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MINERALOGY AND ORIGIN OF THE DISTAL VOLCANOSEDIMENTARY DEPOSIT AT THE HÄLLEFORS SILVER MINE, BERGSLAGEN, CENTRAL SWEDEN

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ABSTRACT

In the Zn–Pb–Ag deposit of Hällefors silver mine, four types of sulfide ores are recognized: 1) stratabound ore associated with manganiferous iron ores, 2) arsenopyrite-bearing stratiform (stratabound ?) ore, 3) galena-rich fissures, 4) galena-arsenopyrite veins. Type 3 and 4 are thought to originate by remobilization from types 1 and 2, respectively. The antipathetic behavior of arsenopyrite with magnetite in the stratabound ores probably reflects environmental conditions during the deposition and early diagenesis. Metamorphic, hydrothermal remobilization led to the formation of many Ag, Pb and Sb minerals. Results of electron-microprobe analyses indicate that the principal sources of silver are argentian galena, freibergite and pyrargyrite. The silver content of galena (up to 0.17 wt.%) has a linear relation with its antimony content. Tetrahedrite-group minerals contain 11.3 to 31.6 wt.% Ag. An extremely silver-rich freibergite (48.2 wt.% Ag) exceeds the previously reported maximum (42.5 wt.%).

Keywords: Zn–Pb–Ag deposit, volcanosedimentary origin, remobilization, silver, antimony, sulfosalts, freibergite, argentian galena, electron-microprobe analyses, Hällefors, Bergslagen, Sweden.

SOMMAIRE

Dans le gîte de Zn–Pb–Ag de la mine d'argent de Hällefors (Bergslagen, Suède), on distingue quatre types de minerai sulfuré: 1) minerai confiné en strates associé à un minerai de fer manganifère, 2) minerai stratiforme (et aussi confiné en strates?) porteur d'arsénopyrite, 3) galène en fissures, et 4) veinules à galène + arsénopyrite. Les sulfures des types 3 et 4 se seraient formés par remobilisation des sulfures des types 1 et 2, respectivement. L'exclusion mutuelle de l'arsénopyrite et de la magnétite dans le minerai confiné en strates refléterait les conditions locales du milieu pendant la déposition et la diagenèse précoce. La remobilisation hydrothermale métamorphique est à l'origine de la formation de plusieurs des minéraux de Ag, Pb et Sb. Les résultats d'analyses à la microsonde indiquent que galène argentifère, freibergite et pyrargyrite sont les hôtes principaux de l'argent. Dans la galène, les teneurs en argent (jusqu'à 0.17% en poids) et en antimoine varient de façon linéaire. Les minéraux du groupe de la tétraédrite contiennent de 11.3 à 31.6% d'argent. Un échantillon de freibergite très fortement enrichi en argent (48.2% en poids) surpasse la teneur maximum établie antérieurement (42.5%).

(Traduit par la Rédaction)

Mots-clés: gîte de Zn–Pb–Ag, origine volcanosédimentaire, remobilisation, argent, antimoine, sulfosels, freibergite, galène argentifère, analyses à la microsonde électronique, Hällefors (Bergslagen, Suède).

INTRODUCTION

The metallogenic province of Bergslagen in central Sweden is known as an important producer of Fe, Zn, Pb, Ag, Cu and, to a lesser extent, Mn, Co, W, Mo, Au, Bi, Ni, Ce, Hg and Se (Tegengren 1924). The exhalative-sedimentary ore deposits (Koark 1962) occur within Proterozoic (1.9–1.8 Ga) felsic metavolcanic rocks, known as the Leptite–Hälleflinta Series. An eastern continuation of Bergslagen is the Orijärvi area in southwestern Finland. The base-metal deposits, often referred to as of the Falun–Orijärvi type, contain Cu and Pb ores more or less separated from each other. Regional mineralogical investigations show that the Cu ores are accompanied by minerals of Zn, Bi, Co, Mo, As, Au, W, Se, Te, Pb, and Ag, whereas Pb occurs in Pb–Zn–Ag ores associated with minerals of Sb, Mn, As, Sn, Hg, Ni and Cu (Zakrzewski, in prep.).

The Hällefors silver mine is a type example of stratabound Pb–Zn–Ag mineralization associated with manganiferous iron ores that occur in carbonate beds intercalated in extremely K-rich acid metavolcanic rocks and in which the high Pb/Cu ratio is accompanied by high Sb/Bi, Mn/Fe and Sn/W ratios. The Hällefors mine also has two features uncommon for Bergslagen: the occurrence of vein-type mineralization in fissures cross-cutting the metavolcanic rocks, and an exceptionally low grade of metamorphism. The premetamorphic fabrics recognized in this study and the ore mineralogy suggest that the primary precipitation took place in a submarine environment as stratabound-type mineralization. Later, diagenetic and metamorphic processes resulted in the mobilization of elements and the formation of fissure-type ores.

The Hällefors silver mine (Silvergruvan) is the most important base-metal deposit in western Bergslagen. Mining activity started in 1635 and focused on the stratabound-type mineralization associated with the manganiferous iron ores in the Old mine. The vein-type ores of the Mellan field were discovered in 1668, followed, later, by the vein ores of

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the Western field (Fig. 1). Mining continued with minor interruptions until 1896. From 1635 to 1896, about 15 t of silver were produced (Tegengren 1924), and numerous abandoned dumps and pits are still in evidence. Recently, an extension of the stratabound orebody of the Old mine was found during a drilling program of Boliden Metall AB. The discovery of 115 000 t of ore containing 142 g/t Ag, 4.8 wt.% Zn and 5.7 wt.% Pb resulted in the opening and entry into production of the New mine during 1977–1978.

Part of the mineralogy presented here is based on the M.Sc. thesis of Nugteren (1978), who carried out microscope and microprobe investigations of samples collected from drill cores and from the dumps. Other data were obtained from underground observations and from regional metallogenic investigations carried out between 1975 and 1980 on the Filipstad map-sheet (Zakrzewski, in prep.).

GEOLOGICAL SETTING

The Hällefors silver mine is located in the northeastern part of the Grythyttan field, defined and extensively described by Sundius (1923). He recognized the volcanogenic nature of the "Leptite-Hälleflinta" Series and established a stratigraphy that was later used throughout Bergslagen. In this model, slates and other metasedimentary rocks are the youngest units, lying concordantly on K-rich and Na-rich units of metavolcanic rocks. In the upper, K-rich portion occur carbonate beds, the host rocks of the stratabound Mn-bearing iron ores and associated Zn-Pb-Ag mineralization.

The metavolcanic rocks are mainly felsic tuffaceous sediments and, to a lesser extent, ignimbrites and rhyolitic lavas. Subordinate are basic rocks, which occur as sheets of spilitic lavas in slates and in felsic volcanic rocks, or as sills cutting the acid

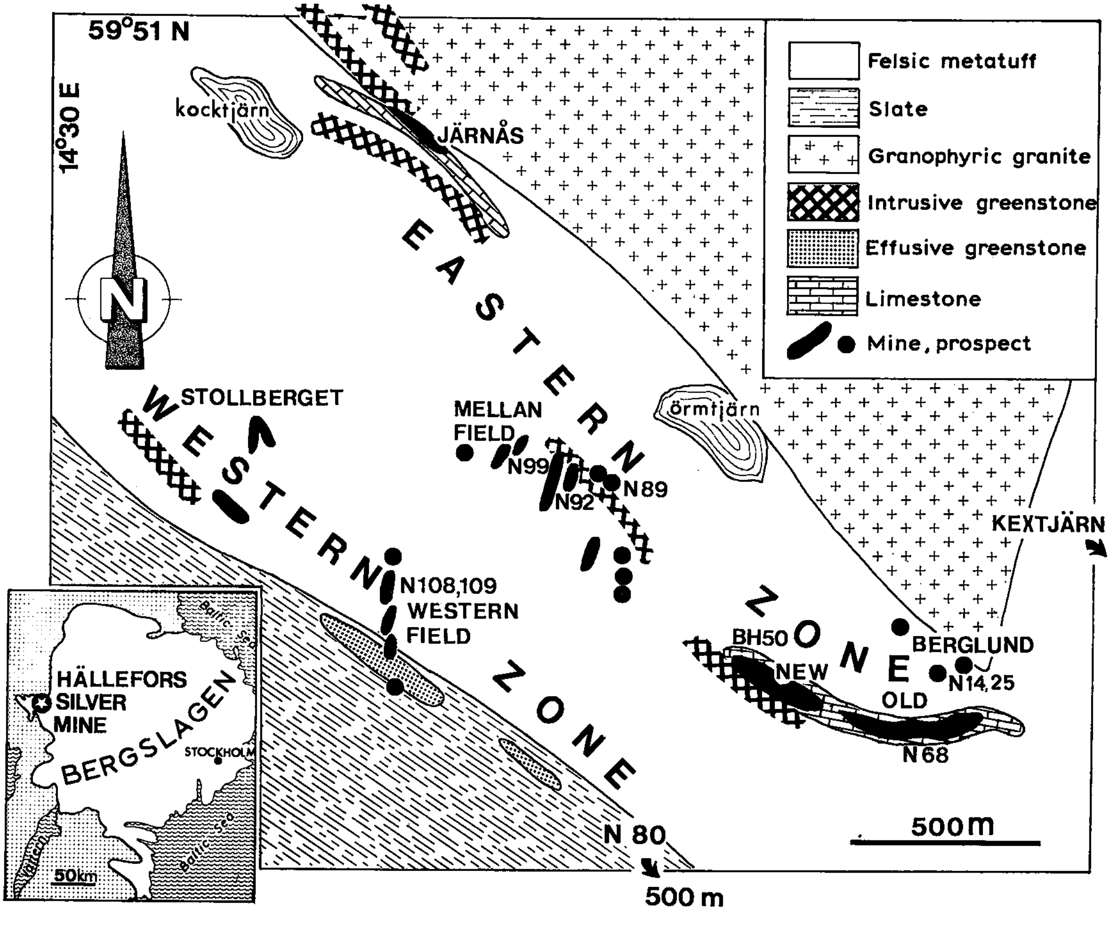

FIG. 1. Geological map of the Hällefors silver mine (after Sundius 1923, Tegengren 1924, Nugteren 1978).

volcanic and granitic rocks (Fig. 1). The tuffaceous sediments contain many intercalations of carbonate, varying in thickness from laminae a few mm thick up to complexes 60 m thick. The tuffaceous beds also occur in slates (Sundius 1923); however, the slates do not contain carbonate beds.

The supracrustal rocks of Bergslagen and their ores were folded and metamorphosed in connection with regional sinking as well as with the intrusion of several generations of granite (Magnusson 1970). In the Hällefors area, the most prominent tectonic event was a W–E compression that caused intense block-faulting, weak cleavage and very weak folding of the metavolcanic rocks. The vitroclastic fabric can still be recognized. The relatively low grade of metamorphism (chlorite subfacies) is, according to Sundius (1923), due to the absence of late kinematic granites. The postorogenic granite truncates rocks of the supracrustal series about 4 km north of the Hällefors silver mine. It caused local recrystallization of "hälleflinta" into "leptite". The oldest synorogenic granite is represented by the granophyric rock situated about 500 m north of the New mine (Fig. 1). Sundius (1923) and Sundius *et al.* (1966) regarded this granite as the source of iron, manganese and the base-metal mineralization introduced into carbonate layers by metasomatic processes, although they recognized the stratabound relationship of Mn mineralization with the K-rich metavolcanic rocks. Field observations (this study) do not indicate an intrusive character of the granophyre massif but suggest that it forms a local basement for the felsic metavolcanic rocks. Another indication of such a relationship is the petrochemical contrast, already recognized by Sundius (1923), between the extremely Na-rich granophyre and the K-rich volcanic rocks. In the Hjulsjö area, about 15 km southeast of the Hällefors deposit, a similar granite–granophyre complex forms a plutonic–volcanic centre in lower, Na-rich units of the Leptite-Hälleflinta Series (van der Velden *et al.* 1982).

Oen *et al.* (1982) interpreted the Grythyttan zone as an intracontinental incipient rift-basin in which an exhalative-sedimentary iron formation was buried under younger volcanic beds and affected by subsequent sea-floor hydrothermal alteration related to subvolcanic intrusions. Hedström (1980) concluded that Hällefors represents a distal, exhalative-sedimentary type of deposit.

MINERALIZATION

The ore mineralization of the Hällefors deposit occurs over an area 2.5 km long and 1 km wide. Two different zones have been recognized (Fig. 1). The Eastern zone includes the important sulfide occurrence associated with Mn-rich iron ores of the Old and the New mines, the sulfide deposits of the Mellan field, and the Mn-rich iron ores of the Järnås and the Kextjärn mines. The Western zone includes the Western ore field, the Stollberget mine and, possibly, local mineralization in slates (N 80) (Fig. 1).

The New and Old mines are situated in a carbonate complex striking parallel to the surrounding metavolcanic rocks (WNW to W) and dipping 30–70° toward the south. This complex, up to 60 m thick and about 800 m long, consists of 1–20-m-thick layers of limestone, dolomite, dolomitic limestone and ore. The transition zone of the carbonate complex into metavolcanic rocks consists of alternating beds, several mm to several dm thick, of carbonate and tuffaceous material. The latter also occurs as intercalations in the carbonate complex and in ores. Numerous sets of faults divide the rocks and ores into small blocks. A detailed description of the New mine is given by Hedström (in prep.).

An average ore of the New mine, as calculated from chemical analyses of Boliden AB, contains magnetite 25 wt.%, galena 6.8%, sphalerite 5.5%, "pyrite" 4.3%, arsenopyrite 1.4% and chalcopyrite 0.06%; the total of the ore minerals is about 43 wt.%. An example of the distribution of these minerals in the ore zone is given in Figure 2 for the drill hole BH 50. This profile shows the spatial relations of the three types of sulfide ores distinguished in the Old and New mines: 1) stratabound magnetite-bearing ore, 2) stratiform (stratabound ?) arseno-

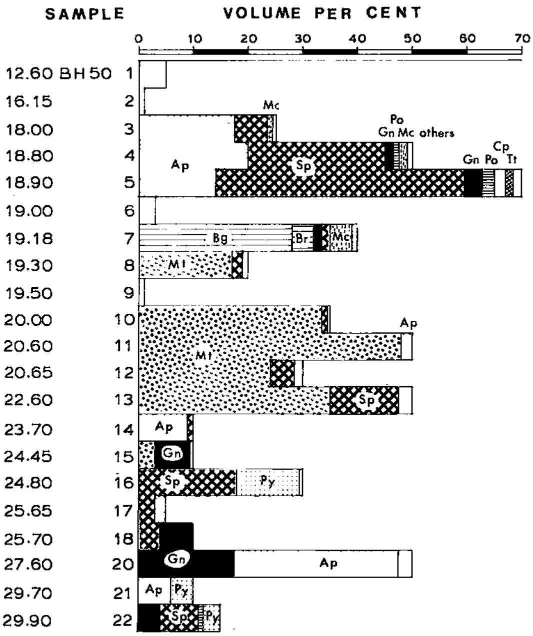

FIG. 2. Ore minerals in polished sections from bore hole BH 50. New mine. Abbreviations as in Table 1.

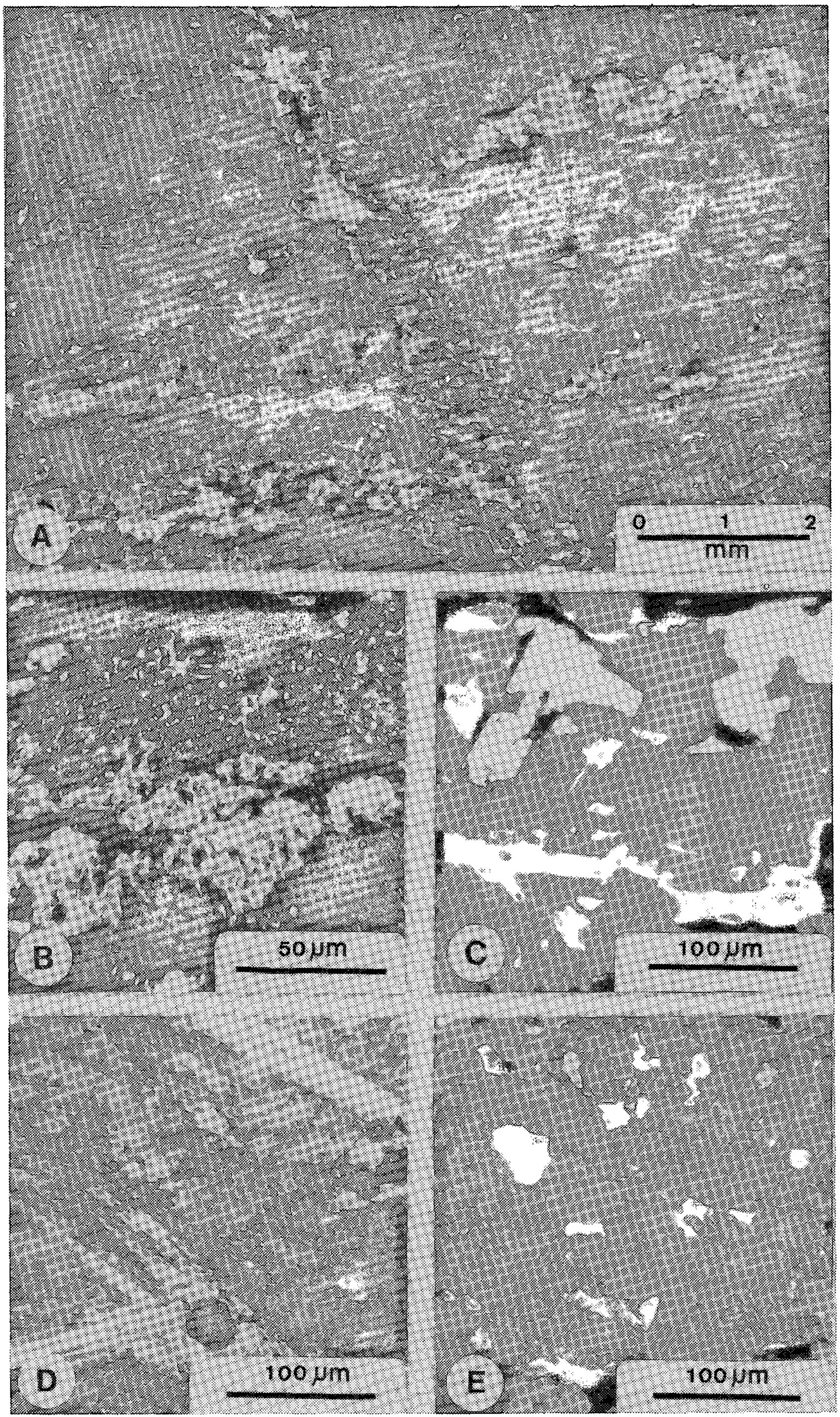

FIG. 3A. Secondary galena–chalcopyrite fissure cuts the primary bands with magnetite, sphalerite, pyrite and arsenopyrite. Alfrida (New mine). B. Spessartite–galena (in upper part) and magnetite–sphalerite bands. Alfrida (New mine). Oil immersion. C. Magnetite–sphalerite–pyrite intergrowths in magnetite-sphalerite bands. Alfrida (New mine). Oil immersion. D. Galena replacing amphibole in remobilized ore. New mine BH 50–4. E. Granoblastic texture of sphalerite. Etched 15 seconds with 50% HI. New mine BH 50–5.

pyrite-bearing ore, and 3) fissure ore remobilized from the magnetite or from the arsenopyrite-bearing types.

The stratabound magnetite-bearing sulfide ore (Fig. 2, samples 8, 9–13) occurs as beds and lenses with sharp contacts against the carbonate rocks. Their thicknesses vary from several dm up to several metres and could be followed for a few hundred metres in the carbonate complex. This type of ore corresponds to the "black carbonate rock' of Sundius (1923) and Sundius *et al.* (1966). It consists of magnetite in quantities varying from a few up to 50 vol. %, Mn-rich carbonate and silicates (knebelite, grunerite and spessartite). The dominant sulfide is sphalerite. Biotite, chlorite and serpentine occur in smaller quantities. Scapolite, tourmaline, epidote, titanite (Nugteren 1978) and pyrosmalite (Sundius *et al.* 1966) occur locally. The chemical compositions of carbonate given by Sundius (1923) and Sundius *et al.* (1966) indicate an iron-rich rhodochrosite $Mn_{0.60}Fe_{0.21}Mg_{0.13}Ca_{0.06}CO_3$. A different composition of carbonate was observed in a sterile, 3–4-m-thick intercalation of "yellow carbonate rock"; the recalculation of data given by Sundius (1923) gave a chemical composition of manganoan ankerite $Ca_{1.00}Mg_{0.36}Fe_{0.26}Mn_{0.22}Ca_{0.14}(CO_3)_2$.

The stratabound magnetite-bearing ore is distinctly banded. The mm-to-dm-scale banding is reflected by varying concentrations of the main minerals and by intercalations of carbonate or metavolcanic rocks. Relics of a probably premetamorphic lamination were observed in a relatively thin (40 cm) bed in the eastern part of the New mine. This ore consists of carbonate–silicate bands containing magnetite, sphalerite, pyrite and arsenopyrite, alternating with silicate (mostly spessartite) bands containing galena and chalcopyrite. Short perpendicular veinlets with galena, chalcopyrite and tetrahedrite cut the primary banding (Fig. 3A). Such an occurrence forms a transition to the fissure ores (see below).

The stratiform (stratabound ?) arsenopyrite-bearing ore (Fig. 2, samples 3–5, 14, 21) occurs as cm-to-several-dm-thick layers and lenses separated from the magnetite-bearing beds by sterile beds up to a few dm thick. This type of ore is often associated with metavolcanic rocks. The most persistent ore-horizon, which occurs in the banded transition-zone between the carbonate complex and the metavolcanic rocks, can be followed for 40 m (Hedström, in prep.). The mineralogy of this type of ore is qualitatively similar to that of the stratabound type, except for the antipathetic behavior of arsenopyrite with magnetite, as illustrated in Figure 2. These relations suggest that the arsenopyrite-bearing ore may represent a stratabound chemical sediment analogous to the stratabound magnetite-bearing type of ore.

The fissure ore (Fig. 2, samples 7,15,20 and probably 16–18,22) occurs as nests and veins up to several dm thick in joints and faults, and chiefly concentrated in bedding joints on the contact with the magnetite-bearing sulfide ore or in the ore itself. Outside the magnetite-bearing ores the veins are rare and only up to several cm thick. The mineralogy of fissure ores is typified by a high proportion of galena or lead sulfantimonides. This type of ore is the richest in silver. Spatial relations, fabrics, mineralogy and geochemistry indicate that the fissure ores originated by remobilization of sulfides from the pre-existing ore beds, and suggest a similar origin for the vein-type ores of the Mellan and Western fields (see below).

The *Berglund prospect* (Fig. 1) is interesting for its proximity to the granophyric granite. Rocks types, limestone, metavolcanic rocks and the magnetite-bearing black carbonate rock, as well as the proportion of ore minerals (Table 1) do not differ very much from the New and Old mines; however, no silver-bearing minerals were found, and tetrahedrite from this location has the lowest Ag content of all measured points (see Table 5).

The *Mellan field* includes several small mines operating on vein-type ores similar to that of the Western mines. An indication of the presence of stratabound type was found only on the dump, where blocks of amphibole–garnet–carbonate rock with magnetite and sulfides are identical with the ore-bearing black carbonate rock of the New mine.

TABLE 1. ORE MINERALS OF THE HALLEFORS SILVER MINE

Location		U	BH	D	Bd	Sl	J	M	St	W
Number of sections		15	24	12	3	1	2	6	3	6
Mineral	Abbr.									
Allargentum	Aa			R				R		R
Antimony	Sb				R			R		R
Dyscrasite	Ds			R						
Graphite				R						
Arsenopyrite	Ap	M	M	M	C	C		M	M	C
Chalcopyrite	Cp	C	C	C	C	C	C	C	C	C
Covellite										
Cubanite	Cb							R		
Galena	Gn	M	M	C	C	C		M	M	M
Gudmundite	Gd	C	C	C				C		C
Marcasite	Mc	C	C	C	C		C	C		C
Pyrite	Py	C	C	C	C	C	C	C		R
Pyrrhotite	Po	C	C	C	C	M	C	C	C	C
Sphalerite	Sp	M	M	M	C	M	R	C	C	C
Stibnite				R						
Boulangerite	Bg	R	R-C	R-C						R-C
Bournonite	Br		R-C	R-C						R-C
Freibergite	Tt	R	C	C				C		C
Meneghinite	Mh			R						R
Miargyrite	Mr									R
Pyrargyrite	Pg	R	R					C	R	C
Stannite	St									R
Stephanite	Sh		R							
Tetrahedrite	Tt				R					
Azurite				R						
Cassiterite			R	R						R
Goethite			R	R		C		C	C	C
Hematite			R	R						
Ilmenite			R	R	R		R	R		R
Magnetite		M	M	M	M		M	R		
Malachite				R						
Rutile				R			R			R

M major; C common but in small quantities; R rare. Location:
U underground New mine, BH drill cores New mine, D dump Old mine,
Bd Berglund mine, Sl mineralization in slates, J Järnås mine,
M Mellan field, St Stollberget mine, W Western mines.

The veins run NNE–SSW and are perpendicular to the layering of the volcanic rocks and greenstones. Veins up to 30 cm thick consists mainly of galena, sphalerite and arsenopyrite (Table 1). Locally, a zonal arrangement occurs, with arsenopyrite along the vein margins and galena in the centre. The absence of magnetite and the presence of quartz as a main gangue are characteristics of the vein-type ores.

The *Järnås deposit* is a magnetite orebody situated in limestone and calc-silicate rock. The ore contains 4.6 wt.% MnO and 0.14% S (Sundius 1923). On the dumps, pyrite and chalcopyrite are quite common; sphalerite and pyrrhotite were found during the microscope investigation.

The *Kextjärn mine* produced iron ore rich in manganese (*ca.* 5% Mn) very similar to that of the Järnås mine. Sundius (1923) described the orebody as lens-shaped, partly imbedded in green calc-silicate rock and partly rimming fine-grained metavolcanic rocks (hälleflinta). The calc-silicate rock contains garnet, hornblende, cummingtonite, dannemorite, anthophyllite, epidote, diopside and magnetite. Pyrite and chalcopyrite are the dominant sulfides, whereas pyrrhotite and sphalerite were found only by use of the ore microscope.

The *Western field* is typified by the presence of vein-type sulfide mineralization, which was exploited in several small mines. The veins run N–S and cut the generally NW–SE-striking volcanic rocks, greenstones and slates. Only traces of carbonates and calc-silicate rocks were noted on the dumps. The sulfides occur in veins up to 50 cm thick or in a system of thinner veinlets brecciating the metavolcanic rocks in a zone up to 3 m thick (Tegengren 1924). The ore contained 38.9 wt.% Pb, 12.8% Zn, 7.0% Fe, 0.285% Sb and 0.156% Ag (Tegengren 1924). Assuming the sphalerite to have a composition $Zn_{0.88}Fe_{0.12}S$ and the remaining Fe to be in arsenopyrite, the recalculation gives 45 wt.% galena, 21% sphalerite and 16% arsenopyrite. The main sulfides in ores found on the dumps are arsenopyrite, galena and sphalerite. Occasionally, hand specimens with bournonite and boulangerite can be found. This type of ore is the richest in mineral species. The complete lack of magnetite and the presence of quartz as the main gangue mineral are striking.

TABLE 2. ORE MINERALS IN SAMPLES INVESTIGATED BY ELECTRON MICROPROBE

Sample	Location	Level	Op	Sp	Po	Py	Mt	Ap	Gn	Cp	Mc	Tt	Others
BH 50 5	New mine	18.90	70	65	3	+	+	20	5	3	+	2	Br
BH 50 6		19.00	3	+					+		+	+	Br,Bg
BH 50 12		20.65	30	15	2	+	80	+	+	+	+	+	
BH 50 15		24.45	10	+	+		30	+	60		5		Pg
BH 50 22		29.90	15	45	5	20			25	+		+	Pg,Gd
BH 51 46		13.70	70	35	2	+	+	+	65		3	+	Pg,Sh
BH 53 44		33.80	30	75	+	+			15	+	+	+	Pg
78 50 L6		56	95	60	+	8	+	+	30		+	+	Pg,Gd
N 60 I	Old mine	dump	30	2	+		95	1	2		+		
N 68 C		dump	30	+	+		90	1	+	4		1	Gd2,Ds,Aa
N 14	Berglund	dump	10		50		35	+	+	+			
N 25 H		dump	5	+	+	+		+	+	+	+	+	Sb
N 80 F	Slate	dump	60	50	30	12		+	8				
N 89 G	Mellan	dump	25	1	3			80	10	3	3	+	Pg,Gd
N 89 I		dump	40	60	20	5		5	10	+	+	+	Pg,Cb,Sb
N 99 G		dump	40	2	+	50		10	30	4	3	+	Pgl
N 108 U	Western	dump	50	2	1			90	7	+	+	+	
N 109 Q		dump	80	45	7			5	40	1		2	
N 109 T		dump	20	5	5	+		+	7	5	+	3	Bg60,Br15,Pg, Gd,St, Mh,Mr

Abbreviations: Op opaque, Sp sphalerite, Po pyrrhotite, Py pyrite, Mt magnetite, Ap arsenopyrite, Gn galena, Cp chalcopyrite, Mc marcasite, Tt tetrahedrite, Br bournonite, Bg boulangerite, Pg pyrargyrite, Gd gudmundite, Sh stephanite, Ds dyscrasite, Aa allargentum, Sb antimony, St stannite, Mh meneghinite, Mr miargyrite.

The excavations of the *Stollberget mine* are oriented in two directions (Fig. 1). The N–S direction is typical for the vein-type mineralization of the Western and Mellan fields, and the NW–SE direction typical for the stratabound mineralization of the New mine. The ore fragments found on the dump are dominated by arsenopyrite and galena and, without indications of their relationship to the country rocks, could be classified as either the vein type or as the stratiform arsenopyrite-bearing type of ore of the New mine. The latter resemblance is even more accentuated by the lack of magnetite and by the occurrence of similar country-rocks, banded metavolcanic rocks, rare limestone and the presence of banded intercalations of calc-silicate rocks.

Ores in slates (N 80) occur in a small prospect in the southern part of the area (Fig. 1). On the dump, impregnations of galena and sphalerite were found in brecciated slates. It is interesting to note up to 1.5 wt.% Co in arsenopyrite from this locality. In several other places, slates are impregnated with pyrrhotite.

ORE MINERALOGY

A list of the ore minerals observed in the Hällefors silver mine is presented in Tables 1 and 2. The observed sequence, based on intergrowth patterns, is: arsenopyrite - pyrite - (magnetite) - pyrrhotite - sphalerite - chalcopyrite - galena - freibergite - boulangerite - bournonite - gudmundite - allargentum - pyrargyrite - miargyrite - stephanite. It reflects the paragenetic succession of the metamorphic hydrothermal remobilization superimposed on the decreasing tendency to idiomorphism. It is interesting to note that Jasiński (1983) predicted, on the basis of thermochemical calculations, the occurrence of several as yet undiscovered Ag–Sb sulfosalts: freislebanite, polybasite, diaphorite and andorite.

Identification of ore minerals in this study is based on microscopic and electron-microprobe investigations. In a few cases, X-ray and etching techniques have been used. Treatment with 50% HI revealed not only the polytypes of pyrrhotite, but also the presence of polysynthetic twinning in sphalerite and its granoblastic texture (Stapel 1980). Electron-microprobe analyses were performed on Cambridge Geoscan and Cambridge MK 9 equipment. The ZAF-correction program of the MK 9 was used for data

TABLE 3. RESULTS OF ELECTRON-MICROPROBE ANALYSES OF ORE MINERALS FROM HALLEFORS

	Sample	Mineral		Weight %										Atomic proportions								
				Ag	Pb	Zn	Fe	Cu	As	Sb	Co/Sn	S	Total	Ag	Pb	Zn	Fe	Cu	As	Sb	Co/Sn	S
1	N68 C	Allargentum		87.8			0.5	0.4		11.4			100.1	0.88			0.01	0.01		0.10		
2	N68 C	Dyscrasite		77.7			0.5	0.1		21.6			99.9	4.06			0.05	0.01		1		
											Co										Co	
3	N60	Arsenopyrite					35.3		41.4	1.1	0.1	21.3	99.2				1.03		0.91	0.01		1.08
4	N80						34.7		42.7	n.d.	1.5	20.9	99.8				1.02		0.93		0.04	1.07
5	N108 U		(9)				35.0		44.5	0.1	0.1	19.5	99.2				1.04		0.99			1.01
6	N89 G		(9)				36.0		42.6	0.1	0.1	22.2	101.0				1.02		0.90			1.10
7	N109 T	Boulangerite	(4)		57.2		0.1			24.4		18.3	100.0		5.32		0.02			3.87		11
8	N109 T	Bournonite	(3)		42.8		0.1	13.0		25.1		19.6	100.6		2.03		0.02	2.00		2.02		6
9	N89 I	Cubanite					40.0	22.6				35.5	98.1				1.94	0.96				3
10	N109 T	Gudmundite					26.6	0.1		57.5		15.7	99.9				0.97			0.96		1
11	N109 T	Meneghinite	(4)		61.9		0.1	1.5		18.9		17.2	99.6		13.34		0.07	1.08		6.94		24
12	N109 T	Miargyrite	(2)	35.5		0.3	0.4	0.6	0.5	41.9		21.1	100.3	1.00		0.01	0.02	0.03	0.02	1.05		2
13	N99 G	Pyrargyrite		60.3		0.2		0.4	1.3	21.6		17.1	100.9	3.15		0.02		0.03	0.10	1.00		3
14	N89 I			61.3		0.1	1.2	0.4		20.6		17.0	100.6	3.21		0.01	0.12	0.04		0.96		3
15	BH51 46			60.2		0.1				22.8	Sn	16.3	99.4	3.30		0.01				1.11	Sn	3
16	N109 T	Stannite		0.1		0.2	13.1	28.0			26.6	29.2	97.2			0.01	1.03	1.94			0.98	4
17	BH51 46	Stephanite		68.3						15.8		15.7	99.8	5.15						1.06		4

Analysts : 3, 4, 5, 6 A. Dijkhof; 9,14 M.A. Zakrzewski; others H.W. Nugteren; n.d. not detected.

reduction. Standards used are: pyrite, rhodonite, stibnite, synthetic troilite and metals. An energy-dispersion system (Link) was used for qualitative identification.

Elements and intermetallic compounds

Allargentum $Ag_{0.88}Fe_{0.01}Cu_{0.01}Sb_{0.10}$ is rare and occurs together with *dyscrasite* $Ag_{4.06}Fe_{0.05}Cu_{0.01}Sb$ as irregular grains up to 0.05 mm in diameter, partly enclosed in gudmundite or galena, and partly associated with magnetite and silicates. The recognition of allargentum and dyscrasite is based on electron-microprobe data (Table 3).

Antimony is rare and occurs as small inclusions in galena of the Berglund prospect, in association with allargentum of the Western field, and in association with galena and pyrrhotite of the Mellan field. Optical identification was confirmed by means of qualitative microprobe data.

Sulfides

Arsenopyrite occurs in almost every polished section, but is found in larger quantities only outside the magnetite-bearing stratabound ores. It has an antipathetic relationship with magnetite, and a sympathetic one with pyrite and galena (Fig. 2). In the upper parts of the ore zone, arsenopyrite, associated with pyrite, forms bands up to 5–10 mm thick. Arsenopyrite may also form grains up to a few mm in diameter, disseminated throughout the ore and the country rocks, primarily those rich in silicates. Cracks in arsenopyrite are filled by carbonates, galena, pyrrhotite, sphalerite and chalcopyrite.

Electron-microprobe data (Table 3) show considerable variations of the As/S ratio: 0.82, 0.84, 0.87, *versus* 0.98. The Sb content in arsenopyrite is zonal, with the core of individual grains generally richer in Sb than the rim. The highest values for Sb are in the Eastern zone (up to 1.1. wt.% in the New mine and up to 0.6 wt.% in Mellan field). In arsenopyrite from the Western zone, the Sb content varies between the detection limit of about 0.05 wt.% and 0.6%. The Co content in arsenopyrite is generally lower than 0.1 wt.%, although the arsenopyrite from slates (N 80) contains up to 1.5 wt.% Co. The Ni content is always lower than the detection limit of the microprobe used, and Sn has not been found. The 0.5 wt.% SnO_2 determined spectrograhically by Sundius *et al.* (1966) is probably due to contamination.

Chalcopyrite is present in almost every polished section, but only in small quantities. In most cases, chalcopyrite is associated with sphalerite and pyrrhotite. Sphalerite inclusions in magnetite and pyrrhotite grains in galena are commonly rimmed by a 1-to-20-μm coating of chalcopyrite. Replacement textures were observed between chalcopyrite, freibergite, bournonite and boulangerite.

Cubanite was only found in the vein-type ore from the Mellan field. It occurs as characteristic lamellae in chalcopyrite and in association with pyrrhotite.

Galena, being a carrier of silver, is economically the most important mineral. The silver is included in the structure of the galena, and also forms many minute (1–10 μm) grains of Ag minerals, the most important being freibergite. In the stratabound ores,

TABLE 4. RESULTS OF ELECTRON-MICROPROBE ANALYSES OF SPHALERITE AND GALENA

	Sample	Sphalerite (at. %)					Galena* (wt. %)		
		FeS	ZnS	MnS	CdS	n	Ag	Sb	n
1	BH50 5	12.0	87.1	0.48	0.37	(3)	0.06	0.11	(4)
2	BH50 12	15.9	82.2	1.50	0.40	(3)	0.02	0.02	(3)
3	BH50 15	11.3	87.6	0.66	0.42	(2)	0.07	0.09	(3)
4	BH50 22	11.5	88.1	0.00	0.41	(3)	0.15	0.30	(3)
5	BH51 46	12.1	87.0	0.52	0.43	(3)	0.02	0.04	(3)
6	BH53 44	11.9	87.2	0.53	0.41	(3)	0.03	0.04	(3)
7	78 50 L6	12.3	87.0	0.29	0.39	(4)			
8	N14	11.3	88.0	0.23	0.52	(3)	0.00	0.09	(3)
9	N80 F	10.5	89.0	0.11	0.43	(3)	0.05	0.06	(3)
10	N99 G	13.3	85.9	0.25	0.61	(2)	0.13	0.18	(3)
11	N89 I	14.1	84.3	0.17	0.42	(2)			
12	N109 Q	11.3	88.0	0.20	0.50	(3)	0.04	0.12	(6)
13	N109 T	13.1	86.2	0.17	0.48	(3)	0.17	0.17	(3)

Analysts: 11 M.A. Zakrzewski; others H.W. Nugteren; * Bi and Se are below the detection limits of microprobe.

galena occurs interstitially between carbonate and amphibole grains and as microfissure infillings in garnet, magnetite, arsenopyrite and sphalerite; it may also replace these minerals and, locally, amphibole (Fig. 3D). In the fissure ores galena forms nearly monomineralic concentrations up to 20 cm thick, which are interpreted here as products of short-distance remobilization from their source beds. Galena is also the main mineral in the vein-type ores of the Western and Mellan fields.

Electron-microprobe data (Table 4) confirm the presence of Ag and Sb in the galena of the Hällefors mine (Sundius *et al.* 1966). The Ag content varies from the detection limit (about 0.02 wt.%) to 0.17%. The Ag:Sb ratio varies from 1:2 to 2:1. Not one sample was found to contain Bi or Se, elements characteristic of the Sikfors-type association of elements (Zakrzewski 1982), in amounts higher than the detection limit of the microprobe (0.07 and 0.03 wt.%, respectively).

Gudmundite is relatively common in ores of the Hällefors deposit. It occurs as anhedral to subhedral grains up to 0.3 mm in diameter, generally polysynthetically twinned, commonly associated with galena, freibergite and pyrrhotite. It may contain inclusions of allargentum, but no traces of Ag were detected during the electron-microprobe analysis (Table 3). The occurrence of gudmundite is an important indication of the temperature of formation because heating experiments on natural gudmundite show that its upper stability is 280 ± 10°C (Clark 1966).

Marcasite forms at the expense of pyrrhotite and commonly is associated with secondary pyrite and magnetite. Larger grains of marcasite contain relics of pyrrhotite, suggesting that the intergrowths have been formed by oxidation of pyrrhotite, according to a reaction $6FeS + 2O_2 = Fe_3O_4 + 3FeS_2$.

Pyrite is a minor constitutent of much of the ore in the region, although in the arsenopyrite-bearing stratiform ores it occurs in moderate abundance. In these ores pyrite is concentrated in thin 5–10 mm bands alternating with the arsenopyrite-rich bands. Euhedral to subhedral grains of pyrite attain a size of up to 5 mm, but on average they are 0.2–0.5 mm in diameter. Pyrite may be replaced by galena and sphalerite. A second generation of pyrite is intergrown with magnetite and marcasite as products of the oxidation of pyrrhotite.

Pyrrhotite is a major component of the ores of the Hällefors silver mine (0–3 vol.% in polished sections); however, in ores enclosed in slates (N 80), it forms up to 30 vol.% of the ore minerals. Relics of pyrrhotite in marcasite and the intergrowths of pyrite with magnetite suggest that the original content of pyrrhotite was much higher. Pyrrhotite occurs also as blebs in magnetite, as exsolution laths in sphalerite and as irregular grains in galena and arsenopyrite. Etching with HI revealed both monoclinic and hexagonal pyrrhotites. The hexagonal variety commonly forms the core of an individual grain, whereas the rim consists of monoclinic pyrrhotite.

Sphalerite forms about 5.5 wt.% (calculated from the Zn content) of the average ore, and is the second most abundant sulfide after galena. It forms aggregates up to several centimetres that show, after etching with HI, a granoblastic texture of polysynthetically twinned anhedral grains 0.1–0.5 mm in diameter (Fig. 3E). In the magnetite-bearing ores, sphalerite forms blebs in magnetite commonly associated with pyrrhotite, or fills the interstitial spaces between the magnetite grains. Inclusions of pyrrhotite in sphalerite are common, but those of chalcopyrite are rare.

Electron-microprobe investigations of sphalerite indicate (Table 4) a relatively constant Cd content and a variable Mn content. As the highest Mn values are found in sphalerite of the Mn-rich magnetite ores, we conclude that the Mn content of sphalerite reflects the bulk Mn-content of the ore and, indirectly, the primary environmental conditions. Sphalerite with a high Mn-content is accompanied by galena poor in Ag, but not all Ag-poor galena is associated with Mn-rich sphalerite. It is still an open question whether this relationship reflects the primary conditions of deposition or is the result of remobilization.

The Fe content of sphalerite does not show significant variations for sphalerite associated with pyrite and pyrrhotite (Table 4, #1,4), or associated with pyrrhotite only (Table 4, #3). The exceptionally high Fe-content of sphalerite from Mn-rich environments (Table 4, #2), together with the positive correlation of 0.75 between Mn and Fe for all sphalerite, suggests that higher amounts of Fe can enter the sphalerite structure in the presence of manganese.

Stibnite is a rare mineral in Bergslagen province. In the Hällefors silver mine, it was discovered on a cleavage plane in a metavolcanic rock from the dump of the Old mine. Stibnite occurs as needles arranged as radial aggregates of 0.5 mm diameter. The identification is based on X-ray powder-diffraction analysis.

Sulfosalts

Boulangerite $Pb_{5.32}Fe_{0.02}Sb_{3.87}S_{11}$ occurs in close association with other Sb-bearing minerals: *bournonite* $Pb_{1.01}Fe_{0.01}CuSb_{1.01}S_3$, gudmundite, meneghinite, Ag-bearing tetrahedrite and freibergite. In places, the sulfosalt-rich concentrations may form lenses and veins up to 10 cm thick. In the New mine such a concentration occurs between the magnetite–sphalerite stratabound ores and the arsenopyrite–sphalerite ores (Fig. 2). Boulangerite forms aggregates of acicular grains 0.1–1 mm across. The interstices are filled with galena and bournonite. The proportion of boulangerite to bournonite varies from 1:10 to 1:5.

Electron-microprobe data for boulangerite (Table 3) show that its composition is close to falkmanite as defined by Mozgova *et al.* (1983). The Sn content of up to 0.2 wt.% SnO_2 in boulangerite from the Hällefors mine (Sundius *et al.* 1966) was not confirmed in the present investigation; it is probably due to contamination with stannite.

Meneghinite $Pb_{13.34}Fe_{0.07}Cu_{1.08}Sb_{6.94}S_{24}$ was first described by Mauzelius (*cf.* Sundius 1923) from the Jan–Olof mine (New mine). During the present investigation, meneghinite was identified in ores from the Western field but was not found in the New mine.

Miargyrite $AgCu_{0.03}Fe_{0.02}Zn_{0.01}Sb_{1.05}S_2$ is rare; it was found in boulangerite-rich ores from the Western field in association with pyrrhotite, chalcopyrite, freibergite and sphalerite. The microscope identification was confirmed by electron-microprobe analysis (Table 3).

Pyrargyrite, theoretically Ag_3SbS_3, shows some nonstoichiometry, as reflected in the Ag/Sb ratio; it may contain up to 1.2 wt. % Fe (Table 3). Pyrargyrite is the second most common Ag–Sb sulfosalt after the minerals of the tetrahedrite–freibergite series. It occurs as small (up to 0.05 mm) inclusions in galena in magnetite-bearing stratabound ores and, much more frequently, in the remobilized fissure-ores of the Old and New mines and in the vein-type ores of the Mellan and Western fields.

Stannite $Cu_{1.94}Fe_{1.03}Zn_{0.01}Sn_{0.98}S_4$ was found in association with freibergite in boulangerite-bournonite-meneghinite-rich ores from the dumps of the Western field. Stannite may also form a thin rim around cassiterite, suggesting that it originated by a reaction between cassiterite and the sulfosalts. The low Zn-content (Table 3) of stannite indicates a low temperature of formation (Nekrasov *et al.* 1979).

Stephanite, theoretically Ag_5SbS_4, occurs as crack-fillings in galena and sphalerite in fissure ores of the New mine. The optical identification, based on the lack of internal reflections typical of other Ag–Sb-sulfosalts, was confirmed by a microprobe analysis (Table 3). The upper thermal stability of stephanite, 197°C (Vaughan & Craig 1978), and the textural relations indicate that it is one of the youngest minerals to have been formed in the remobilized fissure-ores.

Minerals of the *tetrahedrite–freibergite* series $A_{10}B_2Sb_4S_{13}$ (A = Cu, Ag; B = Fe,Zn) are, along with the silver-bearing galena, the principal source of silver in the ores of the Hällefors silver mine. In some polished sections tetrahedrite-group minerals form 1–3 vol.% of the ore minerals.

TABLE 5. RESULTS OF ELECTRON-MICROPROBE ANALYSES OF TETRAHEDRITE-FREIBERGITE SERIES FROM THE HALLEFORS SILVER MINE

Sample	Cu	Ag	Zn	Fe	Sb	As	S	Total
	Weight %							
1 N25	37.7	0.3	n.d.*	6.3	30.3	-**	23.8	98.4
2 N68 C	28.7	13.3	1.2	5.9	28.2	-	23.3	100.6
3 BH50 5	29.8	12.8	2.3	4.8	28.0	-	23.2	100.9
4 BH50 5	26.4	16.6	1.8	5.2	27.4	-	23.0	100.4
5 BH50 6	24.4	19.2	2.6	4.1	27.5	-	22.9	100.7
6 BH53 44	22.4	21.5	1.9	5.5	27.1	-	22.1	100.5
7 BH53 44	15.4	31.6	2.2	4.9	25.5	-	20.2	99.8
8 BH51 46	2.4	48.2	1.6	4.1	24.5	-	18.0	98.8
9 N99 G	24.4	20.3	1.0	5.2	28.0	1.0	22.7	102.6
10 N89 I	2.4	45.3	0.1	6.2	25.5	0.7	20.6	100.8
11 N89 I	27.8	14.4	1.0	5.9	27.6	0.6	23.8	101.1
12 N109 Q	24.7	18.7	1.5	5.4	27.9	0.3	22.2	100.7
13 N109 T	29.8	11.3	1.2	5.2	28.6	0.3	23.9	100.3
14 N109 T	22.7	21.0	0.4	5.9	27.5	0.5	22.4	100.4
	Atomic proportions based on 13 S							
1a N25	10.36	0.06		1.97	4.35			16.74
3a BH50 5	8.42	2.13	0.63	1.54	4.12			16.84
13a N109 T	8.17	1.83	0.23	1.63	4.09	0.08		16.12
2a N68 C	8.07	2.21	0.33	1.88	4.14			16.63
11a N89 I	7.66	2.34	0.27	1.85	3.97	0.14		16.23
4a BH50 5	7.54	2.79	0.49	1.67	4.08			16.57
12a N109 Q	7.27	3.26	0.43	1.81	4.30	0.07		17.14
9a N99 G	7.07	3.47	0.29	1.73	4.23	0.26		17.05
5a BH50 6	6.99	3.24	0.73	1.32	4.12			16.40
14a N109 T	6.66	3.60	0.12	1.98	4.22	0.13		16.71
6a BH53 44	6.65	3.76	0.53	1.85	4.20			16.99
7a BH53 44	5.02	6.04	0.69	1.80	4.32			17.87
8a BH51 46	0.87	10.34	0.57	1.70	4.66		***	18.14
10a N89 I	0.76	8.50	0.03	2.25	4.24	0.19		15.97

Analysts: 10,11 M.A. Zakrzewski; others H.W. Nugteren; * not detected; ** not determined; *** formula calculated on 16 cations is: $Ag_{9.12}Cu_{0.77}Fe_{1.50}Zn_{0.50}Sb_{4.11}S_{11.46}$.

Electron-microprobe investigations (Table 5) show the lowest Ag-content to occur in tetrahedrite from the Berglund prospect (Fig. 1). In the New mine and in the Western field, the silver content varies from 11.3 to 31.6 wt.%, even within a single polished section. The Ag-rich and the Ag-poor phases could be recognized by their optical properties only where in contact; freibergite richer in Ag has a greyish blue tint, and contrasts with the Ag-poor members, which have a greyish brown tint and are somewhat darker.

Riley (1974) proposed the name *freibergite* for members with more than one third of the copper sites occupied by silver (approximately 20 wt.% Ag); he also reported 42.5 wt.% Ag as the maximum value for natural freibergite. During the present investigation, an exceptional freibergite with 48.2 wt.% Ag (Table 5, # 8) was found in a drill core from the New mine. Although the measured S is too low, the recalculation on the basis of 16 cations gives good agreement with the general formula for the tetrahedrite group. Another almost pure end-member freibergite occurs in the Mellan field (Table 5, # 10). In both cases the small grain-size prevented X-ray investigations. This exceptional freibergite is intergrown with pyrargyrite, which in turn is enclosed in galena. There is no correlation between the Ag content of galena and that of the minerals of the tetrahedrite–freibergite series.

Other minerals

Cassiterite was discovered in the black carbonate rock by Sundius *et al.* (1966). They estimated the tin content of the ore to be 0.06 wt.% SnO_2 by means of spectrographic analyses, a value that according to the chemical analyses by Boliden Metall AB is too high. Also, the microscope observations show that tin minerals are rare. Cassiterite occurs as grains up to 0.1 mm in diameter. It is dark brown with a colorless outer zone. In reflected light it may be easily overlooked. In ores from the Western field, cassiterite is rimmed by stannite.

Ilmenite is a relatively common accessory mineral in sulfide ores of Bergslagen. In many cases it is manganoan ilmenite, containing up to 40 mol.% $MnTiO_3$. In the Hällefors mine, ilmenite contains 15 mol.% $MnTiO_3$. It occurs as small disseminated grains in sphalerite and in the groundmass of the felsic metavolcanic rocks. The occurrence of manganoan ilmenite indicates a primary Mn-rich environment (Zakrzewski 1980).

Magnetite is the major ore-mineral in the stratabound sulfide ore (on average, 25 vol.%). In vein-type mineralization of the Mellan and Western fields, magnetite is lacking completely; in the fissure ores of the New and Old mine, it may be present where in contact with the stratabound type. Magnetite forms 0.05–0.5-mm-diameter grains, which are anhedral against arsenopyrite and pyrite but euhedral against other minerals. It displays a weak anomalous anisotropy. A second generation of magnetite occurs as veinlets in cracks in garnet and as intergrowths with pyrite and marcasite formed by oxidation of pyrrhotite. Cataclastic cracks in magnetite may be filled by galena, pyrrhotite, sphalerite and carbonates. Inclusions of sphalerite and pyrrhotite form blebs in magnetite, suggesting that the three minerals were formed almost simultaneously. Magnetite may be replaced by galena. Sundius *et al.* (1966) determined spectrographically 0.58 wt.% MnO and 0.025% SnO_2 in magnetite.

DISCUSSION

The present observations on the ore mineralogy and on the possibly premetamorphic textures of the stratabound magnetite-bearing sulfide ores suggest that the primary precipitation occurred in a carbonate-rich submarine environment. The primary sediment probably consisted of carbonate–silicate (Mn–Fe chlorite or tuffaceous material) and sulfide mud. During early diagenesis the thin lamination and porphyroblasts of arsenopyrite and pyrite were formed. Advanced diagenesis and the action of hydrothermal solutions resulted in the formation of short perpendicular veinlets with galena, chalcopyrite and freibergite (Fig. 3A) cutting the primary or diagenetic banding. Substantially similar are the galena-rich fissure ores of the New mine. Their larger dimensions could be related to a thicker bed of the primary magnetite-bearing ore. The arsenopyrite-bearing stratiform ores from the New mine possibly represent an equivalent of the stratabound magnetite-rich ores.

The epigenetic vein-type ores of the Mellan and Western field are typified by high Ag- and Sb-contents and the presence of many Ag and Sb minerals. These characteristics are similar to those of the fissure ores of the New mine and point to a probably similar origin, remobilization of the pre-existing ores. The presence of arsenopyrite and lack of magnetite suggest a mineral assemblage in the primary ores similar to that of the arsenopyrite-bearing ores of the New mine. The thermochemical calculations in the system Ag–Sb–Pb–S (Jasiński 1983) are in good agreement with the observed paragenesis and indicate the hydrothermal nature of the remobilization.

The spatial association of the Mellan field with the Eastern zone, which runs (Fig. 1) from the Järnås mine through New and Old mines to the Kextjärn mine, suggests that the veins originated by remobilization from the same pre-existing ore-horizon, and that the distance of remobilization approximately equals the maximum length of the veins (a few hundred metres). The spatial relations also suggest that the veins of the Western zone originated from the second ore-horizon, probably situated in the metavolcanic rocks along their transition into slates. Again, the lack of magnetite in this zone sugests a mineral assemblage in the pre-existing ores similar to that of the arsenopyrite-bearing stratiform ores of the New mine.

The distance of remobilization, as visualized by the length of the veins and fissures, seems to be proportional to the relative abundance of carbonates. In the carbonate complex of the New and Old mines, they are centimetres to metres long. In the Stollberget mine, with minor skarn and limestone intercalations in tuffaceous rocks, the veins are up to several tens of metres long. In the Mellan and Western fields, the carbonate and skarn rocks are lacking almost completely, and the veins may be followed for a distance of several hundred metres.

The affiliation of arsenopyrite with silica-rich rocks and magnetite with carbonates indicate that the formation of these two minerals have been controlled by changes in physicochemical conditions; therefore, the antipathetic behavior of arsenopyrite with magnetite probably reflects environmental conditions during the deposition and early diagenesis.

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