SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C AVHANDLINGAR OCH UPPSATSER NR 603

PER GEIJER

TYPES OF SULFIDE ORE AND ASSOCIATED WALL ROCK ALTERATION IN THE ÖSTER-SILVBERG DISTRICT, CENTRAL SWEDEN

STOCKHOLM 1965

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Abstract

The Öster-Silvberg district is a part of the Precambrian sulfide province of Central Sweden, whose most known representative is the Falun mine. At present there is no mining activity in the district, but the Öster-Silvberg mine was in medieval times the chief producer of silver in Sweden, and a number of smaller deposits has also been worked, most of them for zinc. The country rock is generally a fine-grained, bedded potassic leptite, which is interpreted as a metamorphosed rhyolite tuff.

At the Öster-Silvberg mine, argentiferous galena ore and some associated bodies of pyrite and sphalerite occur in an "ore quartzite", which obviously originated through alteration of the leptite and carries, in addition to the quartz, only some mica or occasionally andalusite, and in one variety gahnite. The Stora Loberg occurrence is chiefly a deposit of chalcopyrite and iron sulfides, which together with fluorite and some hornblende largely replace a limestone layer. Alteration of the immediate wall rock has resulted in a quartzite with almandite. The neighbouring Lilla Loberg deposit consists of sphalerite ore in a leptite, which is unaltered except for a sparse impregnation of sphalerite and fluorite. Deposits in the Vallberget group are also largely of this nature, but one type contains low-iron sphalerite and is associated with the development of epidote skarn in the leptite. This is the only known case in the province where introduction of calcium has accompanied the sulfide mineralization. Another feature of interest is that this type is mainly associated with a fissure zone which cuts across the bedding of the leptite, while the other deposits of the district more or less distinctly conform to the latter. The Gumsberget mine contains copper ore; its wall rock shows magnesium metasomatism. At the Skvasselbo occurrences sulfides, as galena, form streaks in a schistose quartz-mica rock with porphyroblasts of gahnite.

The origin of the deposits is discussed, with special regard to the chemical relation between sulfide ore and alteration of the wall rock.

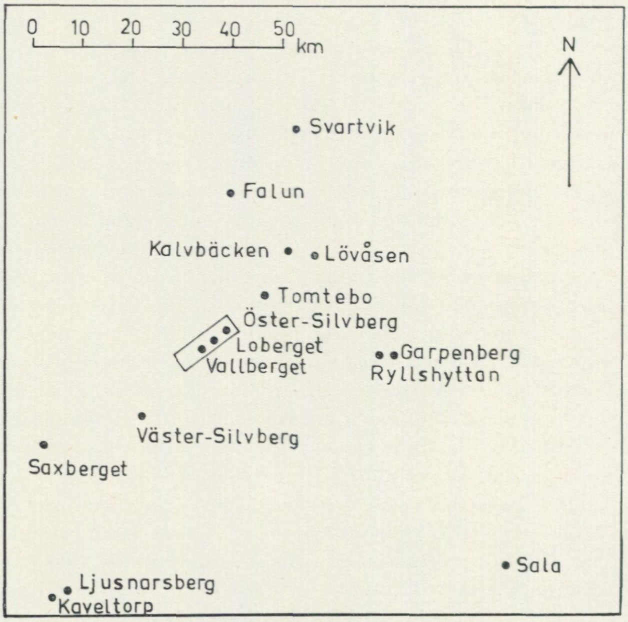

Fig. 1. Map showing position of the Öster-Silvberg district (in rectangle) in relation to other sulfide deposits of the same province.

Introduction and acknowledgements

The Öster-Silvberg mine, many centuries ago the chief producer of silver in Sweden, is situated 27 km south of Falun (Fig. 1). It lies at the northeastern end of a belt, about 8 km long and 2 km wide, in which there occur numerous but generally small deposits of sulfide ores, most of them with zinc as the predominant metal. This belt forms a subprovince in the larger province of sulfide mineralization in Central Sweden, to which belong such deposits as Falun, Sala, Garpenberg, Saxberget, Kaveltorp, and many others (Fig. 1).[1] The geological unity of this metallogenetic province is evident. Ores in carbonate rocks, such as those of Sala and Kaveltorp, conform in all their features to the world-wide type of pyrometasomatic deposits in such rocks. Other occurrences, in the metamorphic siliceous volcanics (leptites) of the ore-bearing supracrustal Leptite series, are accompanied by the kind of wall rock alteration that has become known as the Falun-Orijärvi type. Almost all the deposits in the Öster-Silvberg district are immediately associated with leptites, only two are in carbonate beds intercalated in the latter. The origin of the various kinds of sulfide mineralization in the province has been referred to metasomatic processes, characterized particularly by the introduction of large quantities of magnesium, during an epoch when the Leptite series was being folded and intruded by primorogenic (synkinematic) granites, the Earlier Svecofennian granite group. The geological age of the whole complex is Svecofennian, and the mineralization occurred before the last phase of the Svecofennian cycle, i.e. somewhat more than 1 800 million years ago. For general surveys of the various aspects of the mineralization the reader is referred to papers by Magnusson (1950), Wickman *et al.* (1963), and myself (Geijer 1962, 1964).

Active mining in the Öster-Silvberg district ceased about 40 years ago. More recently only some exploration has been carried out there. None of the mines is now accessible, all having filled with water, and the only underground examination that I have had the opportunity of making was a rather cursory visit to the Öster-Silvberg mine, then partly dewatered, in 1916. Much can still be learned about the geology of the deposits, however, from the study of outcrops, dumps, old mine maps and some recent drill holes. The most interesting that can be ascertained in this way concerns the variations in ore type and in the accompanying alteration of the wall rock of the ore bodies. In fact, virtually all the various kinds of wall rock alteration that are more or less common at the other sulfide deposits of the province, are encountered, and in addition, in the Vallberget group, a peculiar but clearly related type which has not been found elsewhere. Therefore the results of a study are of considerable value for the understanding of the nature of the mineralization also in the province as a whole.

[1] In the following text, "the district" refers to the ore-bearing zone at Öster-Silvberg as defined above, and "the province" to the larger metallogenetic province of which it forms a part.

My first visit to the district was in 1915, whilst working for Sveriges Geologiska Undersökning. It was very brief, but resulted in some observations that would not have been possible in later years. About a week was spent there in 1938 for Aktiebolaget Zinkgruvor, then owner of the mines. Some supplementary observations were made in 1963 and 1964. The present mine owner, Bolidens Gruvaktiebolag, through its chief geologist, Dr. E. Grip, and Dr. N. Pilava has courteously placed at my disposal certain records, and cores from recent diamond drilling, which have furnished information of value about the Vallberget deposits. The laboratory work has been done at the Mineralogical Department (RMA), Swedish Museum of Natural History, whose curator is Prof. F. E. Wickman. The microphotographs and an X-ray diffraction diagram have been taken by Dr. E. Welin. For all the aid thus received I wish to express my sincere gratitude. I also wish to state my appreciation of having this report printed in the publications of Sveriges Geologiska Undersökning, in which institution it was my honour to serve for such a large part of my time as an active geologist.

General geology of the district

The Öster-Silvberg district occupies the central part of the area covered by the geological map sheet »Säter», published in 1953, the Precambrian geology of which was treated by S. Hjelmqvist. The distribution of the main rock units as shown in Fig. 2 is taken from this map. In addition to the Leptite series, which is the oldest element, several later units are represented. A large granite body belonging to the Earlier Svecofennian group (compare above) forms the boundary of the belt of Leptite series to the northwest and north. Within the belt there are some basic intrusions, chiefly gabbroic rocks, belonging to a group of forerunners to the Earlier Svecofennian granites. These basic rocks are not marked in Fig. 2. Late Svecofennian granite occurs north of the Öster-Silvberg mine. Dike rocks are not indicated in Fig. 2. Some of those occurring are amphibolites, but the majority are diabases, most of them belonging to a system of northeast-striking dikes which are very numerous in this and adjacent areas. The diabases represent the youngest element in the bedrock and are without interest for the subject of this paper.

The belt of Leptite series consists chiefly of leptites. Beds of spilitic greenstones, now in the amphibolite facies, are intercalated at some places. Layers of limestone are also encountered, but they are generally of no great thickness. In Fig. 2, limestone has been marked only where attempts have been made to exploit it.

Two chemically and texturally different types of leptite occur in the district. One is a fine-grained, even-grained and often distinctly bedded potash leptite, with microcline, sometimes also a little albite, together with quartz and small

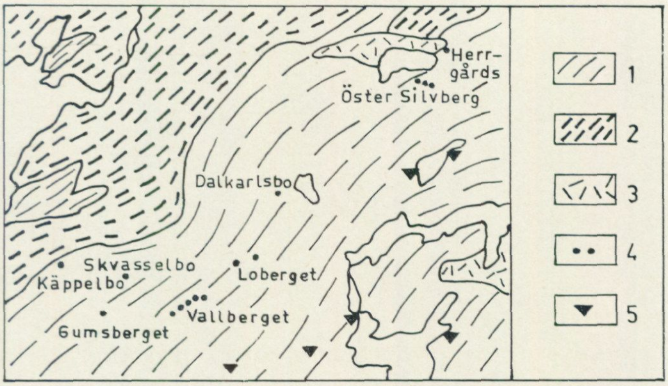

Fig. 2. Sketch map of the Öster-Silvberg district: main geological features, and position of mines. Scale 1:100 000. 1 Leptite series; 2 Earlier Svecofennian granite; 3 Late Svecofennian granite; 4 Sulfide mines; 5 Limestone quarry. Adapted from Hjelmqvist 1953.

amounts of micas and opaque minerals. The other type consists essentially of a sodic oligoclase and quartz, and originally was porphyritically developed, with phenocrysts of both minerals. In the present state of the rock, the phenocrysts are granulated by recrystallization and therefore difficult to discern megascopically. So far as I have been able to find out, the former type is by far the more common one in the ore-bearing belt, and it forms the country rock around all the sufide deposits except at the small Herrgård "mine" (p. 24). This occurrence is situated north of the Öster-Silvberg mine (Fig. 2); the same leptite type (with sodic oligoclase) has also been identified about 300 and 650 m S of the latter mine, the country rock of which is the potassic leptite (compare p. 8). A stratigraphic distribution of the two types of leptite thus seems probable.

The nature of the rock sequence is clearly volcanic, with the limestones representing the only non-volcanic element. The textural development of the leptites, with one type fine- and even-grained and the other with a high proportion of phenocrysts, makes it most probable that they were originally tuff deposits. The spilites apparently were originally slaggy beds of aa lava, probably impregnated with calcite before metamorphism, as is the case in other parts of the same geological province. Dips in the formation are generally either nearly vertical, or moderately steep to the SE. Examples will be cited in the following. Remarkably strong linear structure has been noted in spilite but is never so well developed in the leptites.

The Öster-Silvberg mine

The mine (Fig. 3) had its heyday in the fourteenth and fifteenth centuries[1]. It is first mentioned in an act of A.D. 1367, but then in a way showing that it must already have been active for some time. Figures for the period mentioned

[1] Historical data on the mining in the district have been compiled by Tegengren (1924).

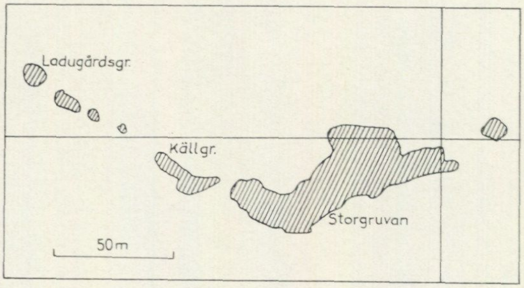

Fig. 3. Surface openings, Öster-Silvberg mine. Scale 1:3200 (note: the position of the coordinate cross is the same in Figs. 3, 5 and 6).

indicate a yearly production of silver somewhat exceeding one metric ton, representing a considerable sum under the conditions of the time. In A.D. 1500—1503, however, the mine was reported inactive because of destructive falls of rock. Later in the century a considerable production was maintained, but the chief mine was abandoned in 1597, and mining continued only on the less important western part of the deposit. After 1641 the only serious attempts were made about 1750—1760 (some work was done also about the middle of the 19th century), and the total production of silver since 1630 is estimated at only 91.5 kg. During World War I the chief mine was again made accessible, and some exploratory work was done in 1918—1920. The results were not encouraging, however, as only some small bodies of sphalerite and pyrite were encountered, and the workings were again left to fill with water.

The mine openings at the surface are shown in Fig. 3. The main source of the production was an ore body in the eastern part of the deposit, Storgruvan, with a very steep southerly dip and a steep plunge to the east-northeast down to the 120 m level, further down almost vertical.

The country rock at some distance from the ores is a non-porphyritic potassic leptite. Thus an outcrop 80 m south of Källgruvan consists of microcline and quartz, the latter markedly subordinate, tattered flakes of biotite and some opaque grains. The rock shows great variations in grain size, probably reflecting an original stratification, the microcline grains measuring about 0.08—0.15 mm and 0.02—0.03 mm. On the dumps there is a large amount of another type, probably deriving from the last drifting north of the ore zone in Storgruvan. This leptite consists of microcline and quartz, the latter in ordinary rhyolitic amounts; the grain size is even and slightly above the minimum in the former type.

Going north, towards the mines, from the outcrop just mentioned, the same rock, seemingly unaltered, is seen to continue up to a couple of meters from the western mine openings, where it is, without any well-defined boundary, succeeded by a white, schistose rock of quartz and muscovite. Similar rocks are exposed north of the western mines for a width of at least 75 m. They are partly white mica schists, occasionally with small knobs of andalusite, and partly more massive muscovite quartzites.

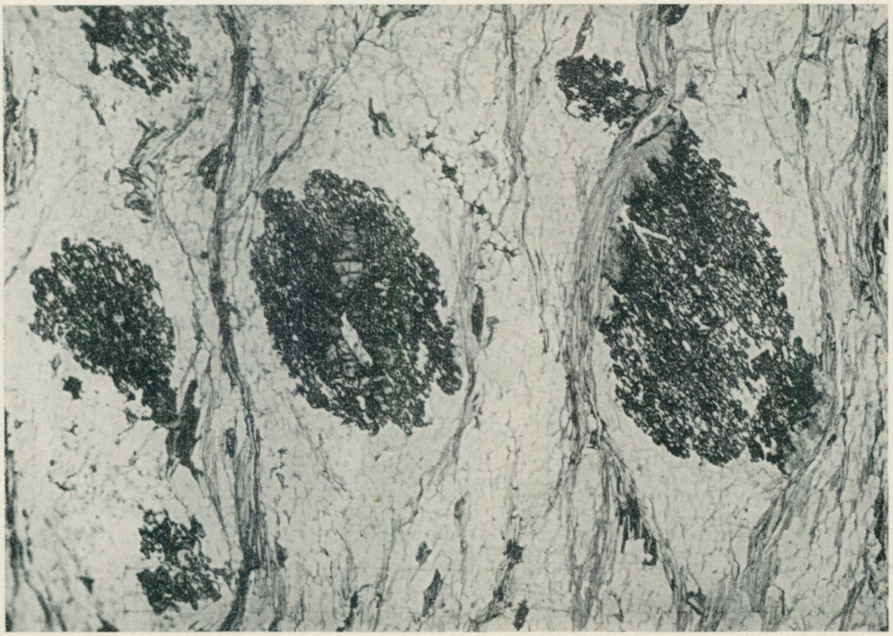

Fig. 4. Poikilitic porphyroblasts of gahnite in schistose quartz-muscovite rock, western part of Öster-Silvberg mines. Microphoto of thin section, ord. light, x 11. E. Welin, photo.

The surface rock left between the western openings is a white mica schist with evenly distributed porphyroblasts of gahnite and narrow streaks of galena. The gahnite grains are rounded and show an extreme blastopoikilitical development, only small portions being free from inclusions of quartz (Fig. 4). The inclusions are always much smaller than the quartz grains of the surrounding matrix. Similar differences, though less pronounced, have been noted in the case of silicate metasomes in the altered rocks accompanying the sulfide deposits of the province, such as the large ovoids of cordierite (Geijer, 1917, p. 117, 184, 1923, p. 22). Since this development of the cordierite indubitably is a primary feature (see Geijer, 1964), the enclosed quartz grains must also represent the original alteration products. The somewhat more coarse-grained matrix, on the other hand, may possibly have suffered later textural changes. The texture of these altered rocks is a subject on which many observations have been published, but which so far has not been systematically studied.

In Storgruvan, the main part of the deposit, the immediately ore-bearing rock is fairly well known from underground observations and from the dumps; according to specimens collected in the 18th century (RMA) the same rock type occurred also in Källgruvan. This rock is quartzite, often glassy, parts of which are an almost pure quartz rock — this type predominates in the older dumps — but often with some biotite, generally as subparallell plates, small flakes

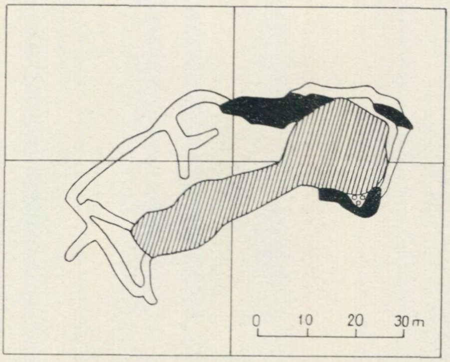

Fig. 5. Öster-Silvberg mine, 104 m level. Scale 1:1 600. Hachured: open stope (mainly on lead ore); circles: lead ore; black: pyrite-sphalerite ore; blank: barren rock. From the mine map.

of muscovite and in some varities much andalusite. While wholly similar rock types are found with sulfide ores at other places in the province, it is noteworthy that cordierite, anthophyllite and almandite have not been identified at Öster-Silvberg, although rock varieties containing them are common in such associations.

It is evident that the Öster-Silvberg ores occur in a zone within which the potassic leptite has been altered to the quartzose rocks described. Evidence for this origin of the latter is also to be found on the mine map, as illustrated by Fig. 6. Within this altered area the lead-silver ore occupied the central parts, forming a columnar body, which, to judge from the extent of the workings, continued downwards to the 215—220 m level of the mine. Near it, the quartzite contains some small ore bodies, consisting chiefly of pyrite and sphalerite in varying proportions and with very little lead. These ore bodies are found on the northern side of the central, lead-silver ore body, and sometimes also, at the eastern end of the latter, to the southeast of it. Fig. 5 illustrates these relationships. On the 220 m level, where apparently the lead-silver ore has given out, some pyritic ore still continues; according to the reliable mine map (von Fieandt 1917) alteration to quartzite is there restricted to the immediate surroundings of the sulfide bodies (Fig. 6).

The zinc-pyrite ore has been accessible for study in both recent and some older mine workings. Its contact with the quartzite is sometimes a slip surface, but elsewhere it is »frozen to» the wall rock, and even sends vein-like projections into it. Sometimes such veins contain rounded inclusions of quartzite. The proportions between the sulfides vary, from fairly rich zinc ore to pyrite with only a little sphalerite. Galena is always quite subordinate, and copper (presumably as chalcopyrite) still more so, the maximum figure reported being 0.9 per cent (Tegengren 1924). The sphalerite is red in thin sections. Gangue minerals are quartz and fluorite. The presence of the latter is unusual in a siliceous sulfide ore of the province. The fluorite is occasionally seen to form bands, up to 10 cm wide, in the ore.

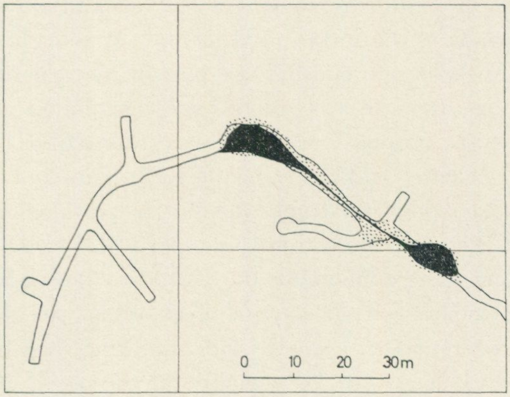

Fig. 6. Öster-Silvberg mine, 220 m level. Scale 1:1 600. Black:pyrite-sphalerite ore; dotted: "ore quartzite"; blank: leptite and diabase. From the mine map.

As to the nature of the rich lead-silver ore of Storgruvan no direct information is available. However, from what is known about Källgruvan (compare below) and the general character of the deposit, it can be concluded that it consisted essentially of argentiferous galena. Probably it also contained a little pyrite and quartz. The figures for the silver production in medieval times indicate that the ore largely occurred as a compact body of such size that smelting ore could be obtained by simple means. For the reported production could hardly have been maintained under other conditions, bearing in mind the technical equipment of the time and the limited ore area. More is known about Källgruvan, from the period of activity about the middle of the 18th century. It was reported in the 1750s to be at least 48 m (27 fathoms) deep (Hülphers 1762). This is more than twice the depth assumed on the mine map. Lead ore was said to occur as bands, which at the surface were only a hand's breadth but sometimes increased downwards to a width of 1.2 m. From this description it can at least be concluded that the galena formed bands or streaks of rich ore. The nature of this ore can be learned from a number of specimens (RMA). They consist of galena, partly also of pyrite, and quartz as scattered grains or as lumps a few cm in diameter. In one sample a little biotite and two grains of garnet are also seen. This is the only known occurrence of garnet at the Öster-Silvberg mine. The wall rock is also represented in one sample, it is a rather coarse-grained biotite quartzite. Another sample from Källgruvan consists wholly of sphalerite and quartz. Pyritic ore has also been encountered there, but the reported width, 26.7 m (Schreber 1762) must be greatly exaggerated. Anyhow, the two last-mentioned facts show that in Källgruvan, just as in Storgruvan, the rich galena ore — with some pyrite but apparently without sphalerite — was accompanied by bodies of zinc ore and pyrite close by. Thus the distribution of the different ore types does not indicate any true depth zoning, even if pyritic ore in Storgruvan goes down somewhat further than the other varieties.

Very little is known of the workings NW of Källgruvan. The observations made at the surface and mentioned above indicate that there was no continuous workable ore body in this part of the deposit, and the small extent of the workings shows that it cannot have contributed significantly to the production. There exists, however, one source of information about Ladugårdsgruvan (Fig. 3). It is a letter of 1543 from the King, Gustav I (Vasa), to the Crown's manager at Öster-Silvberg, from which it is pertinent to translate the following passage: "We understand from thy report, Mårten Hellsing, that thou hast caused stripping to be done above the Ladugård prospect and hast got down to the bedrock, which is a band of pure silver ore ... So it seems strange to Us that thou dost not report to Us, how wide and long the ore band is to be seen in the bedrock or at least sent Us a sample of the ore ... Our order is that thou dost further inform Us about these things and sendeth Us a piece of that ore with all further information about how much silver the same ore contains, and what We else need to know ..." Unfortunately, the manager's reply does not appear to be preserved. It seems clear, however, from the quoted report and from the unpleasant consequencies that would have followed a misleading statement to the sovereign, that there was actually at the surface an occurrence of the rich galena ore, which thus was represented also in the westernmost part of the mineralized zone, even if the total amount of it appears to have been rather small there.

Various assays from the 17th and 18th centuries report the silver content of Öster-Silvberg galena to be from 1053 to 4335 g/t (0.105 to 0.434 per cent). A remarkable fact is that the silver produced contained about 10 per cent gold. There is only one parallel known in the province: at Garpenberg, galena concentrates from the siliceous copper ore body called Bergsmansgången contained gold and silver in amounts comparable to those at Öster-Silvberg (Lindroth in Tegengren 1924). At the latter mine neither pyritic ore nor zinc ore contains more than 45 and 70 g/t of silver, respectively, which corresponds fairly well to their contents of galena. Gold does not seem to have been determined. The possible presence of silverbearing minerals, other than galena, in Öster-Silvberg ore is being studied by another investigator. Here may only be pointed out that there are no reasons for assuming that the ore extracted during the earliest mining was essentially richer in silver than the later samples quoted above.

The Loberget group

This group of deposits is situated about 4 km SW of Öster-Silvberg, in the general direction of the strike of the Leptite series. The intervening area is mostly drift-covered, with few outcrops. At the Loberget mines the contry rock is a light gray, potassic leptite, non-porphyritic and fine-grained; in thin sections it is identical with the variety mentioned above as found in the waste dumps at Öster-Silvberg.

There are two mines at Loberget, both since long inaccessible underground, viz., the Stora ("Big") and Lilla ("Little") Loberg mines[1]. The former worked an ore body in which copper was the economic metal. According to the mine map this ore body was tabular, about 60 m in length and 10 m in width, with a dip of about 60° SE and a steep plunge to the NE. The vertical depth of the mine is about 70 m; the ore body is exposed at the bottom with undiminished area. The ore minerals are mainly pyrrhotite, pyrite and chalcopyrite, occurring in a matrix of granular limestone with fluorite. Most of the ore left at the mine is too badly weathered for detailed study. Some sphalerite, reddish brown in thin sections, has been noted. The gangue minerals in addition to the fluorite include a hornblende, with strong absorption colours. The amount of fluorite in the ore must have been considerable, as Witt (1906) states that the ore was especially valued at the copper smelter because of its content of this mineral.

It is evident that the sulfides, accompanied by fluorite and some hornblende, partially replace a bed of carbonate rock. The nature of the wall rock encountered in the workings can be seen from the material on the waste dumps. These consist to some extent of leptite, belonging to the type mentioned above, and for the rest of a rather fine-grained, highly quartzose rock with the pink blotches of almandite garnet poikilitically intergrown with quartz that are so often found in ore quartzite of the province, and with stellate aggregates of a black, apparently iron-rich anthophyllite. Since the workings extend only a little into the wall rock, it can be concluded that the alteration which resulted in this product affected only the immediate surroundings of the ore body.

The Lilla Loberg mine lies 320 m WSW of the mine just described and probably somewhat to the north of its strike direction. The deposit consisted of three lenses of high-grade zinc ore, arranged *en échelon* within a length of 45 m and with a maximum lens width about 10 m. On the bottom level, 55 m, the deposit had changed to a tabular ore body 50 m in length and with a varying width, up to 2 m. Dip and plunge were the same as in the Stora Loberg mine. The leptite surrounding the deposit shows a regular banding, which is marked chiefly by the distribution of sphalerite. The quantity of this mineral is such that much of the material in the dumps might be called a lean zinc ore. A little galena is also present. The zinc content of the bands varies. Fluorite and some calcite are associated with the sphalerite. A thin section of a zinc-rich seam shows that the sulfide is evenly distributed in a potassic leptite of ordinary nature, without any other deviating features in composition, texture, or grain

[1] Swedish mine names generally end with the suffix "gruvan" (the mine). In rendering them in English the inconsequent but practical principle is here followed that names derived from personal or place names are generally given in the form exemplified by Hedvigsgruvan = Hedvig mine, while names of other types are not translated (e. g. Mellangruvan, which means "the middle mine").

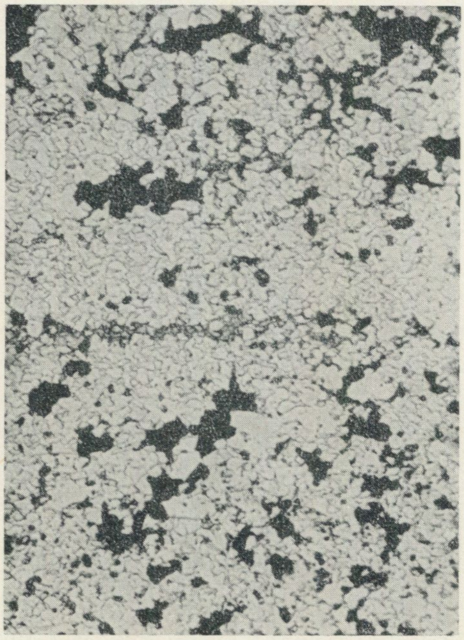

Fig. 7. Impregnation of sphalerite in leptite, Lilla Loberg mine. Microphoto. of thin section, ord. light, x 27. Black is sphalerite, white microcline and quartz, gray fluorite. The stripe of fluorite across the middle of the figure is parallel to the bedding. E. Welin, photo.

size. The sphalerite grains are squeezed in between those of microcline and quartz. Fluorite, in smaller amounts, occurs with the same distribution and textural development, and also as thin stripes parallel to the bedding (Fig. 7).

Mineralization closely related to that of the Lilla Loberg mine is found about 300—400 m NE (i.e., in the strike direction) from the latter. The only place accessible to study on my visits was a small prospecting pit about 100 m NNE of the Stora Loberg mine. It showed bands of zinc ore, up to several decimeters in width, and of galena, in the leptite.

The Vallberget group

The Vallberget deposits begin 650 m SW of the Lilla Loberg mine, in the strike direction of the leptite; on this stretch there are scattered outcrops but no known occurrence of ore. The Vallberget group comprises a number of generally small occurrences of sulfides, chiefly zinc ore, within a belt about 600 m in length (Fig. 8).

The northeasternmost deposit is the one that has been worked in the Hedvig (or Ceres) mine. According to the mine map it consisted of a series of lenses of zinc ore, the most important of which had its top about 55 m below the surface, a length along the plunge of 100 m and a maximum strike length of 20 m. The dip was 55°SE and the plunge steeply NE.

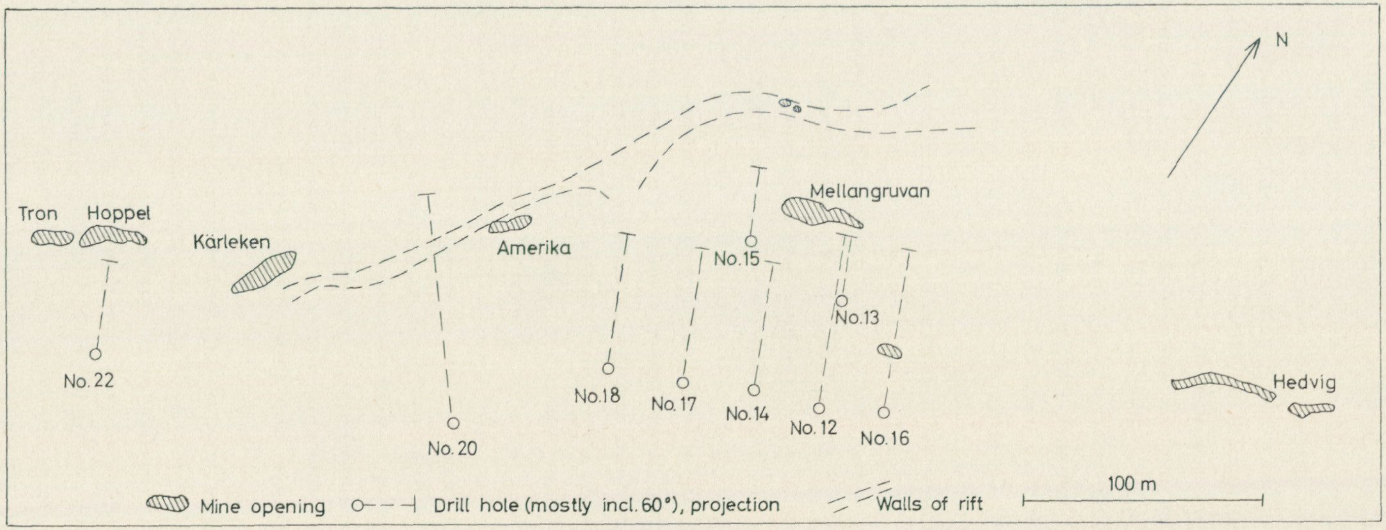

Fig. 8. The Vallberget mine group.

The ore taken out during the working period 1894—1904 was reported to be 2464 t, representing less than 10 per cent of the sum of ore and waste rock extracted. Apparently this ore was rich. It is said to have consisted of a fine-grained mixture of sphalerite and galena, enclosing small pellets of mica.

The mine opening immediately beyond can, by a process of elimination, be identified with the one described by Cronstedt (1781) as the Bovall or Tverkers mine. Cronstedt states that this mine, which evidently at his time hade been long abandoned, was worked in 1688, and gives the following details about it: depth 42 fathoms (75 m), ore body a 'vein', up to 1 1/2 foot wide, of rich galena ore, the silver content of the galena being about 0.05 per cent. According to a note on the map of the Hedvig mine, there have been found in this lead mine also lenses of quartz with boulangerite. There is nothing improbable in this statement, but confirmation is lacking.

Around the two mines the bedded potassic leptite, light red or gray in colour, is well exposed. In the band of rock left between the two openings this leptite contains some very thin streaks of sphalerite along the bedding, and similarly arranged lenses of bluish gray quartz, up to a few decimeters wide. Northeast of the Hedvig mine, again, there are only traces of zinc ore in the leptite, confirming the evidence of the mine map that the strike length of the deposit was remarkably short. According to this map, the ore bodies were surrounded by skarn, and no other kind of rock was encountered in the workings. Examination of the outcrops and the dumps does not confirm this, however. Also the material in the dumps (apart from a little amphibolite) is leptite and lean ore. The discarding of the latter is explained by the fact that no concentrating plant existed which might have utilized it. This ore contains sphalerite in the form of seams, up to about 1 dm wide, generally following the bedding of the leptite — also in its plications — as at the Lilla Loberg mine, but also often anastomosing. Sometimes a little green skarn is seen, occurring in the same way. Much more common than this skarn is bluish gray quartz, as in the outcrop mentioned above, forming bodies up to some decimeters in width and with a fine network of sphalerite veinlets. A thin section of ore-banded rock shows a fine-grained potassic leptite with seams of somewhat coarser grain, which also contain much epidote (colourless in the section) and muscovite; sphalerite occurs only in these latter bands.

It has not been possible to identify any material derived from the lead mine.

From near these mines, the Vallberget hill slopes southwestward, the last mine in the zone, at the foot of the slope, lying about 50 m lower than the Hedvig mine. Numerous outcrops and a number of drill holes make it possible to get a fairly good idea of the bedrock. Wholly predominant is the even-grained leptite, including portions altered in connection with the sulfide mineralization. In addition there are only some small occurrences of amphibolite, at least part of which represent dikes, and some narrov dikes of diabase. A drill hole at the foot of the slope has also encountered a non-porphyritic leptite that consists of sericitized plagioclase and quartz.

The potassic leptite shows bedding, marked by the jointing. Its strike is mostly straight with only local contortions. The dip is moderately steep SE, about 55°—60°. Obliquely across the strike, in a more northerly direction, run several marked fisures. Along one of them a rift has been eroded (Fig. 7), the floor of which is a couple of meters wide at the most, but always covered.

Several zinc deposits occur in the leptite. Some of them contain sphalerite with a moderate content of iron, essentially the same as the sphalerite in the Lilla Loberg and Hedvig mines. This applies to an unnamed prospect 160 m SW of the last-mentioned mine, and to the ore bodies worked in the Hoppet mine at the end of the zone. The other occurrences, four in number, represent a type not found elsewhere in Sweden. Their sphalerite is very low in iron, and the sulfide mineralization was associated with the development of epidote skarn, and silicification. The relations to the structure of the Leptite series are also unusual.

At the prospecting pit which is situated 160 m SW of the Hedvig mine, in the strike direction, no information about the sulfide occurrence can be obtained at the surface. The surrounding leptite is unaltered, but contains some stripes of vein quartz at the southwestern end of the opening. A drill hole, no. 16 (see Fig. 8), directed beneath the site showed one band of zinc-lead ore, only a few decimeters wide, and further down several, wider bands within a zone of about 3 m. It is doubtful whether anyone of them is continuous with the occurrence which must have caused the prospecting pit, as the dip then indicated — 70° and 80°, respectively — is steeper than that of all other sulfide deposits in the group. A core sample from the main, lower zone consists of an extremely fine-grained sulfide ore of a yellowish brown colour, with sparse porphyroblasts of pyrite and small, rounded inclusions of non-sulfidic minerals. Microscopic examination reveals a mixture of sphalerite, yellowish brown in a thin section, galena and pyrrhotite, with the sphalerite dominating, in which, in addition to the pyrite crystals, lie single mineral grains or aggregates of quartz, chlorite (penninite) and fluorite. More rare are phlogopite, also as rounded inclusions in the sulfides, and clinozoisite. The latter mineral is noted as isolated crystals in the sulfide matrix; one perfectly euhedral crystal is zonal, with a core of dull brown colour. The texture of the sulfide mass varies: in spots it has the appearance of being primary, but it mostly suggests recrystallization after local crushing.

The following features of this ore are especially important for the interpretation of the sulfide mineralization in the district: its "ball ore" character (with rounded inclusions of non-sulfidic minerals); the indications of recrystallization; the colour of the sphalerite, which indicates an iron content probably slightly lower than in those previously described, in spite of the association with pyrrhotite; the combination of gangue minerals, which includes phlogopite, chlorite, clinozoisite and fluorite and thereby forms a kind of link between the other types of sulfide concentrations at Vallberget.

Further in the direction of the strike, the Hoppet mine (incl. the older Tron workings) marks the end of the Vallberget group (Fig. 8). The mine map, with notes, some ore left at the surface, and the dumps enable one to get a fairly good idea of this deposit. The only specified production data available are from a 9 month's period in 1889—1890, when the production of sorted ore was 1736 t out of a total of 3 386 t of ore and waste rock extracted. The mine seems to have been abandoned not long afterwards.

On the whole, the wall rock at Hoppet appears to be unaffected by alteration. In a drill hole, however, some development of secondary quartz and muscovite has been noted. Two narrow, parallel tabular ore bodies were worked. The ore consists chiefly of sphalerite, yellowish red in thin sections. Associated are galena in varying but generally subordinate amounts, pyrite and pyrrhotite. The iron sulfides are not quantitatively prominent, except in one, apparently subordinate, ore variety with rather much quartz. In the zinc-lead ore the most conspicuous gangue mineral is fluorite, in small stripes. One variety also contains much golden-yellow phlogopite, occurring as euhedral plates enclosed in the sulfides, or, more rarely, in the fluorite. The deposit thus shows a marked kinship with the ball ore of drill hole no. 16 (compare above). Also at Hoppet there occurs ore with a typical ball ore development, but apparently only as a local phase. Its rounded inclusions consist of white vein quartz with some coarse-grained microcline. It looks as if this ore variety had brecciated and partly replaced an ordinary quartz vein. A sample of it was included in the study of the isotopic constitution of ore lead in Sweden by Wickman *et al.* (1963), as no. 75[1].

As already stated, the rest of the sulfide concentrations in the Vallberget group represent a special type, with a sphalerite that is unusually low in iron. Another feature of this mineral is its remarkable form of weathering. Ore that has been exposed to the atmosphere is coated with a dull black substance, similar to oxidic manganese compounds and quite unlike the submetallic black weathering crust of ordinary sphalerite. The alteration is not confined to the surface in contact with the air, but is simlarly developed also in the interior of the grains. Because of this property, one of my specimens was included in Gabrielson's study on the minor consistuents of Swedish sphalerites (Gabrielson 1945). The sulfide was not separated in a pure state, but the analytical figures did not indicate any property which might explain the kind of weathering. Especially noteworthy is the fact that, with 0.03 per cent Mn, the specimen proved to be the one lowest in manganese — and also in iron — among all the Precambrian sphalerites included in Gabrielson's investigation.

[1] Through an oversight on my part, the sample, collected in 1938, had been wrongly labelled "Nedre Vallbergsgruvan". After restaking in 1939, the Hoppet mine falls within the claim called Västra Vallgruvan.

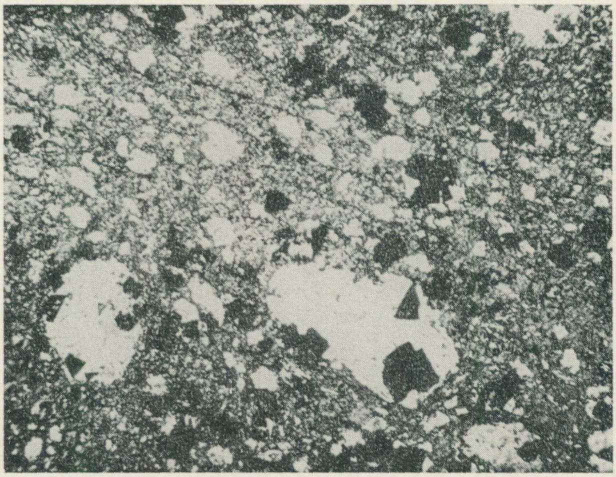

Fig. 9. Ore from Mellangruvan, Vallberget. Microphoto of thin section, ord. light, x 9. Black is pyrite, dark gray sphalerite, white chlorite and (in some of the smaller areas) quartz. E. Welin, photo.

The ore body worked in Mellangruvan (Fig. 8) is the largest occurrence of this type. It was the subject of some regular mining in the 1880's, and again in 1915—1916. From the latter period a production of 375 t zinc-lead ore is reported with 30 per cent Zn and 20 per cent Pb, and in addition 1178 t of concentrating ore. I have noted 1915 in my field diary (SGU archives) that, according to a communication by Mr. Y. Söderqvist, M. E., the ore was like that of Saxberget, which means that it was a fine-grained ball ore. Apparently, this characteristic refers to the lump ore. At the mine I have recovered some samples of an ore type corresponding to this description. There is also a stockpile of low-grade zinc ore of a different type, presumably representing the concentrating ore that was also reported.

From these data, and valuable evidence from several drill holes, it can be concluded that the ore body of the first-mentioned type is vein-like, up to a couple of meters in width and with a length of at least 25 m. It has a regular SE dip of 60° and thus conforms, at least approximately, to the bedding of the leptite.

The richer ore left at the mine shows a fine-grained mass of sulfide minerals, with very numerous inclusions. The largest inclusions, up to several decimeters in size, all consist of quartz and are ellipsoidal in shape; the smaller inclusions are similar or spherical. Microscopic examination reveals that this structure continues into much smaller dimensions, down to less than 0.01 mm, but with more irregular shapes. The smaller inclusions consist of quartz, chlorite (penninite) and epidote, alone or two together. The quartz is always a crystalline aggregate, and similar to the quartz bands described above from the Hedvig mine. The epidote occasionally shows zonal structure, with a brown or pale red core, which is optically isotropic or nearly so. The sulfide matrix consists of sphalerite, gray in thin sections, and pyrite in euhedral grains. The latter are frequently developed also in the chlorite pellets, where sphalerite does not enter. As seen from Fig. 9, this ore, which to the naked eye appears rich, contains a high proportion of such inclusions.

A sample from the same ore body, where cut by a drill hole about 80 m below the surface, is of poorer ore, the sulfides forming veinlets in a rock consisting of epidote and quartz and with probable relict features of leptitic texture. The chief sulfide is sphalerite, which contains a few minute grains of chalcopyrite on fissures, and not part of any exsolution pattern; there is also a little galena. Another sample from the ore-bearing zone penetrated by the drill hole is a leptite, only slightly affected by alteration.

The production that was sorted out as concentrating ore is presumably represented by the quantity of lean ore stacked at the mine. This is a very fine-grained skarn rock, white with a light greenish tinge, in which occur small and irregular, branching patches and veinlets of sphalerite, always coated with the sooty black film. From the analysis of a flotation concentrate it can be concluded that Fe in the sphalerite is below 1.4 per cent. It is gray in thin sections. Microscopic examination reveals that the skarn consists almost exclusively of epidote. The optical properties of this mineral vary, often within a single grain, and indicate a range from clinozoisite to moderately iron-rich varieties. In order to get a figure for the average composition, a quantitative determination of iron was made; it gave 7.33 per cent Fe_2O_3 (A. Parwel, RMA). In view of the extremely light colour of the skarn, this is an unexpectedly high figure. In angles between the epidote grains can occasionally be seen a mineral that is probably an iron-poor clinochlore (leuchtenbergite).[1]

From two drill holes and the outcrops it is clear that in the hanging-wall of the vein-like ore body the leptite is completely replaced by quartz and epidote over a horizontal width of 35 m or somewhat more. The relative proportion of these two minerals varies, from a quartzite with only some scattered grains of epidote to almost pure epidote skarn (a more rare type). In one sample of the latter a conspicuous amount of titanite occurs. The quartzite is finely crystalline, hardly coarser in grain than the unaltered leptite, and thereby differs from the usual development of ore quartzites in the province, and also from the quartz inclusions in the ball ore.

Evidently, the sphalerite ore in epidote skarn represents a phase of this alteration; probably it occurs in the immediate hanging-wall of the vein-like ball ore body. Its width may not be great, and in the drill holes directed towards the deposit nothing corresponding to it has been encountered, the impregnation seems therefore to have faded out in depth. As already stated, where the deposit is cut by a drill hole at 80 m vertically below the surface, the sulfide-bearing

[1] Optical data: colourless in thin sections, or slightly pink; refraction low; birefrigence up to 0.013; biaxial, positive, with a large axial angle.

zone contains portions of seemingly unaltered leptite. The foot-wall, as far as known, does not show any alteration effects.

All the three other occurrences belonging to the same type as Mellangruvan are associated with the rift mentioned above (Fig. 8). About 50 m NNW of Mellangruvan there are two small prospecting pits, close together, in the wall of the rift, which is here deeper than elsewhere (several meters). Nothing can now be ascertained about the extent of the deposit, but its nature is clear from material left at the pits. It is similar to the poorer ore variety of Mellangruvan, the only difference being that the epidote skarn is light grayish green, a little stronger coloured than at the latter deposit. However, the optical properties do not indicate an iron content higher than at Mellangruvan. The sphalerite, too, is of the same character as at Mellangruvan, including the weathering and also the texture.

The Amerika mine, or rather prospect, is situated just in the low southeastern rim of the rift. The southwestern continuation is covered, but to the northeast the rock is well exposed, consisting, at least for a width of several meters, of a very fine-grained, light gray epidote skarn. A thin section from a sample taken 8 m from the opening, in the strike direction, shows in addition to the epidote only a little muscovite and some veinlets of quartz. The skarn is criss-crossed by narrow zones of crushing, which are older than the quartz veins. The small dumps show sphalerite in a dark grayish green epidote skarn. In view of this colour it is surprising to find that the optical properties of the epidote indicate a content of iron lower than that in the sample just described. The grain size varies spotwise, from about 0.15 or even 0.40 mm down to about 0.03 mm. In ore samples there are also some quartz grains, and patches of quartzite like the one developed in the hanging-wall of the Mellangruvan ore body. The sphalerite is the same iron-poor variety, gray in thin section and with a dull black weathering coating.

The deposit of the Kärleken mine occurs in a similar way to the one just described, but is situated in the opposite rim of the rift. There, too, the exposed (north-northeastern) continuation shows epidote skarn. The ore body seems to have been somewhat larger than that of the Amerika mine, but otherwise wholly similar to it. Ore left at the mine is sphalerite of the characteristic low-iron variety with a black weathering film, and the skarn, of a rather dark grayish green colour, consists entirely of epidote, with the grain size varying in streaks. As to the textural relations one notes that the epidote sometimes occurs as euhedral crystals enclosed in the sphalerite, but even near-by may occur as irregular fragments in it (Fig. 10). A little galena is associated with the sphalerite. There occurs also a variety of the epidote skarn which is greenish white and does not carry any ore minerals.

At none of these three zinc deposits along the rift has there been found any material of the ball ore type represented by the richer ore of Mellangruvan. This

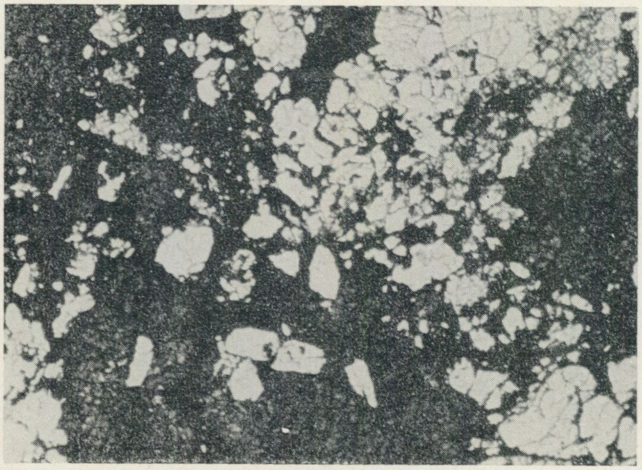

Fig. 10. Sphalerite (dark) in epidote skarn, Kärleken, Vallberget. Microphoto. of thin section, ord. light, x 27. E. Welin photo.

negative evidence is, of course, not conclusive, since such ore may have been transported from the mine. However, the apparently short strike extension of the workings may be taken as an indication that such vein-like ore bodies were probably not present.

There are at Vallberget also, E of the strike direction from the Hedvig mine to Hoppet, two very small concentrations of sulfides, different from those so far described. One of them contains pyrrhotite, associated with some dark green hornblende. The other has pyrrhotite and pyrite, with quartz; the wall rock is quartzitic, with bands of biotite and almandite which show an intense folding.

The Gumsberget mine

This is a small deposit with copper as the only metal of possible economic interest. The mine has long been abandoned, no map of it exists and in consequence the extent of the underground workings is unknown. The part of the deposit that contains a sufficient copper content to be regarded as an ore body has been reported by Köjer (in Tegengren, 1924) to be about 50 m in length and 4 m in width, with an average copper percentage of 1.25, the chalcopyrite occurring both disseminated and concentrated in richer streaks. Accompanying sulfides are pyrrhotite and pyrite; Hjelmqvist (1953) has also noted the presence of sphalerite.

The deposit occurs in a zone of light gray, rather fine-grained quartzite with sheaves and stellate aggregates of anthophyllite. In streaks this rock grades into vein-like segregations of quartz, between which it is rich in biotite. The sulfides, to judge from the product left at the mine, occur chiefly in these coarser quartz aggregates, in the form of short, winding veinlets. Nearby there are outcrops of mica schist, which, to judge from its megascopical appearance, probably contains cordierite. No garnet has been observed at this deposit.

A prospect NNE of the mine has chalcopyrite, pyrite, galena and sphalerite, in quartzite and mica schist (Hjelmqvist 1953).[1]

The Skvasselbo group

This designation is here used for a chain of small sulfide occurrences, about 570 m in length and covered by three mining claims (position, see Fig. 2). No regular mining appears to have been undertaken, but at several places there are a couple of narrow openings. The surrounding rock is fairly well exposed. From observations on these outcrops and on the small dumps, the following picture of the mineralized zone has been obtained. It is obvious that richer ore varieties may have occurred than those thus recorded, but the general nature of the mineralization can be satisfactorily ascertained.

The southwesternmost occurrence is exposed by stripping and in a test pit. Leptite in the southeast grades towards the sulfide-bearing zone first into a fine-grained quartzite, which in turn changes into a quartz-rich, light mica schist. Stripes of sphalerite and pyrite are reported, but it is clear that the sulfide mineralization is very weak.

The next exposure is in an outcrop area of somewhat greater extension. The rock is a mica schist with evenly distributed porphyroblasts of gahnite, some millimeters in size, and with a sprinkling of pyrite. Mostly the schist does not contain any other mica than muscovite, in small plates, but one variety has biotite in greater amounts and crystal size. The gahnite occurs in the same way in both, generally as irregular, somewhat poikilitically developed porphyroblasts (Fig. 11) and only occasionally with a tendency towards the development of crystal faces. Galena occurs in this schist as disseminated grains and as small stripes parallel to the schistosity. The whole development of the zone is strikingly similar to the western part of the Öster-Silvberg deposit (above, p. 9).

Finally, the northeasternmost occurrence in this group is in a rock of somewhat different aspect and wholly without gahnite. Microscopic examination shows that it is a rather coarse-grained quartzite, with some anthophyllite, small grains of garnet, and muscovite in fine aggregates, apparently pseudomorphs after andalusite or cordierite. Sulfides occur, together with some quartz, as stripes in the schistose quartzite. Pyrrhotite and sphalerite predominate, and are accompanied by pyrite and a little galena.

[1] The occurrence of grayish-green garnet has also been reported from this place, but it is practically certain that the observation refers to gahnite.

Fig. 11. Porphyroblast of gahnite in quartz-mica schist, Skvasselbo group. Micropho-to. of thin section, ord. light, x 11. E. Welin, photo.

Small and isolated sulfide deposits

In addition to the deposits described above there are at three places in the district occurrences of sulfide minerals that have been the subject of some exploratory work (for position, see Fig. 2).

The *Herrgård* mine is situated about 600 m NE of the main Öster-Silvberg mine. It is an elongated pit, about 3 m in width and said to be 10 or 12 m deep; ore is reported to be present at the bottom with a width of about 1 m. Ore left at the surface is fine-grained and consists of pyrrhotite, pyrite, sphalerite and a little chalcopyrite. It contains small pellets of biotite. Apparently, the ore body is related to the ball ore type. Its length is probably less than 20 m. Eastwards from the old opening only a weak impregnation of sulfides continues for some 10 or 20 m. The wall rock of the deposit is a quartzite with mica, chiefly muscovite; this rock continues eastwards somewhat further than the sulfide impregnation in it. An outcrop sideways more away from the ore zone shows a schistose rock consisting of quartz, oligoclase-albite, and much muscovite in irregular streaks. It is probably a partly altered leptite. Eastwards, where the alteration zone has given out, the bedrock is leptite, of the type with sodic oligoclase as the predominant feldspar.

The *Käppelbo* mine is in a sulfide-bearing zone, 2 to 4 m wide, surrounded by a leptite without noticeable bedding. The rock of the zone is partly a rather fine-grained quartzite, but most of it is glassy quartz, occasionally with thin and irregular streaks of biotite. The only sulfides that have been identified are pyrite and pyrrhotite, unevenly disseminated in the quartz rocks.

The *Dalkarlsbo* mine is a long, narrow pit. The rocks show a streaky alternation of quartzite — fine-grained or glassy — with skarn. In the latter are diopside and actinolite, and also narrow yellowish-white bands, probably of clinozoisite. Occasionally the association of garnet (of almandite colour) and biotite can be seen. Sulfides present include pyrite, pyrrhotite, and some chalcopyrite. They occur chiefly in the skarn, the character of which indicates that the development of the rock before the sulfide mineralization was an alternation of leptite and calcareous seams.

Discussion

UNITY AND GENERAL CHARACTER OF THE SULFIDE MINERALIZATION IN THE DISTRICT

The observations above show clearly that all the kinds of sulfide deposits in the Öster-Silvberg district, however much they may vary in mineral composition and texture, in their structural relations to the Leptite series and the nature of the accompanying rock alteration, must have been closely connected with regard to the mode and time of their formation. Most have so much in common with deposits in other parts of the province as to make it evident that the district is to be regarded as a subprovince in the latter. The only apparent exception is the zinc ore associated with epidote skarn, at Vallberget. However, this type is distinctly connected with the others of the district, not only spatially but also by having important features in common with some of them. Thus, for instance, the ball ore of Mellangruvan is, apart from the low iron content of its sphalerite, similar to that described from drill hole no. 16, including the characteristic presence of zonal epidote, while the latter occurrence is, in turn, genetically related to the ordinary ore of Hoppet, as shown by the presence in both of phlogopite and fluorite, a mineral combination never encountered elsewhere in the province except in some deposits in carbonate rocks. Also the mode of emplacement of the ores conforms to the usual pattern of the province, with the sole exception of some among the occurrences of the Mellangruvan geochemical type.

The ball ores of the district present some features of general interest. For several deposits of this type elsewhere in the province, the question has been seriously considered, whether they may not represent secondary features due to mobilization of the products of the original mineralization. Another interpretation, which, also from my own observations, seems more probable, is that the ball ore bodies, generally vein-like, represent the last phase of one essentially continuous process of ore formation. Several facts in the Öster-Silvberg district cannot be reconciled with the first alternative. Thus, for instance, the ball ore of Mellangruvan contains the same characteristic sphalerite as the America and Kärleken ore bodies, but the latter represent another relation to the structure. The interpretation that best fits the facts seems to be that the vein-like ball ore bodies mark channelways which ascending mineralizing solutions have followed. This view is, among other things, supported by the fact that sometimes vein-like quartz bodies have, at least in part, occupied the space now filled with ball ore. This is illustrated by Mellangruvan and Hoppet. Ball ore bodies elsewhere in the province often exhibit signs of considerable crushing and subsequent recrystallization. Examples are also found at Vallberget. At Hoppet the quartz inclusions in the ore show the effects of intense crushing, but nothing corresponding is seen in the sulfide matrix. At Mellangruvan, again, also the quartz inclusions are mechanically unaffected. Assuming, as above, that the ball ores mark channelways, it is to be expected that these planes of weakness in the rock have been the loci of movements not only before but also sometimes after the sulfide mineralization.

As to the conclusion, applied to the whole province, that the sulfide mineralization took place during the folding of the Leptite series and the concomitant intrusion of the Earlier Svecofennian granites, the facts observed in the Öster-Silvberg district are all consistent with this interpretation. Little in the way of new, confirmatory evidence can be adduced, however. Yet it is worthy of note that the mineralization at the Öster-Silvberg mine shows strong indications of having been directed by the structure of the folded country rock, in analogy with what has been noted in some other ore bodies of the province and also in many sulfide deposits in other regions, as, for instance, Boliden in Sweden.

It is appropriate to consider, in the light of the evidence from the Öster-Silvberg district, two alternatives to the interpretation here accepted, which have been proposed for the whole metallogenetic province or for part of it.

An origin through an exhalative-sedimentary process has been suggested as a likely possibility by Koark (1962). It has been shown, however, that this interpretation is incompatible with facts already known (Geijer 1964), and the district furnishes new evidence for the distinctly epigenetic nature of the mineralization. Certainly, at both the Lilla Loberg and the Hedvig mines it is possible to select hand specimens with ore bands which may suggest a sedimentary bedding. But on a larger scale the mineralization also there, and particularly at the Hedvig mine with its anastomosing bands, shows clearly that such sedimentary--looking details are deceptive. Attention may also be called to the banding, apparently even more regular and on a much larger scale, at the Sullivan mine, British Columbia, (Swanson 1950), where nevertheless the epigenetic origin of the mineralization is proved by the nature of the accompanying wall rock alteration. At Vallberget one has also to remember the close genetic connection with deposits whose epigenetic nature is evident, as those of the Mellangruvan type.

Another alternative to the generally accepted interpretation of the mineralization in the province was applied by Tuominen and Mikkola (1950, 1951) to the classic occurrence at Orijärvi in Finland. These authors have maintained that the cordierite- and anthophyllite-rich rocks which there, and at many other localities in the province, are associated with the sulfides, do not derive from any introduction of Mg in connection with a granite intrusion, as assumed by Eskola (1914), but are products of metamorphic differentiation. It has been pointed out that, at least for the larger, Swedish part of the province, this hypothesis encounters a number of incompatible facts (Geijer 1962, 1964).[1] In the Öster-Silvberg district the country rock, in contrast to what is assumed by Tuominen and Mikkola for the Orijärvi region, is always of a kind that must originally have been very poor in magnesium. Its present nature, outside the immediate neighbourhood of the sulfide deposits, does not give any evidence of changes compatible with the assumption that the local concentrations high in magnesium, as at Gumsberget, were due to the migrating out of other components. Furthermore, as pointed out in the following section, there exists a geochemical relationship between magnesium and the elements occurring as sulfides, which, like the other chemical relations between wall rocks and ores, must be considered in a genetical interpretation.

THE TYPES OF WALL ROCK ALTERATION, AND THEIR RELATIONS TO THE SULFIDE ORE TYPES

As a background to the information about these relations that can be obtained from the Öster-Silvberg district, a survey will first be given of what is known about the subject from other parts of the province.

Alteration of the leptites, which originally consisted of alkali feldspars, quartz, and very small amounts of biotite, has resulted in rocks made up of quartz, biotite, muscovite, andalusite, cordierite, anthophyllite and almandite garnet, in all the various combinations that are consistent with the mineralogical phase rule. The proportions vary within very wide limits. Virtually pure quartz rocks occur, but generally one or several of the silicates mentioned are also present. Varieties

[1] Unfortunately, the manner in which the differentiation is assumed by Tuominen and Mikkola to have occurred, was then misrepresented (compare Mikkola 1965). The arguments against explaining the relevant phenomena in Sweden by metamorphic migration are, however, independent of the supposed nature of the process.

with an essential content of cordierite and anthophyllite or of almandite, are particularly common. It is the very large scale on which, especially, cordierite-rich rocks occur that forms the chief ground for the conclusion that great amounts of magnesium must have been introduced from outside into the Leptite series. (Compare on this subject especially Geijer 1962.)

Only few sulfide concentrations in the province are found in virtually unaltered leptites. Examples (outside the Öster-Silvberg district) are represented quite locally among the lead-zinc deposits of the Garpenberg-Gransjö zone, and by a few deposits with iron sulfides, occasionally also some chalcopyrite, and generally of a fahlband type, as at Sveden east of Falun (Geijer 1917).

With regard to the association of metals in ore and in the altered wall rock, the following relations are statistically conspicuous. Largescale introduction of magnesium, resulting in cordierite-anthophyllite quartzite and the like, has been common in connection with ores containing copper (as chalcopyrite) in any essential quantity, but has so far nowhere been proved where the predominant sulfides are galena and sphalerite. The same applies to the introduction of iron, which has led to the development of almandite quartzite (often also with anthophyllite), with the exception, however, that also one lead deposit, the Kallmora silver mine, is accompanied by this type (Geijer 1936). With zinc ore in leptites this form is nowhere associated, although there are known several examples in carbonate rocks of the combination of sphalerite with andradite garnet.

In the Öster-Silvberg district one only rarely encounters the alteration implying a considerable addition of magnesium, which from its role at Falun and at Orijärvi has come to be regarded as typical of the mineralization in the sulfide province. As already stated, the sulfide particularly associated with this kind of alteration is chalcopyrite, and the district does not represent any exception from this rule, since the only typical case is at Gumsberget, which is also the only occurrence of copper ore in leptite in the district. Some introduction of magnesium, however, has occurred also at the northeastern prospect in the Skvasselbo group, although this occurrence, with iron sulfides, sphalerite, and a little galena, so far as is known does not contain any copper. Yet even this case illustrates, in a way, the general tendency of the fractionation of elements in the mineralizing process. Just as there is a contrast between the middle Skvasselbo occurrence, where the only metal introduced into the wall rock is zinc (as gahnite), and the one just mentioned, with some anthophyllite, possibly also cordierite, so is also the difference in the proportion between the sulfidic metals a marked one, lead being quite predominant in the former but wholly subordinate in the latter. It is impossible to decide whether the development of biotite in a number of ore quartzite occurrences in the district, as at the Öster-Silvberg mine, might be a sign of addition of magnesium. If so, however, the amount must always have been inconsiderable.

An instructive example of magnesium metasomatism occurs in an outcrop about 900 m north of the Lilla Loberg mine. In the leptite there is a band, 2 to 3 m wide, of anthophyllite quartzite, containing also a little garnet in small grains, not as the large poikilitic porphyroblasts characteristic of the almandite quartzite. No sulfides were observed, but a slight limonite stain indicates a very weak impregnation of pyrite. There are no distinct boundaries between the quartzitic rock and the adjacent leptite. Larger areas of cordierite- and anthophyllite-bearing quartzite rocks, without sulfide concentrations, occur NE of Gumsberget and (outside the area of Fig. 2) SW of it, in the same leptite belt (Hjelmqvist 1953).

Typical almandite quartzite occurs at only one place in the district, the Stora Loberg mine, where it is immediately associated with the sulfide deposit that replaces a carbonate bed. This, also, is a copper ore, although the chalcopyrite is subordinate in comparison with the iron sulfides. Thus on this point, too, the district illustrates the general rule which has been found to apply to the whole province.

Similarly, the relations between lead and zinc ores and wall rock are in accordance with experience from other parts of the province — with one curious exception, however, the Mellangruvan type. At the Öster-Silvberg mine there is no clear evidence of any introduction of magnesium or iron in connection with the silicification of the wall rock, but possibly some small amounts have been added in the biotite-bearing varieties of the quartzite. It may be noted that this applies also to the ore bodies which consist essentially of pyrite. At the Lilla Loberg, Hedvig and Hoppet mines no wall rock alteration whatever has been proved. Possibly, however, the epidote associated with sphalerite in the ore bands in leptite at the Hedvig mine may indicate an alteration of the same nature as at the deposits of the Mellangruvan type, though on much smaller scale. The last-mentioned group of deposits, with low-iron sphalerite, on the other hand, is accompanied by an alteration that, as already stated, has no counterpart elsewhere in the province. The only unusual feature of the large-scale silicification is the rather fine grain of the product. But instead of the micas and the other silicates occurring in ore quartzites elsewhere in the district, epidote is here found as virtually the only mineral beside the quartz, and almost pure epidote skarn is immediately associated with the sulfides. The great variations in the proportions between epidote and quartz make it impossible to decide whether aluminia has been added to the alteration zone or not. This is a situation common in the study of hydrothermal or related alteration of Al-bearing rocks. It is to be noted, however, that at Vallberget aluminia is particularly associated with the ore in the zone where mineralizing solutions appear to have ascended. It is, then, more probable that this material was introduced from below than that it was concentrated towards the channel from the adjacent rock.

Although an irregular distribution of aluminium is commonly found in the immediately sulfide-bearing rocks of the province, which may vary from almost pure quartz aggregates to concentrations of aluminous silicates, indications of longer transport of this element, as in the case now considered, are seldom observed. Attention may be called, however, to the rock consisting chiefly of coarsely crystalline cordierite and anthophyllite which at two places in the neighbourhood of the Falun mine, in different rocks, forms a sharply bounded, dike-like body (Geijer 1917, p. 118). In no case have there been found cogent reasons to assume that aluminium was an original constituent of the ore-forming solutions.

As to the iron in the epidote skarn at Vallberget, its amount seems too high to be explained through internal movements of material in the affected rock, and one must conclude that it was added in connection with the mineralization. This is remarkable, in view of the general absence of any introduction of non-sulfidic iron into the wall rock at the other zinc deposits of the district, and the particularly low iron content of the sphalerite that is associated with the epidote.

Still more noteworthy is the addition of calcium which is represented by the epidote skarn. Otherwise it is, in the whole province, a rule without exception that the alteration of leptites in connection with sulfide mineralization implies a loss of calcium, in most cases a virtually complete loss. A seemingly simple explanation of the exception would be that the calcium had been extracted from calcareous beds in the Leptite series, before the ore-forming solutions reached the crust level where the deposits were formed. This, however, would be contrary to all experience from the province, as such effects have never been observed elsewhere in it, not even in the numerous cases were ore-forming solutions have clearly been in contact with limestone. Whatever the derivation of the calcium might be — from the same original source as the ore-forming solutions or secondarily from limestone — it is evident that the solutions have been able to transport it and therefore must have differed, in some essential respect, from those elsewhere active as ore-forming agents.

It remains to consider the type of alteration which is characterized by gahnite porphyroblasts in schistose rocks of quartz with subordinate muscovite, or occasionally biotite. This type is represented in the western part of the Öster-Silvberg mine and in the Skvasselbo group, the chief associated sulfide being in both cases galena. No exact counterpart has been observed elsewhere in the province, but gahnite is there frequently found in other types of alteration products, sometimes in considerable quantity, as in the massive ore quartzite at Näverberg (Geijer 1917) or in biotite-rich schist at Garpenberg. In ore quartzites it is sometimes found also in segregated lenses or veins of quartz, which do not contain any third mineral. Apparently not only zinc but also aluminium has been present in the solutions that deposited these quartz segregations. Since, in other occurrences of ore quartzites, similar quartz bodies contain andalusite, it is a reasonable conclusion that the physical requirements for the formation of this silicate were fulfilled also in the veins that contain gahnite. This indicates that probably Zn and Al were carried in equivalent amounts in the solutions. In the case of the gahnite-bearing rocks of the Öster-Silvberg district one must therefore take into account the possibility that the aluminium contained in the gahnite was introduced, like the zinc. This would mean that the first step in the mineralization was the general silification of the rock, and that zinc and aluminium to form gahnite were introduced later, presumably contemporaneously with the galena in the ore zone.

A striking feature is the even distribution of the porphyroblasts of gahnite. It is wholly analogous to the development of the likewise poikilitic garnets in the almandite quartzite, or of cordierite and anthophyllite in other kinds of alteration products. Thus non-sulfidic iron, magnesium and zinc, in this type of mineralization, soaked through the rock and reacted with it, all in a similar pattern.

CONCLUDING REMARKS

The picture of the mineralization in the Öster-Silvberg district, as it appears from the above, may be summarily presented as follows.

The district forms a belt, elongated in the strike direction of the Leptite series. During a certain period and at a number of places, solutions ascended in this folded formation, altering its rocks, forming bodies of sulfide ores and often also causing more extensive alterations. As in other sulfide deposits in the province and in those with a comparable mode of formation elsewhere, the lastmentioned process has preceded the emplacement of the sulfide ores. This is here indicated by the inclusions of quartzite in the zinc-pyrite ore of the Öster-Silvberg mine, by the relations between skarn and ball ore at Mellangruvan, and also, as already pointed out, by the role of the gahnite. Therefore the conventional expression "wall rock alterations" may be somewhat misleading, as the alteration in question occurred before the emplacement of ore. Certain areas, referred to above, may perhaps represent loci of alteration where the process, for some reason or other, came to an end before the later, sulfide-bearing differentiates could reach them.

The evident consanguinity of the various deposits indicates derivation from a common source. At the same time, however, individual deposits, or groups of deposits, show characteristic geochemical features which make it clear that, when the solutions reached the crust level where deposition took place, they represented different fractionation products from the original source. As to the relative age of the various types one can only point out that those of the Mellangruvan type are probably formed somewhat later than the other deposits at Vallberget, since most of them are associated with the rift that cuts across the line marked by the latter.

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