SVERIGES GEOLOGISKA UNDERSÖKNING

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C. DAVIDSONS BOKTRYCKERI AB, VÄXJÖ

ABSTRACT

"Ball ores" occur in several of the areas of sulfide mineralization in the Precambrian of Central and southern Sweden. They consist of a sulfide matrix in which are embedded very numerous inclusions of rocks and/or minerals. These inclusions are rounded, often spherical. The common form of a ball ore body is dike-shaped. The characters of the ball ores have, somewhat vaguely, been ascribed to secondary influences. Comparison is now made with the "pebble dikes", mostly barren, which are known from several districts of hydrothermal sulfide mineralization in the western United States and in Australia. From this comparison it appears that the ball ores were formed by fluids injected under very high pressure, the rounding of the inclusions being due to attrition during this process and to corrosion. For the way in which the sulfides of the ball ores were introduced, several possible explanations are discussed. Most likely they were either injected in the solid state as a pulp, or were carried chemically in the injected fluid. A third theoretically possible explanation, implying that they were introduced metasomatically in an originally barren pebble dike, appears improbable.

CONTENTS

INTRODUCTION

The term "ball ore" – in Swedish "kulmalm" – has been used for a peculiar form of ore that is found in several of the sulfide deposits of Central Sweden, all belonging to the Falun metallogenic province of Svecofennian age (*i. e.* somewhat more than 1800 m. y.). Characteristic of such ore is that it is made up of a sulfide matrix (in which may enter sphalerite, galena, chalcopyrite, pyrite, and pyrrhotite) which is studded with inclusions of country rock and/or minerals of the most varying dimensions. The most conspicuous of these inclusions are well rounded, often spherical – hence the name. While other, common ore varieties of the province clearly have been formed by high-temperature replacement, whether in the metamorphic siliceous volcanics (leptites) or in limestone or dolomite, the ball ores mostly, and always in their more spectacular development, form dike-like bodies.

Ball ore structures have also been described from the Åtvidaberg-Bersbo district in southern Sweden, which probably belongs to the same metallogenic epoch as the Falun province. They have there been characterized as "conglomerate-like" (Törnebohm 1885).

Evidence that ball ores have formed later than associated ores of other types has led to discussion of the possibility that they should represent material secondarily mobilized from the latter. The present writer, on the other hand, has maintained that they "represent the last phase of an essentially continuous process of ore formation", and that "the dike-like ball ore bodies mark channelways which ascending mineralizing solutions have followed" (Geijer 1965, p. 26).

There is a striking similarity between the ball ore dikes and the "pebble dikes" that have been described from a number of hydrothermal sulfide deposits in the Cordilleran part of the United States (e. g. Farmin 1934, Byrnes 1961; "sand or breccia dikes", Spurr 1923), and from Mt Morgan in Queensland (Cornelius 1967). Hydrothermal pebble dikes have been defined as "dike-like bodies, composed of well-rounded to angular fragments of clay to gravel size (Wentworth scale) particles that have been subjected to autogenous grinding and/or corrosion. Inherent in this genetic definition is the premise that fluids, emanating from a magmatic source or driven from host rocks in response to high thermal and pressure gradients surrounding a magma chamber, provide ample energy to induce "milling" of fragments along conduit fractures" (Cornelius 1967, pp. 853–854). The emplacement of the pebble dikes is attributed to the phenomenon of fluidization. In the pebble dikes of Tintic, Utah, "pebbles range in size from 1/10 to 15 inches in diameter and many of them are smoothly rounded to a roughly spherical form" (Farmin 1934, p.

360). Both phenomena – ball ores and pebble dikes – are associated with hydrothermal sulfide mineralization, but the Swedish ball ores have probably formed at somewhat greater depth than the pebble dikes.

Although thus important analogies suggest a certain similarity in origin, there is the fundamental difference that no pebble dike has been reported to contain sulfides in a manner comparable to that of the Swedish ball ores. At Mt Morgan the sulfides of the large replacement deposit occur also in the pebble dikes, but they belong to the fragmental material in them. A contrasting example is reported from Colorado, where a pebble dike in the Idaho Springs district has been later cemented by jasperiod quartz with some concomitant deposition of sulfides, without, however, reaching ore grade (Spurr 1923). In the Swedish ball ores, on the other hand, the sulfides generally make up more than half the weight.

Typical ball ore deposits are not many, and only a few of them have proved sufficiently large to form the base for independent mining operations. Yet they deserve particular attention in our attempts to trace the details in the sulfide mineralization of the Falun-Orijärvi type. The occurrence in them of evidently secondary features has tended to obscure the fact that, when these later effects are discounted, we find a type of deposit which is in a close genetical connection with the other, more common and "normal" ore varieties of the province, but differs from them in important respects, including the way of emplacement, and which therefore must carry important information on the nature of the mineralization process as a whole.

Little has been published on the ball ores, and this is scattered in descriptions of the various occurrences. There does not exist any comprehensive survey of the ball ore phenomenon as such. Having been interested in the problems of the ball ores all since my first field experience of them, in 1914, but not now being in a position to take up a thorough study, I have found it desirable to stimulate interest in the subject by bringing together facts from my own experience and from published data, in order to clarify and delineate the problem, and also to discuss to what extent the pebble dikes, unaffected, as they are, by later tectonic influences, may offer a new way of approach.

OCCURRENCES OF BALL ORE

THE FALUN METALLOGENIC PROVINCE, CENTRAL SWEDEN[1])

Saxberget may be called the classic example of a ball ore. It is the largest occurrence of its kind in the province, and also the one of the greatest scientific interest. The following presentation of it is, so far as the ores are concerned, based mainly on my own observations during earlier stages of the mining,

[1]) Recent data on the general characters of this province may be found for example in Wickman *et al.* 1963 and in Geijer 1964.

down to the 140 m level (partly published, Geijer 1917), and on Landergren's (1931) description of the wall rocks and the important feature represented by granite and pegmatite dikes in the ore.

The general features of the deposit are shown in Fig. 1. There is a body of ball ore, about 350 m in length, with a dip of 35° to 50°. Its foot wall is an unaltered even-grained leptite, consisting essentially of alkali feldspars and quartz. The hanging wall, on the other hand, is profoundly altered, in the way characteristic of the Falun-Orijärvi type of sulfide mineralization, its present

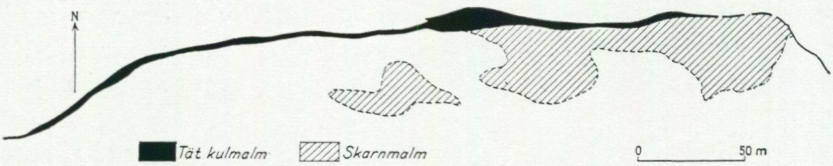

Fig. 1. Ore bodies in the Saxberget mine. Black is zinc-rich ball ore, hachured areas skarn ore and dolomite. After the mine map (from Magnusson 1953).

chief components being quartz, cordierite, anthophyllite, almandite garnet and sillimanite. It encloses a strongly deformed body of dolomite, which is to a large extent replaced by sulfide minerals (chalcopyrite, galena, sphalerite, pyrite, and pyrrhotite), with or without a pronouncedly magnesian skarn, mainly of amphiboles but also containing biotite, chondrodite, and olivine – a typical pyrometasomatic mineral assemblage. In some parts of the skarn body there have also been found concentrations of magnetite, which explain that the originally drift-covered deposit was located magnetically (S. Landergren, personal communication).

It is clear that the ball ore body follows the plane of a fault. Its average thickness has been estimated to be about 1 meter, but there are great variations, which swellings and with pinchings down to only a few centimeters. The greatest thickness, according to the official mine map, was in the eastern and middle parts in the uppermost portions of the deposit. The contacts with the wall rocks are sharp; locally, some biotite has been developed at them. Against the skarn ore the boundary is, on the whole, distinct. The ball ore's nature of a later injection is evident already from the numerous inclusions of skarn ore that are found in it. There was also, in a certain depth – around 60–85 m – at the middle of the length of the ball ore a broad spur or "horn", which with an evenly curving course penetrated into the skarn ore body. Its shape is known only from the mine map, which shows a smooth transition in contours and no marked set-off against the main ball ore body. The width at the base was about 15 m, and the length to the pointed end about 20 m. The particular properties of this spur will be specially considered in the following.

Another offshoot, of quite insignificant dimension, I have observed on the

100 m level, also near the middle of the deposit. This one was in the form of a vein, about 15 cm thick, which penetrated into the hanging wall rock. Like the main ball ore body (compare below) it contained "numerous silicate balls".

The sulfides in the ball ore are the same as in the dolomite and skarn complex, but in other proportions. No exact figures can be given, but it is obvious that the proportion of sphalerite is very much higher in the ball ore. In fact, the latter has in the mine been spoken of as "the zinc ore", in contrast to the ore varieties associated with dolomite and skarn. The sulfides form a very fine-grained mass, mostly of a grayish brown colour determined by the sphalerite. Sometimes, small euhedral cubes of pyrite are seen in it.

In this matrix are scattered innumerable inclusions, ranging in size from more than a decimeter in diameter down to microscopical dimensions. Among these inclusions two different kinds can be distinguished. One kind is fragments of the associated rocks, as the "ore quartzite" of the altered hanging wall, skarn, skarn ore, and dolomite. To this group belong all the larger inclusions. They are generally more or less rounded, often spherical; at least the harder ones are often coated by a slicken-sided film of chlorite. There also occur, but more rarely, angular slabs of the wall rock, which may exceed one meter in length. Inclusions of granite and pegmatite apparently occur in a way somewhat different from those of other rocks; they will be specially considered in the following (p. 22).

The inclusions of the other kind consist wholly of a black mica. They occur regularly all through the ore body and are often spherical in shape. Their diameter rarely surpasses 2 cm.

As to the matrix in which these inclusions of various kinds are embedded, the following description is based on microscopic examination of a number of random samples from the upper levels of the mine. These samples show a matrix made up essentially of sphalerite with very numerous inclusions which are, on the whole, evenly distributed. There are occasional small fragments of the same kind as the large inclusions, as "ore quartzite" or skarn (even isolated amphibole grains), but most common by far are inclusions of mica, evidently of the same nature as those that are megascopically conspicuous. This mica is optically uniaxial, very weakly coloured, pleochroic in a light reddish brown and a faint bluish green to almost colourless. A considerable portion occurs as isolated plates, sometimes fragmental, but much of it occurs in the form of well-rounded aggregates (Fig. 2). These often show an ellipsoidal form, instead of the spherical one that is most common in the larger, megascopically notable mica inclusions. The size of the mica plates is rather uniform, but sometimes one finds, in close proximity to an inclusion of the ordinary nature, a likewise rounded one in which the mica plates are much smaller. Evidently, inclusions from originally different parts have here been brought together in the ball ore.

Fig. 2. Ball ore, Saxberget. Thin section, ord. light, ×15. Black is sphalerite, light areas mica. H. Nairis photo.

Sphalerite is often seen to penetrate into the mica balls, or along the cleavage planes of isolated plates. A peculiar feature sometimes observed is a cloud of very small biotite plates in the sphalerite, as if an inclusion had been mechanically dissolved in the latter.

In two slides there has been found in each a grain of a sodic plagioclase, the largest one some millimeters in length. The smaller grain, which is clearly fragmental, is full of well-developed mica plates, of the same nature and dimensions as those forming the ordinary inclusions. These features will be discussed in connection with the special problem presented by the granite and pegmatite dikes.

It remains to consider a special form of ball ore, quite different from the type now described and restricted in its occurrence to the large spur projecting into the skarn ore of the hanging wall. On the mine map this spur, like the whole ball ore body, is marked as zinc ore, but towards the end it is shown to contain also much copper ore, apparently as inclusions and along one side. The amount of copper ore may have been greater than thus indicated, however. There are reasons to assume that this part contributed materially to the quantity of copper ore that was the main product of mining at Saxberget during its earlier years. And the mine foreman, at a time when this part was already exhausted (1914), spoke of the spur as "a vein of copper ore", in contrast to the "zinc ore" of the main ball ore body. An amount of copper ore from the locality in question was in 1914 still stock-piled at the mine. This chalcopyritic ore contained some biotite plates and amphibole, but its chief gangue mineral was cordierite, occurring as single grains (never aggregates) which ranged in size from more than 3 cm down to microscopical dimensions. The largest grains are seen to have a dark bluish colour and be almost glass clear. The shape is always smoothly rounded, in a way that distinctly indicates corrosion, not attrition (Fig. 3). The largest grains are quite fresh, those of medium size show a slight peripheral alteration to pinite and the smallest grains have been altered throughout.

The relations between copper ore of this nature and the associated zinc ore was well illustrated by a piece of broken ore which showed the two in contact. There was a straight boundary zone, a couple of centimeters wide, with much biotite in plates, but right up to this zone the two ore types kept their characteristic features, the zinc ore with mica pellets and the copper ore with cordierite individuals.

An ore of the nature as this copper ore cannot have belonged to the skarn ore association. For, as is to be expected from geochemical reasons, nowhere in the province has cordierite been encountered in such pyrometasomatic deposits in carbonate rocks. Nor can the cordierite be derived from the altered country rock, in which its development is always quite different. And it is even doubtful whether anywhere else in the province – where cordierite is so common in the altered siliceous rocks associated with the sulfide mineralization – there has been found any cordierite similar in properties to the larger grains in this copper ore of Saxberget.

Evidently one can conclude that before the emplacement of the zinc-rich ball ore there had been injected into the skarn ore complex a copper ore, carrying as its chief gangue mineral cordierite in corroded grains. It is not, however, possible to decide whether this copper ore was an immediate fore-runner to the zinc-rich ball ore which partly took the same course, or an earlier formation, possibly even ante-dating the faulting.

Garpenberg. The sulfide ores at Garpenberg, of many different types, occur within a rather extensive area of alteration. Massive quartz-rich types – "ore quartzites" – are rare, and the predominant rock types are more or less mica-rich schists. Thus there is a belt of light-coloured fine-grained schist, in which chalcopyrite, accompanied by fluorite and quartz, forms stripes along the vertical schistosity planes and fills the cross-joints perpendicular to them. More common are dark schists, their colour being determined by a varying but often very high content of biotite. Galena and sphalerite occur as streaky concentrations in such schists, forming ore bodies. There are also ores consisting of galena and pyrite, with a quartz gangue – a type uncommon in the province – and other forms of "hard ore". Dolomite occurs within the mine-

Fig. 3. Copper ore, Saxberget. Thin section, ord. light, ×15. Corroded grains of cordierite (light) in chalcopyrite-rich sulfide matrix (black). H. Nairis photo.

ralized area and has to some extent been replaced by skarn (mainly tremolite) with some sulfides, but such concentrations of ore minerals are insignificant compared with the other kinds of ore.

A series of ball ore bodies occurs in a zone within the mineralized area. Quantitatively they are of little importance. These steeply dipping ore bodies are dike-like: fairly straight, very long in proportion to their width and, in contrast to the ball ore of Saxberget, without any marked variations in width. The contacts with the wall rock are always sharp – as sharp, in fact, as in any igneous dike.

The ores are, in general features, similar to the ball ore of Saxberget. The composition of the sulfide matrix is, however, somewhat different, thus there is but little galena. Pyrite, chalcopyrite, and sphalerite are the main components of the matrix in several dikes, among them the Latvind ore body. This ball ore dike is the largest of its kind at Garpenberg, but reaches only about half the length of the Saxberget ore, with a width to be measured in decimeters. For at least a good deal of its length it cuts a massive, quartz-rich rock. A sample of Latvind ore has been available for microscopic examination. Its sulfides are sphalerite and a little galena. It contains rather much mica, somewhat more strongly coloured than the one just described from Saxberget and pleochroic in light yellowish brown. Most of it is in the form of scattered plates or bunches of such, but there is also in the section a rounded aggregate of mica together with some grains of quartz. In addition to the mica there occurs, somewhat more sparingly, a common hornblende, pleochroic in a dirty green and very light yellow. This hornblende is often directly associated with the mica.

Some other ball ore occurrences at Garpenberg, of smaller dimensions, are pronounced copper ores, with chalcopyrite and pyrite as the chief constituents of the matrix. An interesting observation concerns a narrow dike of this nature – its width may not have much surpassed one decimeter – which at that locality did not carry any visible inclusions. It consisted of pyrite and chalcopyrite in a peculiar distribution, the ore showing along one side the brass colour of pyrite and along the other the greenish yellow of chalcopyrite.

Several of these latter ball ore occurrences, which set up in the dark schist, have been observed to cut across the schistosity – at a low angle, but quite distinctly. Some of the Garpenberg ball ore dikes have been found to have a kind of strike continuation in the form of a string of large quartz lenses in the schist.

Ryllshyttan. The ball ore occurrence at this locality, situated about 2 km SW of the Garpenberg deposit, is one of the smallest on record but presents some features of special interest. The Ryllshyttan mine, now idle, worked a rich sulfide deposit of pyrometasomatic origin, with sphalerite greatly preponderating, and also an associated magnetite ore with skarn. The leptite surrounding the ores and associated unreplaced remnants of dolomite and limestone has in places been altered into an "ore quartzite" of one of the types commonly associated with sulfide mineralization of the Falun-Orijärvi type, a rock consisting of quartz, almandite garnet, and biotite.

There is no ball ore in the mine. The occurrence referred to is found at the surface nearby, where a prospecting trench is cut through leptite close by an area of the ore quartzite just mentioned. The trench shows in the leptite two bands of biotite schist, each about 0.5 m wide. In one of these there are streaks of galena and sphalerite. In the other – which on one side grades into almandite quartzite – there is a straight seam of sulfide ore, 1 to 1.5 cm wide[1]). Megascopically it appears as if galena was the main constituent, but microscopic examination shows more sphalerite. Small flattened, ellipsoidal inclusions of biotite, up to about 2 mm in size, are discernible to the naked eye.

A thin section shows that the schist adjoining the sulfide seam consists chiefly of biotite, pleochroic in light yellowish brown and colourless, and thus essentially similar to the mica of the Latvind ore body at Garpenberg. In addition there is not a little of hornblende with exactly the same properties at that occurring in the Latvind ore, as described above. The ore consists of

[1]) A sample was included in a study of lead isotope proportions (Wickman *et al.* 1963).

a very fine-grained mass of sphalerite, with subordinated galena. It is full of inclusions, not only of the form already mentioned but also more irregularly shaped ones of varying size. The material is mica and hornblende, both of the same kind as in the adjoining schist, and together with them some quartz.

The occurrence thus shows several features of interest. In both cases in the trench the sulfide mineralization has followed where the country rock had already been altered into a biotite schist. Yet the sulfides occur in different ways. The material of the inclusions in the ball ore may all be derived from the adjacent rock. There is also to note the similarity to Latvind with regard to the character of the enclosed silicates. The presence of hornblende in both cases is the more remarkable as otherwise the only sulfide mineralization with which this mineral is associated in the province is the pyrometasomatic one in carbonate rocks. And then the hornblende is chiefly found with chalcopyrite and the iron sulfides, not with those parts of the same deposit in which galena and sphalerite predominate.

Mellangruvan at Vallberget. As seen from the description of the small deposits that form the Vallberget group in the Öster-Silvberg district (Geijer 1965) ball ore structures are found in several of them. Most interesting in this respect is the Mellangruvan mine. What is known or can be inferred about this mine, where operations ceased in 1916, is as follows. The ore body reached a couple of meters in width and a length of at least 25 m; it had a rather steep dip parallel to the bedding of the adjacent leptite. The latter appears to be wholly unaffected by alteration on the foot wall side, but in the hanging wall it has been extensively altered into fine-grained quartz and epidote, generally with the quartz predominating. Of the products from the mine, part was an epidote skarn with a weak mineralization of sphalerite. The rest was the ball ore, which is reported to have contained about 30 per cent Zn and 20 per cent Pb. What remains of broken ore and can be studied represents a lower grade, but there cannot be any doubt that it is otherwise comparable to the richer ore.

This ore contains ellipsoidally rounded inclusions, up to several decimeters in size, of fine-grained, light bluish gray quartz. Microscopic examination reveals that what looks to the naked eye like a rich sulfide matrix is actually a sphalerite mass filled with inclusions of varying size, even down to less than 0.01 mm, of quartz, chlorite, and epidote. The chlorite, of a light green colour in thin sections, occurs in part as well-rounded aggregates, similar to the mica inclusions at Saxberget, but the smaller inclusions are more irregular (Fig. 4). The nature of the quartz inclusions is noteworthy. It is evident that this is not an ordinary vein quartz, nor is it derived from the altered hanging wall, which has another character. Instead it is wholly analogous to the quartz which at the Hedvig mine, about 150 m from Mellangruvan, forms bands and lenses in the leptite, occurring in the same way as sphalerite there, and partly associated with it (Geijer 1965). This quartz may be called jasperoid, and it is

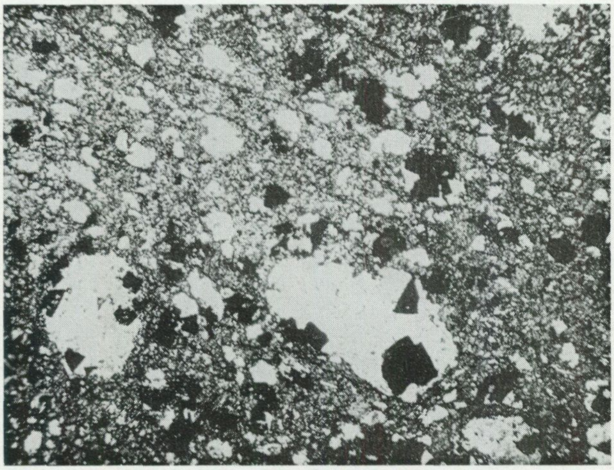

Fig. 4. Ore from Mellangruvan, Vallberget. Thin section, ord. light, ×9. Black is pyrite, gray sphalerite, white chlorite and (in some of the smaller areas) quartz. E. Welin photo. (From Geijer 1965).

clear that it is genetically associated with the sulfide mineralization. It is also to observe that the quartz inclusions at Mellangruvan do not show any crushing phenomena.

These facts indicate the following geological history. During a first mineralization phase, solutions ascending along a bedding fissure in the leptite altered the rock on the hanging wall side. Although it is not possible to indicate the time required for this process, it is clear that it must have been one of considerable duration. Presumably later the fissure was sealed by the deposition of jasperoid quartz; some sphalerite may perhaps also have been introduced. Finally this filling was broken up by a fluid under high pressure, whose injection also followed the previously active conduit, and which brought in the sulfides.

The presence of chlorite instead of mica may be an indication of a lower temperature of formation. Other features which set Mellangruvan and some neighbouring deposits apart from more common forms of sulfide mineralization in the district are the very low percentage of iron in the sphalerite (Geijer 1965) and the association with epidote.

Not dike-shaped ore bodies. In the occurrences so far described the ore has always the form of a fissure filling. Nowhere within the province do rounded inclusions of country rock occur in any other kind of ore bodies. It is important to note, however, that rounded aggregates of mica are not restricted to the dike-like occurrences, but are sometimes found also in phases of ore bodies whose relations to the country rock decidedly indicate an origin by replacement. Unfortunately, very little has been noted about the relations between the ore varieties containing those mica pellets and the rest of the ore body, because the interest attached to these relationships was not realized at the time of study.

One example is found at Garpenberg, where rich galena ore with small pellets of biotite forms part of the Zinkgruvan ore body, whose contact relations to the country rock can only be interpreted as due to replacement (compare Geijer 1964, p. 15). Though it appears natural to refer also the ball-containing parts to a process of the same nature, this is not a necessary conclusion. For the ore body also contains lenses of vein quartz, sometimes with sulfides, which might have been developed through deposition in openings in the deformed biotite-rich schist, and a similar origin may perhaps be ascribed to the ore varieties with biotite. In any case, however, the occurrence cannot be interpreted in the same way as the ball ore dikes.

Mention must also be made of the Hedvig mine in the Vallberget group (Geijer 1965). Information on the underground conditions in this long ago exhausted mine can be obtained only from the mine map and its brief text. According to this source the ore consisted of sphalerite and galena, with enclosed small pellets of mica, and formed a set of elongated lenses following each other *en échelon* along the steep plunge. To judge from these data, combined with surface observations, the deposit was probably formed by replacement. However, the picture of it as given by the mine map appears to be rather schematical. It is not wholly excluded, therefore, that it was in reality more closely related to the dike-shaped ore body of Mellangruvan, quite near (compare above).

Highly interesting are Magnusson's observations from the Ljusnarsberg district (Magnusson 1940), especially as they concern the development of ball ore structure in typical pyrometasomatic deposits in carbonate rocks – thus in a genetic type different from all other occurrences of ball ores: "In biotite-hornblende skarn one often sees how the skarn minerals are kneaded together into rounded balls in chalcopyrite and pyrrhotite. The biotite plates have then frequently been strongly bent, and the hornblendes broken" (Magnusson 1940, p. 85, transl.). It must be noted that such a deformation of mineral inclusions has never been observed in the occurrences described above.

Since there will be described in the following section deposits in which large rounded single quartz grains, alone or together with inclusions of other kinds, determine its ball ore nature, some words may be said about the occurrence of such quartz grains in ores of the Falun province. No observations on exactly similar quartz inclusions are available from the ball ore dikes of the province, though they may occur in the little studied copper-rich dikes of Garpenberg. Quartz inclusions in an ore variety in the Hoppet mine at Vallberget are of another kind, being rounded fragments of ordinary vein quartz (Geijer 1965). Sometimes, however, rounded single quartz grains are found in occurrences supposedly formed by replacement, though these grains never reach any conspicuous dimensions. Thus in the Digervåla fahlband zone, near Ludvika, a concentration of pyrrhotite, with some chalcopyrite, contains rounded grains of quartz, and also some biotite which, however, does not form aggregates (Geijer 1917).

THE ÅTVIDABERG-BERSBO DISTRICT, SOUTHERN SWEDEN

Sulfide mineralization in this district shows in part very distinct affinities to that in the Falun metallogenic province, with its characteristic magnesium metasomatism of the Falun-Orijärvi type. It lies too far from any typical deposit of this province, however, to be considered a part of it. Absolute datings of the geological units concerned are not yet available for either region, but general similarity in the geological development makes it probable that the two geographically separated provinces belong to the same metallogenic epoch.

There are two groups of ore deposits in the districts, at Åtvidaberg and Bersbo, about 9 km apart. At Åtvidaberg the sulfides occur chiefly in a gneissic granite, presumably belonging to the Earlier Svecofennian group. This relationship to the granite means a marked contrast to the Falun province, where there is only an uncertain case of a deposit having formed in a granite (of this group), in spite of the close association between the Earlier Svecofennian granite invasion there and the sulfide mineralization which is evident from other facts[1]).

At Bersbo, on the other hand, the sulfides are in the supracrustal rocks older than the granites. In both areas active mining ceased long ago – at Åtvidaberg about 1872, at Bersbo in 1902. Knowledge of the geological conditions is therefore regrettably incomplete. Available descriptions are by Törnebohm (1885), who already had to relay largely on information furnished by the mining representatives, and by Sundius (1921), who gave a detailed account of the general geology of the region and especially studied the products of an early phase of the mineralization at Åtvidaberg. The present writer has only made a brief study, in 1915 (Geijer 1917).

Åtvidaberg. The main ore-bearing unit is a siliceous, rather alkaline gneissic granite. Only insignificant mineralization occurs in the leptites and the amphibolites of extrusive origin which make up the older, supracrustal series. The granite is accompanied by tourmaline-bearing pegmatites and by quartz-tourmaline veins.

All the ore deposits of any practical interest are found in narrow but long zones in the granite, parallel to its schistosity. Sundius (1921) mentions widths

[1]) The possible exception referred to is the old Mårtanberg mine. It lies in a granite of the group in question, but it has not been possible, as the mine is inaccessible, to decide whether the deposit replaces granite or forms an inclusion in it (Geijer 1917). However, comparison with later observations on incipient alteration in granite porphyry dikes in the Falun mine make the first-mentioned alternative the more probable one.

from a few decimeters up to 5 or 7 meters, while the length runs into several hundred meters. The main minerals of these zones are quartz and an iron-rich biotite, but there can also be much magnetite and tourmaline. Sundius refers the development of these zones to metasomatic processes when rest solutions were gathered into them at the end of crystallization in the granite, which rock was being protoclastically deformed. From his detailed study he rejects an earlier interpretation (Geijer 1917) that the solutions active in this process were derived from deeper portions of the granite intrusion. Recently Saksela (1970), after discussing the microscopic evidence, has concluded that the zones are the products of late-magmatic processes.

In the zones in question there is often a mineralization of pyrite and chalcopyrite – never, it seems, notably rich. Sundius refers it to a stage somewhat later than the alteration already described. There are also, however, in them occurrences of richer copper ores, and it is here that one encounters the ball ore structure.

It is sufficient to consider the chief mine at Åtvidaberg, Mormorsgruvan. Its geology is known chiefly from Törnebohm (1885), whose description is largely based on data communicated by G. Nordenström. The rich ore occurred along the middle of a steeply dipping zone of the nature described, its immediate foot wall being a fine-grained mixture of quartz, biotite, and tourmaline, with some pyrite and chalcopyrite, while the hanging wall consisted of epidote, biotite, and quartz. In parts the uppermost element in the foot wall was a seam of magnetite ore. Between these walls thus occurred the richer ore, consisting of pyrite and chalcopyrite (bornite being also reported) and showing a "conglomerate-like" development, with large rounded quartz grains and balls of the magnetite- and tourmaline-bearing wall rock, of magnetite ore, and, as a single observation, of the gneissic granite.

The dimensions of the mine workings are as follows: length about 60 m, width 4 to 7 m, depth 407 m. For "the ore" Törnebohm (op. cit.) reports a width of 0.3–3 m. All that is known about the deposit indicates that this ore formed a dike, or a greatly flattened pipe, along the middle of the earlier developed zone. It is clear that this zone existed in the way now shown by its remnants, when the ball ore was introduced. This later element must have formed an injection from below. The fact that here, as elsewhere at Åtvidaberg, ores of this nature are restricted to the characteristic zones, and never follow any other planes in the granite, suggests a close genetic relationship between the two. It appears then probable that both the substances forming the older extensive zone, and those that gave rise to the later, richer ore, came from the same deep-seated source.

Bersbo (mainly after Törnebohm 1885 and Tegengren 1924). The sulfide mineralization occurs within a narrow zone of alteration, about 1.5 km in total length, which follows the bedding structure of the supracrustal rocks.

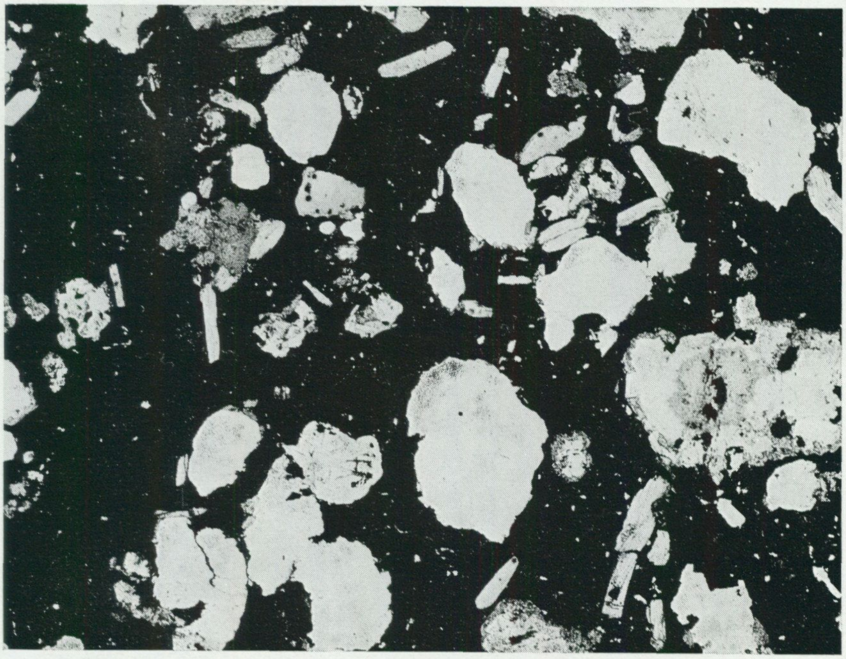

Fig. 5. Zinc ore, Bersbo. Thin section, ord. light, ×15. Black is sphalerite, the larger white areas are single quartz grains. H. Nairis photo.

The alteration is distinctly of the Falun-Orijärvi type, with quartz, cordierite, andalusite, sillimanite, and cummingtonite; the sulfides of economic interest are chalcopyrite and sphalerite. For most of its length this ore-bearing zone is very narrow, a width of only 1 to 2 m being reported. The sulfides appear to occur disseminated or in streaks. At the southern end, however, conditions are different. The zone bends there with a regular curve, and at the steeply plunging, wrinkled crest (or keel) of this fold a wholly different type of ore occurred, in the form of a set of rich ore shoots which were followed with mining down to a depth of about 350 m, where workable ore gave out. These ore shoots are described as having the form of "lumps"; apparently each unit was rounded and without any pronounced length axis. The thickness reached up to 18 m. The ore which formed these ore shoots consisted of iron sulfides, chalcopyrite, and sphalerite, with stalks of amphibole and octahedra of magnetite. It enclosed numerous "rather large" rounded grains of quartz, which caused it to be designated as "conglomerate-like" and compared to the ore of Mormorsgruvan (Törnebohm 1885), and also smaller inclusions of feldspar, hornblende, and garnet, but apparently no foreign fragments of whole rocks.

No specimen is preserved of this ore, whose chief value was in copper. At the time of my visit, in 1915, there still remained a pile of broken ore at the mine, but this always had sphalerite as its main component. The structure, however, corresponded wholly to Törnebohm's description of the copper ore. A specimen shows two rather conspicuous quartz grains enclosed in the sphalerite, regularly oval in shape and measuring 10 by 8 and 8 by 6 mm, respectively. Presumably the "rather large" quartz grains mentioned by Törnebohm reached greater dimensions, since they determined the conglomerate-like aspect of the copper ore.

Microscopic examination of the zinc ore sample shows that quartz is the chief gangue mineral, occurring as separate crystal grains similar in shape to those megascopically identifiable, or somewhat more elongated. The rounded shape is always pronounced, but in detail the contours are frayed by encroaching sphalerite (Fig. 5). There are no signs of mechanical influences on these quartz grains, not even any strain shadows. In addition there are the minerals already mentioned by Törnebohm; these are often distinctly fragmental.

That such ball ore has not been wholly restricted to the large ore bodies is shown by an observation on an outcrop near the greatest mine, where a narrow seam of similar ore occurs in a bedded and broken leptite (Geijer 1917).

THE DIFFERENT KINDS OF INCLUSIONS IN BALL ORES

The preceding review of occurrences shows that the rounded inclusions whose presence characterizes a ball ore can, with regard to their nature and their derivation, be divided into several categories. As an introduction to the discussion of the genetical problem of the ball ores the following groups may be distinguished:

1. Fragments of rocks.
2. Aggregates of mica plates (or chlorite).
3. Single grains of quartz (or cordierite).

Inclusions of the two last-mentioned kinds are often found together with such of the first category, but occur also without this association.

As to the inclusions of rocks, those in the Saxberget ore may perhaps once have existed as clasts, presumably then still angular, in a fault breccia, but at Garpenberg, for instance, this interpretation is excluded. Probably the general explanation is that the fragments were, in analogy with the formation of the pebble dikes, by the injected fluid broken from the country rock.

A special aspect of these relations is presented by Mellangruvan at Vallberget and Mormorsgruvan at Åtvidaberg. In both these deposits the ball ore has been injected into a narrow zone formed by an earlier phase of the same mineralization process, and the inclusions are, at least chiefly, derived from this earlier deposit. In other words, the same narrow zone has served as an conduit for the mineralizing fluids during both stages of the process.

The two remaining groups show the important difference from the one already treated that they also, even if more rarely, are found in not dike-shaped ore bodies. Comparing these two kinds one faces the puzzling situation that the relative distribution of mica and quartz suggests a similarity in origin, but their development is so unlike as to indicate quite different relationships to the sulfides.

As to the distribution, mica inclusions are common in ores of sphalerite and/or galena, but only exceptionally found in the other common sulfides. Rounded quartz grains, on the other hand, are mostly encountered in ores of chalcopyrite and the iron sulfides. The zinc-rich ore from Bersbo, described above, is one of the recorded exceptions, but it must be remembered that it formed a subordinate portion of an ore body the bulk of which was decidedly a copper ore. Rarely are the two kinds of inclusions found together in the same ore body. This is the case, however, in the small sulfide deposit at Roland, NW of Falun, where ore of sphalerite and pyrite contains rounded quartz grains and more irregular "lumps" of biotite (Geijer 1917).

This relative distribution might make one inclined to ascribe a similar origin to the mica balls and the quartz grains. Other facts, however, decidedly indicate that these two kinds of inclusions are not genetically comparable. The quartz grains are invariably single. They must be regarded as a normal gangue to the sulfides. Their rounded shape can hardly, as in the case of the rock inclusions, be referred to attrition through milling in the ore-forming fluid, because of the relatively great hardness of the mineral and the lack of granularity which could have made the inclusions easier to disintegrate. Their rounded shape therefore appears to be due to corrosion. It is not necessary to conclude that this corrosion was wholly effected by the sulfides (compare Fig. 5), the rounded shape may have been acquired before this process set in. The rounded large cordierite individuals in the copper ore at Saxberget form a noteworthy parallel to the quartz grains. In their case, it is evident that the shape is determined by corrosion and not by any peripheral replacement. It is of interest in this connection to compare what is reported about mineral inclusions in the sulfide ores of Bodenmais, in Bavaria. These ores, consisting of iron sulfides, sphalerite, and galena, with some chalcopyrite, occur concentrated as streaks in a gneiss with granite injections. The gneiss contains cordierite and almandite but it is not possible, from the data available to me, to form an opinion whether this composition is the result of an alteration of the Falun-Orijärvi type, or of metamorphism of an aluminium-rich sediment. The sulfides contain rounded grains of quartz and of cordierite, which are described as looking as if they were etched or superficially fused crystals ("in gerundeten, wie geätzten oder abgeschmolzenen Kristallen", Steltzner and Bergeat 1906, p. 909).

The rounded mica inclusions in the dike-shaped ball ores, on the other hand, appear to be in their origin more nearly comparable of those of the country rock. If they were to be regarded as paragenetically associated with the sulfides, as the quartz grains are, the aggregates would have to be interpreted as the result of a process of agglomeration or "pelletizing" of mica plates. And this appears incompatible with the clearly fragmental nature of a large part of the separate plates, the texture of the aggregates showing nothing of the kind. Also, direct evidence of another origin is found in the ball ore seam at Ryllshyttan, whose inclusions clearly are derived from the adjacent biotite rock. If one accept this case as a general explanation of the mica balls, their original source must be sought in such replacement veins, often only vaguely defined against the surrounding rock, which are common in many of the mineralized areas of the province and often consist wholly of biotite. They belong to those phenomena for which the term *sköl* (plural: *skölar)* has been used for centuries in Swedish mining geology.[1]) The two bands of biotite rock at Ryllshyttan, in one of which the seam of ball ore occurs, would in all probability, if their whole extension were known, be classed as *skölar*.

This hypothesis implies that the inclusions of mica would be, as to their place in the geological events, comparable to those of jasperiod quartz at Mellangruvan and those of magnetite ore and associated rocks at Mormorsgruvan, although the mica balls may sometimes have been subjected to longer transport. It also reduces the seemingly great difference in nature between the mica balls in dike-shaped ore bodies, and those occurring in other forms of ore.

THE GENETICAL PROBLEM OF THE BALL ORES

The observations related in the above survey do not permit the formulation of any detailed hypothesis to explain the origin of the ball ores – this will require a special, systematic study of the subject. On the other hand, the compilation confirms the opinion expressed in the introduction that the ball ores represent a phase of the sulfide mineralization in the provinces concerned whose interpretation would lead to a better understanding of this mineralization process as a whole. The ball ores must not be regarded as freaks of only secondary interest. Furthermore, the facts here related appear to make possible

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1) The term seems to have been originally employed for the mantles consisting mainly of biotite or chlorite which separate the large bodies of pyritic ore at Falun from the siliceous country rock, but its use was early extended to cover similar geological bodies also when occurring wholly within the barren rock; of later years its use has been further widened (brief account of its earlier use has been given, in Swedish, in Geijer 1917).

a presentation of certain alternative interpretations between which the choice must lay, and thus to point the way for further studies.

It is practical to concentrate attention on the dike-shaped deposits, which represent the great majority of the occurrences and which are the only ones that carry inclusions of the first category as defined above (p. 18).

The first step must be to find out how these deposits looked originally, before any secondary features were impressed upon them. One then finds that no satisfactory information in this respect can be obtained from the texture of the sulfide matrix. What little that is known on the subject indicates that the generally fine-grained sulfide mass, at least often, has a texture indicative of recrystallization. As will be shown in the following, this may not necessarily be due to later deformation, but this is decidedly the most probable explanation. Very fine grain in the sulfides is not in itself any proof of crushing. Thus in the most fine-grained ore examined, the ball ore seam at Ryllshyttan, the even distribution of the subordinate galena in the sphalerite shows that the small grain size must be a primary feature.

While thus the sulfide texture presumably is determined by secondary processes it is, in my opinion, quite clear that the distinctive feature of the ball ores, their content of rounded inclusions, is essentially an original character. This is a subject that has never been discussed in print, and but little in informal verbal discussions. My impression is that the secondary features have then been over-emphasized. This is, after all, not surprising. There is an a priori reason to suspect that considerable deformation has taken place after the emplacement of the ore. These ore bodies occupy planes of weakness, which might be expected to have functioned as loci of movements also after the sulfide mineralization. The most common sulfides in them are softer than the wall rocks, and are easily deformed, which facts may also have contributed towards localizing movements to *within* these tabular ore bodies. And attention has hitherto been wholly focussed upon Saxberget, where already the slicken-sided inclusions give evidence of internal glidings. But Saxberget is exceptional, in two respects. The ore body follows the plane of an important fault, a situation without any parallel elsewhere. Also, Saxberget has, in contrast to all the other occurrences, been subjected to the Late Svecofennian processes of deep-seated igneous metamorphism.

At Garpenberg, for instance, there are no reasons to suppose that such processes have affected the ball ores. From detailed mapping of the zone with ball ore dikes there, I had the decided impression that the pattern of inclusions must be a primary feature. This is, of course, a subjective opinion, based on a sum of details, on a total picture that cannot be communicated to someone else. One trait may, however, be pointed out. Even assuming that movements have taken place internally it seems inconceivable that there would not also have been some slipping along the contacts, if the movement had been strong enough to influence markedly the inclusion pattern. But the Latvind ore body, for instance, which was to its full width exposed in the roof of a drift, gave no evidence of any slipping between the ore and its massive wall rock on both sides.

At Mellangruvan the absence of any effects of crushing in the inclusions of quartz rock likewise speak against the idea that this material should have been subjected to later deforming forces.

The granite and pegmatite dikes at Saxberget, briefly mentioned above, require to be specially considered, since their relations to the ball ore presents a puzzling feature which has led to a good deal of discussion. The following presentation of these relations is wholly based on the description of Landergren (1931). Besides cutting the skarn ore, these dikes are found within the ball ore body, apparently injected along the same fault plane as the latter. Landergren found it most probable that the dikes were formed first, and after them the ball ore. "Therefore one finds . . . more often a strong brecciation of the pre-existing pegmatite material than inclusions of it" (Landergren 1931, p. 327, transl.). The relations are thus somewhat different from those existing between the ore and the other kinds of foreign material in it.

From his observations Landergren found it most probable that Saxberget should represent two different epochs of sulfide mineralization, the skarn ore belonging to that of the Falun province in general, and the ball ore being genetically connected with the Late Svecofennian granite. He pointed out, however, that also other occurrences of ball ore, as those at Garpenberg, had to be considered.

With the observations on ball ores that are now available there can be no doubt that they form a phase of the sulfide mineralization of the Falun metallogenic province. Since Saxberget otherwise conforms in every significant way to the type, it appears impossible to attribute it to a later, Late Svecofennian mineralization, because of the relations of the dikes. These relations must therefore be interpreted from the assumption that the ball ore body existed before the intrusions took place. One must reckon with the possibility that some of the irregularities in the intrusions may be due to the surrounding medium, the sulfide ore. Most of the features that seem to indicate that the ore formed later than the dikes must, however, be referred to later changes, which may have been both chemical and mechanical. The former, in the form of movement and redeposition of sulfides, may in part have been directly caused by the intrusions. It is interesting to compare these relations at Saxberget with what Väyrynen (1939) has described from Outokumpu in Finland. In this large tabular body of pyritic copper ore, which occurs in a sedimentary quartzite and largely brecciates it, there are also some pegmatite dikes. "The pegmatite dykes cutting the ore body do not run continuously across the ore, but are broken into pieces, so that it would seem that they were older than the ore, or that deformation had occurred in the ore after their formation. But neither of these views seem to have any validity. The pieces of the pegmatite dykes have not been dislocated, but proceed along the same line across the ore" (Väyrynen 1939, p. 85). That the pegmatite dikes are actually younger than the ore is "indicated by the fact that the ore between the separated portions of the dyke is different both in texture and in composition from what it is at the side, as Mäkinen first pointed out. It seems from this that in connection with the formation of the dykes the ore was partly fused or dissolved and recrystallized" (Väyrynen 1939, p. 86).

Before leaving this subject it is necessary to consider the occurrences of feldspar in the ball ore of Saxberget, as described above. At first sight these may perhaps seem to furnish an argument against the interpretation here accepted. However, the following points must be noted. The abundant mica in one grain shows that the feldspar belongs with the mica inclusions. If derived from a dike, they must either be remnants of an otherwise completely replaced one – an interpretation wholly incompatible with the characters of the deposit – or be far transported fragments. The samples are from a part of the deposit in which no dikes have been encountered. The feldspars should thus have been subjected to a long transport within the ore body, an idea incompatible with the known pattern of the dikes in the ore, and also with the lack of any signs of pressure effects in the feldspars.

To return to the general question of the inclusions in the ball ores: it is quite clear that the pattern thus found in so many occurrences is an original feature, though it has at Saxberget, and perhaps also in some other deposits, been affected by tectonic forces after the sulfide mineralization was completed. What must be emphasized, therefore, is that the ball ore structure cannot be dismissed as "secondary", or "due to tectonization".

How, then, is the ball ore structure to be explained? It cannot be a question of mineralized fault breccias, because of the common and characteristic rounding of the inclusions. In fact, the only known parallel to the ball ores in this their most characteristic feature is found in the pebble dikes. The latter also represent the same form of emplacement as the dike-shaped ball ores, and like them represent phases of hydrothermal mineralization.

The rounding of the inclusions in the pebble dikes has been ascribed to attrition during milling in the fluid, and/or corrosion. As to the latter factor, it has already been pointed out that a clear example of corrosion is represented by the cordierite at Saxberget, and that it is the most probable cause of the rounding of quartz grains. It is, however, impossible to say to what extent it may have contributed in shaping the rock inclusions.

Assuming then that the fissure-filling material of the ball ores, like that of the pebble dikes, was brought in by a turbulent fluid under high pressure, there are three ways in which the introduction of the sulfides may have taken place:

1. The sulfides were introduced in solid form, as part of the fragmental material.

2. The original filling was in the form of a barren pebble dike. The sulfides came later, being metasomatically introduced by incompletely replacing this original filling.

3. The sulfides were contained chemically in the injected fluid, and were deposited when some "carrier" or solvent escaped.

With our present restricted knowledge as regards both the ball ores themselves and the physico-chemical processes that may be reckoned with in postmagmatic mineralization, it does not appear possible to eliminate definitely anyone of these different interpretations. But it is valuable to consider the arguments that can be adduced for and against each of them.

When considering these alternative interpretations the high content of sulfides must be remembered, the ball ore occurrences are always of ore grade.

The first explanation is the one that has been found by Cornelius (1967) to apply to the sulfides in the pebble dikes of Mt Morgan. There, however, the sulfides form only a restricted portion of the filling, and they occur partly as distinct fragments. No such structure has ever been observed in the ball ores – except the inclusions of skarn ore at Saxberget, which are irrelevant in this connection. It might be argued that a fragmental structure can have been effaced by later movements within the ore body, but it is highly improbable that the supposed pulverizing of ore fragments could have been so thorough as to make no trace of the original structure discernible in anyone of the numerous occurrences.

The question takes on another aspect, however, if one assumes that the sulfides were transported as a kind of pulp. This explanation would fit all the characters of the ball ores. Incidentally it may be pointed out that it would mean that the sulfide texture indicating recrystallization may not always be a sign of later crushing, after the emplacement. The idea rests, however, on two conditions: the existence of earlier formed high-grade sulfide concentrations that were thus reduced to pulp, and a process through which this comminution was effected. As to the latter factor, the large amount of "fines" in typical pebble dikes gives evidence of the possibility. A remarkable example of a sulfide deposit evidently analogous to our ball ores and interpreted in the way now discussed is furnished by the recently described Strathcona Mine in the Sudbury district, Ontario (Greenman 1970). This description is of so much interest for our discussion that it deserves to be quoted in full. "On the north range of the Sudbury Basin, a grey granitic breccia occurs between the south dipping Nickel Irruptive and the underlying Archean gneiss. It is separated from the main body of the Irruptive by a second noritic intrusion, the xenolithic norite. The breccia is dike-like in character, has a metamorphic texture, and contains most of the nickel-copper sulfide ore mined in the area.

The distribution of inclusions in the grey breccia shows a central concentration through the body, and this supports the hypothesis that the breccia is intrusive. The silicates in the matrix are uniformly distributed, but the oxides and sulfides are concentrated at the center and at each margin of the body. The form and composition of the oxide minerals are very similar to their counterparts in the xenolithic norite, and are interpreted as having been derived, along with the sulfides and many of the inclusions, from the body. The plagioclase in the breccia has a highly ordered structure (Naldrett and Kullerud, 1965), similar to that in the nearby gneiss, and its compositional zoning is patchy. These two factors suggest that the breccia matrix was never magmatic. The breccia is interpreted as having been intruded in a fluidized state shortly after the injection of the xenolithic norite, which itself post-dates the Nickel Irruptive".

Although no rounding of the fragments in the breccia is mentioned, it is clear that this ore body forms a remarkable counterpart to our ball ores. The fact that its origin can, evidently on strong evidence, be ascribed to fluidization of earlier formed material therefore means a weighty argument for interpreting the latter in the same way.

If one accepts this interpretation of the ball ores, one can infer the onetime existence, somewhere in depth, of otherwise unknown ore bodies. Whether anything of them remains in situ is, of course, another matter, but the possibility indicates that the problem of the ball ores may perhaps not be one of exclusively theoretical interest.

As already mentioned, remobilization has been discussed as a possible explanation of the ball ores. The process just delineated is, however, the only form in which the general principle can be applied to them. Remobilization in the usual geological sense – solution, transport, and redeposition – would mean a process that had to face difficulties of both the first and the third interpretation as defined above. And no fact can be adduced in support of it.

As to the second possibility, reference has already been made to a case that illustrates this sequence: Idaho Springs, where some sulfides were later introduced into the pebble dikes (Spurr 1923). Assuming a similar history would explain all that is known about Mellangruvan. The other ball ore occurrences, however, as those of Saxberget and Garpenberg, give a different picture. The features in them that indicate replacement are unimportant, and may even be wholly due to the later rearrangements with which one has to reckon. And at Saxberget (Garpenberg is not sufficiently known for a statement on the subject) such features are restricted to inclusions of mica. There is no evidence of any similar relations between sulfides and fragments of siliceous rocks, although otherwise in the province metasomatism is the common form of the introduction of sulfides into these altered rocks. The sulfides are always restricted to within the walls of the fissure, the adjacent rock being wholly unaffected. The small offshoot observed at Saxberget is entirely of the same nature as the main ore body, a fact that emphasizes the limitations of the mineralization. It must also be remembered that there is not known in the province a single case of one even partly barren pebble dike. If replacement has taken place, it has always gone so far as to reach ore grade in every part of the dike. A remarkable corrolary of accepting replacement as the way in which the sulfides were introduced would thus be that the injection of a pebble dike was in every case followed by an intense replacement by sulfides, strictly limited to the pebble dike, and – at Garpenberg – showing great chemical differences between the individual dikes in a swarm.

It is, of course, possible that Mellangruvan, in spite of all similarities to the other occurrences, was formed in another way than these, by replacement as indicated. For all other dike-shaped ball ore deposits this interpretation appears highly improbable. But improbable is not the same as impossible, and the process in question cannot be definitely eliminated from the list of possible interpretations of the dike-shaped ball ores in general.

The third interpretation, and one that presents a plausible explanation of all the facts known about the dike-shaped ball ores, implies that the ore substances were carried chemically in the injected fluid and, when some volatile substance necessary for this transport had left the system, were deposited so as to fill all the space not occupied by the inclusions.

This hypothesis, however, assumes a physico-chemical process which cannot be explicitly defined with reference to theoretical or experimental data. Yet the ball ores are not the only kind of post-magmatic mineralization that, in contrast to most of the various types of such ores, is difficult to explain as the work of dilute solutions. It is sufficient to refer to the pyrometasomatic mineralization in carbonate rocks. Although deposits of this nature are common and have been much studied, we are still largely ignorant about the details of the process, as the form in which the various substances were introduced, and the reactions that took place. An example of such ores that directly invites a comparison with the ball ores here described is presented by the occurrences in the Ljusnarsberg district described by Magnusson (1940), to which reference has already been made because of their tendency to develop a ball ore structure (above, p. 14). Magnusson's interpretation of the relations between the sulfides and the associated skarn silicates is that the former formed a melt when fluorine was bound in the silicates. Whether the term melt should be the right one or not, the case is certainly of interest for the interpretation of the dike-shaped ball ores.

Those features of the ball ores which indicate injection, as the offshoots of the Saxberget ore body, have their counterparts in sulfide deposits in which ball ores are not encountered. Thus Ödman, in his monograph on the Boliden deposit in northern Sweden (Ödman 1941), described and figured cases where massive sulfide ore bodies send out fissure-filling offshoots. These and other observations caused Ödman to interprete certain ore bodies at Boliden as products of pneumotectic injection.

From the Vihanti deposit in Finland, which almost certainly belongs to the same metallogenic province as Boliden, Rouhunkoski (1968) has described and figured pyritic bodies intruding and brecciating a sedimentary quartzite. A certain analogy to the ball ores is further indicated by the fact that the quartzite fragments thus enclosed in pyrite show "rounded contours". These relations have been summarized in the words that the pyritic ores of Vihanti occur as displacement bodies, while the associated zinc-rich ores are products of replacement (Wennervirta and Rouhunkoski 1970, p. 564).

In the Falun mine, where there is abundant evidence of sulfide introduction by replacement, I have observed a small sulfide body whose relations to the wall rock are similar to those just described.[1]) There is a body of probably rich zinc ore, about one meter in width and with a vertical position, parallel to the schistosity of the adjacent mica schist. The contacts on both sides are straight and perfectly sharp, but on one side the ore sends out an offshoot, perpendicular to the contact and thus also to the schistosity. This offshoot, which evidently follows a cross joint in the schist, contains an inclusion of the schist, sharply rectangular in the visible section and about one decimeter in length.

Other examples might be quoted, from deposits that once were classified as "intrusive pyritic deposits".

Like the structure of the ball ore dikes, the relations just described cannot be interpreted as the gradual work of dilute solutions in analogy with, for instance, such fissure-filling veins that show crustification. In spite of the lack of theoretical and experimental support, therefore, the process as briefly defined above must be considered one of the most probable explanations of the ball ores.

So far, this discussion has considered only the dike-shaped occurrences of ball ore. In important respects analogous to them, but indicating a somewhat different form of emplacement, is the "conglomerate-like" ore of Bersbo. This deposit lacks the inclusions of rocks which form such a conspicuous feature of the dike-shaped occurrences, containing such foreign material only in the form of inclusions of so small sizes that they are generally single mineral grains, often fragmental. As to the large quartz grains which give to the Bersbo ore its characteristic aspect, they have their counterpart at Mormorsgruvan in the same district. Apparently they were in both cases introduced together with the sulfides. Although but little is known about the main part of Bersbo, so

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[1]) The observations were made incidentally during work in other parts of the mine, and only the striking relations to the wall rock were registered. The locality is south of the largest pyritic ore body.

much is clear that there is a most marked contrast between on one hand the ordinary development of the long and narrow ore-bearing zone, with its typical replacement character and a modest content of sulfides, and on the other hand the large and fairly rich "conglomerate-like" ore shoots at the crest of the fold. In this respect, too, Bersbo is analogous to Mormorsgruvan, where the earlier formed alteration zone with but little sulfides was locally split up by a later injection of much richer ore. It is clear that one has to do, in both cases, with two forms of sulfide mineralization, which differed from each other in important respects, yet undoubtedly were closely connected, not only in time but also as to their ultimate source. As a probable explanation of these relationships it may be suggested that the main Bersbo deposit was formed by filling voids developing along the bedding planes of the supracrustal series, as Mormorsgruvan and similar deposits were formed by fissure-filling. This idea finds a certain support in the fact that the ore shoots are just where the structural conditions may have been especially favourable for a process of this nature. Gaseous or tectonic pressure, or both, may account for the unusual shape of the ore bodies.

As to the occurrence of aggregates of mica and individual quartz grains, both kinds well rounded, also in ore bodies whose relations to the country rock indicate another form of emplacement than by injection, little can be added to the presentation (above p. 14). It must be remembered that inclusions of country rock are never found in these ores. They are restricted to those deposits whose mode of formation can be assumed to correspond to that of the pebble dikes. Possibly there is the difference that in the latter cases the structure is a product of both attrition through milling and of corrosion, but in the other ones only of corrosion.

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