspicuously that there is always a most distinct gap in mineral composition between the ores and the igneous rocks with which they are associated. The most striking feature is the complete lack of any feldspar in the ores — except as occasional foreign inclusions — while the rocks always predominantly consist of feldspars, in the Swedish province to about 60 to 80 per cent. Thus the effects of the differentiation process are like those of limited miscibility (Geijer 1935). This, of course, does not imply any change from the opinion that the volatiles have played a decisive role in the fractionation.

Also when, in more recent years, ore deposits of this type have become the subject of detailed study in certain other countries, investigators tend to seek the explanation of the features encountered in a magmatic intrusion in which volatile compounds have had essential influence. The term pneumatitic may not have come into use, but the idea is the same as indicated by it.

One has the general impression that these ores were emplaced at no high temperature — hardly, in any case, higher than that of granite pegmatites. Thus there are never reported any distinct thermal effects in the immediate wall rock. That the designation magmatic is correct is, however, clear from the essentially similar characters of these intrusive ores and the undeniably magmatic extrusive ones of Laco.

It does not seem likely that further field studies will provide more light on this particular problem. The ordinary ore type does not, as a rule, contain any minerals which directly indicate that any unusual quality or quantity of volatile magma constituents have been active in their formation. The Laco ores, however, form a remarkable exception by their content of scapolite, whose presence in this mineral assemblage may well justify the designation "pneumatitic extrusive" for these deposits.¹⁾ Otherwise the mineral composition of the ores is notably monotonous. And, as mentioned above, it was in the Kiruna district not the properties of the ore bodies, but other, clearly related geological features — the apatite dikes, and the vesicle-fillings consisting of the ore-forming minerals — that led to the hypothesis quoted above.

¹⁾ Scapolite is also reported to be conspicuous at Bouqueró-Chañar, but this occurrence is interpreted as a product of replacement and therefore not included here.

As to the general geological relations of the ores, it is noted that they are generally associated with igneous rocks with an intermediate or high content of silica. The frequency of a volcanic environment was stressed by Geijer (1931 b), but it is now clear that this proportion was then overestimated, and that the ore type is found also with rocks of deep-seated emplacement.

Real progress, therefore, appears to be obtainable only through experimental work, and the difficulties confronting an attempt to reproduce the natural conditions for the fractionation are obvious. A simple experiment was carried out by Fischer (1950), who melted a mixture of sodium silicate, fluorite, magnetite and apatite, with the result that the two ore-forming minerals were segregated as a separate melt. Although not directly comparable to any natural conditions, this experiment certainly deserves attention. Hope of better information on the questions involved has recently been indicated by Park (1972). It is reasonable to expect that data on the geochemistry of the ore minerals will prove useful in correlation with experimental results.

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 SGU = Sveriges geologiska undersökning

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