

SVERIGES GEOLOGISKA UNDERSÖKNING

SER C NR 706

AVHANDLINGAR OCH UPPSATSER

ÅRSBOK 68 NR 13

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GUNNAR JUVE

ORE MINERALOGY AND ORE TYPES  
OF THE STEKENJOKK DEPOSIT,  
CENTRAL SCANDINAVIAN  
CALEDONIDES, SWEDEN



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## ABSTRACT

Stekenjokk is a pyritic base metal mineralization (Kieslagerstätte) belonging to an extensive copper-zinc province of the central Scandinavian Caledonides. It is interbedded in a volcanic-sedimentary rock series, in a low-grade metamorphic nappe sequence. The total reserves are estimated to be 15 million tons, assaying 1.43 % Cu, 3.03 % Zn, 0.3 % Pb, 20.1 % S, 53 ppm Ag and 0.25 ppm Au.

The mineralizations do not have any absolute preference for a particular host rock composition. The main ore horizon is located on or near the contact between a series of acid volcanic tuffs and fine-grained carbonaceous phyllites. The tendency to be located on contacts or transitions between different host rock types is maintained even for the thinnest sulphide strata.

The ore bodies are considered to be of pre-tectonic age. The sulphide masses are, therefore, metamorphosed in the same facies as the surrounding rocks. The textures and morphology of the ore bodies are controlled by a two-phase fold system. Major thrusts and local dislocations in the area are considered to be of post-ore age.

Pyrite, pyrrhotite, sphalerite and chalcopyrite are the dominant minerals present. Galena is subordinate and arsenopyrite is a very minor constituent. Sulphominerals and tellurides have a certain economic importance as silver carriers.

The main types of mineralizations are: massive, banded, fine-grained pyrite ore as the most important type; brecciated pyrrhotite-chalcopyrite ore, subordinate; widespread, thin stratabound disseminations of sulphides; and lateral secretions, mostly chalcopyrite impregnations, in marginal positions to the massive ores and locally of economic value.

The base metal proportions are seen to have a large spread across the layers. However, both the spread and the average proportions are remarkably similar throughout the ore body, regardless of variations in the intensity of mineralization. This similarity suggests a homogeneous source of mineralization during the whole period of primary deposition.

It is suggested that the ores may have been formed contemporaneously with the volcanic-sedimentary rock sequence of which they are an integral part, and thus are metasediments themselves.

## INTRODUCTION

### PREVIOUS WORK

The Stekenjokk deposit, discovered in 1918 is one of the major pyritic base metal deposits of the Swedish Caledonides. Early descriptions were given by Tegengren (1924, p. 99) and Högbom (1925). Since 1954 it has been subject to a thorough economic geological investigation by a dense drilling network and important underground workings. Results from these investigations have been reported by Zachrisson (1969, 1971) and Helfrich (1969) as well as in many unpublished reports.

### PRESENT INVESTIGATIONS

The present work started in 1968. Underground mapping and sampling lasted for only five weeks during 1969 when subsurface investigations finished, and the mine was flooded. Examination of drillcores was done mainly at the SGU office at Malå and laboratory work at the SGU Geochemical laboratory in Stockholm. In order to facilitate mineralogical and chemical calculations and diagrammatic work, several computer programs were elaborated. Six drillholes representing three sections across the ore body were chosen for detailed sampling. 256 samples have been analyzed for main and trace elements. A rather heterogeneous material of 1055 ore analyses from 1954—1971 has been incorporated into the new material.

Polished and thin sections have been collected from selected parts of the whole occurrence, in drillholes and in the mine. A special sampling by means of large hand specimens has been made in the mine and studied as polished slabs.

By a combination of large spread and local concentration of specimen distribution, an attempt has been made to obtain a representative sampling. The present paper summarizes the microscope work and gives a description of the mineralogy, petrography and chemical characteristics of the ores. A paper concerned with the metamorphic history of the deposit is under preparation.

## GENERAL GEOLOGY

### REGIONAL STRUCTURES

The Stekenjokk deposit is situated in the Västerbotten — Jämtland Caledonides of northern Sweden (Figs. 1 and 2). The major tectonic unit of the area is the Seve-Köli Nappe Complex, which probably has been thrust more than 100 km eastwards towards the foreland of the Caledonian geosyncline. The complex may be divided into two main units; the lower Seve part which consists of high grade (amphibolite facies) metamorphic rocks and the upper Köli part which is more low grade (greenschist facies). Detailed mapping has shown that the Köli complex often consists of several separate nappe units.

"The existing structures are mainly the result of two periods of deformation.

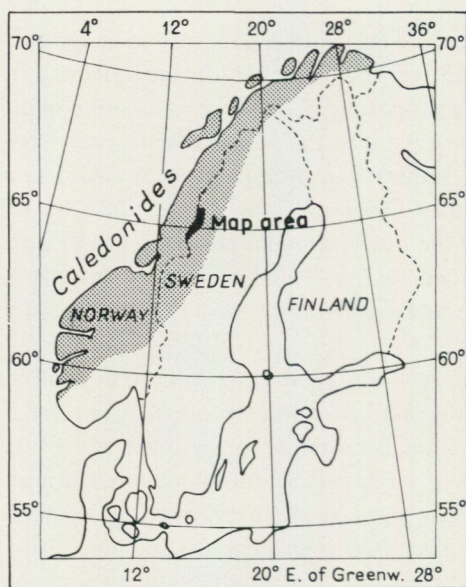


Fig. 1. Key map, showing location of Fig. 2.

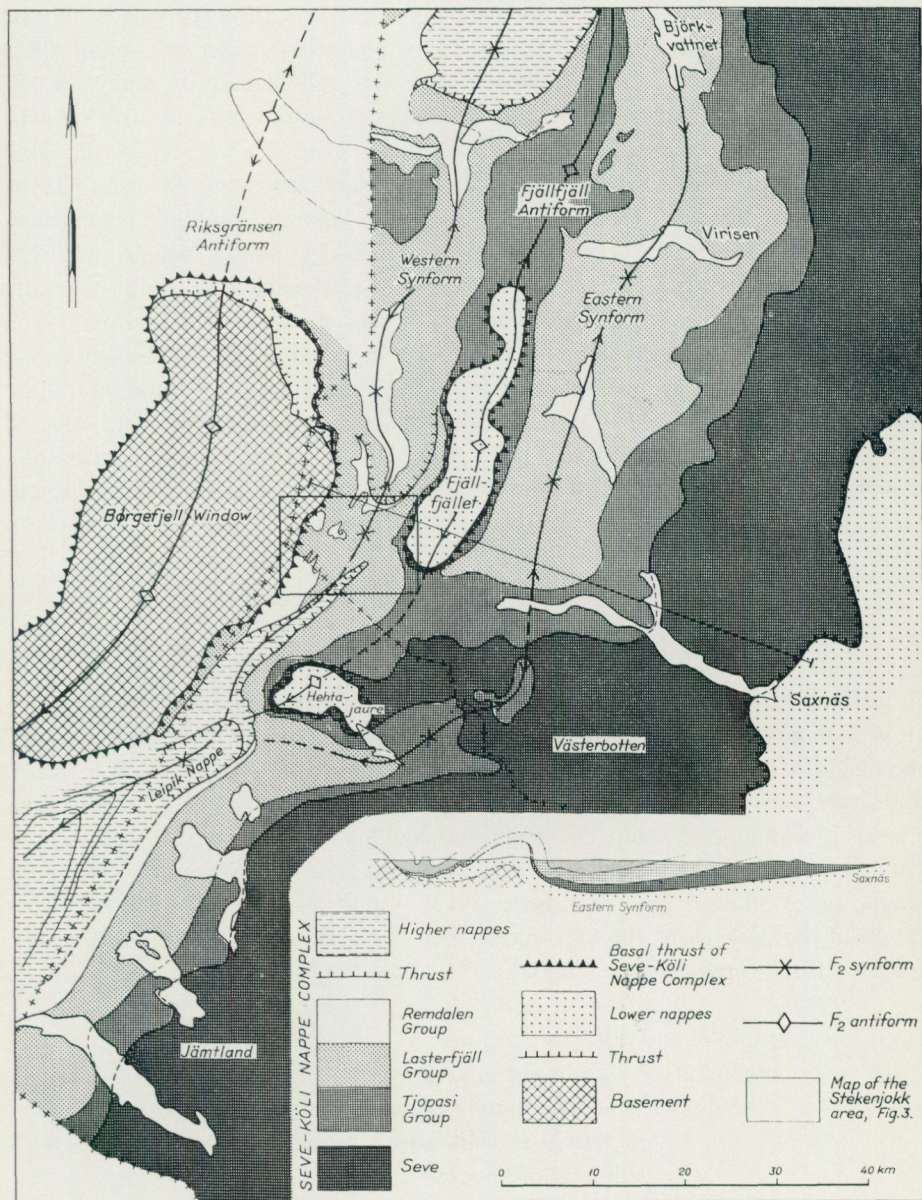


Fig. 2. Generalized geological map of the northern Jämtland—southern Västerbotten Caledonides. Simplified after Zachrisson 1969, 1971.

Four major, north-trending  $F_2$  folds, referred to as the Riksgränsen Antiform, the Western Synform, the Fjällfjäll Antiform and the Eastern Synform, dominate the structure of the areas, folding the compositional banding, the regional schistosity and the thrust-sheets. The deformed penetrative schistosity ( $S_1$ ) is related to an early phase of isoclinal folding,  $F_1$ , with locally preserved, minor folds which sometimes attain more regional dimensions. Their axes are nearly E—W in the north, and turning NW—SE when going southwards in the Western Synform, so that in the Stekenjokk area they partly become N—S. Possibly associated with  $F_1$  are local and also more regional low angle thrusts, e.g. the Gelvernokko Nappe. The whole Seve-Köli Nappe Complex was transported eastwards prior to the above-mentioned  $F_2$  phase, which produced more open folds with NE—SW to NNE—SSW orientation and generally steep-dipping axial surfaces" (Zachrisson 1971, p. 644). Zachrisson (1969, p. 4, 26—27) was also aware "that at least in some areas the sequence was laid in quite large, recumbent folds (pre- $F_1$ )" prior to the formation of the  $S_1$ -schistosity, and this early phase of deformation also seems to have affected the Stekenjokk area (Zachrisson 1971, p. 650). In the following, Zachrisson's use of the symbols pre- $F_1$ ,  $F_1$ ,  $F_2$  and  $F_3$  (and associated schistositities) is adapted.

## STRATIGRAPHY

A lithostratigraphic subdivision of the rock units within the three Köli groups (Fig. 2) is given in Table 1. In the Eastern Synform corals and brachiopods date the Slätdal Limestone (near base of Lasterfjäll Group) to uppermost Ordovician, and graptolites assign a Middle to lower-Upper Llandovery age to the Broken "Series" (Kulling 1933 and in Strand and Kulling 1972). Based on correlation with the fossiliferous rock units in the Eastern synform, the Stekenjokk volcanics should be of Silurian age (Zachrisson 1971, p. 644). A more detailed representation of the geology of the Stekenjokk area is given in Fig. 3. The local stratigraphy can be summarized as follows:

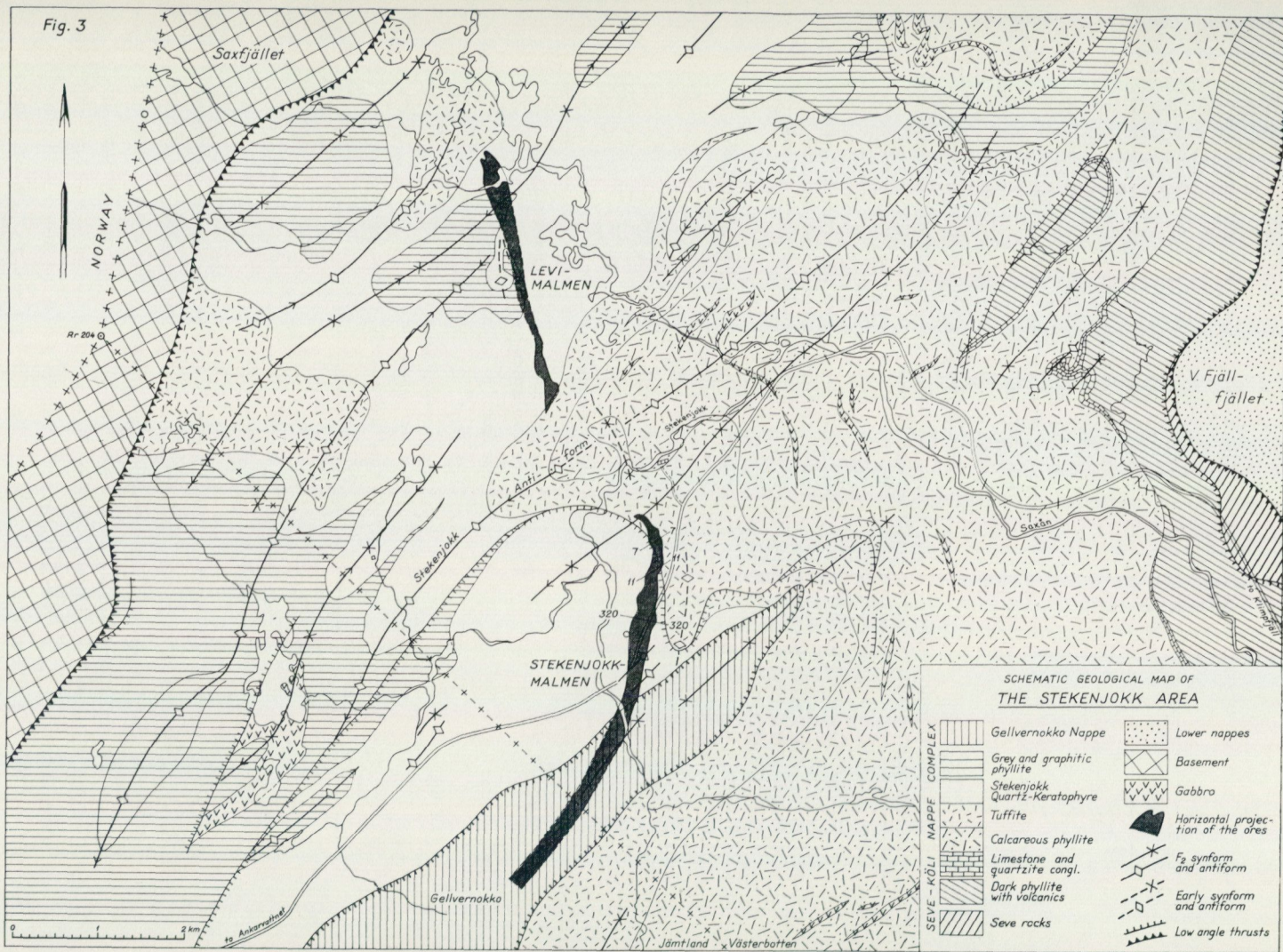
- (top) graphitic and lustrous phyllites  
conglomerate with quartz and quartzite pebbles (Portfjäll)  
Stekenjokk volcanics, dominantly quartz-keratophyres,  
greenschists with tuffitic intercalations;  
sulphide ore bodies  
tuffites, carbonaceous phyllites with local gabbro intrusions  
greenschists
- (bottom) calcareous phyllites with gabbro intrusions.

TABLE 1. Lithostratigraphic subdivision of the Köli rocks, from Zachrisson 1971.

Group	Formal lithostratigraphic units	Lithologies
Rem- dalen Group	Frems Phyllite	Dark phyllites (quartz phyllites and graphitic phyllites)
	Remdalen Greenschist	Basic volcanics Quartz porphyry and limestone Basic volcanics
Group	Portfjäll Conglomerate & Remdalen Quartzite Conglomerate	Graphitic phyllites and quartz phyllites Calcareous phyllites with limestone horizons Quartzite conglomerate, quartzite or quartz phyllite
	Las- ter- fjäll Group	Basalt — quartz-keratophyre formation & Lasterfjäll Quartz-Keratophyre-bearing Formation & Stekenjokk Quartz-Keratophyre
Blåsjö, Lasterfjäll & Lövfjäll Phyllite		Calcareous phyllites, in Western Synform with gabbro intrusions
Broken "Series"		Dark, graphitic phyllites
Bellovare Slättdal Limestone Formation Vojtja Conglomerate		Basic volcanics or green tuffites Limestone Quartzite conglomerate or quartzite
Tjo- pasi- Group	Gilliks "Series"	Dark phyllites or coarse, clastic rocks, sometimes polymict conglomerates
	Seima "Series"	Basic and acid volcanic rocks
	Rotik Conglomerate Ro Conglomerates	Dark phyllites Serpentine conglomerate Quartzite conglomerate Varied sedimentary, tuffitic and volcanic rocks

The Stekenjokk ore bodies (Stekenjokkmalmen and Levimalmen) are stratiform deposits associated with both volcanic and sedimentary rocks. They often form a border mineralization lying between a dominantly pyroclastic unit and layers of pelitic, generally carbonaceous sediments. Deposits of similar type are found in the Western Synform over a strike length of more than 200 km, and similarities regarding rock types, stratigraphy and ores may be noted with other Caledonian areas as described by Foslie (1926, 1955), Carstens (1936), Oftedahl (1958 a, b, c), Vokes (1957, 1958, 1962, 1963, 1968), and Gjelsvik (1968).

Fig. 3. Schematic geological map of the Stekenjokk area, from Zachrisson, 1971.



## MAIN ROCK TYPES

Except for the gabbro sills, all the country and host rock members are considered to have been emplaced through sedimentary processes. They consist of alternations of volcanic ashes, with addition of detrital, chemical and biogenic material. Sedimentary structures are locally preserved, but intense isoclinal folding makes the use of way-up criteria futile.

Thick limestone horizons are lacking in the sequence, but thin, pure layers and a considerable carbonate admixture in different parts occur. They indicate, together with the occasionally high carbon-content, a shallow or near-shore location of the sedimentary environment.

As a basis for chemical and mineralogical work, seven different rock types have been distinguished (Table 2).

All the rocks are metamorphic and generally schistose, but the prefix "meta" is as a rule omitted in the text. The shorter term keratophyre is also mostly used instead of quartz-keratophyre, although most of them contain more than 10 % free quartz.

In the following discussion analyses of samples with < 2.5 % S will generally be used (for black phyllite < 10 % S). They are given in Table 3, generally in three subgroups with increasing S-content. Analyses of quartz veins are excluded because of the heterogeneous character of the material.

## QUARTZ-KERATOPHYRE

An important part of the total rock volume consists of quartz-keratophyres and affiliated rock types, termed chlorite-sericite quartzites. Out of 256 drillcore

TABLE 2. Rock type classification of 256 samples from six drillholes.

Drillhole number Rock type	Section 2			Section 10	Section 17		All holes
	12	31	61020	49	59012	59014	
1. Quartz-keratophyre	23	33	25		26	18	125
2. Greenschist					1	3	4
3. Tuffite	9	18	11	2	12	19	71
4. Black phyllite	4	2			5	4	15
5. Limestone					1		1
6. Gabbro	11	13	5	7	1		37
7. Quartz vein	2	1					3
	49	67	41	9	46	44	256

Table 3. CHEMICAL ANALYSES OF HOST AND COUNTRY ROCKS (sterile or with low sulphide content). Calculated mean composition of silicate fraction after withdrawal of ore fraction and trace element fraction. Correction for sulphur is incorporated (see Appendix). (The sum consists of the radicles or elements in frame)

ELEMENTS	QUARTZ-KERATOPHYRE			GREENSCHIST			TUFFITE			ELEMENTS					
	00<S<05 Samples	05<S<10 Samples	10<S<25 Samples	00<S<10 Samples	00<S<05 Samples	05<S<10 Samples	10<S<25 Samples	00<S<05 Samples	05<S<10 Samples		10<S<25 Samples				
SiO <sub>2</sub> %	70.15	72	70.93	26	71.52	14	50.13	4	55.72	22	57.04	12	56.52	11	SiO <sub>2</sub> %
Al <sub>2</sub> O <sub>3</sub> %	13.12	72	12.63	26	13.30	14	16.88	4	14.79	22	15.76	12	15.94	11	Al <sub>2</sub> O <sub>3</sub> %
MgO %	3.05	72	3.22	26	3.83	14	5.80	4	5.87	22	5.48	12	7.59	11	MgO %
TiO <sub>2</sub> %	0.25	72	0.21	26	0.24	14	1.25	4	0.49	22	0.55	12	0.48	11	TiO <sub>2</sub> %
CaO %	1.76	72	1.55	26	1.43	14	6.40	4	5.36	22	4.28	12	4.68	11	CaO %
MnO %	0.06	72	0.09	26	0.06	14	0.18	4	0.13	22	0.12	12	0.11	11	MnO %
BaO %	0.01	65	0.03	25	0.02	14	0.01	3	0.02	17	0.03	11	0.03	10	BaO %
CO <sub>2</sub> %	1.35	58	1.32	20	1.46	9	3.13	4	4.17	20	2.84	12	3.82	11	CO <sub>2</sub> %
C %	0.07	72	0.18	26	0.34	14	0.05	4	0.07	22	0.19	12	0.44	11	C %
Na <sub>2</sub> O %	3.54	72	2.48	26	2.05	14	4.17	4	3.17	22	3.07	12	2.18	11	Na <sub>2</sub> O %
K <sub>2</sub> O %	1.39	72	1.62	26	1.82	14	0.69	4	1.10	22	1.65	12	1.85	11	K <sub>2</sub> O %
H <sub>2</sub> O>105° %	2.15	72	2.22	26	2.99	14	4.60	4	3.60	22	3.53	12	4.15	11	H <sub>2</sub> O>105° %
H <sub>2</sub> O<105° %	0.13	51	0.13	22	0.22	11	0.25	4	0.16	21	0.18	11	0.15	10	H <sub>2</sub> O<105° %
Fetot %	2.34	72	2.77	26	3.29	14	7.40	4	4.43	22	4.33	12	4.96	11	Fetot %
FeO %	2.11	72	1.64	26	0.48	14	6.91	4	4.59	22	3.35	12	2.66	11	FeO %
Fe <sub>2</sub> O <sub>3</sub> %	0.82	69	1.16	26	1.76	14	2.87	4	1.31	22	1.63	12	1.96	11	Fe <sub>2</sub> O <sub>3</sub> %
FeHNO <sub>3</sub> %	2.31	7	2.27	26	2.84	14	-	-	-	-	3.41	12	3.90	11	FeHNO <sub>3</sub> %
FeHCl %	-	-	1.20	3	1.42	11	-	-	-	-	1.83	3	2.81	10	FeHCl %
S %	0.23	59	0.71	26	1.54	14	0.44	3	0.20	20	0.72	12	1.58	11	S %
Cu %	0.0028	72	0.0069	26	0.0221	14	0.0085	4	0.0065	22	0.0137	12	0.0408	11	Cu %
Zn %	0.0087	72	0.0147	26	0.0720	14	0.0142	4	0.0148	22	0.0335	12	0.0393	11	Zn %
Pb %	0.0008	72	0.0028	26	0.0071	14	0.0004	4	0.0008	22	0.0011	12	0.0042	11	Pb %
As ppm	4.00	32	7.00	22	16.57	14	-	-	6.50	14	24.64	11	19.90	10	As ppm
Bi ppm	0.26	72	0.61	26	1.31	14	0.40	4	0.36	22	0.49	12	4.06	11	Bi ppm
Mo ppm	2.81	47	3.69	26	8.77	13	1.50	2	2.13	16	3.25	12	12.64	11	Mo ppm
Sn ppm	1.25	4	-	-	3.80	5	-	-	0.95	6	1.20	2	1.67	3	Sn ppm
Ag ppm	0.13	72	0.27	26	1.29	14	0.28	4	0.25	22	0.50	12	1.00	11	Ag ppm
Co ppm	4.21	71	5.69	26	7.71	14	17.50	4	12.09	22	12.25	12	14.00	11	Co ppm
Ni ppm	3.33	72	17.41	26	23.93	14	10.00	4	26.59	22	36.25	12	34.55	11	Ni ppm
V ppm	6.39	72	43.85	26	65.71	14	197.50	4	125.68	22	129.17	12	128.18	11	V ppm
SUM	99.83		99.28		101.30		103.07		100.39		99.52		102.41		

ELEMENTS	BLACK PHYLLITE			LIMESTONE		GABBRO				ELEMENTS				
	10<S<2.5 Samples	2.5<S<5 Samples	5.0<S<100 Samples	1 Sample	0.0<S<0.5 Samples	0.5<S<1.0 Samples	1.0<S<2.5 Samples	2.5<S<5 Samples						
SiO <sub>2</sub> %	61.25	2	59.20	3	56.48	5	1.90	44.16	23	47.28	9	45.65	2	SiO <sub>2</sub> %
Al <sub>2</sub> O <sub>3</sub> %	13.70	2	13.67	3	15.68	5	1.00	13.73	23	14.09	9	14.80	2	Al <sub>2</sub> O <sub>3</sub> %
MgO %	2.80	2	2.67	3	3.48	5	1.40	5.31	23	4.86	9	5.20	2	MgO %
TiO <sub>2</sub> %	0.69	2	0.70	3	0.82	5	0.11	3.61	23	3.41	9	3.55	2	TiO <sub>2</sub> %
CaO %	4.45	2	4.90	3	4.58	5	50.10	8.47	23	6.76	9	6.00	2	CaO %
MnO %	0.08	2	0.08	3	0.10	5	0.46	0.26	23	0.24	9	0.23	2	MnO %
BaO %	0.07	2	0.10	3	0.13	5	0.00	0.02	16	0.01	5	0.01	2	BaO %
CO <sub>2</sub> %	2.85	2	2.63	3	2.26	5	41.70	3.04	22	2.30	9	2.00	2	CO <sub>2</sub> %
C %	1.71	2	6.57	3	7.13	5	0.01	0.11	23	0.47	9	0.43	2	C %
Na <sub>2</sub> O %	0.21	2	0.65	3	0.29	5	0.05	2.46	23	2.46	9	2.75	2	Na <sub>2</sub> O %
K <sub>2</sub> O %	3.98	2	4.00	3	4.17	5	0.05	0.30	23	0.17	9	0.20	2	K <sub>2</sub> O %
H <sub>2</sub> O>105° %	3.40	2	3.50	3	3.26	5	0.90	4.80	23	4.21	9	4.50	2	H <sub>2</sub> O>105° %
H <sub>2</sub> O<105° %	0.30	2	0.23	3	0.33	4	0.10	0.29	22	0.26	9	0.15	2	H <sub>2</sub> O<105° %
Fetot %	5.25	2	7.17	3	9.42	5	1.60	10.85	23	10.87	9	11.40	2	Fetot %
FeO %	1.23	2	2.77	3	2.14	5	0.30	11.82	23	11.26	9	11.68	2	FeO %
Fe <sub>2</sub> O <sub>3</sub> %	2.62	2	2.02	3	2.08	5	0.98	3.01	23	2.93	9	2.65	2	Fe <sub>2</sub> O <sub>3</sub> %
FeHNO <sub>3</sub> %	4.40	2	6.30	3	8.44	5	1.50	-	-	10.20	9	10.40	2	FeHNO <sub>3</sub> %
FeHCl %	-	-	6.53	3	5.04	5	-	-	-	-	-	10.45	2	FeHCl %
S %	2.36	2	3.63	3	6.32	5	0.63	0.22	23	0.72	9	1.20	2	S %
Cu %	0.0175	2	0.1227	3	0.6634	5	0.0041	0.0028	23	0.0115	9	0.0080	2	Cu %
Zn %	0.0100	2	0.0763	3	0.2148	5	0.0070	0.0146	23	0.0183	9	0.0175	2	Zn %
Pb %	0.0018	2	0.0082	3	0.0288	5	0.0015	0.0011	23	0.0006	9	0.0008	2	Pb %
As ppm	0.50	2	25.00		424.00	5	12.00	5.56	16	25.75	8	25.00	2	As ppm
Bi ppm	0.70	2	3.10	3	3.88	5	1.10	0.31	22	0.60	9	0.30	2	Bi ppm
Mo ppm	0.50	2	39.33	3	95.40	5	2.00	1.45	11	3.13	8	-	-	Mo ppm
Sn ppm	-	-	7.00	3	10.00	5	0.00	1.63	16	1.54	5	2.00	2	Sn ppm
Ag ppm	0.55	2	1.93	3	7.30	5	0.10	0.38	23	0.52	9	0.85	2	Ag ppm
Co ppm	17.50	2	21.67	3	31.00	5	15.00	17.91	23	15.56	9	17.50	2	Co ppm
Ni ppm	40.00	2	80.00	3	80.00	5	15.00	11.52	23	7.22	9	5.00	2	Ni ppm
V ppm	260.00	2	655.00	3	691.80	5	45.00	212.83	23	196.11	9	227.50	2	V ppm
SUM	99.04		103.46		102.60		98.96	101.10		100.45		99.65		

samples which have undergone complete chemical analysis, 125 were logged as quartz-keratophyres in the drillcore reports. Of these, 72 contain less than 0.5 % S and may be considered as normal, unmineralized rock samples. Mean values for these analyses, and of two groups with increasing S-content are given in Table 3.

Variations in composition linked to the content of sulphur are mainly those of the base metals, iron, magnesium and the trace elements. A change in the Na<sub>2</sub>O content from 3.5 % in the first group to 2.1 % in the second group may be noted. This may indicate differences in the primary depositional conditions and/or be due to metamorphic effects.

The volcanics are mainly of acid character, fine- to medium-grained quartz-keratophyres which throughout the stratigraphic pile are considered to be of pyroclastic origin. Transitions between layers of different rock types are highly variable. They may be compositionally sharp, but mostly they are gradual in the form of fine-laminated alternations of the components involved. To draw a strict boundary between two distinct rock types may be difficult on most scales. The establishment of limits between green-coloured keratophyres, greenschists, and some green tuffites is for instance always difficult in the field. The keratophyric rocks also show complete transitions into chlorite-sericite quartzite. Some characteristic types of quartz-keratophyres are described below:

1. Hard, dense, fine-grained, fine-banded rock. Foliation shown by chlorite and sericite. Sometimes weak shades of carbonaceous material. Colour: white to light grey with greenish, bluish or yellowish shades. The rock type grades into varieties with higher sericite-chlorite contents.
2. Porphyroidal varieties:
  - a) with feldspar laths, often with anhedral outline,
  - b) with quartz megacrysts, mostly clear blue in colour,
  - c) combination of a and b.Porphyroidal horizons of varying thickness occur at several levels, and generally with good persistence along the strike.
3. Greenish quartz-keratophyre, low in quartz with gradational transition into green tuffite.

The mineralogical constituents of the quartz-keratophyres are: Main minerals: plagioclase (albite), quartz, chlorite (green or colourless), muscovite (sericite).

Minor minerals and accessories: biotite, epidote/clinozoisite, calcite, actinolite, titanite, tourmaline, apatite (traces only), zircon, rutile, magnetite, ilmenite.

*Albite.* The plagioclase is generally of albite composition. Twin lamellae are common and of even thickness. Sometimes the lamellae are bent. Exterior crystal faces are rare in the ground mass but quite common in small individual megacrysts or assemblages, some of the "porphyromorph" assemblages, however,

have a pronounced ragged outline, with suture-like, zig-zagged intergrowth between the individuals. The grain size is generally small (0.02—0.25 mm), but the megacrysts may attain 2—3 mm, and exceptionally, albite laths of some porphyroidal horizons may be 4—8 mm long. The total volume of the albite megacrysts only seldom attains 5—7 %. The dominating texture is pilotaxitic, which together with the accompanying sheet-silicates give the rock a somewhat irregular banded texture on the microscale. In the porphyroidal and semiporphyroidal varieties plagioclase has a more or less pronounced tendency to be oriented parallel to the general banding.

Some of the keratophyres are so rich in albite that they may locally be considered as a monomineralic rock (in bands of varying thickness). Here, mutual grain boundary angles of  $120^\circ$  in the so-called triple junction points are well demonstrated. This is interpreted as a relatively certain sign of recrystallization (Smith 1948, 1964; Stanton 1964).

The albite individuals often have inclusions of sericite and chlorite, the amount and proportions of which seem to reflect the conditions of the matrix. The distribution of the inclusions is often quite random, but in many cases the albite individuals have their inclusions in zoned patterns of different types:

1. Centre free of inclusions, circular zone of inclusions, and border zone free of inclusions.
2. Central zone with inclusions, rest of individual free.
3. Border zone with inclusions, centre free.

No particular type of inclusion geometry is characteristic for any particular keratophyre type. However, the simplest forms, the one with random distribution and the two with inclusion-free border zones seem to prevail. Both in the zoned types and in those with randomly distributed inclusions, the included sericite-chlorite assemblages tend to be mutually parallel. They are often also parallel to the foliation of the surrounding rock.

The second most important inclusion in albite is quartz. Small rounded or elongated blebs are frequent in the border zones of many anhedral albite individuals or assemblages. With random distribution the other silicate constituents are also found as inclusions in albite. No consequent distribution patterns can be outlined.

*Quartz* is, next to albite, the most important constituent of the keratophyre group, but because of its small grain size it is often difficult to evaluate the quartz content. It occurs normally in the fine-grained rock mass as anhedral grains of up to ca 0.1 mm. A wide range of "acidity" of this rock group prevails, but a continuous compositional transition from the most quartz-rich keratophyres to normal quartzites was not apparent.

Quartz megacrysts are colourless, milky or blue. They may be coexisting and

are locally found together with albite megacrysts in the same rock volumes. 1—2 mm diameter is the general size of quartz megacrysts in porphyroidal quartz-keratophyres, the upper size limit being about 3—4 mm.

The total volume occupied by quartz megacrysts only seldom seems to attain 5 %. Under the microscope it is seen that some varieties have a gradual increase in grain size. This may give up to 10 vol. % of quartz grains which are clearly larger than the grain size of the matrix. In all observed quartz varieties, the individuals may have undulatory extinction or not. Some of the quartz megacrysts of size 0.5—1 mm show undulatory extinction in the centre and a normally extinguishing rim all round. Apart from the appearance in the matrix and as megacrysts there are in some parts of the deposit numerous microscopic veins consisting of quartz and some carbonate. They are interpreted as microscopic developments of the vein systems observed all over the occurrence.

*Sheet silicates* comprise chlorite and sericite, often in lamellar intergrowth, occurring mainly in the groundmass of the rocks. Their relative proportions are difficult to estimate, especially in cases where the chlorite is colourless or shows bleached margins. Thus, large volumes of rock which appear to carry only sericite actually contain important quantities of chlorite.

#### GREENSCHIST

The term greenschist is used for green, fine-grained (grain size  $< 0.2$  mm), foliated rocks with basic chemical composition, relatively high in Mg, Ca, Fe, medium in Al and medium to low in Si. 4 samples of the 256 studied were classified as greenschist (Table 3). The greenschists are interpreted as metamorphic basic tuffs. Continuous transitions into rocks called green tuffites occur. Their mineralogy is dominated by albite and chlorite. The epidote (clinozoisite) content is always notable, however variable. Other constituents are, in falling order, actinolite, white mica and carbonate. These are the same constituents met with in the green tuffites, and chemically the greenschists are similar to the more basic members of this group.

#### TUFFITE

Tuffites represent a great deal of the sequence and apparently consist of mixtures of volcanic and terrigenous sediments in various proportions. They are characterized by layered alternations between the different components. The rhythm of banding may be on the millimetre, centimetre or decimetre scale, often with two members in irregular combination. It is often possible to distinguish between the following varieties:

- Green tuffite — dominated by green chlorites, often containing some carbonate and/or epidote. An important sub-type is a motley tuffite: green-coloured with white-grey patches, high in carbonate, with or without irregular splashes of epidote.
- Grey tuffite — dominated by colourless or grey chlorite, micas and/or some carbonaceous material.
- Graphitic tuffite — characterized by a marked content of carbonaceous material. (Transition to black phyllite, see below.)

These types may sometimes be followed stratigraphically over considerable distances. However, in the majority of cases mixtures between them are met with. Therefore the subdivision was not maintained for the chemical analytical program.

22 of a total of 71 tuffite samples contain less than 0.5 % S. Mean values of chemical analyses are presented in Table 3. The host rocks of the sulphide mineralizations are frequently of tuffitic character. Notable increases in the contents of MgO and C, a weak increase in the K<sub>2</sub>O-content and marked reduction of the Na<sub>2</sub>O-content take place when the mineralization intensively increases. This may indicate differences in the primary depositional milieu, or reflect the possible effects of metamorphic processes.

#### BLACK PHYLLITE

15 samples were classified as black phyllites. Analyses are given in Table 3. The group covers a wide range of composition. The name implies that these fine-grained sediments owe their colour to the content of organic matter. No particular work has been done to identify the organic constituents. However, reflected light microscopy reveals that only a small part of it is graphite. The mean carbon content in the analyzed black phyllite samples is 5.4 %. The critical lower limit for samples classified as black phyllite in the drilling reports lies about 0.5 — 1.5 % C. The highest assays lie about 13 — 16 % C.

Pelitic, quartzitic and calcareous types can be distinguished. Black phyllites also show gradual transitions to other sedimentary members such as graphitic grey tuffite, graphitic green tuffite, graphitic keratophyre and carbonaceous limestone.

The sulphide content of the black phyllites is relatively uniform, but the quartz-rich varieties seem to be poorer in ore minerals than pelitic or calcareous types. According to the microscope investigations the quartz-feldspar-rich varieties may also contain much fine-grained sheet-silicates. The roundness of some quartz grains probably indicates brecciation or a detrital origin. No precise stratigraphy has been elaborated for the different types which occur alternately.

Because of the strong deformation the black phyllites show varying thicknesses and are sometimes assembled in chaotic masses in fold hinges.

### LIMESTONE

Only one of the analyzed samples was classified as limestone (Table 3). Several pure limestone horizons of small thickness, 0.1 — 0.5 m, are found in the stratigraphic succession. They are difficult to follow from drillhole to drillhole and are too thin to constitute reliable stratigraphic reference horizons.

The content of calcite is very high throughout these restricted horizons. Magnesite and ankerite occur as accessories. No dolomitization process seems to have taken place. Locally a low organic carbon content is seen, as thin bands or vague bluish shadows well marking the primary depositional layering. These bands and shadows show that the limestone has undergone a pronounced plastic deformation during the folding.

### GABBRO

37 samples were classified as gabbro, the mean values of the analyses are given in Table 3. Gabbro occurs as relatively thin sills. Discordant relationships are difficult to prove. They have as a rule a marked schistosity, parallel to the foliation of the adjacent rocks. Deformation and metamorphism have produced a transitional contact zone characterized by a lighter border facies. Often these contacts show no evidence of a primary intrusive nature. In most cases the schistosity is developed all through the section of the sill. Its intensity, however, generally decreases away from the contacts. In more central parts the texture of the gabbro, with plagioclase laths and hornblende in random orientation or a pilotaxitic flow texture, gives evidence of an eruptive origin. Plagioclase (An<sub>20-35</sub>) and common hornblende (green-brownish) are the main minerals of the gabbro. The plagioclase of the unaltered central part of the gabbro is more calcic than that of the normal country rocks (albite). In important volumes, however, it is partly altered to a mixture of epidote/zoisite and albite, and the common hornblende transformed into lighter-coloured actinolite and/or epidote. Important amounts of chlorite may be present. Calcite is not uncommon in the border zones, where muscovite also may occur. The scarce biotite observed is generally somewhat bleached and often obviously being transformed to chlorite. Muscovite is intimately intergrown with chlorite.

An accessory content of pyrrhotite and pyrite is generally found. Richer mineralizations of pyrrhotite and some chalcopyrite are in places found in the contact zone of the gabbro sills.

The sulphide content of the gabbro sills may be interpreted in different ways:

1. A primary constituent of the intrusive.
2. Derived from the rock pile which the gabbro intruded and incorporated by:
  - a) contamination during the intrusion itself,
  - b) metamorphic contamination through mobilization and redeposition.

The content of sulphides in the gabbro samples is on the whole quite small. 23 samples contain less than 0.5 % S. The difference in sulphide content does not imply any radical chemical changes, neither does the above-mentioned transformation into gabbro border facies.

#### QUARTZ VEINS

Three of the 256 analyzed samples were classified as quartz veins. Two types of quartz veins occur in the area:

1. Quartz veins of first generation. Concordant to subconcordant. Consist partly of primary material, partly of mobilized wall rock material. In places they are intensively reworked by metamorphic processes. Direct transitions exist to quartz-rich portions of surrounding keratophyre.
2. Quartz veins of second generation. Fillings of cross-cutting tension cracks generated at a late stage of the metamorphic development. Low-temperature aqueous solutions are considered to be the medium of transportation and redeposition.

The three analyzed samples are highly variable in composition. No further quantitative analytical work has been done on the different vein materials. The main interest of the three analyses is merely as a basis for mineralogical work. They can not be taken as representatives of the vein material as a whole and are therefore not presented here.

#### THE STEKENJOKK ORE BODY

The Stekenjokk mineralizations consist of stratiform sulphide layers interbedded in a water-lain series of acid volcanic tuffs, tuffaceous sediments and fine, often carbon-rich detrital and chemical sediments. Gabbro sills have intruded the series, but generally represent similarly concordant and stratiform bodies with foliated margins. The sulphides do not have any absolute preference for a particular host rock composition, but have a tendency to be located on or near borders of different depositional facies of the host layers. Their gangue is often of varying composition in the sense that the precise border between the hanging and foot wall rock units may lie within the ore itself. From the main ore horizons,

the mineralization intensity fades out in the hanging wall and foot wall directions in the form of thinner and fewer sulphide layers. The main ore horizon of the Stekenjokk deposit lies near the contact between acid pyroclastic rocks and a black phyllite unit. Each individual sulphide layer exhibits a remarkable persistence parallel to the primary depositional layering of its host rock. There is a striking analogy in the respective patterns of alternations between sulphide and silicate layers, and between different types of silicate layers.

A detailed account and discussion of the structural setting of the Stekenjokk ore bodies was presented by Zachrisson (1971). His investigations demonstrate "that the regional, major fold phases are of fundamental importance for an understanding of the geometry of the ore bodies:

- a. The general shape and thickness of the ore in cross section and its variations along the main axis of the ore body is controlled by the  $F_1$  phase, the ore bodies being located in the hinge and in the limbs of major  $F_1$  folds.
- b. The  $F_2$  folding is superimposed and refolds the  $F_1$  structures of the ore bodies."

He concludes (1971, p. 651) that the strong tectonic control related to the  $F_1$  phase and certain mineralogical alterations might favour "an early hydrothermal epigenesis" of the ore bodies. However, considering the apparent pre- $F_1$  age, the distinct banding and often very perfect stratigraphic control which indicate a syngenetic emplacement, Zachrisson states that a final conclusion on the genesis could not be given. He also mentions the possibility that the alteration phenomena might be of metamorphic affiliation.

The present investigation mainly supports Zachrisson's structural observations.

1. The first fold phase ( $F_1$ ) is isoclinal with flat-lying axial plane (Fig. 4) and variable amplitudes, probably from hundreds of metres down to the micro-scale. Stress minimum zones around crests of folds and in drag folds are the most important localizations for thickened bodies. Thin sulphide strata concordant with the sedimentary layering may be followed from fold limbs into zones up to 30 times as thick in fold hinges. The main Stekenjokk ore body (Figs. 5,

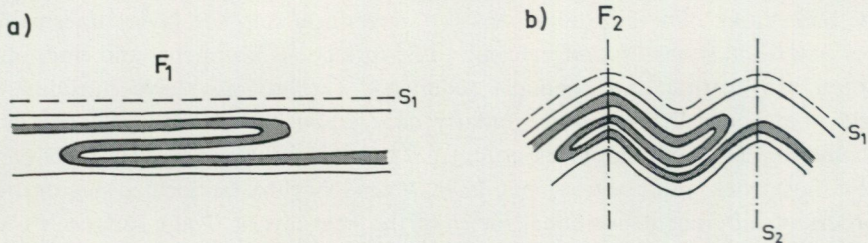


Fig. 4. a) Isoclinal  $F_1$  fold with flat-lying axial plane schistosity b)  $F_1$  fold and related schistosity deformed by  $F_2$  folding with sub-vertical  $S_2$  crenulation cleavage.

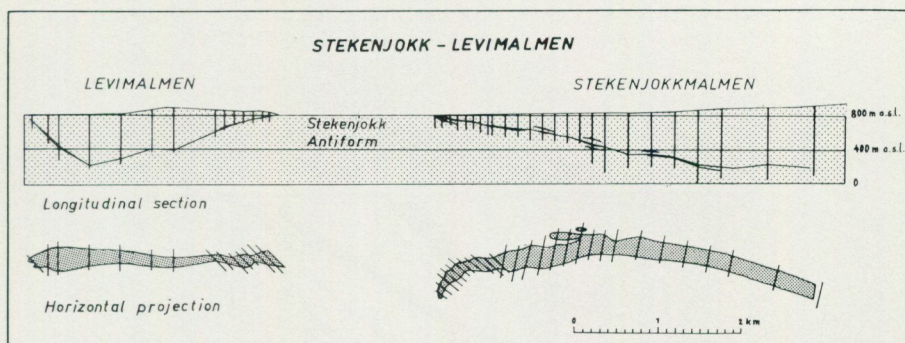


Fig. 5. Longitudinal section and horizontal projections of the Stekenjokk ore bodies, following Zachrisson, 1971.

6 and 7) is located around the crest of a major  $F_1$  fold, giving its cross section a sickle-shaped shape (ore axis is coinciding with the  $F_1$  fold axis). All pre-existing mineral layers seem to have been thickened with maintenance of the main mineralogy and primary structures (banding). On a detailed scale, however, a selective mobilization and redeposition can be observed. Mobile minerals such as chalcopyrite and sulphosalts have moved more readily than others into the stress minimum zones. The phenomena, described as "internal and lateral secretions"\* , have in places given rise to exclusive though volumetrically unimportant ore types.

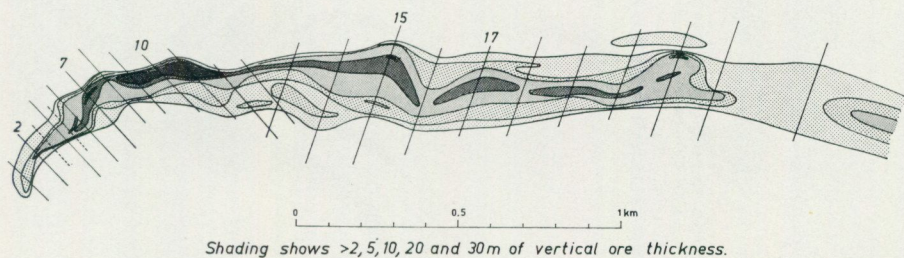
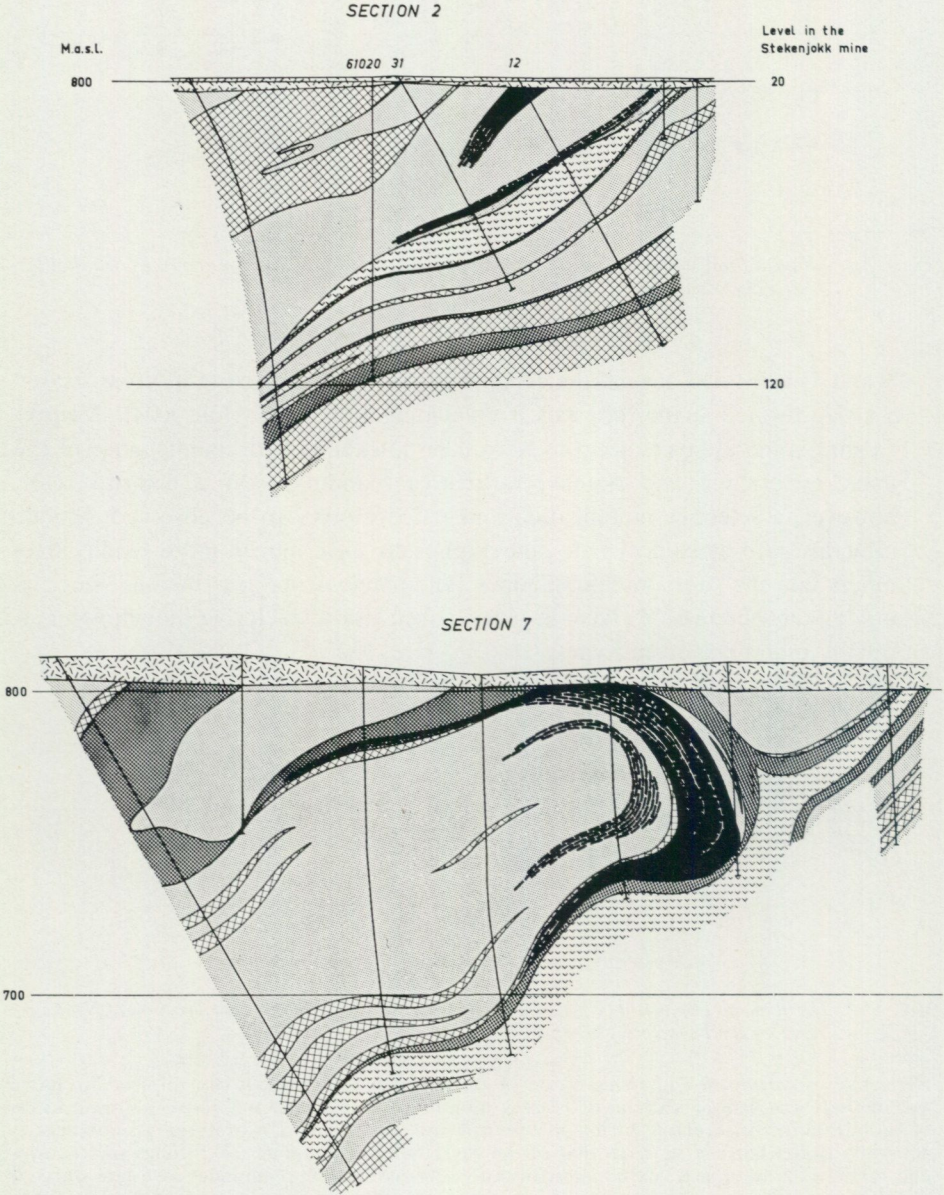








Fig. 6. Horizontal projection of vertical ore thicknesses. Stekenjokk ore body. Numbers refer to drill sections shown in Fig. 7.

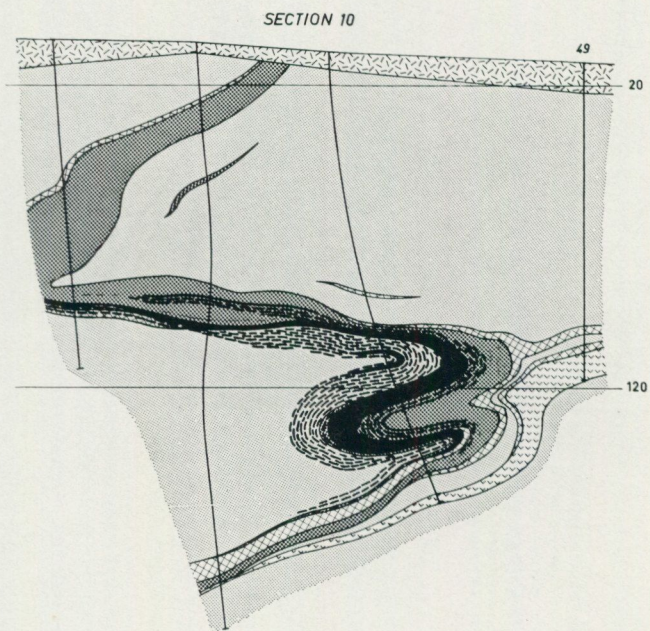
\*Selective mobilization and redeposition of ore and gangue minerals are referred to above as "internal and lateral secretions". Stress minimum zones contain relative concentrations of mobile minerals, created during metamorphism. The grain size of these assemblages is generally somewhat coarser than that of the surrounding rock material. Fillings of fractures and other voids by quartz, carbonates (occasionally zeolites) and sulphides at a late stage of the metamorphism are also expressions of metamorphic secretions. In spite of the low grade of metamorphism of the Stekenjokk deposit, analogies with certain "hydrothermal" mineralizations has led the author to adopt the term "meta-ore pegmatite" (Lawrence 1967) for such concentrations of mobile ore minerals. Further, the term "meta-hydrothermal veins" or "meta-deuteric veins" can be applied to the late depositions in fractures by the agency of low-temperature aqueous solutions.

Fig. 7. Five vertical cross-sections through the Stekenjokk ore body. Drillholes sampled for full chemical analyses in sections 2, 10 and 17. Scale 1:2500.

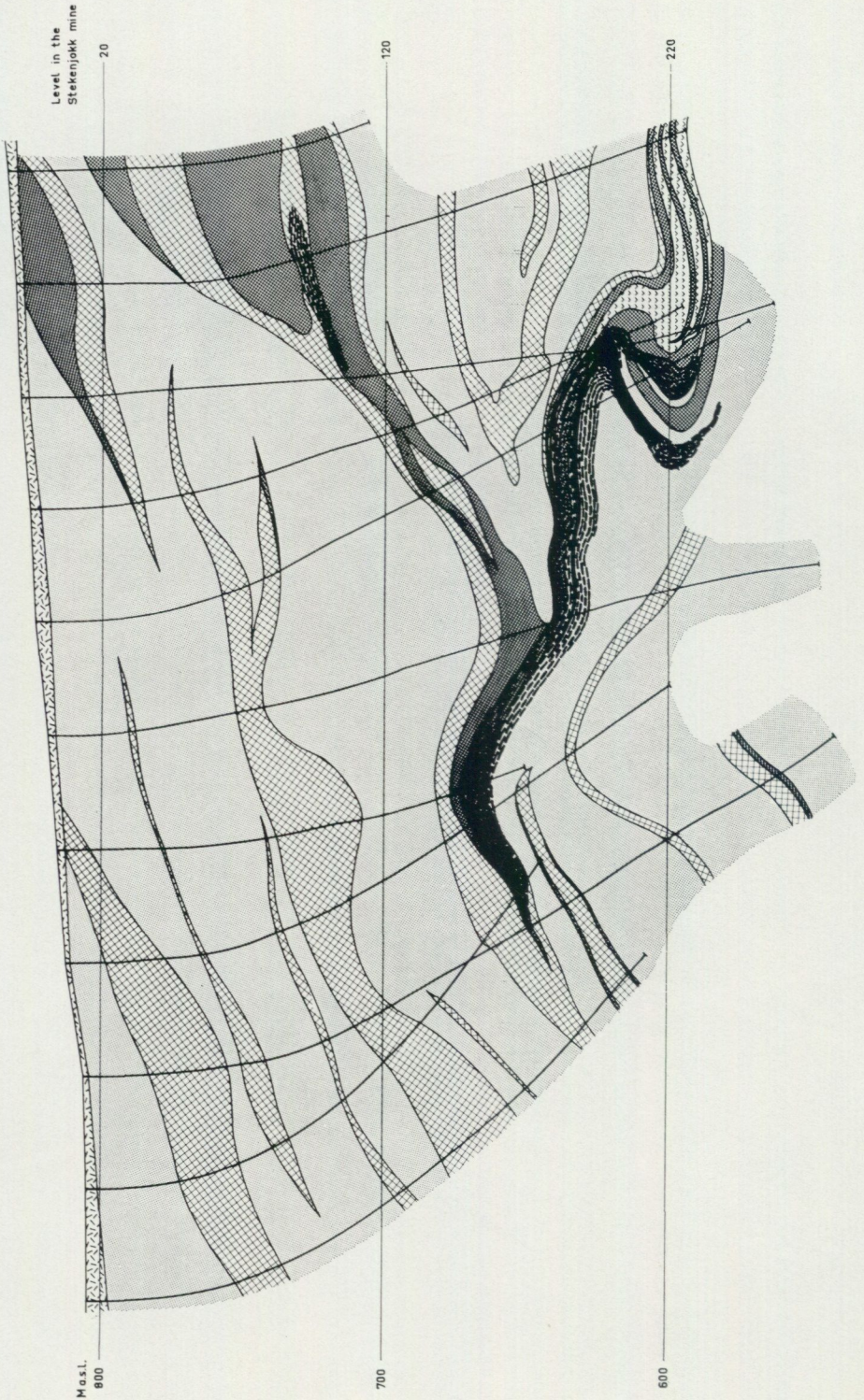


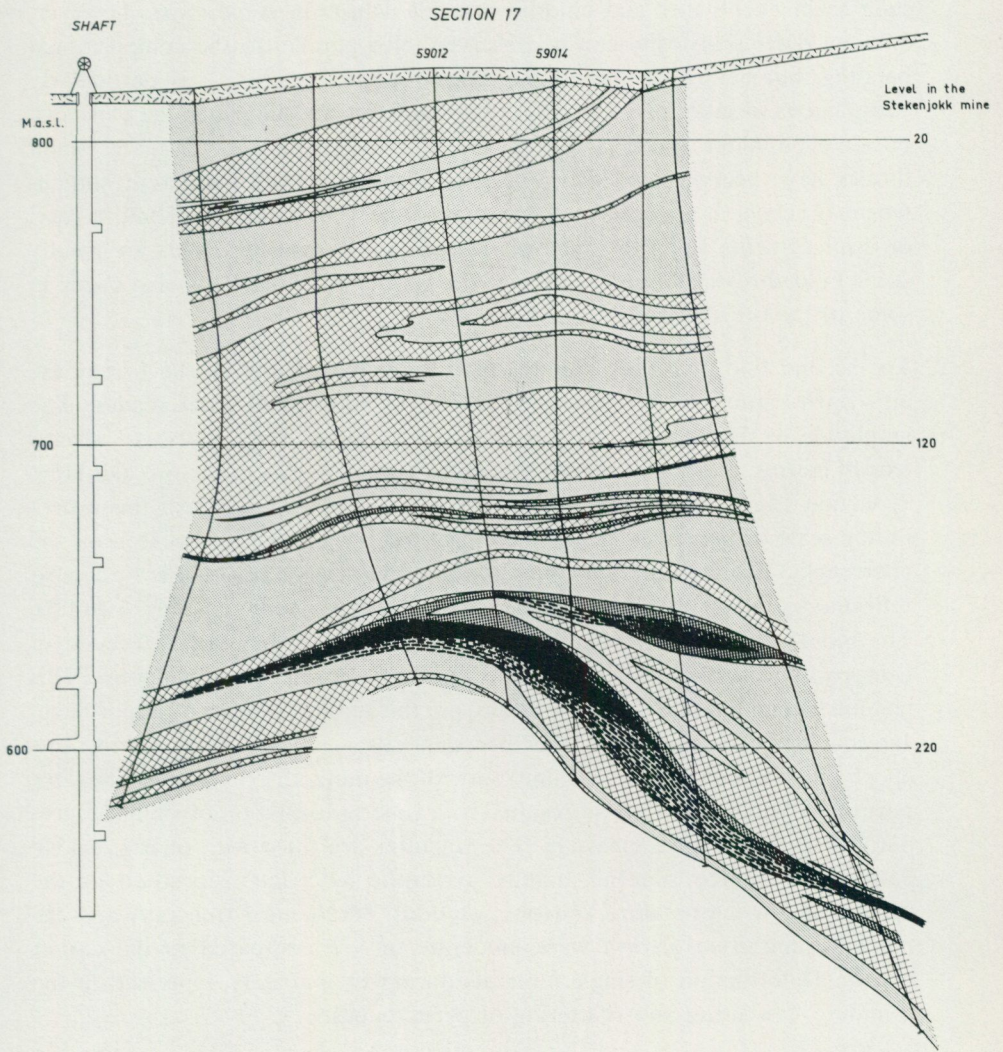
**LEGEND**

-  Glacial drift
  -  Quartz-keratophyre
  -  Tuffite (plus greenschist)
  -  Black phyllite
  -  Ore, massive
  -  Ore, disseminated
  -  Gabbro
- 59012 Ddh, sampled for whole-rock analysis



SECTION 15





A marked penetrative schistosity parallel to the compositional banding and the  $F_1$  axial plane is observed in the wall rocks. It is mainly due to the preferred orientation of sheet-silicates and is best developed in soft rocks such as black phyllite and chloritic-sericitic schist. In some cases, however, an even older schistosity can be observed, also parallel to the compositional banding, but deformed around the hinges of the  $F_1$  folds. It is particularly conspicuous in more massive quartz-keratophyres and indicates the existence of an even older (pre- $F_1$ ) fold phase. During the  $F_1$  epoch many small thrusts have been created along borders between rocks of different competence. Brecciation is occasionally seen along such borders. Small fold thrusts or displacements along the axial plane of minor parasitic  $F_1$  folds are locally seen. Fold thrusts along the limbs of the greater isoclinal folds also occur in some of the ore sections.

2. The second fold phase ( $F_2$ ) refolds the isoclinal structures of the first phase into open symmetrical folds with vertical to subvertical axial planes. The amplitude of this second phase within the ore varies from metres to several tens of metres, as seen in the cross-sections perpendicular to the ore axis (Fig. 7, section 15; cf. Zachrisson 1971). Smaller parasitic folds repeat this aspect on the scale of the cross-cuts of the mine, and the pattern is also seen on the microscale. The amplitude of the  $F_2$  folding on a more regional scale is also reflected by the gently undulating course of the main ore body (Figs. 4 and 5). The more open fold style indicates that the  $F_2$  phase has not succeeded in compressing the rock pile in the same way as the former phase (phases). This tectonic epoch has not given rise to any ore thickening patterns of importance. Internal and lateral secretions of ore minerals were also weak during this epoch and are non-existent in many parts of the mineralized volume. The later part of the second fold phase resulted in a general formation of small fissures parallel to the  $F_2$  axial cleavage. The fractures are filled with quartz, calcite and some sulphide material, mainly pyrrhotite — a late deposition by the agency of low-temperature aqueous solutions. Mechanical transport and the metamorphic grain growth were moderate or low compared to the earlier phases. Deformation of single minerals during  $F_2$  is mainly expressed in the rounding, fracturing and shattering of pyrite cubes.

Thus, the form of the ore bodies is on all scales controlled by a two-phase fold system. The first fold phase ( $F_1$ ) is an isoclinal folding with flat-lying axial plane which gave important ore thickenings in stress minimum zones, mostly around crests of folds and in parasitic drag structures. The main axis of the deposit coincides with the  $F_1$  fold axis.

The second fold phase ( $F_2$ ) remodelled the ore bodies by an open folding with a vertical to subvertical axial plane, but had little influence on further relocalization of the sulphides.

## ORE MINERALS

### PYRITE, $\text{FeS}_2$

*General aspects.* Pyrite is volumetrically the most important sulphide of the deposit (see Table 10 p. 60). It is the only major ore constituent which generally develops crystal faces. Because of its nearly ubiquitous occurrence and conspicuous crystal forms pyrite generally dominates the textural picture of the mineralizations, as seen in the compositional banding and the grain-size variation patterns. Two main types of primary pyrite distribution may be distinguished: continuous bands, and zones with disseminated pyrite — mostly as aggregates, but often also as single individuals. Disseminated, small somewhat flattened nodules which are made up of tiny pyrite individuals are found as exceptions. They can in some cases be interpreted as having an origin as framboids\*. Both types have generally concordant wall rock contacts.

The form of pyrite aggregates is mostly somewhat lenticular or stratiform. The aggregate outlines are as a rule intensively zig-zagging, following the pyrite faces towards the matrix. The internal geometry is dictated by the fact that when pyrite meets pyrite, the competition between the individuals leads to a more or less granoblastic, equigranular texture (Smith 1948, 1964; Stanton 1964). The grain boundaries meet at triple junction points where they strive to form  $120^\circ$  angles with each other (Fig. 8). Cubic outline is consequently a rare phenomenon in the denser pyrite aggregates. The degree of admixture of softer minerals dictates both the crystal form and the grain size. The aggregates, interpreted as having an origin as framboids, are altered by recrystallization, the grain size being often 5—15  $\mu$ . The aggregates are as a rule agglomerations of former framboids, where the individuals are enlarged or overgrown. They often occur in the form of spherulites or small lenses of up to 1—3 mm.

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\* Definition given by J. Kalliokoski and L. Cathles (1969): "Framboids are raspberry-like aggregates, from less than 4 microns to more than 25 microns in diameter, made up of 1/2 to 5 micron grains, or granules of pyrite. Framboids, in turn, can form 0.2 to 0.7 mm clusters...".

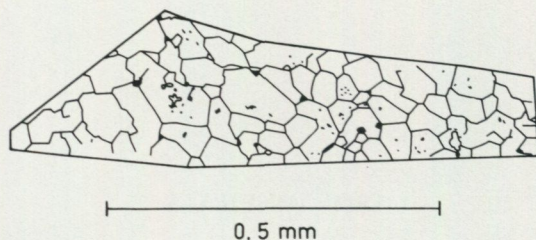


Fig. 8. Grain boundaries in massive pyrite nodule revealed by etching with dilute  $HNO_3$ . Small black spots are alien inclusions or interstitial material which in places have influenced the pyrite growth.

As a rule transitions between the above-mentioned types are met with. Locally, the densest concentrations of pyrite in aggregate form are found in the nodules (Fig. 9). Correspondingly the grain size is also smallest here. The largest individuals are found among the single disseminated crystals, where sizes of up to 1—1.5 cm are not infrequent.

It is of importance to notice the relatively frequent grouping of two distinct grain-size classes in many localities, as illustrated by a histogram summing up the grain-size distribution of 34 specimens of massive ore (Fig. 10). The same type of distribution is also met with in many of the disseminated ore types. This shows the existence of two main size classes of pyrite, which in places are undoubtedly two different generations and elsewhere due to fragmentation of existing grains.

*Anisotropy, colour, reflectance.* The Stekenjokk pyrite is usually weakly anisotropic. Through appropriate polishing methods this effect could be reduced, but



Fig. 9. Zoned and deformed pyrite nodule, consisting of individuals of 10—50  $\mu$ . Darker shade in outer zone is due to minute interstitial particles. Dark band across right part is due to etching.

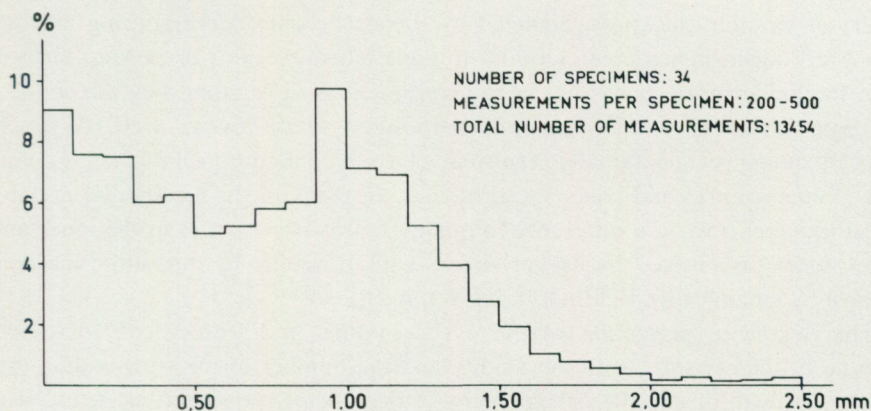


Fig. 10. Frequency distribution of pyrite grain size.

never totally eliminated. Its colour is clear brass-yellow. Darker shades may be due to bad polish, finely distributed impurities or porosity in the crystal. The investigated specimens gave reflectance values lying within the range R 51—54 %. A Leitz MPV reflectometer and a reflectance standard of R 38.6 % (NIRKM Silicium standard) were used for the measurements. Sometimes zones of lower reflectivity occur in bigger individuals (2—3 mm). These are primarily zones or bands along and parallel to the crystal faces (cf. below).

*Morphology of grains.* The cube is the dominating habit of the Stekenjokk pyrite. Usually the exterior form of the crystals has not reached full development, and subhedral forms dominate. Pyrite individuals contained in the same volume and of comparable size may show variable shape and perfection, which again may suggest the presence of more than one generation of the mineral. Some exceptional and volumetrically unimportant occurrences of pyritohedrons are found as thin bands in the normal ore types, but are best developed as depositions on fissures, where pyritohedrons of up to 2—3 mm have grown in vug-like voids together with quartz and calcite. The octahedral habit of pyrite has not been observed.

Twinning according to the (110) law is observed in some dense aggregates of pyrite, but never in isolated crystals. The frequency of this type of twinning is very low, and other types of twinning have not been observed.

Distinct zoning in the pyrite crystals is a relatively rare phenomenon in Stekenjokk, but a few types have been registered in different localities. One type consists of irregular and changing distribution patterns of inclusions which are more frequent in the outer zones than in the interior. The phenomenon is mentioned in the section dealing with the different inclusions found in the mineral. Another type of zoning is that some individuals are built up of consecutive

layers of variable thickness. Some of the bands become darker during etching. These are again in some cases found to have more irregular or porous surfaces than the lighter ones. It has not been determined as to whether they are connected with variations in the chemical composition of the pyrite itself. A simple form of zoning is exceptionally seen to involve whole nodular aggregates, showing fine-grained centres and coarse-grained rims. In many of the framboidal nodules also there seems to be a difference in quality between the pyrite in the inner and outer zones, as marked by darker shades caused mainly by interstitial material (shown by etching with  $K_3MnO_4 + H_2SO_4$  in Fig. 9).

The degree of perfection of the pyrite outlines is lowered with increasing volume of the crystals. Both the quality and the number of the surrounding matrix minerals influence the development of the crystal faces. Pyrites included in one single phase are more perfect than those situated in a polyminerale aggregate. Smaller pyrites included in one single sulphide — usually sphalerite or chalcopyrite — have often attained a high degree of perfection.

Irregularities (embayments or other changes of directions) on a pyrite face usually occur just at its meeting point with the interface of two matrix minerals.

Among the larger individuals, which normally have embayed and ragged outlines, those contained in a silicate matrix show the best development of plane crystal faces (Figs. 11 and 12). This is particularly the case if the silicate rock is fine-grained and texturally homogeneous, or if it consists of only one mineral. Minerals which are seen to destroy or cut into the pyrite outlines are first of all arsenopyrite and gudmundite. Muscovite generally shows more complex relationships. Pyrite breaks into this mineral, destroying clusters and bending the lamellae. However, in some cases muscovite sheets are seen to penetrate into pyrite grains. Mostly, the linearity of the penetrated face is perfect except at the place where muscovite runs into it or makes indentations in the pyrite crystal. Actinolite and hornblende needles exceptionally exhibit the same type of intergrowth with pyrite. Embayments on the pyrite faces in contact with sphalerite and chalcopyrite are frequent. In most respects the relationships seen at Stekenjokk correspond closely to those reported from similar deposits by Stanton (1959) and Vokes (1963, p. 33 and 38).

*Inclusions.* Inclusions in pyrite are frequent, but some few localities or mineralization types have totally inclusion-free pyrite. The very fine-grained pyrite nodules of the black phyllites show a high degree of purity, and even medium-grained disseminated pyrite in various host rocks may be without alien inclusions. The dense pyritic massive ores which sometimes are low in copper and zinc, have also a low frequency of inclusions in pyrite.

The nature of the inclusions reflects the surroundings in the sense that the relative frequency of the main minerals is essentially the same within the investigated pyrite grains as outside. Even the composite inclusions reflect to a

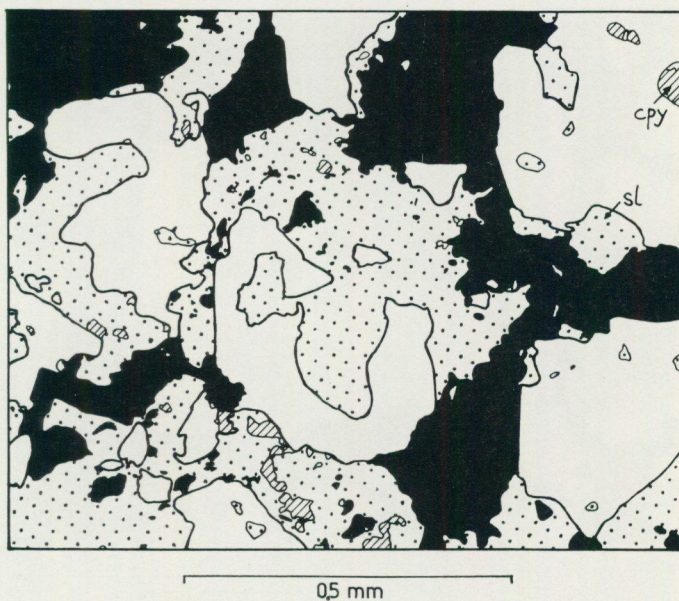


Fig. 11. Pyrite showing rectilinear borders towards silicates (dark) and curved borders towards sulphides (mostly sphalerite).

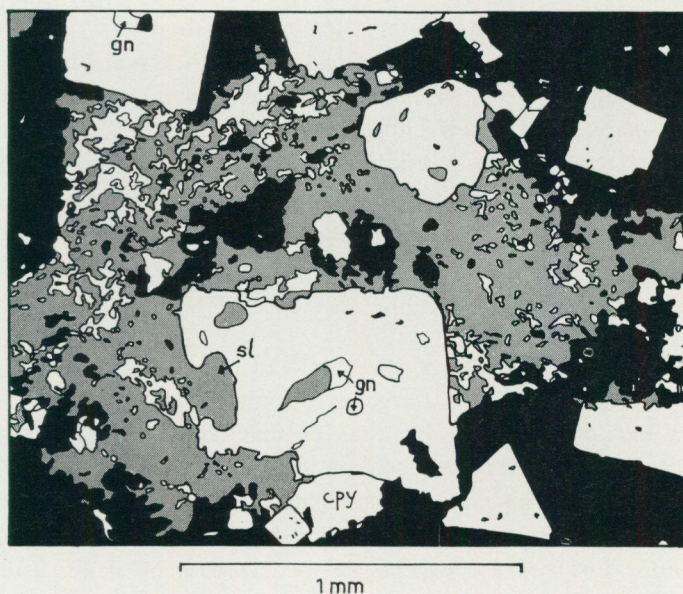


Fig. 12. Pyrite with borders of higher perfection towards silicates (dark) than towards sulphides. Sulphide matrix, mostly intimate intergrowth between sphalerite and chalcopyrite.

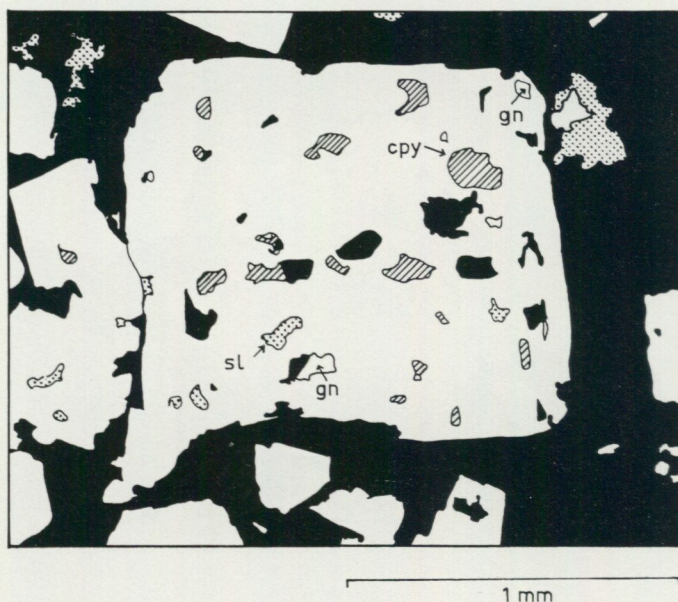


Fig. 13. Pyrite with inclusions of chalcopyrite, galena, sphalerite and silicates. Elongated and partly rectilinear outlines of inclusions in some cases parallel to pyrite faces.

certain degree the neighbouring areas. If for instance there is a very dense intergrowth of sphalerite and chalcopyrite outside the pyrite grain, the frequency of composite inclusions of these two minerals is higher than elsewhere.

In the same manner as the perfection of a crystal is inversely proportional to its size, the relative content of inclusions is notably greater in the larger, often ragged individuals.

The percentage of each crystal's volume occupied by alien inclusions can be estimated to 5—15 % in large parts of the massive ores, and may in very coarse-grained varieties of zinc- and copper-rich massive ores go up to nearly half the volume of the crystal.

Grain growth and availability of alien material to be included have obviously been favoured by deformation. Large pyrite crystals in intensively deformed surroundings are richer in inclusions than crystals of the same size which grew in less disturbed places. The geometry of the individual inclusions is variable. Many of them show a tendency to be elongated parallel to the pyrite faces (Fig. 13). The nearer the centre of the crystal they are situated, the higher is their degree of roundness. There are exceptional occurrences of small, usually equidimensional pyrite crystals with just one well-rounded chalcopyrite or sphalerite inclusion situated exactly at their centre.

A study of the frequency of different inclusions in pyrite is presented in

Table 4. The 24 samples investigated are all of massive ores ( $\geq 50$  vol. % sulphides). 20 of these are markedly dominated by pyrite (approximately 1—4 vol. % pyrrhotite as free grains). 4 samples represent massive, brecciated pyrrhotite-chalcopyrite ore containing big pyrite individuals. These pyrites, which mostly are roughly rounded and corroded by the brecciation, contain few true inclusions. The table expresses the numerical frequency of each mineral or mineral combination as inclusions, but not their respective volumes. Pyrrhotite inclusions are sometimes relatively big, - bigger for instance than inclusions of galena.

Pyrrhotite is one of the main sulphides whose frequency as inclusions (1.73 %) in pyrite apparently does not reflect its frequency as a free mineral in the ore. Its frequency as a part of composite inclusions (sum: 5.49 %) gives a more correct impression. For the smaller and rarer inclusions the picture is rather complicated. Sulphosalts and some of the noble element compounds are sometimes more frequent in chalcopyrite than in pyrite, sometimes less. Special mention must be made of inclusions of pyrite in pyrite, which are not infrequent, as revealed on etched surfaces (Fig. 14). Small, sometimes perfectly euhedral cry-

TABLE 4. Inclusions in pyrite. Frequency of occurrence expressed in percentages.

gangue	31.09 %	gangue/gn	0.54 %
sl	20.99 "	sl/cpy/po	0.52 "
cpy	16.19 "	sl/po	0.36 "
gangue/sl	6.99 "	cpy/gn	0.28 "
gn	5.93 "	sl/gn/cpy	0.07 "
gangue/cpy	5.27 "	sulf/acc	0.06 "
sl/cpy	2.89 "	aspy	0.05 "
po	1.73 "	gangue/sl/po	0.05 "
gangue/po/cpy	1.49 "	gangue/aspy	0.03 "
cpy/po	1.40 "	gangue/cpy/gn	0.03 "
sl/gn	1.34 "	gangue/sl/gn	0.03 "
gangue/po	0.96 "	gangue/sl/cpy/gn	0.03 "
gangue/sl/cpy	0.93 "	sl/aspy/gn	0.02 "
gangue/sl/cpy/po	0.71 "		

Abbreviations

po = pyrrhotite  
 cpy = chalcopyrite  
 sl = sphalerite  
 gn = galena  
 aspy = arsenopyrite  
 sulf = sulphosalts, fahlore  
 acc = accessories

Number of inclusions counted: 8579

Number of ore samples: 24

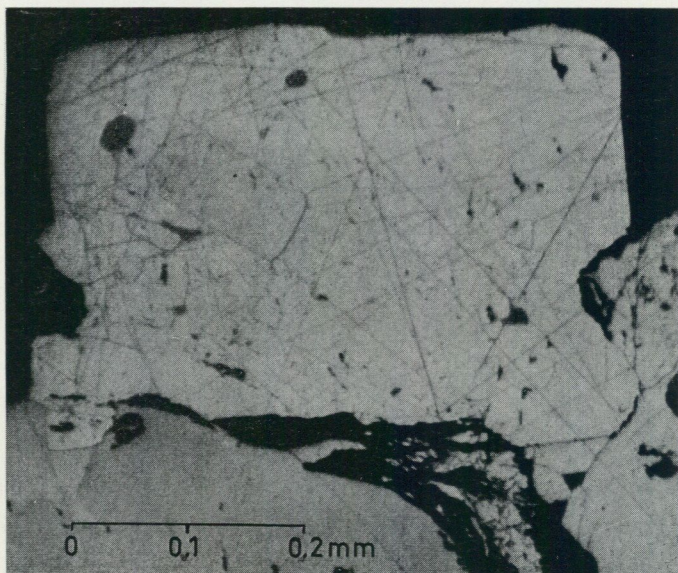


Fig. 14. *Pyrite crystal included in pyrite. Etched surface.*

stals or debris of deformed individuals may be totally overgrown by a new generation of the mineral.

*Distortion, deformation and crushing of pyrite.* An exceptional, but widespread development of pyrite is represented by more or less elongated parallelepiped-shaped crystals (Fig. 15). Their longest dimension may be up to six times the shortest. All angles remain at ninety degrees, and the longest dimension is lying in the plane of schistosity. As far as their direction could be determined, it was parallel to the corresponding fold axis. In other cases the cross-section of single individuals may appear losenge-shaped (Fig. 16) with the longest axis lying in the best developed plane of schistosity. All angles of these individuals deviate from ninety degrees, and the longest dimension of the individual crystals is again parallel to the strongest fold direction of the area. Well rounded pyrite individuals are found in the so-called "brecciated ore types" (see p. 106) together with rounded fragments of resistant gangue minerals and wall rock.

Debris from the originally complete crystals may be found in the surrounding matrix. The effect is usually a combination of cracking of the individual's interior and an increased roundness of its outline. Rounded pyrites are also not uncommon in a pure silicate matrix. As a rule their interior has then not disintegrated, and cracks and fissures are usually not to be observed.

Fragmentation is met with in many localities, but continuous volumes of fragmented pyrite seem to be small and restricted to local zones of tectonic

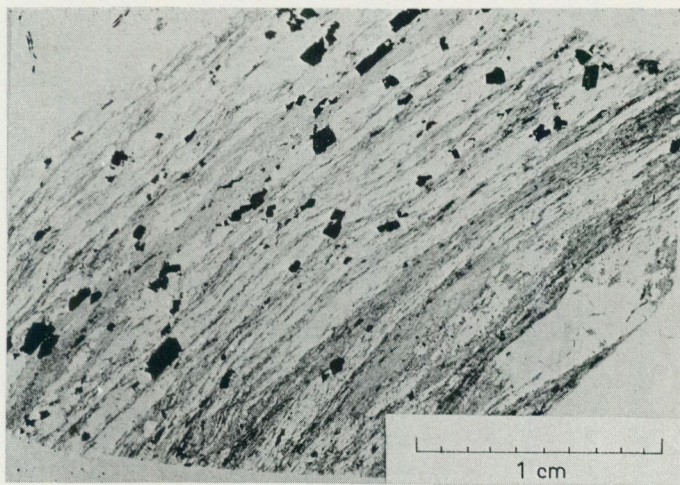


Fig. 15. *Pyrite crystals deformed during growth. Thin section of tuffitic rock.*

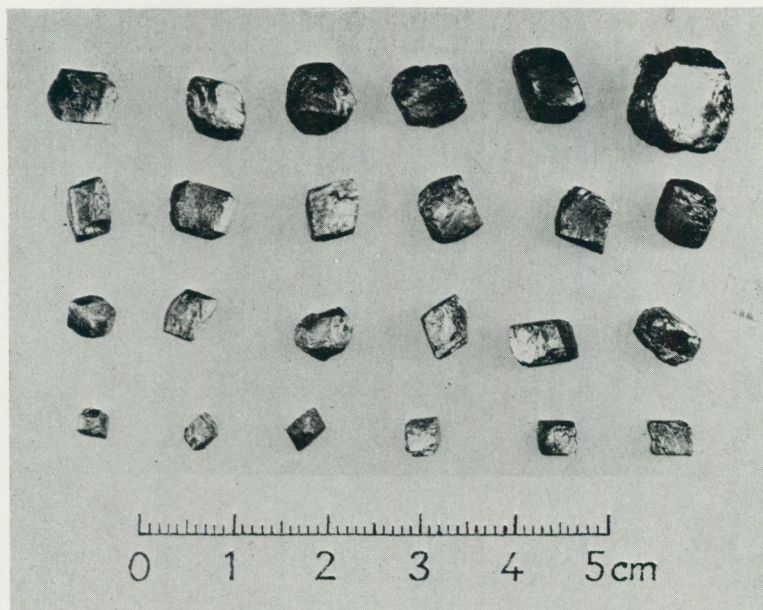


Fig. 16. *Pyrite crystals deformed during growth and after the increase in volume had stopped. Separated pyrite from intensively folded chloritic schist.*

disturbances. In some places, however, evenly distributed fine-grained pyrite fragments which undoubtedly resulted from cataclasis, give volumetrically important grain-size classes. Otherwise, all stages of cracking and crushing of the mineral can be seen. Generally, the fracturing seems to be without any preferred directional pattern. In detail it is seen that fractures follow both the (100)- and the (110)-planes, and possibly also the (111)-planes, as well as random combinations of the first two (cf. Figs. 17, 18 and 19).

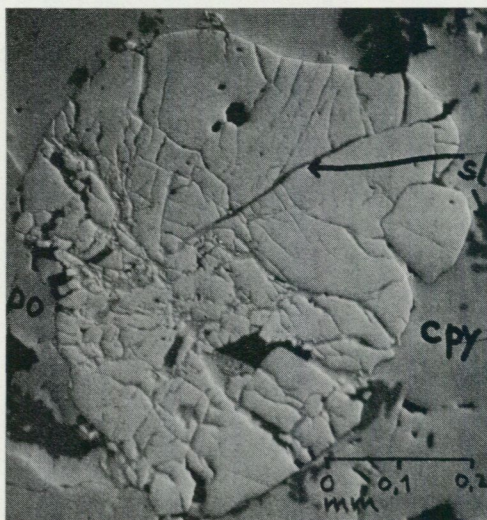


Fig. 17. Fractures in pyrite, seemingly not following any determinable crystallographic directions. The grain is well rounded. The cracks are filled with chalcopyrite and some sphalerite. The surrounding mineral is mainly chalcopyrite.

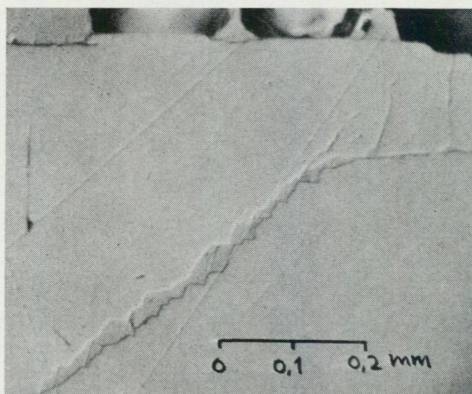


Fig. 18. Fracture in pyrite, following the (110)- or (111)-planes, and partly the (100)-planes. Fracture filled with chalcopyrite. Interference contrast objective.

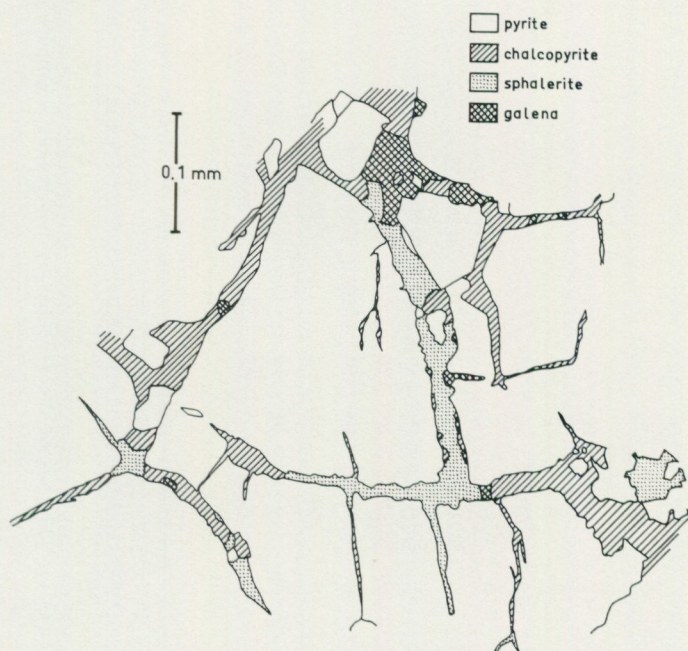


Fig. 19. Crack filling in cataclastic pyrite. Chalcopyrite in some of the narrower cracks.

*Concluding remarks about pyrite.* Pyrite dominates as a rule the textural picture of the mineralizations. It occurs nearly all over the mineralized volume, however in highly variable amounts and proportions. Being the only major sulphide with generally well developed crystal faces, the study of its cracks, inclusions and contacts with the other ore and gangue minerals is decisive for the understanding of the development of this ore deposit. It indicates that Stekenjokk contains pyrite of syngenetic origin, and that the whole deposit has undergone a regional metamorphism. It contains metamorphosed pyrite whose primary origin is uncertain, and exceptionally, pyrite is found to be a product of the metamorphic processes.

The minor constituents of the Stekenjokk pyrite were studied in concentrates separated with the help of heavy liquids, a magnetic separator and hand-picking. Trace element analyses of the concentrates are given in Table 5. They underline the observations done in polished sections; an important admixture of copper, zinc and lead is due to tiny inclusions and otherwise locked grains of base metal sulphides, which even the most careful separation (-200 mesh) could not eliminate. The content of silver and some of the other trace elements is certainly also influenced in the same way. Grain growth has resulted in very intimate relationships between coexisting sulphides. Regarding the regional metamorphism of the deposit it is concluded that the Stekenjokk pyrite concentrates have a normal

TABLE 5. Constituents of pyrite, determined with Hilger quartz spectrograph. Registration on photo plates. Values in ppm, if not otherwise marked. Analyst: B. Rajandi

Elements Samples	Cu	Pb	Zn	Co	Ni	Cr	V	Mo	Ti	Mn	Ag	Se <sup>1</sup>	Bi	Sn	Ag <sup>2</sup>	Au <sup>2</sup>	
J69— 5	4500	170	900	310	10	<10	<20	10	160	10	15	90	<30				
J69— 8	2500	400	700	140	<10	<10	<20	10	120	35	40		<30				
J69— 9B	600	170	~1 %	130	<10	<10	<20	10	90	40	55		<30				
J69— 9D	2500	140	380	150	<10	<10	<20	10	80	15	15		<30				
J69—16A	1000	600	~1 %	260	10	<10	<20	10	<25	<10	10	50	<30				
J69—16B	2000	1100	~1 %	310	<10	<10	<20	10	20	10	20	65	<30				
J69—16F	1500	200	>1 %	140	<10	<10	<20	10	20	25	20	20	<30				
J69—28	600	90	<300	200	<10	<10	<20	<10	35	10	10	210	<30				
J69—30A	1500	3000	>1 %	65	<10	<10	<20	10	140	60	45		<30				
J69—31A	2200	1500	~1 %	220	10	<10	<20	15	20	20	15	75	<30				
Flot.conc. I	1500	2300	4800	110	25	<10	<20	150				35	40	<10	<10	31	0.3
Flot.conc. II	1500	2500	5300	110	25	<10	<20	160				35	20	10	<10	31	0.3

For all samples Sn, Ga, In <10 ppm  
Ge, Sb <100 ppm

Flot.conc. I and II are two splits of a pyrite concentrate from flotation experiment on 925 tons of ore executed by the Boliden Company. Sulphur contents are respectively 50.1 % and 50.0 %.

1 Se determined by X-ray fluorescence spectrography.

2 Ag and Au determined by the classical fire assay method.

composition as compared to other deposits of similar type, and particularly to other pyritic occurrences of the Caledonian mountain range (Carstens 1941 a, 1941 c, 1942 a; Fleischer 1955; Keith and Degens 1959; Saager 1966, 1967; Mitchell 1968).

The significance of the trace element contents of the sulphides is discussed in the section Aspects of the geochemistry of the ore minerals, p. 87.

### PYRRHOTITE, $\text{Fe}_x\text{S}_y$

*General aspects.* Pyrrhotite is an important constituent of the Stekenjokk ore body, and is present all over the mineralized volume (see Table 10). However, its relative and absolute quantity is highly variable from place to place, more variable than those of pyrite, sphalerite and chalcopyrite.

Some disseminated horizons up to 2—3 m thick may have pyrrhotite as the only sulphide. In the brecciated, partly massive pyrrhotite-chalcopyrite ores it may occupy up to 2/3 of the total volume. In the massive pyrite-dominated ores, however, the pyrrhotite content may be as low as 1—4 vol. %.

The content of pyrrhotite has been estimated both by direct microscope point-counts and from chemical analyses by a specially devised computer program, the KISMOD (see Appendix). Comparison shows that this program (see Table 10 and Figs. 66—70) generally gives a correct representation of the pyrrhotite/pyrite relationship except for some of the mineralizations with low total sulphide content. This is due to the extraction during the analysis of some iron from the chlorites, which makes the proportion pyrrhotite/pyrite too high for the majority of samples containing much of these iron-bearing sheet silicates. For the analyses with less than 3—4 vol. % sulphides, the pyrrhotite/pyrite calculation (by the KISMOD program) may not be reliable in some cases. In analyses rich in chlorite and with 5—15 vol. % sulphides, the pyrrhotite content may be up to 10—20 % (relative) too high and the pyrite volume correspondingly too low. This is shown by comparison of microscope counts and chemical analyses which provides good control and verifies that the KISMOD program generally gives a correct representation of the pyrrhotite/pyrite relation.

Some common modes of occurrence of pyrrhotite, as observed in the mine, are described below:

1. Totally pyrrhotite-dominated disseminations up to 2—3 m thick, concordant to the layering in black phyllite or tuffite. Also thinner bands in alternation with pyrite-dominated horizons. The mineralization type shows a good persi-

stence along the strike, but may transgress into hanging wall or foot wall zones which are pyrite-richer in other places. This phenomenon occurs in connection with an intense, local deformation of the host rock and is interpreted as a metamorphic transformation from pyrite to pyrrhotite.

2. Disseminations of pyrrhotite-chalcopyrite, often with intermingled pyrite individuals disposed concordant to the layering. The softer sulphides often lie in the stress shadows of the somewhat deformed pyrite, each mineral aggregate flattened parallel to the schistosity. The type is transitional to purer pyritic types. There are gradual transitions across the strike, and well banded alternations between the pyrrhotite- and pyrite-rich types are not infrequent.
3. In massive, pyrite-dominated banded ores pyrrhotite normally makes up 3—10 % of the total volume. Continuous bands of the mineral are rare, but it occasionally takes part in the banded texture even of this ore type, however with a more patchy distribution. In transitions to less massive and pyrrhotite-richer types, the banded textural picture may be more distinct, although much more discontinuous than for instance in the case of sphalerite and chalcopyrite.
- 4a. Massive pyrrhotite-chalcopyrite ore, still with some pyrite and containing angular and rounded pieces of wall rock and pyrite crystals. The type may be interpreted as weakly to intensively brecciated ("durchbewegt", cf. Vokes 1969). Pyrrhotite may occasionally make up 2/3 of the total volume. This type may be localized in perfectly concordant positions, when emplaced in tectonic disturbance zones along schistosity and/or bedding planes, but where this ore type can be followed along the strike it is often seen to change its stratigraphic position, forcing its way along discordant passages.
- 4b. Small veins of pyrrhotite and chalcopyrite near or within the massive, pyrite-dominated ores. They represent lateral or internal secretions in connection with tectonic disturbances, mostly together with quartz and calcite, and may as a rule easily be traced back to their source. There is a clear gradual transition between type 4a and 4b.
5. Pyrrhotite is by far the most frequent sulphide in rather sterile and always uneconomic secondary occurrences of quartz-calcite veins of supposed low-temperature deposition in fissures of  $F_2$  to post- $F_2$  age.
6. Irregular disseminations in gabbro border facies rocks, with aligned trains of flattened specks of pyrrhotite parallel to the schistosity. Dissemination of isotropically distributed small pyrrhotite aggregates in the unaltered parts of

the gabbro. As the frequency of pyrrhotite (and other sulphides) is apparently higher in the altered parts of the gabbro (border facies) than in the unaltered parts, it may be assumed that pyrrhotite is formed *in situ* during alteration, or pyrrhotite is picked up (contamination) from the wall rocks during the intrusion and crystallization period.

All in all, pyrrhotite is visible in most parts of the mineralizations. In the textural picture of most ore types it does not, however, play any important role. As an individual mineral pyrrhotite is best observed in late meta-deuteric veins and in lateral secretions, — more generally in the tectonically disturbed parts of the mineralizations, whereas it is difficult to evaluate the quantitative role of this constituent in the more uniform ore types.

*Qualities of single individuals and aggregates.* Crystal faces are usually not seen in Stekenjokk pyrrhotites, except in a few cases where the mineral occurs in contact with galena and sulphosalts. Actually, all "grains" are aggregates with allotriomorphic outlines, consisting of anhedral individuals. Triple junction point development is as a rule nearly perfect. The geometry of the bigger aggregates is patchy, with irregular outlines fitting well in between the harder minerals they meet with. They occur concentrated and do not have long tentacles jutting out in the surroundings as do corresponding aggregates of chalcopyrite. Pyrrhotite occurs as a typical matrix mineral when accompanying pyrite.

Usually the mineral takes a good and even polish. In some samples small sickle-shaped particles were torn out of the section surfaces during grinding. An alignment of these scars can be discerned, probably caused by an oriented cleavage. The reflection pleochroism is mostly distinct, though sometimes weak. Anisotropy is always relatively strong.

Twinning is not infrequent, but is by no means the rule. It has not been possible to connect twinning in pyrrhotite to rock volumes which had especially undergone strain, in contrast to sphalerite, where both twinning and grain size could be related to strain.

Deformation, probably by translation and resulting in the formation of "sub-parallel lensoid discs" (Ramdohr 1969, p. 586) within an individual or an aggregate is seen only in a few cases. This is perhaps an indication that much of the pyrrhotite in Stekenjokk was formed, or at least recrystallized in a relatively stress-free environment.

A lamellar variety which is somewhat darker and harder than the ordinary pyrrhotite is occasionally observed at high magnification and in oil. According to a non-systematic survey over 30—40 specimens the occurrence of this type is rare and randomly distributed in bigger individuals of pyrrhotite. The lamellae are thin with parallel or subparallel sides, those with subparallel sides exhibiting a somewhat lancet-like form with sharply tapering ends. The parallel thin bands

persist through the whole host individual. This type is definitely not to be confused with the above-mentioned observations of lensoid discs, which probably are caused by deformation. Etched specimens were not investigated. These lamellae are interpreted as a result of transformation from hexagonal to monoclinic pyrrhotite accompanied by a possible submicroscopic mixing phenomenon (Ramdohr 1969, p. 586). The type is described by Vokes (1957) from the Birtavarre ores where it is widespread. Both Vokes (1963) and Saager (1966) have noted its existence in various Rana district deposits.

In the mine or in drillcores it is possible to observe that the qualities of pyrrhotite differ somewhat within the deposit from one locality to another. One variety has a bronze-brown metallic luster and is generally quite coarse-grained, often consisting of isolated clusters or patches. This variety occurs mostly in the quartz veins of first and second generation, and some of the lateral and internal secretions directly in connection with massive ores. They may also occur as big splashes in some disseminated mineralizations. The aggregates are often brittle, with irregular, sometimes conchoidal fracturing. The more common type has a dull brown colour, a finer grain, and frequently shows a "porous" surface, full of small holes. This is the general appearance of pyrrhotite all over the mineralized volume. The two varieties are however found in highly different proportions in various localities. They seem partly to substitute for each other in different assemblages and host rock environments, but no further study of their distribution has been carried out. An attempt was made with the ore microscope to distinguish between the two types, but the clean mineral surfaces were identical in all respects. Reflectance measurements (not standardized) were very similar. For the time being it can be concluded that the lustrous bronze-coloured variety has significantly greater grain size, less complicated intergrowth with other minerals (no interlocking outlines, very few inclusions), and that this may be the reason for its different appearance in hand specimen. Further work is needed to clarify the problem.

The intergrowth with the other ore minerals and the gangue illustrates well pyrrhotite's position as a sulphide of medium strength in the crystalloblastic series. With chalcopyrite and sphalerite it exhibits mutual, suture-like boundaries, and especially with chalcopyrite, mutual and highly intimate interlocking. Towards softer minerals such as galena it mostly exhibits a convex outline.

*Inclusions.* Chalcopyrite is frequently included in pyrrhotite; sphalerite is markedly less common. The other inclusions and their frequency is rather similar to those observed in sphalerite, but the rare trace minerals and particularly galena are even rarer in pyrrhotite.

*Primary and metamorphic pyrrhotite.* Pyrrhotite is regarded as a primary (pre-metamorphic) mineral as well as being of metamorphic origin. Corrosion by pyrr-

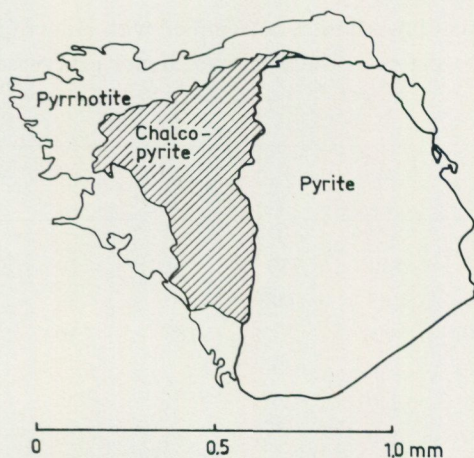


Fig. 20. *Intermediate stage in the formation of a mixed pseudomorph after pyrite. Half of the volume of a pyrite crystal is replaced by pyrrhotite and chalcopyrite. The host rock is a graphitic phyllite.*

hotite on minerals other than pyrite has only exceptionally been observed. There is a relative rarity of pyrrhotite as inclusions in pyrite, even in some specimens which carry much pyrrhotite as free grains in the matrix. It is suggested that such pyrrhotite-pyrite relationships can be interpreted as indications of late formation of pyrrhotite in relation to pyrite. If this be the case, pyrite should have stopped its poikilitic growth when pyrrhotite was still forming in the matrix.

Whole pseudomorphs of pyrrhotite after pyrite are occasionally seen in the disseminated ores, where pyrrhotite aggregates fill in square or lozenge-shaped spaces in which regular or malformed pyrite crystals probably were present before an eventual transformation. The inclusion frequency and geometry are identical with what is seen in pyrite crystals of the same size and outline, and they are in marked contrast with the nearly inclusion-free small pyrrhotite grains of the surroundings. This pseudomorphism is interpreted as if each pyrite crystal was transformed into pyrrhotite due to escape of sulphur. A gradual transition from the one to the other has not been seen in any continuous series of observations, and whole pseudomorphs have not been noted in the massive ores. However, with a seemingly random distribution within the deposit, all stages of transformation are seen. Sometimes pyrrhotite occurs in combination with chalcopyrite (Fig. 20).

*Composition of pyrrhotite.* From X-ray powder films of pyrrhotites from flotation concentrates it was seen that the mineral has a metal deficiency corresponding to the approximate formula  $\text{Fe}_6\text{S}_7$  —  $\text{Fe}_9\text{S}_{10}$ . The formula  $\text{Fe}_7\text{S}_8$  was chosen

TABLE 6. Constituents of pyrrhotite, determined with Hilger quartz spectrograph. Registration on photo plates. Values in ppm, if not otherwise marked. Analyst: B. Rajandi

Elements Samples	Cu	Pb	Zn	Co	Ni	Cr	V	Mo
J69—5, run 1	>1 %	110	750	40	<10	<10	<20	<10
J69—5, run 2	~1 %	180	4000		<30	<30	<30	<30
J69—8	3500	1000	>1 %	180	<10	<10	<20	<10
J69—16A	2500	150	6500		<30	<30	<30	<30
J69—16B	7000	240	>1 %		<30	<30	<30	<30
J69—25, run 1	2000	290	>1 %	75	<10	<10	<20	<10
J69—25, run 2	7500	750	8000		<30	<30	<30	<30
J69—28	4000	530	>1 %	370	10	<10	<20	20
J69—30A	2600	750	>1 %	150	<10	<10	<20	20
J69—31A	>1 %	500	>1 %	370	15	<10	<20	10

for the KISMOD calculation program (see Appendix). Laboratory work directed towards distinguishing the chemistry and crystallography of the varieties observed under the microscope was not successful.

Concentrates of pyrrhotite were investigated for their content of minor elements (Table 6). Intimate intergrowth with other main sulphides is responsible for the high contents of copper, zinc and lead. For the discussion of other minor elements contained in pyrrhotite, the reader is referred to p. 87.

### SPHALERITE, ZnS

*General aspects.* Sphalerite is volumetrically the most abundant base metal sulphide of the Stekenjokk deposit (see Table 10). The mineral has a typically banded distribution. Bands with ragged upper and lower borders often have a great persistence. Continuous layers of only a few millimetres' thickness can be followed several metres along the strike. In alternation with pyrite and thin layers of gangue, sphalerite contributes significantly to the general banded appearance of a large part of the massive ores.

Ti	Mn	Cd	Sb	Sn	Ag	Ga	In	Ge	Bi
170	20		<100	<10	250	<10	<10	<100	<30
<300	<30	<300	<100	<10	<30	<10	<10	<100	<30
600	25		<100	<10	40	<10	<10	<100	<30
<300	<30	<300	<100	<10	<30	<10	<10	<100	<30
<300	<30	<300	<100	<10	<30	<10	<10	<100	<30
140	20		<100	<10	10	<10	<10	<100	<30
<300	<30	<300	<100	<10	<30	<10	<10	<100	<30
<20	25		<100	<10	120	<10	<10	<100	<30
190	40		<100	<10	20	<10	<10	<100	<30
<20	10		<100	<10	55	<10	<10	<100	<30

These continuous bands grade into a patchy distribution of sphalerite aggregates within certain layers, thus still keeping the general stratiform distribution.

In the massive ores sphalerite acts as a perfect interstitial mineral vis-à-vis pyrite. In the disseminated ores, sphalerite is frequently seen in the pressure-shadow tails of pyrite, mostly together with chalcopyrite and pyrrhotite. In off-shoots, where sphalerite in isolated patches may be the only sulphide, it has perfectly adapted its geometry to the dynamo-metamorphic conditions. Contemporaneous recrystallization of silicate and sulphide is in many cases quite obvious. Particularly it is seen that a strong grain growth has taken place along the silicate (often quartz)/sphalerite interface, while surrounding silicates may have retained a finer grain size.

Disseminations with nearly isotropic distribution also occur, each aggregate being flattened parallel to the host-rock foliation.

*Qualities of single individuals and aggregates.* Ragged zig-zag outlines of sphalerite illustrate the difficulties of developing crystal faces in most of the mineral assemblages of the deposit. Crystal faces are seen as exceptions in intergrowths with fahlore and chalcopyrite.

The outline of the aggregates is controlled by the stronger minerals, especially pyrite. In contact with pyrrhotite and chalcopyrite and the moderately strong gangue minerals mutually zig-zagging interfaces are developed. The aggregates

consist of multiple anhedral individuals of highly variable grain size: 10—500  $\mu$ . The majority probably have a size range of 30—75  $\mu$ .

The hand specimen colour is generally medium brown with a light brown to reddish streak. Dark brown samples are found at several localities in vein-like off-shoots from the ore bodies and in some of the first generation quartz veins. In one of the latter it occurs together with a particular sulphosalt enrichment in a so-called meta-ore pegmatite. Main minerals here are boulangerite and sphalerite. Galena and chalcopyrite are subordinate.

In transmitted light the colour is relatively light brown, with weak, but distinct shading variations, even within one and the same aggregate. No consistent zoning patterns have been found in this shading geometry. In reflected light microscopy, the colour is medium grey, mostly with a weak bluish tone. It is fully isotropic under all ordinary circumstances. The internal reflections are bright red — burgundy red. Sometimes pure yellowish areas and exceptionally greenish tones are seen. The latter may come from adjacent or included minerals.

*Inclusions.* Since sphalerite is described as a typical matrix sulphide, it tends to include within its aggregates all other coexisting sulphides and gangue minerals. However, many of the minerals embedded in sphalerite aggregates are located on interfaces and cannot be regarded as true inclusions.

While pyrite without doubt is the most frequent contact mineral of sphalerite, it seems to be relatively rare as true inclusions. Frequent inclusions are chalcopyrite, pyrrhotite and gangue. Generally, the geometry of both pyrrhotite and chalcopyrite inclusions is of mutually equivalent character towards the host. On the whole they appear to be of approximately the same crystallization strength. Occasionally, inclusions of chalcopyrite have been observed as equidimensional rounded blebs in parallel alignment, possibly indicating exsolution.

Because of the general scarcity of galena in the whole ore body, this mineral is also rare as an inclusion. In the few places where it is abundant, intergrowth of convex sphalerite and concave, cusplike galena is always seen. But galena grains less than 10—20  $\mu$  are generally well rounded. These small galena droplets are probably all contained within one single sphalerite individual. It is logical to ascribe their rounded form to the fact that they are true inclusions which do not join any grain boundaries of the host mineral.

The content of rare trace minerals included in sphalerite is relatively small. Its role as a carrier of rare elements as inclusions may probably be seen in connection with its mobility during metamorphism. Compared to the mobility of galena and chalcopyrite, sphalerite is a relatively inert mineral. The availability of other mobile components during post-depositional mobilization has probably been lower for sphalerite than for galena and chalcopyrite.

*Deformation.* Cataclastic effects are observed in sphalerite as exceptions. Even in localities where pyrite has suffered a rough cataclasis or in the brecciated

pyrrhotite-chalcopyrite ores with rounded pyrites and quartz pebbles, the exterior borders (outlines) only show minor signs of plastic deformation. Etching reveals a more complicated picture with variable grain sizes within the aggregates and a pronounced development of twins. The twin lamellae are sometimes bent. In a few cases, small glidings across lamellae were seen. They are interpreted as healed fracture dislocations (not as growth dislocations).

*Composition of sphalerite.* For the determination of the iron content of sphalerite 6 specimens each weighing between 0.5 and 1.5 kg were collected in the mine. Through separation with heavy liquids, a magnetic separator and hand-picking, sphalerite concentrates of about 100 mg of each were obtained. In addition to this two split samples from a flotation product produced by the Boliden Company from 925 tons of ore, were selected. The samples were analyzed for iron by titration with  $K_2Cr_2O_7$ . Separate fractions were then analyzed for their trace element content. Results are presented in Table 7.

According to microscope work, it may be concluded that the contents of Cd and Mn are entirely lodged in the sphalerite lattice, while the contents of Fe and Cu are partly due to inclusions. The high Pb content is mainly ascribed to inclusions.

The Ag content of the sphalerite concentrates is variable, but with a high mean value for the seven J69 samples (105 ppm). The probable admixture of the two important silver-bearing minerals galena and chalcopyrite is definitely too low to be solely responsible for the silver in the sphalerite concentrates. This indicates that much of the Stekenjokk silver (53 ppm Ag for the whole ore body) is contained in sphalerite, either in the lattice or in inclusions of silver-richer compounds (fahlore, tellurides etc.).

However, a study of 154 samples with more than 0.3 ppm Ag (see p. 147) shows that the proportion Zn/Ag is highly variable and that zinc contents are not necessarily accompanied by high silver contents. Copper and silver show a much more stable co-variance (see under Chalcopyrite, p. 54) than zinc and silver.

Comments on the other minor constituents of sphalerite are given in the section Aspects of the geochemistry of the ore minerals, p. 87. All in all the Stekenjokk sphalerites appear to have contents of minor elements reflecting the polymetallic milieu which it is part of and the metamorphism undergone by the deposit (Oftedal 1941, Gavelin and Gabrielson 1947, Fleischer 1955, Saager 1966, Rouhunkoski 1968). However, these few trace element analyses of sphalerite did not encourage any attempt to determine palaeotemperatures (Barton and Toulmin 1966).

TABLE 7. Constituents of sphalerite. Analytical methods, see below. Values in ppm, where not marked otherwise.

Elements Samples	S <sup>1</sup>	Fe <sup>1*</sup>	Cd	Mn	Cu <sup>3</sup>	Pb <sup>3</sup>	Co <sup>3</sup>	Ni <sup>3</sup>
J 69—8		4.6 %	3000 <sup>3</sup>	400 <sup>3</sup>	1900	1000	<10	
J 69—16A		8.3 "	2300 <sup>3</sup>	320 <sup>3</sup>	3300	400	10	<30
J 69—16B		8.4 "	1500 <sup>3</sup>	300 <sup>3</sup>	3400	750	<10	<30
J 69—16F		8.1 "	3000 <sup>3</sup>	220 <sup>3</sup>	1200	400	<10	
J 69—30A		8.8 "	700 <sup>3</sup>	290 <sup>3</sup>	3200	2000		<30
Flot.conc. I	31.2 %	6.43 "	3300 <sup>2</sup>	260 <sup>2</sup>				
Flot.conc. II	31.3 "	6.41 "	3300 <sup>2</sup>	260 <sup>2</sup>				
J 69—4		8.8 "	3000 <sup>3</sup>	280 <sup>3</sup>	2800	3300	10	
J 69—25			2400 <sup>3</sup>	400 <sup>3</sup>	2100	145	<10	

Methods: 1 — wet chemical  
 2 — atomic absorption  
 3 — emission spectrography on photo plate, analyst: B. Rajandi  
 4 — classical fire assay

Flot.conc. I and II are two splits of flotation product of 925 tons of ore.

### GALENA, PbS

*General aspects.* Volumetrically and by weight galena is the third base metal sulphide of the Stekenjokk deposit. Calculations of the volumetric variations of galena by the KISMOD method are shown in Table 10, p. 60, indicating a relatively low content of galena. About 0.3 weight % Pb is the mean value for the 15 million tons of ore at Stekenjokk (Zachrisson 1971). The distribution of the mineral throughout the deposit is disperse and sometimes seemingly rather erratic. Ore analyses demonstrate a correlation between zinc and lead. The search for galena in an occasional ore sample is also best directed through careful examination for inclusions in sphalerite, however, the positive correlation between the two is not always directly observable. Galena is a minor constituent even within seemingly pure sphalerite volumes. It mostly appears under the microscope as randomly distributed thin bands or wedges, sometimes visible in hand specimens as light small stars on the brown sphalerite surface.

Conspicuous concentrations of galena occur in the coarse-grained meta-ore pegmatites, particularly in the type where boulangerite and sphalerite are enriched, but also in assemblages consisting of arsenopyrite/gudmundite and fahl-

Cr <sup>3</sup>	V <sup>3</sup>	Mo <sup>3</sup>	Ti <sup>3</sup>	Sb <sup>3</sup>	Sn <sup>3</sup>	Ag <sup>3</sup>	Ag <sup>+</sup>	Au <sup>+</sup>	Ga <sup>3</sup>
		<10		<100	<10	65			10
<30	<30	<30	<300	<300	<10	100			25
<30	<30	<30	<300	<300	<10	120			10
		<10		<100	<10	25			30
<30	<30	<30	<300	~350	<100	150			
		} 200			} 25		} 136	} 0.7	25
		<10		150	<10	150			25
		<10		<100	<10	130			20
									10

For all samples: Ge < 30 ppm  
 In < 100 " "  
 Te not detected

\* For the KISMOD calculations a mean value of 6.5 % Fe in sphalerite was chosen.

ore. Generally, tectonic traps such as stress minimum zones and off-shoots on dislocations (small fold thrusts) are places where local galena enrichments may be found. As the most mobile of the common sulphides, galena has taken part in all movements to new openings — low pressure fields, cracks etc. Crack fillings are often composite, galena and chalcopyrite forming a couple which frequently occur together there. However, because of the general scarcity of galena in the whole deposit, there is no rule that galena is found even in such favourable places. Galena is, for instance, only exceptionally found in the typical stress shadow tails of pyrite.

Under the microscope nothing anomalous regarding the colour has been observed, but the mineral may be very weakly anisotropic. The anisotropy was below the detection limit of a Leitz MPV reflectometer.

*Patterns of intergrowth.* The typical intergrowth between galena and its most frequent host — sphalerite — is generally that sphalerite develops convex outlines when included in galena, and the latter adopts complicated forms, such as concave splashes with cusped tentacles within a sphalerite host. Thus, in an intimate intergrowth of approximately equal parts, sphalerite will appear as a series of more or less rounded aggregates lying in a galena matrix (Fig. 21).

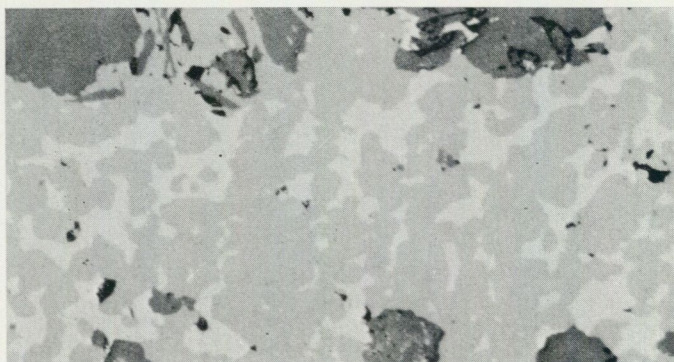


Fig. 21. *Typical intergrowth pattern — convex sphalerite with concave galena. 260 X.*

Smaller inclusions of galena in sphalerite or other stronger sulphides have, however, as a rule adopted a rounded bleb form (see under Sphalerite, p. 46).

Another tendency, which is clear, but not so conspicuous, is that in large volumes of galena with minor sphalerite as the only partner, the larger galena aggregates may have adopted a rounded form, while sphalerite lies as more or less cusped fillings between the borders of convex galena grains. In the same galena grains sphalerite is usually also seen as rounded inclusions. Therefore this pattern is rather confusing and may be difficult to discover. This is particularly the case in Stekenjokk where occurrences of larger galena concentrations are very rare.

It is, however, well demonstrated how the mutual intergrowth patterns between the two components are influenced by at least three factors:

- a) relative grain size: galena included in one single sphalerite individual is rounded. Galena in an aggregate of sphalerite is usually cusped,
- b) crystallization strength: sphalerite is "stronger" than galena, and therefore adopts convex forms in a galena aggregate,
- c) relative amounts of the two components: the minor component has a tendency to lie in cusped volumes on grain borders of the major one.

Intimate intergrowth between galena and chalcopyrite is rarely seen, except in the cases where they occur as crack fillings in pyrite or arsenopyrite.

There is a notable frequency of rare minerals occurring in intergrowth with galena. This is certainly connected with galena's role as one of the more mobile minerals of the assemblage. Fahlore, boulangerite, different silver-tellurides, claus-

thalite, probably bournonite and silver glance (acanthite) are more obvious in galena concentrations than elsewhere. Regarding the common intergrowth of galena and fahlore it is not possible to determine which mineral is the host and which is the guest. However, a concentration of galena need not imply an increase in the fahlore content, but in bigger concentrations of fahlore, the galena content is always higher than in the surroundings.

*Inclusions.* No statistical analysis of the inclusions in galena has been carried out. Only volumetric appraisal based on routine microscopy can be given. Principally the major sulphides of the deposit are found as inclusions. Particularly in the few galena concentrations where the mineral may fill up all interstitial room, the rest of the rock constituents, major sulphides and gangue, act as inclusions in galena aggregates. In the more commonly occurring type of galena, only sphalerite occurs as volumetrically important inclusions. Pyrite grains are rarely totally surrounded by galena. Chalcopyrite is also relatively seldom found as inclusions, probably an expression of the mutual antipathy indicated above.

#### *Composition of galena.*

Semiquantitative analysis by emission spectrography on photo plate (analyst: B. Rajandi) of one galena sample, separated by heavy liquids, magnetic separator and hand-picking: 0.1—1 % Si; 0.01—0.1 % Mn, As, Sb, Ag, Mg; probably 0.03—0.05 % Ag; 0.001—0.01 % Cu, Bi; trace amounts of Te, Tl, Sn. See also Aspects of the geochemistry of the ore minerals, p. 87.

TABLE 8. Microprobe analyses of galena in two polished sections (results recalculated to 100 %). Analyst: B.-M. Nilsson

Elements	Samples J69—24 V	J69—24 I
Pb	85.78 %	86.40 %
S	13.79 "	13.15 "
Fe	0.20 "	0.10 "
Cu	0.10 "	0.10 "
Zn	0.10 "	0.20 "
Ag*	0.1 "	0.1 "

\* The Ag values are imprecise because of the small quantities.

CHALCOPYRITE,  $\text{CuFeS}_2$ 

*General aspects.* Volumetrically, chalcopyrite is the second base metal sulphide of the deposit (see Table 10).

The large scale geometry of the mineral distribution is due to a primary stratiform and layered appearance which is concordant with the sedimentary layering of the host rock. This distribution pattern is overlapped by a metamorphic mobilization and redeposition system. The existence of these patterns is noted here, but in the following mainly the form and local distribution of single aggregates and individuals of chalcopyrite will be dealt with. Regarding both intensity and extent of occurrence, graded transitions between three general types are met with.

They are disseminations, patches and bands:

1. Disseminations are of two types:

- a) Chalcopyrite as free grains or in intergrowths with other sulphides which are an integral part of the rock in the sense that they occupy small volumes similar to those of the host rock constituents. The sulphide aggregates are usually equigranular.
- b) Chalcopyrite lying on cracks or along boundaries between host rock grains. These are of variable size. Transitions and mixtures of a) and b) are frequent.

2. Patches of irregular size and distribution are found in the massive and disseminated ores as well as in different wall rocks. Some of the first generation quartz veins also contain irregular bodies of chalcopyrite. The development of these clusters can sometimes be followed directly from a pre-tectonic distribution form.

3. Bands of chalcopyrite are here defined as continuous volumes rich in the mineral and persisting over a certain distance and showing approximately constant thicknesses along the strike. Bands corresponding to these definitions are thought to have a primary depositional origin which is concordant to the general compositional banding.

Compared with the extensive sphalerite bands in the massive ores, the chalcopyrite bands have much more irregular and often "flamy" outlines. The thicknesses of continuous bands of chalcopyrite are on the whole greater than for the sphalerite-rich bands, but they vary within wider ranges than these.

*Qualities of single individuals and aggregates.* Euhedral crystals of chalcopyrite have not been found in the deposit. Neither have single crystal faces been observed with certainty. Due to the anisotropy of the mineral there is generally

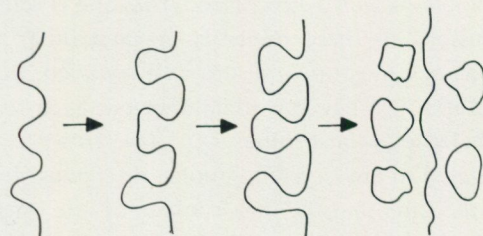


Fig. 22. *Supposed development from mutual embayments to mutual inclusions along boundary chalcopyrite/sphalerite.*

no risk of mistaking aggregates for single individuals. However in smaller blebs and inclusions it can be difficult.

The grain forms vary from rounded or elongated blebs in the smallest occurrences to highly irregular aggregates with concave allotriomorphic outlines, often with tentacles stretching out in between grain boundaries or into cracks. The mineral demonstrates well its faculty to adopt the forms of its surroundings and must have been extremely mobile during the metamorphism. In many cases one is tempted to consider it as more mobile than galena, but this can probably be ascribed to the higher availability of chalcopyrite. In crack fillings, for instance in cataclastic pyrite, it fills up the long "fjords" and goes often further into them than the accompanying galena. Chalcopyrite has, as in the case of galena, a pronounced tendency to be smeared out as thin films along deformed grain boundaries. However, in intergrowth with galena, it is seen that chalcopyrite has a greater crystallization strength and exhibits convex aggregate outlines towards it. Boundaries with sphalerite and pyrrhotite are generally mutually embayed, none of these minerals being markedly stronger than chalcopyrite.

The borders towards sphalerite are often extremely lobate. The lobes may mutually interlock important volumes of the respective minerals. A further development of this is that the lobes are cut off and become mutual inclusions in the two adjacent species (Fig. 22). As for the other matrix sulphides, the textural features of pyrite greatly influence the shape of chalcopyrite. A general picture of pyrite-rich ores is that chalcopyrite merely represents a part of the interstitial filling. Its outlines are thus partly rectilinear zig-zagging due to pyrite and partly gently curved or embayed due to the other sulphides and the gangue. Exception to the last statement must be made for the very strong gangue mineral muscovite, which in some cases can even transgress and deform the rectilinear pyrite boundaries.

When chalcopyrite occurs as small inclusions, it has mostly adopted a well rounded form. This seems particularly to be the case when chalcopyrite is included in one single individual of the host mineral. This behaviour is seen in sphale-

rite, galena and pyrrhotite as well as in chalcopyrite, and is often observed for the smaller mutual inclusions of these minerals in each other. When all smaller chalcopyrite inclusions of a host mineral are well rounded, they often also have a size of striking uniformity. They can sometimes be taken for exsolution blebs, as in the case of sphalerite as host mineral (p. 48). However, their distribution can not usually be related to any crystallographic directions. In pyrite, where one can be sure most of the time that the host consists of one single individual, even the smaller inclusions are often elongated. The degree of elongation has a tendency to increase with the distance from the centre of the crystal. An exceptional type of inclusion is when several neighbouring pyrite crystals all have one single, well rounded chalcopyrite bleb placed in their exact centre. The phenomenon is mentioned under pyrite (p. 34).

Together with pyrrhotite and sphalerite, chalcopyrite is generally found in the pressure shadows of deformed pyrite crystals of disseminated ores. The types of intergrowths in which chalcopyrite is involved are uniform all over the occurrence. However variable the grain size may be, the associated characteristics are approximately the same all over.

In this assemblage there is a tendency to sympathetic co-variation between chalcopyrite and pyrrhotite. Similarly, an antipathetic co-variation between chalcopyrite and galena appears probable. The first co-variation, chalcopyrite-pyrrhotite, is distinct on all scales. However, important enrichments of chalcopyrite can take place without noticeable increase in the pyrrhotite content. Examples are given from the quartz veins and from "contact" enrichments against impermeable walls.

The other one, chalcopyrite-galena, is often difficult to demonstrate, the reason being partly the general scarcity of galena all over the deposit.

Microscopy provides, however, good indications: in equal areas of chalcopyrite and sphalerite in a section, the majority of galena lies in sphalerite. Following up the problem by considering the chemical analyses, the copper-lead correlations appear rather random. A specimen high in chalcopyrite can also have a high galena content. As a rule the specimen is then also high in sphalerite. This rule has also serious exceptions on the strictly local plane. As mentioned, galena and chalcopyrite, mobile as they both are, often accompany each other as crack-fillers, for instance in cataclastic pyrite and as rims on grain boundaries of gangue minerals. However, there is seldom intimate intergrowth between them, a low frequency of mutual inclusions and relatively abrupt borders.

As mentioned above, the intergrowth with pyrrhotite is intimate, but not too fine-grained. In spite of pyrrhotite being placed higher than chalcopyrite in the crystalloblastic series, the mutual boundaries frequently reveal that the two minerals may be of equal "formational strength". The chalcopyrite inclusions in pyrrhotite and sphalerite are thus mostly rounded, but have frequent concave embayments.

Zoning of any persistent type is not observed in the chalcopyrite, neither regarding growth phenomena nor distribution of inclusions.

*Inclusions.* Inclusions in chalcopyrite are first of all the other matrix sulphides, sphalerite and pyrrhotite. Pyrite and gangue minerals are also important. The pyrite crystals are often too big to be completely included in the chalcopyrite volumes.

A series of minor mineral inclusions are common for both pyrite and chalcopyrite: fahlore, arsenopyrite, gudmundite and noble element compounds, either as alloys or as tellurides and selenides. These minerals very often occur as composite inclusions. They are considered to belong to the more mobile components. Exsolution is not common in the Stekenjokk chalcopyrite, but the following features have been locally observed: sphalerite is seen in several cases as small, somewhat irregular stars. In some places aligned, small blebs (5—10  $\mu$ ) could possibly be taken for exsolution bodies. The specimens in which they are found contain other sphalerite inclusions of different size and random distribution.

*Twinning in chalcopyrite.* Twinning is frequent and probably present in chalcopyrite from all parts of the deposit, however with a strongly variable intensity of development. It is always seen in the form of lamellae, mostly very thin, and of uniform thickness within one and the same grain, but their thickness may vary a great deal from place to place. Generally they are perfectly rectilinear, but locally bent and otherwise distorted twins are seen.

In intensively deformed parts it is seen that the harder minerals, such as pyrite and arsenopyrite, react by being broken up and cracked. The softer minerals, such as chalcopyrite, are smeared out and much of the movements are translated along the twinning planes.

As differences in twinning density can be correlated to a certain degree with the intensity of deformation, their primary cause must be of dynamic character. It is for instance seen that chalcopyrite of the low temperature deposits in the second generation quartz veins have much thicker and fewer twins than is generally seen in the ores. "Oleander-blatt"-twinning was not observed, which indicates that the inversion was not obtained.

Cataclastic effects are seldom seen in chalcopyrite. They are even comparatively rarer than in sphalerite. This is taken as an indication that these two minerals have the ability to absorb movement through the development of twins.

*Composition of chalcopyrite concentrates.* The minor constituents of the chalcopyrite concentrates (Table 9) reflect the intimate intergrowth with the other main sulphides, and to a certain degree also the minor inclusions, for instance of fahlore. Thus the high Ag content must for the most part be attributed to

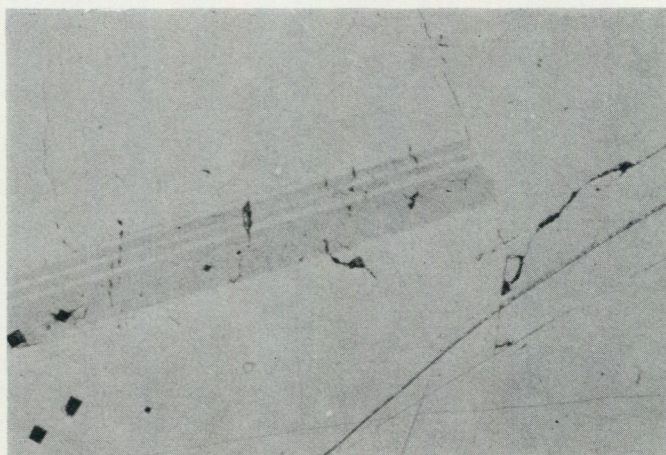


Fig. 23. *Cubanite lamellae in chalcopyrite. The chalcopyrite is an aggregate of many individuals. Cubanite is developed only in one of them, and stops against the border towards another individual. Black squares from hardness measurements. Ca 80 X.*

impurities in the concentrates. Particularly, it is noted that the flotation concentrates are Ag-rich (410 ppm) than the hand-picked powder fractions.

Considering, however, the relative amount of possible silver-bearing inclusions in chalcopyrite it may be concluded that an important part of the silver must be lodged in the mineral lattice. Regarding other minor constituents of chalcopyrite, the reader is referred to Aspects of the geochemistry of the ore minerals, p. 87.

TABLE 9. Constituents of chalcopyrite, determined with Hilger quartz spectro-Analyst: B. Rajandi

Elements Samples	S <sup>2</sup>	Pb	Zn	Co	Ni	Cr	V	Mo	Ti
J 69—5, run 1		180	>1 %	140?	10	<10	<20	<10	190?
J 69—5, run 2		180	8.000		<30	<30	<30	<30	<30
J 69—16 B		800	>1 %		<30	<30	<30	<30	<30
J 69—28, run 1		700	>1 %		<10	<10	<20	<10	<20
J 69—28, run 2		100	7.000	<10	<30	<30	<30	<30	<30
Flot.conc I	29.2 %							} 120	
Flot.conc II	29.4 %								

1. Classical fire assay method.
2. Wet chemical method.

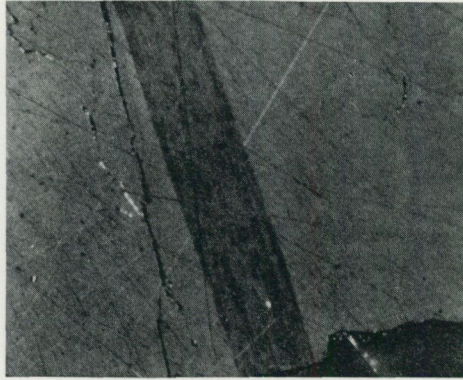


Fig. 24. *Cubanite in chalcopyrite. The cubanite body consists of a multitude of individuals. Crossed nicols. 65 X.*

CUBANITE,  $CuFe_2S_3$

Cubanite is exclusively found as lamellae in chalcopyrite and must be considered as a secondary product from this mineral. However widespread, it is a very minor constituent and was probably formed at a late stage of the metamorphic recrystallization of the ores (Figs. 23 and 24).

graph. Registration on photo plates. Values in ppm if not marked otherwise.

Mn	Cd	Ag	Ag <sup>1</sup>	Au <sup>1</sup>	Sb	Sn	Ga	In	Ge	Bi
15		80			<100		<10	<10	<100	<30
<30	<300	110			<300	<80				
<30	<300	240			<300	<80				
20		120			<100		<10	<10	<100	<30
<30	<300	60			<300	<80				
} 120			} 410	} 2.5	} 310	} 120	} 30			} 30

TABLE 10. Mean content of the main ore minerals (volume percent) related to increasing sulphur content (weight percent) in 686 samples. Calculations from chemical analyses by the "KISMOD" program.

Minerals	Sulphur content 0—<5	5—<10	10—<15	15—<20	20—<25	25—<30	30—<35	35—<40	40—<41	All samples
Pyrite	1.20	3.22	5.46	12.00	18.33	26.84	37.25	45.96	57.93	16.57
Pyrrhotite	3.05	5.89	9.86	9.67	11.01	10.22	8.27	7.69	5.65	8.17
Sphalerite	0.40	0.91	1.97	3.23	5.15	7.24	9.36	9.86	8.90	4.26
Chalcopyrite	0.38	1.22	3.32	4.22	4.88	5.19	4.53	5.17	3.25	3.36
Galena	0.015	0.039	0.030	0.085	0.153	0.202	0.183	0.176	0.075	0.161
Mean volume of sulphides	5.05	11.28	20.64	29.21	39.52	49.69	59.60	68.86	75.80	32.52
Nr of samples	45	171	97	81	74	71	93	50	4	686

MACKINAWITE, (Fe, Ni, Co)S, AND  
VALLERIITE, (CuFeS<sub>2</sub>) . (Mg, Al, Fe) (OH)<sub>2</sub>

Mackinawite and possibly also valleriite are minor constituents which are spread over important parts of the sulphide volume. Their mode of occurrence and distribution have however not been systematically investigated, and determinations were only carried out with help of the ore microscope. As the two minerals in most crystallographic orientations have a similar aspect, the majority of the observations are not definitive. Of about a dozen observations of elongated grains, mainly as a film on chalcopyrite grain boundaries, three were determined as mackinawite.

In some cases mackinawite/valleriite was seen on the border between cubanite and chalcopyrite, but the small (1—2  $\mu$ ) elongated, lamellar grains could not be identified more precisely.

Some small (1—4  $\mu$ ), elongated grains were observed on the contact between chalcopyrite and pyrrhotite and as inclusions in chalcopyrite. In one case feather-like rims on silicate inclusions were observed. None of these occurrences could be identified with certainty.

COVELLITE, CuS

Covellite is a very minor constituent, and is generally found in small areas along chalcopyrite boundaries. It is considered to be an *in situ* transformation product from chalcopyrite.

BORNITE, Cu<sub>5</sub>FeS<sub>4</sub>

Bornite is a trace constituent with erratic distribution. It is observed on the boundary between chalcopyrite grains and gangue minerals, and in several cases as small inclusions in chalcopyrite.

MOLYBDENITE,  $\text{MoS}_2$ 

This mineral is also seen only in trace amounts, but its distribution is probably more general than that of bornite. Small (0.05—0.3 mm) inclusions of molybdenite are found in the major sulphides, mostly in pyrite. Exceptionally they are seen to cross the boundary between two minerals. The grain form is elongated, with parallel sides. In some cases a weak bending is seen.

Vokes (1963, p. 58) and Saager (1966, p. 52) have registered molybdenite as a minor, but widespread constituent in different Caledonian massive pyritic ores. The mineral could be interpreted as being formed prior to the crystallization and deformation of the including and accompanying sulphides. It seems as if molybdenite should be a very early mineral in a possible crystallization sequence, or more probably — that it is relatively unwilling to recrystallize under metamorphic conditions. This may also be the case in Stekenjokk. The observations are, however, relatively few. At present no conclusions can be drawn regarding the relative age of formation and deformation of molybdenite in relation to the co-existent minerals. Emission spectrography (Tables 5, 6, 7 and 9) shows that the separated fractions of the main sulphides are poor in Mo ( $< 30$  ppm) while the concentrates from the ore dressing experiments are richer (100—200 ppm) in this element.

ARSENOPYRITE,  $\text{FeAsS}$ , AND GUDMUNDITE,  $\text{FeSbS}$ 

Arsenopyrite is a minor, but constant constituent of the ores. There is a general spread of the element As all over the occurrence, no marked anomalies have been found, neither regarding special ore types nor host rocks.

Arsenopyrite has two modes of occurrence. The one is an even distribution of single crystals or small clusters. The other is in concentrations of the more mobile fraction of the sulphide mass, as lateral or internal secretions in relative low-pressure zones. These assemblages, which are meta-ore pegmatites, are generally characterized by considerable contents of As, Sb, Ag, Au, Te, Pb and Cu. Important minerals are the fahlore group tennantite-tetrahedrite, arsenopyrite, gudmundite, chalcopyrite and galena. The common iron sulphides pyrite and pyrrhotite accompany them in variable amounts.

During routine microscopy of the ores, no anomalous characteristics of arsenopyrite were discovered. Gudmundite was first suspected when studying

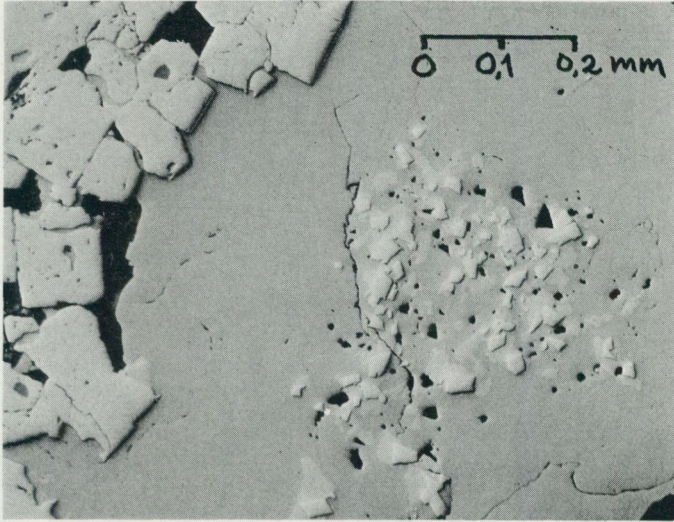


Fig. 25. *Arsenopyrite and chalcopyrite included in fahlore. Arsenopyrite shows a nearly exclusive preference for location in chalcopyrite. Upper left: pyrite. The textural picture may be interpreted as the result of the breakdown of fahlore into arsenopyrite and chalcopyrite. Photo with interference contrast objective.*

samples of the more coarse-grained meta-ore pegmatites. Its existence was verified through qualitative analyses with the microprobe (photographic recording). It is clear that a part of what has been registered as arsenopyrite during the routine microscopy in fact can be gudmundite, but the major part of the antimony compound seems to be located just in these concentrations of mobile minerals. Due to the different hardnesses and optical properties it was here relatively easy to distinguish between arsenopyrite and gudmundite. They were never found in intergrowth with each other. Unfortunately, no chemical analyses of Sb were made, neither in the old routine ore analyses nor in the actual full silicate + ore + trace element analyses.

However, from available information it is fair to conclude that while arsenopyrite has two modes of occurrence, the general disperse one, and the one in the meta-ore pegmatites, gudmundite has only one, namely that of the meta-ore pegmatite concentrations. Arsenopyrite is the "strongest" of all constituents in the assemblage. It always occurs with rectilinear outlines, in euhedral to subhedral crystals. Pyrite and occasionally gangue minerals can disturb its form. Inclusions are rare. (It is believed that the few cases where other minerals disturb the outlines of arsenopyrite are caused by former inclusions on their way out, pushed by an autopurification process).

It is seen how this strong mineral has literally exerted a physical pressure on the surroundings. Adjacent minerals are often bent and sometimes even cracked.

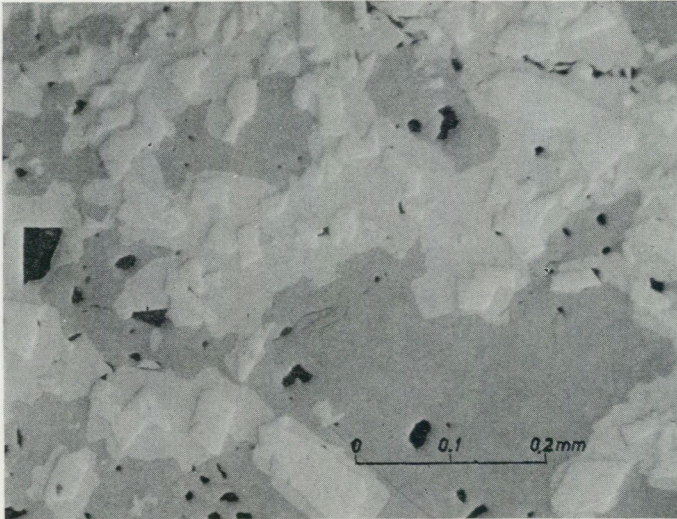


Fig. 26. Same feature as above. Larger fields of chalcopyrite contain larger arsenopyrite crystals.

Arsenopyrite has itself quite frequently been subject to cataclastic effects. The cracks are, similarly to pyrite cracks, filled with the mobile constituents, mostly chalcopyrite. When the mineral occurs concentrated in the meta-ore pegmatites, fahlore and tellurides may dominate the crack fillings, together with chalcopyrite. Here, small droplets of gold, or a gold-silver alloy are especially seen in contact with arsenopyrite or gudmundite. Different types of contact occur: on the interface between arsenopyrite or gudmundite and fahlore; on the junction borders of arsenopyrite or gudmundite, pyrite and pyrrhotite; and finally in cracks together with a dominantly silver telluride.

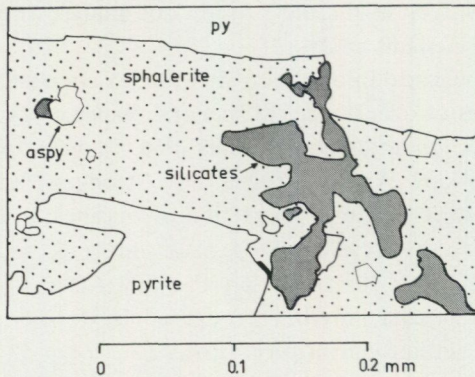


Fig. 27. Composite inclusion in pyrite where arsenopyrite crystals are floating in sphalerite. Chalcopyrite not present.



Fig. 28. *Irregular zoning in arsenopyrite. Crossed nicols. 60 X.*

The grain size of arsenopyrite often parallels that of the bigger pyrites in the assemblages. The size of a large part of the observed arsenopyrite crystals lies about 0.5—1.2 mm. In the meta-ore pegmatites single individuals of elongated coffin-form may attain 6—8 mm and exceptionally 14—15 mm. In the same milieu developments of multitudes of small, 0.05—0.1 mm long, and equidimensional crystals are found in fahlore matrix and in some cases in chalcopyrite which again is included in fahlore (Figs. 25 and 26). Small euhedral to subhedral crystals also occur included in sphalerite (Fig. 27). With crossed nicols it is frequently seen that the bigger arsenopyrite crystals, both in the common massive ores and in the meta-ore pegmatites, are zoned. They may have an even, massive inner zone and a rim of variable thickness, parallel to the four respective edges, which consists of fine irregular lamellae (Fig. 28); or the zoning may have the opposite or a combined pattern. Only the smaller crystals seem to be homogeneous.

#### GLAUCODOT, (Co, Fe) AsS

Glaucodot is found in one specimen of meta-ore pegmatite material. It occurs in a tennantite-chalcopyrite matrix as euhedral, small crystals. Because of unusual colour and brightness, they were checked qualitatively for Co, Ni, As, Sb and Fe on the microprobe. A sporadic admixture of glaucodot in the ore is possible.

#### FAHLORE (TETRAHEDRITE-TENNANTITE), $\text{Cu}_3(\text{Sb, As})\text{S}_{3-4}$

Minerals of the fahlore group form a widespread, but minor constituent. Their distribution is characterized by two patterns:

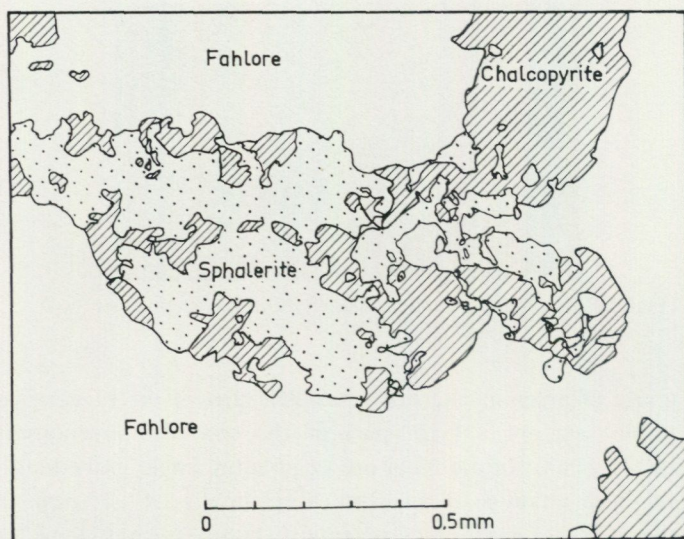


Fig. 29. *Chalcopyrite and sphalerite included in fahlore. Some small fahlore inclusions in chalcopyrite, but none in sphalerite.*

1. A general disperse and even distribution all over the ore volume, particularly as inclusions in the main sulphides.
2. Enrichments as lateral and internal secretions (meta-ore pegmatites) in which the more mobile ore components are concentrated (As, Sb, Ag, Au, Te, Pb and Cu).

Intimate intergrowth and mutual inclusions of fahlore and all the major sulphides are observed. Intergrowth with sphalerite seems to be rarer than with pyrite and chalcopyrite (Fig. 29) An eventual breakdown of fahlore into arsenopyrite (gudmundite) and chalcopyrite is illustrated in Figs. 25 and 26.

A certain variational range in composition of the fahlores over the whole deposit may be suspected. In the meta-ore pegmatites brownish-grey varieties dominate when seen under the microscope. This colour shade indicates that the fahlore is of the tetrahedrite type, rich in Sb. This is confirmed by six quantitative analyses performed on the microprobe (Table 11).

The analyses were carried out on samples all taken from one meta-ore pegmatite, a secretion from a massive 1/2 m thick pyritic ore layer, which lies on the contact between sericite quartzite and black phyllite. Three of the analyses show a marked Sb-dominance versus As.

Two of them have important As contents. Ag shows the highest values in specimens high in Sb. Hg, determined by emission spectrography on photo plate (analyst B. Rajandi) was 70 ppm in tetrahedrite of J69-24II. Pb was not found

TABLE 11. Microprobe analyses of fahlore (tetrahedrite-tennantite). Analyst: J. Malmqvist

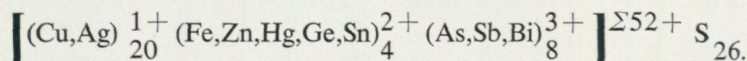
Samples Elements	J69 24I	J69 24II	J69 24III	J69 24V	J69 24VII	J69 24VIII	RM530380 standard from Mus. of Nat. Hist.
S	25.36	25.70	25.81	27.38	24.28	26.78	27.60
Fe	3.52	3.78	3.84	3.49	4.58	4.32	1.70
Cu	37.34	37.63	39.44	39.70	35.73	36.01	35.64
Zn	4.20	4.22	4.59	4.41	3.12	3.12	5.80
As	5.83	5.77	10.56	8.29	1.55	2.39	1.70
Ag	1.45	1.44	0.90	1.59	2.61	2.57	0.70
Sb	23.98	17.64	14.03	18.80	25.64	29.45	23.70
Sum	101.68	96.18	99.17	103.66	97.51	104.64	96.84 uncorrected
Analyses recalculated to 100 %							
S	24.94	26.72	26.02	26.41	24.90	25.59	28.50
Fe	3.46	3.93	3.87	3.37	4.70	4.12	1.76
Cu	36.73	39.12	39.77	38.30	36.64	34.42	36.78
Zn	4.13	4.39	4.63	4.25	3.20	2.98	6.00
As	5.73	6.00	10.65	8.00	1.59	2.28	1.76
Ag	1.43	1.50	0.91	1.53	2.68	2.46	0.72
Sb	23.58	18.34	14.15	18.14	26.29	28.15	24.48
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00

in any of the samples. Apart from the relatively few occurrences in the meta-ore pegmatites, where fahlore aggregates sometimes cover several square centimetres of continuous surface, it is not possible to give any chemical estimates from the microscope work. The most common type of observed fahlore in Stekenjokk, the minute inclusions in pyrite and chalcopyrite with a convex, more or less rounded form, generally shows a somewhat more greenish-bluish colour than the large aggregates mentioned above. This can partly be due to the small size of the majority of the inclusions. This type of finely distributed fahlore is present in practically all parts of the Stekenjokk mineralization. A few qualitative analyses performed in connection with other mineral investigations indicate that some of the smaller common fahlore inclusions are relatively rich in As. It is therefore correct at the present stage to leave open the question of definitive and general composition of this minor constituent in Stekenjokk, and its nomenclature can not be more precise than "fahlore".

*Formula.* The cell structure of the fahlore group is incompletely known. It crystallizes in the isometric system and shows "some similarity to sphalerite" (Ramdohr 1969, p. 554). Based on considerations of the structure of the group, Ramdohr (op.cit.) states that the "formula" should be  $\text{Cu}_3(\text{Sb, As})\text{S}_3$  or  $\text{Cu}_3(\text{Sb, As})\text{S}_4$ .

The latter formula corresponds to the composition of the two possible mix-crystal series of the enargite group (Ramdohr 1969, p. 573). None of the enargite minerals have been identified with certainty in the Stekenjokk mineralization. It is however very probable that the green, isotropic variety of enargite is not uncommon as minute inclusions in the main sulphides — especially in pyrite and chalcopyrite.

In Klockmanns Lehrbuch der Mineralogie (1967) Ramdohr and Strunz present a formula which is based upon the structural determination of tennantite (binnite) by Pauling and Neumann (1934):



For the pure end members of the group Ramdohr and Strunz (1967) give tennantite as  $\text{Cu}_3\text{AsS}_{3.25}$  and tetrahedrite as  $\text{Cu}_3\text{SbS}_{3.25}$ .

Springer (1969) made 21 microprobe analyses of tetrahedrites and tennantites from various localities and found Klockmann's formula to be valid in all the cases.

According to qualitative scanning analyses and emission spectrography on the Stekenjokk material it may be assumed that the only elements entering the structure in major amounts are those analyzed quantitatively on the microprobe: S, Fe, Cu, Zn, Ag, As and Sb. It is further assumed that Sb and As are interchangeable and do not substitute for any other elements. Cu is partly replaced by Ag, Fe and Zn. A calculation of the chemical composition according to Klockmann's formula is given in Table 12.

TABLE 12. Composition of Stekenjokk fahlore according to formula with  $(\text{Sb} + \text{As}) = 1$

Elements Samples	Cu	Zn	Fe	Ag	(Cu+Zn+ +Fe+Ag) index sum	Sb	As	(Sb+As) index sum	S
J69—24I	2.140	0.234	0.230	0.050	2.654	0.717	0.283	1.000	2.878
J69—24II	2.669	0.291	0.351	0.061	3.372	0.653	0.347	1.000	3.613
J69—24III	2.421	0.274	0.327	0.033	3.055	0.450	0.550	1.000	3.140
J69—24V	2.369	0.256	0.237	0.056	2.918	0.586	0.414	1.000	3.236
J69—24VII	2.432	0.206	0.355	0.105	3.098	0.911	0.089	1.000	3.276
J69—24VIII	2.069	0.175	0.282	0.087	2.613	0.883	0.117	1.000	3.048
RM 530380 standard	2.577	0.409	0.141	0.030	3.157	0.895	0.105	1.000	3.956

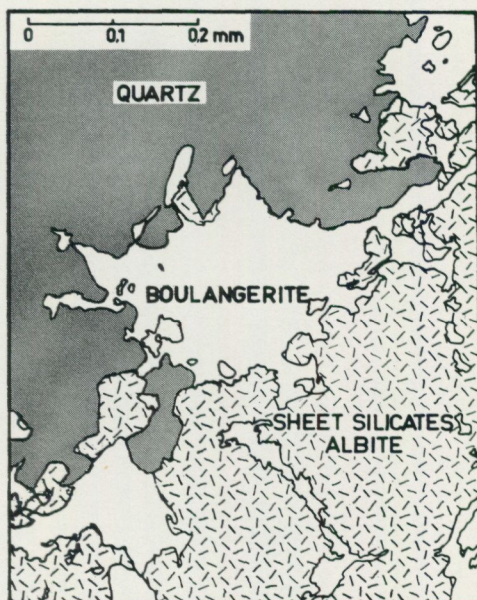


Fig. 30. *Boulangerite concentration in first generation quartz vein.*

The formula for the mean value of six Stekenjokk fahlore analyses can be given as  $(\text{Cu}, \text{Zn}, \text{Fe}, \text{Ag})_{2.95} (\text{Sb}, \text{As})_{1.00} \text{S}_{3.20}$ .

The six samples appear, on average, to correspond to Klockmann's formula (Ramdohr and Strunz 1967) and the results obtained by Springer (1969).

The substitution of copper by zinc, iron and silver is extensive, amounting at its maximum to nearly 21.5 % of the  $(\text{Cu} + \text{Zn} + \text{Fe} + \text{Ag})$  sum.

The corresponding formula for standard RM 530380 of the National Museum of Natural History, Stockholm will be  $(\text{Cu}, \text{Zn}, \text{Fe}, \text{Ag})_{3.16} (\text{Sb}, \text{As})_{1.00} \text{S}_{3.96}$ .

The standard sample has a higher Zn/Fe ratio and a markedly higher sulphur-content than the Stekenjokk fahlores. Its formula is in fact approaching that of the enargite mix-crystal group (Ramdohr 1969, p. 554).

#### BOULANGERITE, $\text{Pb}_5 \text{Sb}_4 \text{S}_{11}$

Boulangerite probably has a dualistic distribution pattern similar to that of fahlore. Firstly, it is seen as small bleb-formed inclusions in the main sulphides and particularly in intergrowth or contact with galena. Secondly, it occurs locally in some of the meta-ore pegmatites. In greater concentration it was seen only in one place: a first generation quartz vein together with dark sphalerite, some galena and chalcocite (Fig. 30).

TABLE 13. Microprobe analyses of boulangerite. Analyst: J. Malmqvist

Elements	Samples	J69—18A	J69—18B	J69—18E
Fe		0.04	—	0.10
S		19.68	19.80	19.55
Zn		0.08	0.08	0.83
Sb		26.57	26.20	26.34
As		—	—	?
Pb		59.29	56.49	59.74
Ag		trace	—	0.10
Sum		105.66	102.57	106.66

Analyses recalculated to 100 %

Fe		0.04	—	0.09
S		18.63	19.30	18.33
Zn		0.08	0.08	0.78
Sb		25.14	25.54	24.70
As		—	—	?
Pb		56.11	55.08	56.01
Ag		—	—	0.09
Sum		100.00	100.00	100.00

In three microprobe analyses performed on the mineral (Table 13), no As was registered. Trace elements of boulangerite from J69-18B, determined by emission spectrography on photo plate (analyst B. Rajandi), were reported as < 0.1 % of Cu, Mn, As and Bi and approximately 0.01 % of Ag. Traces of Si, Mg, Al and Ti are present.

*Formula.* According to Ramdohr (1969, p. 758)  $Pb_5Sb_4S_{11}$  is the most probable formula for boulangerite. In three analyses carried out on the microprobe, other elements are not present in more than trace amounts, with the exception of Zn in one case. Metal proportions, calculated on 11 sulphur atoms, are given in Table 14.

TABLE 14. Composition of Stekenjokk boulangerite according to formula with 11 S-atoms

Samples	Elements	Pb	Sb	S	Zn	Fe	Ag
J69—18A		5.127	3.902	11	0.023	0.014	—
J69—18B		4.858	3.833	11	0.023	—	—
J69—18E		5.202	3.904	11	0.230	0.031	0.016

### JAMESONITE, $Pb_4FeSb_6S_{14}$

Jamesonite was found as an inclusion without crystal outlines in a big galena grain from the above-mentioned boulangerite concentration. It was optically identified according to the weak differences in pleochroic colours that can be registered between this mineral and boulangerite (Ramdohr 1969, p. 757). A few needle-like tiny inclusions in galena, and particularly in galena blebs included in pyrite, may also be jamesonite.

### ACANTHITE — SILVER GLANCE, $Ag_2S$

Acanthite was identified with some uncertainty by optical means. Some small inclusions in galena, fahlore and chalcopyrite were recognized by the low reflectance, the scratchy surface and softness of the mineral. Crystal faces were never seen. Probably it is present also in pyrite. Especially in larger composite inclusions it was possible to discern the characteristics of the mineral.

### BOURNONITE, $CuPbSbS_3$

Bournonite is a minor trace mineral whose distribution is difficult to characterize. It is found as inclusions in pyrite, chalcopyrite and galena. Otherwise it is found in those meta-ore pegmatites where boulangerite is conspicuous. As minute inclusions in the major sulphides, which apparently is the most frequent mode of occurrence, it may have been mistaken for several other minerals such as galena, As-rich fahlores, tellurides, boulangerite.

### GOLD, Au

Native gold or gold alloys probably occur sporadically over a great part of the total ore volume (Figs. 31—34). They are best observed in the coarse-grained developments (meta-ore pegmatites) within the borders of the massive ores, and occur in three different types of assemblages:

1. In contact with arsenopyrite and/or gudmundite, together with pyrite and pyrrhotite (Figs. 33 and 34), and as single-phase inclusions in pyrite, preferably in the neighbourhood of arsenopyrite inclusions. This is observed both in meta-ore pegmatites and in the fine-grained massive ore.

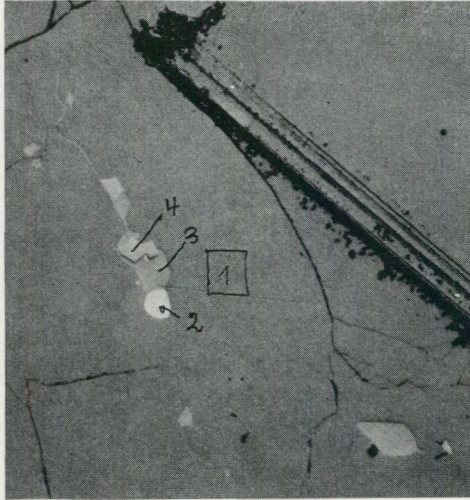


Fig. 31. *Microphoto, reflected light, interference contrast.* 1 — fahlore, 2 — gold-silver alloy, 3 — galena, 4 — arsenopyrite. 136 X.

2. As isolated inclusions in fahlore.

3. As inclusion in the silver-telluride hessite,  $\text{Ag}_2\text{Te}$ , which itself is included in fahlore (see Fig. 35).

The two last types of assemblages are solely observed in coarse-grained meta-ore pegmatites, where the more mobile ore constituents, as well as quartz and carbonate are enriched. Arsenopyrite occurs as cm-long crystals, and fahlore is seen with the naked eye. The observed grains of native gold vary in size from 2—20  $\mu$ , most of them being about 4—8  $\mu$  in diameter.

They have been identified with the help of reflectance measurements and the microprobe analyzer. As native gold was found in a relatively large part of the samples, a rapid X-ray photo technique was used on the microprobe, in order to sort out the distribution patterns of the different elements.

An auxiliary reflectance standard of native copper from Porsanger, Norway was used. Its reflectance was, in all measurements in white light, between 75 % and 83%. The gold droplets were subsequently measured against a natural pyrite standard (R 53.5—55.0 %) and the auxiliary copper specimen. Reflectance in white light varied between 68 % and 76 %. Measurements in green light of the wave length 546 nm gave between 75 % and 79%. This latter result may indicate a possible admixture of silver in the compound. It was confirmed with the help of the microprobe analyzer that silver may in places be an important constituent of the alloy (up to 20—30 % of total weight) (Fig. 34).

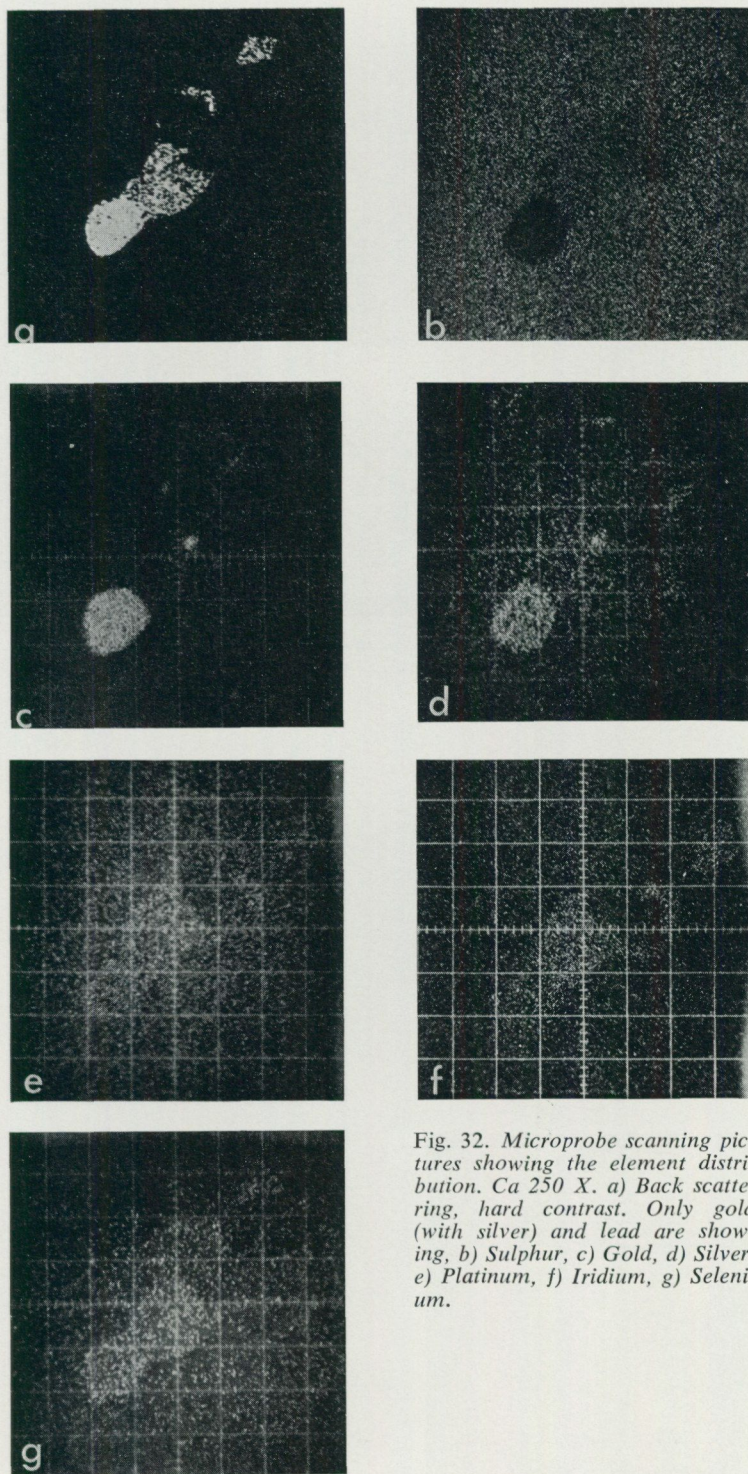


Fig. 32. Microprobe scanning pictures showing the element distribution. Ca 250 X. a) Back scattering, hard contrast. Only gold (with silver) and lead are showing, b) Sulphur, c) Gold, d) Silver, e) Platinum, f) Iridium, g) Selenium.

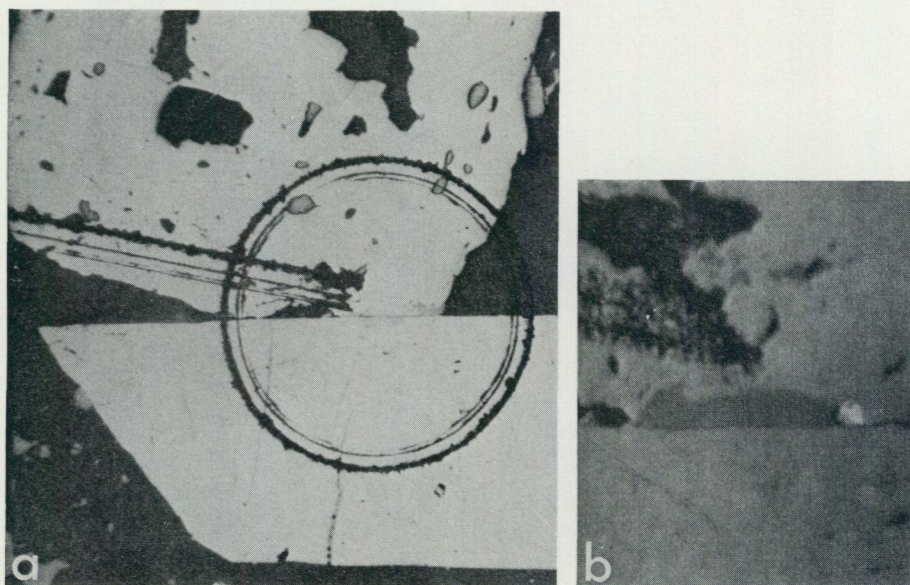


Fig. 33. *a)* Droplet of a gold-silver alloy on the junction between arsenopyrite, pyrite and pyrrhotite. 63 X. *b)* Position of droplet at the end of elongated pyrrhotite rod. Ca 500 X.

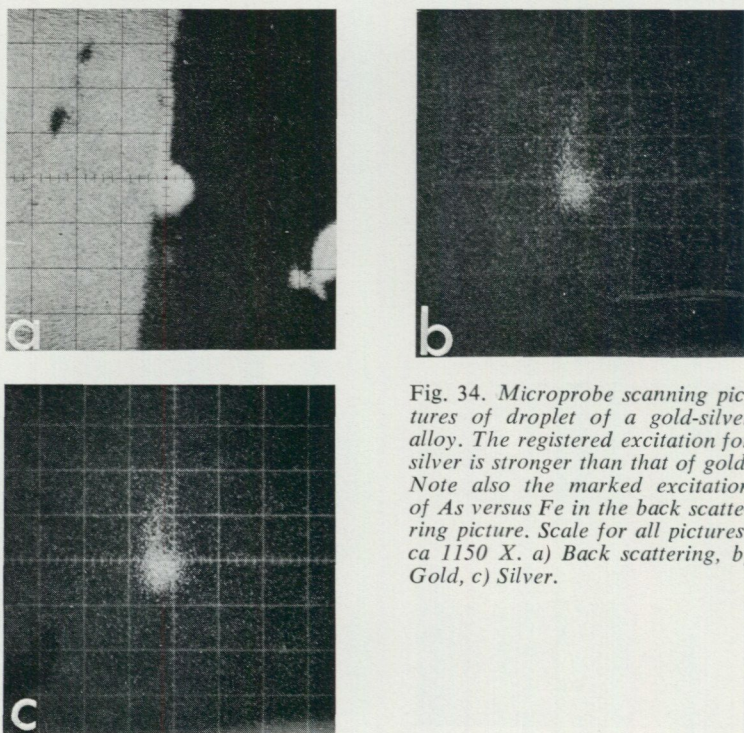


Fig. 34. *Microprobe scanning pictures of droplet of a gold-silver alloy. The registered excitation for silver is stronger than that of gold. Note also the marked excitation of As versus Fe in the back scattering picture. Scale for all pictures: ca 1150 X. a) Back scattering, b) Gold, c) Silver.*

## TELLURIDES

HESSITE,  $\text{Ag}_2\text{Te}$ 

Hessite is a trace mineral which possibly is widespread in Stekenjokk. It is however visible and identifiable first of all in the meta-ore pegmatites, and it has usually a close connection with the minerals of the fahlore group.

Hessite has been identified in the following types of intergrowth and milieu:

1. Inclusions in fahlore. In a few cases droplets of a Au-Ag alloy are found in hessite (Figs. 35—36).
2. Inclusions in pyrite, in contact with a Bi-Te compound which also is completely without sulphur and is not completely identified (Figs. 39—40).

Both 1 and 2 are found in the meta-ore pegmatites.

3. As minute inclusions, mostly composite, together with fahlore in pyrite and chalcopyrite. Once it was found on an interface between pyrrhotite and galena.

These finds were made in massive, relatively fine-grained pyrite ores. The mineral's identity was established with the help of the microprobe analyzer and its optical properties. The low polishing hardness and the many scratches seen on even small surfaces are typical features. Its bireflectance was hardly noticeable, neither in air nor in oil. Further, the lamellar texture mentioned in text-books is not general (Ramdohr 1969, p. 420) and is well developed only in some small inclusions of hessite. Its anisotropy is distinct, but weak under great magnifications. Its reflectance was measured against the Si standard (R 38.6 %) and the pyrite standard (R 53.5—55.0 %) and was in white light found to be somewhat higher than the values given in text-books (Cameron 1961, Table 3: hessite — R 38.5 %), namely between 39.5 % and 41.2 %. However in green light with wavelength 546 nm the range 38.6—40.2 % was found.

The chemical composition of hessite was tested in a series of microprobe scanning pictures (Fig. 36) taken on the same grain as in Fig. 35. Negative results were obtained for Sb, Zn, Pb, Co and very weak concentrations for Ir, Ni and Os. The latter is probably disturbed by Cu in the surrounding fahlore.

## UNIDENTIFIED SILVER-TELLURIUM COMPOUND

An unidentified Ag-Te mineral occurs together with galena as a crack-filling in arsenopyrite (Fig. 37). Probably the same mineral has been observed as tiny inclusions in pyrite and galena. Its characteristics are however uncertain. Comparative studies between the different observations are difficult.

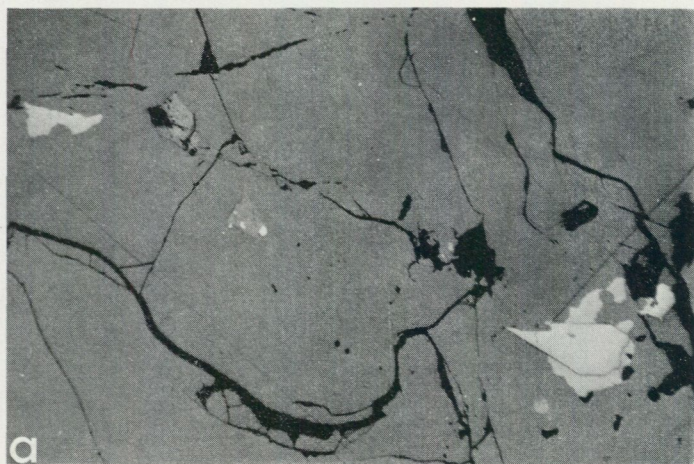
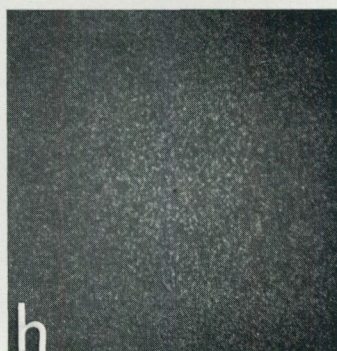
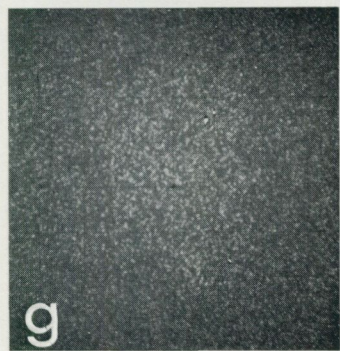
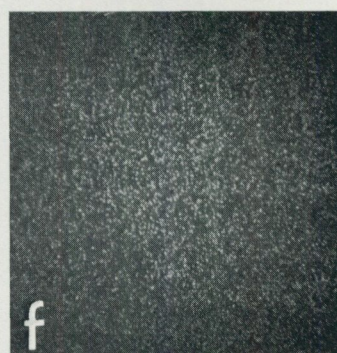
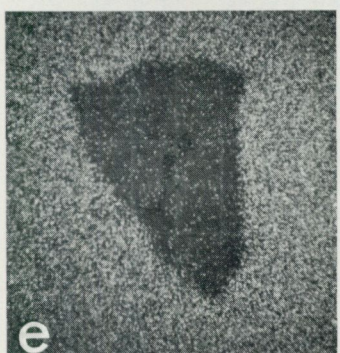
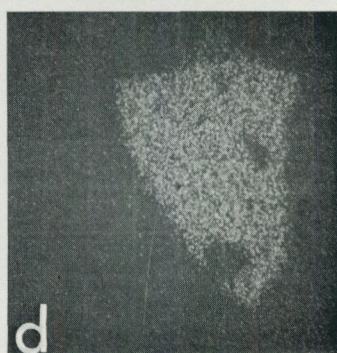
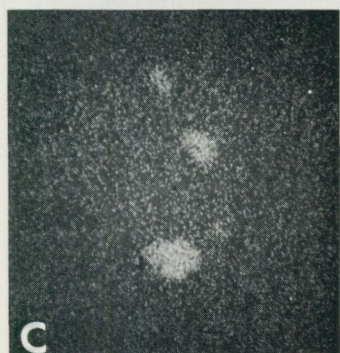
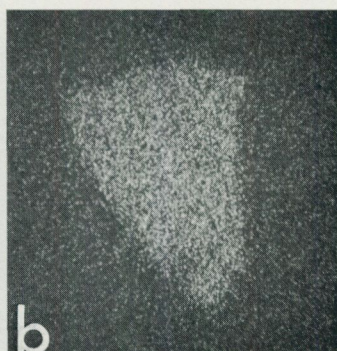
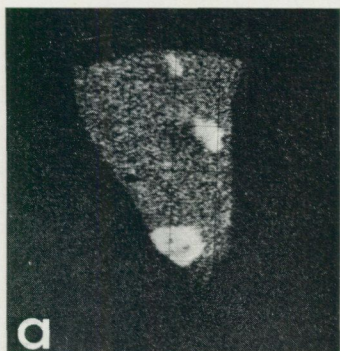


Fig. 35. *Fahlore with inclusions of hessite. a) Hessite (single and with droplets of gold) and chalcopyrite (single and with one arsenopyrite crystal). 125 X. b) Hessite containing three droplets of gold seen under ordinary light in oil immersion. Detail from Fig. 33 a. 960 X. c) The hessite grain, consisting of several individuals, demonstrates the anisotropy of the mineral under crossed nicols. 960 X.*

Fig. 36. *Microprobe scanning pictures showing elemental distribution in a grain of hessite containing droplets of gold. Scale for picture a: ca 900 X. Scale for pictures b—h: 910 X. a) Back scattering picture, b) Silver, c) Gold, d) Tellurium, e) Sulphur, f) Platinum, g) Selenium, h) Bismuth.*



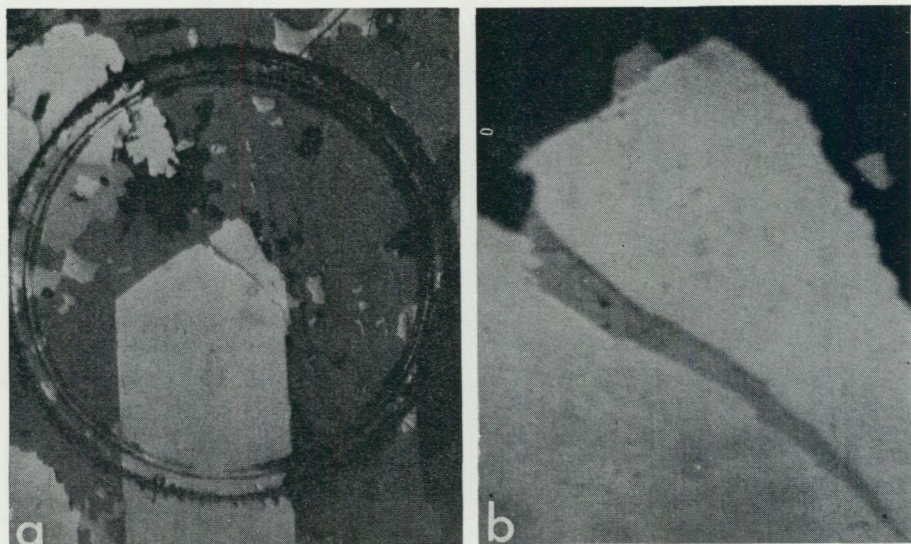


Fig. 37. *a) Localization of crack filling of Ag-Te compound and galena in arsenopyrite. 100 X. b) Ag-Te compound, scratched surface in outer part. Galena in inner part. Ca 800 X.*

Most probably the mineral is softer than galena, and in the arsenopyrite crack it exhibits a very scratchy and uneven surface. A weak, but distinct pleochroism from white to yellowish pink is seen. The reflectance seems to be somewhat higher than that of galena. There is a weak and indistinct anisotropy effect, its irregularity probably being caused by the uneven surface. In the arsenopyrite crack filling the pleochroism indicates that only one individual is present.

The elements Pb, Zn, Cu, Fe, Sb, As, S, Se, Bi, Te, Au, Ag, Co, Ni were tested on the microprobe (Fig. 38). No elements except Ag and Te reacted upon the microprobe excitation. The registration of these two was, however, strong and distinct. Because of the optical properties of the compound it could be identified neither as hessite ( $\text{Ag}_2\text{Te}$ ) nor as empressite ( $\text{AgTe}$ ). As the mineral is observed as a crack filler and inclusions in common sulphides, it might have a widespread distribution in the mineralization.

#### BISMUTH-TELLURIUM COMPOUND

An unidentified Bi-Te mineral was in one case found in contact with hessite in an inclusion in pyrite (Fig. 39) and has also been observed as a single inclusion in pyrite and probably in arsenopyrite and chalcopyrite. It has a more even

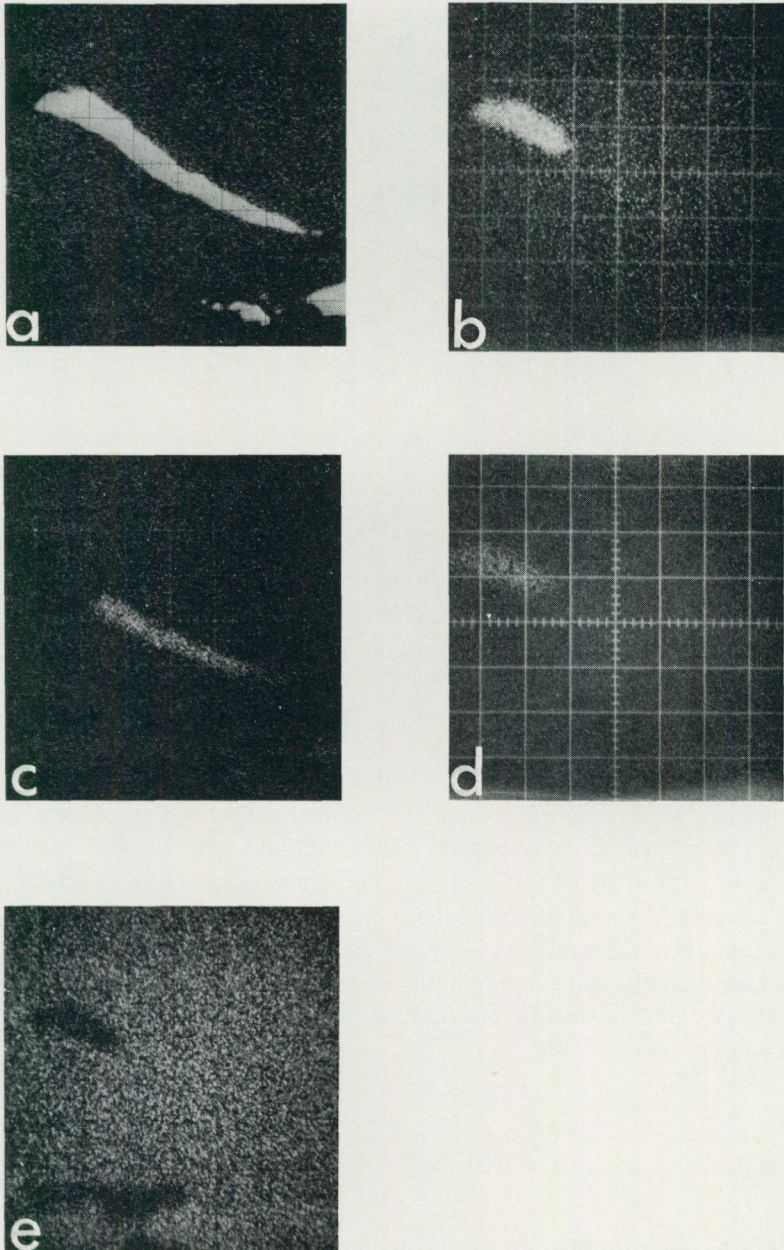


Fig. 38. Series of microprobe scanning pictures showing distribution of Ag, Pb, Te, S in crack filling in arsenopyrite. Scale for all pictures: ca 575 X. a) Back scattering picture, b) Silver, c) Lead, d) Tellurium, e) Sulphur.

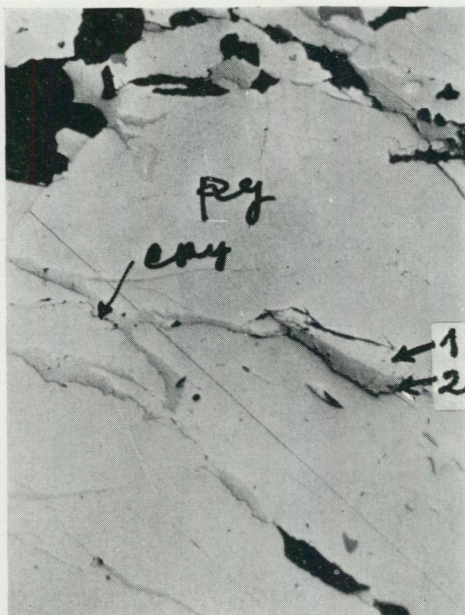


Fig. 39. Unidentified Bi-Te compound (1) and the silver telluride hessite,  $Ag_2Te$  (2) as inclusion in cracked pyrite. Reflected light, interference contrast. Ca 105 X.

surface than hessite and is somewhat harder. It has a lustrous metallic appearance with a weak greenish shade and distinct anisotropy in bluish to grey colours. The reflectance was measured in white light (pyrite standard) and was found to be very high (R 60—75 %). The small size of the observed grains hinders accurate determinations of the mineral's optical characteristics.

The main chemical constituents of the composite inclusion were analyzed on the microprobe (Fig. 40). Additional runs show a low Pb-content of the Bi-Te compound. Co and As are slightly enriched in both minerals compared to pyrite, but the contents are very low.

#### SILVER-BISMUTH MINERAL

A highly reflectant (R 60—70 %) silver-bismuth mineral was found as minute, prismatic inclusions in chalcopyrite in two specimens (Fig. 41). The mineral does not tarnish in air. It is significantly softer than chalcopyrite. Measurements of absolute hardness were not possible because of the small size of the inclusions.

The colour is white with a very faint yellowish pink shade. Pleochroism is not visible. The anisotropy effect is very weak, but distinct.

A qualitative investigation was performed on the microprobe. Runs were made to detect Bi, Ag, Sb, S, Te, Se, Cu and Pb (Fig. 42). Bi is the most important constituent, Ag the second most. Sb, S, Te, Se, Pb gave no reaction on the scanning pictures. Cu gave a very weak reaction, but this may come from the surrounding chalcopyrite.

### BREITHAUPTITE, NiSb

Breithauptite is found as subhedral, small inclusions or on boundaries between the common sulphides pyrite, pyrrhotite, chalcopyrite and galena (Fig. 43). The observations are few (15—20). The fact that breithauptite is not found in contact with sphalerite or in other environments may only be a coincidence. The mineral has a marked tendency to develop crystal faces. Mostly prismatic or platy outlines are seen. Euhedral crystals are however not observed. All grains seem to consist only of one individual. The size is small; the greatest measured dimensions lie generally between 5 and 50  $\mu$ . The biggest grain was about 0.1 mm long and had small rounded inclusions of the surrounding mineral pyrrhotite.

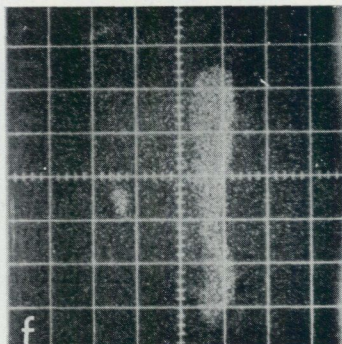
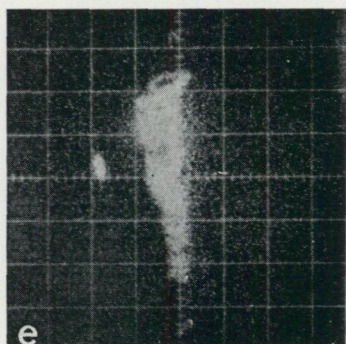
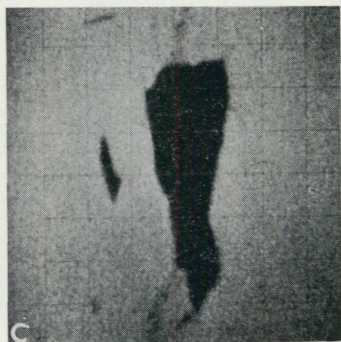
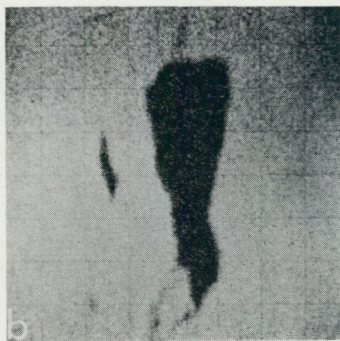
No particular concentrations of breithauptite are found. Because of the low number of observations nothing conclusive can be said about its general distribution within the total ore volume. However, as all observed individuals occur in intimate relationship with the more common ore constituents, it is possible that breithauptite is widespread in Stekenjokk.

The polishing hardness is about the same as that of pyrrhotite, and markedly higher than that of galena. Possibly, it is harder than chalcopyrite, but is again distinctly softer than pyrite. Because of quite distinct pleochroism (yellowish pink to pink with a violet tint) and anisotropy (pink to grey with a bluish tint) the recognition of bigger individuals is not complicated. The characteristics are best seen in oil immersion, but are also distinct in air. However, the smaller grains were difficult to identify, their aspect being influenced by the surrounding minerals.

A small grain, 7.5  $\mu$  x 3.5  $\mu$  large was run on the microprobe for a qualitative analysis of Cu, Fe, Pb, Zn, Co, Ni, Sn, Bi, Au, Ag, S, As, Sb, Se and Te. Only Ni and Sb could be discriminated from the surroundings as belonging to the actual mineral.

### CLAUSTHALITE, PbSe

Clausthalite has been identified with certainty only in three cases. The mineral was found in one sample from a meta-ore pegmatite (two individuals) and in one



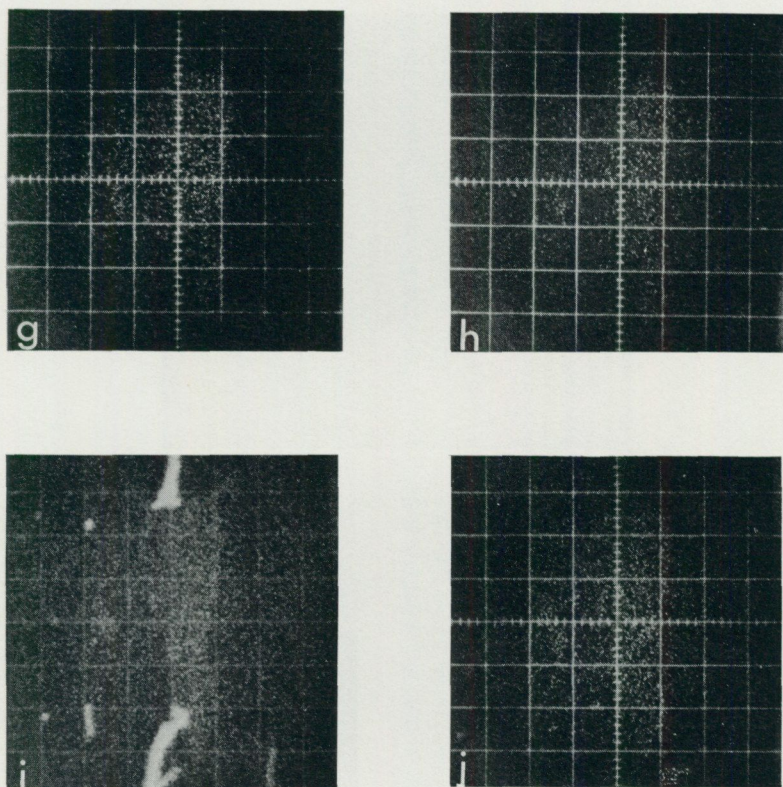


Fig. 40. Microprobe scanning pictures showing the distribution of S, Fe, Te, Ag, Bi, Au, Sb, Cu, Ni in composite inclusion of hessite ( $Ag_2Te$ ) and an unidentified Bi-Te compound. 205 X. a) Back scattering, b) Sulphur, c) Iron, d) Tellurium, e) Silver, f) Bismuth, g) Gold, h) Antimony, i) Copper, j) Nickel. See Fig. 39.

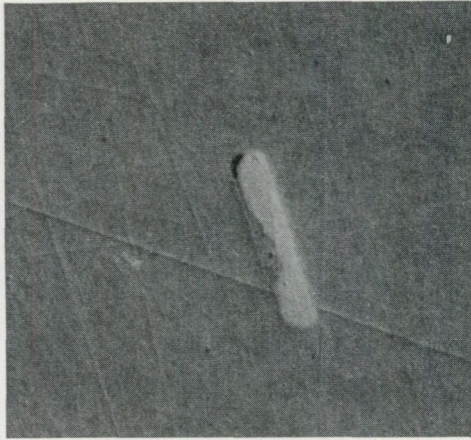


Fig. 41. Inclusion of silver-bismuth mineral in chalcopyrite. The embayment on the left side is caused by another unidentified mineral. This has a rectilinear border towards chalcopyrite further left. 910 X.

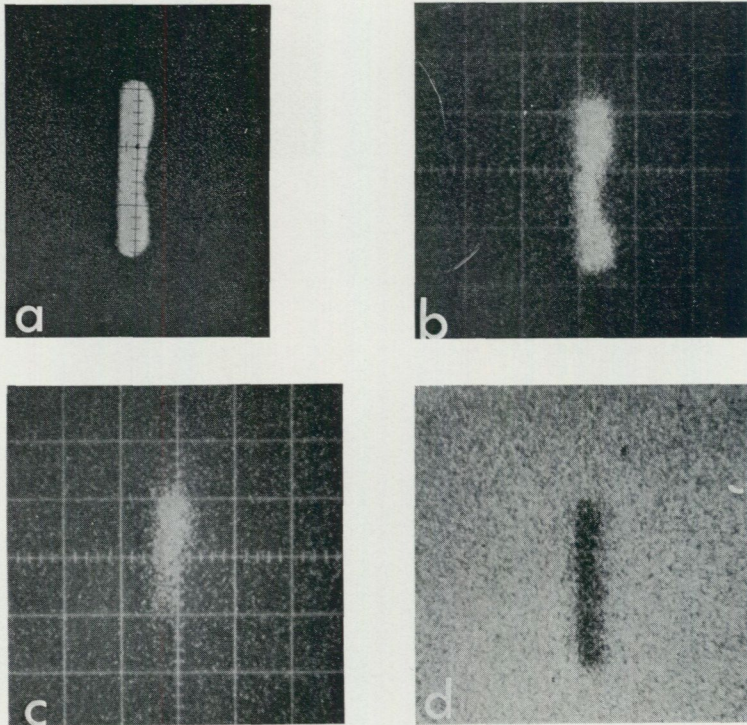


Fig. 42. Microprobe scanning pictures showing elemental distribution in an unidentified Ag-Bi compound included in chalcopyrite. 880 X. a) Back scattering picture, b) Bismuth, c) Silver, d) Sulphur.

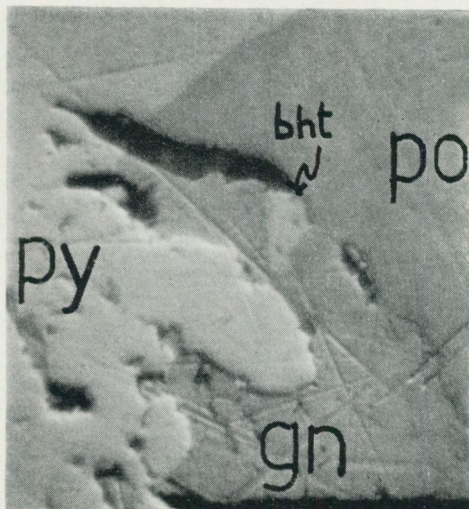


Fig. 43. *Breithauptite in contact with galena and pyrrhotite. 800 X.*

sample from a massive pyrite ore. In all three cases it was seen as minute inclusions (5—25  $\mu$ ) in pyrite. Two of these were rounded blebs. The third was a 25  $\mu$  long, wedge-formed inclusion. Because of the similarity with galena, it is probable that some small clausthalite inclusions have been mistaken for this more common mineral. The wedge-formed inclusion lies in a subhedral pyrite grain which in its turn is included in a grey fahlore. The inclusion is elongated, parallel to the border of the pyrite grain in which it lies. The clausthalite grain has a very light but clear sky-blue shade and a very even surface with no polishing scratches and no cleavage marks. Under crossed nicols the extinction is never total. The grain was subjected to a qualitative analysis on the microprobe. Pb and Se were the only elements which gave distinct reactions on the excitation. Bi gave a very weak reaction, whereas S, Fe, Zn, Cu, Ag, As, Sb and Ti were totally negative.

#### UNIDENTIFIED PRISMATIC MINERAL

A strongly pleochroic and anisotropic mineral is found in the same specimen as the breithauptite which was investigated with the microprobe. It lies on the boundary between the same galena grain and the adjacent pyrite, forming a prism 5  $\mu$  long and 1  $\mu$  wide. The colour in ordinary light, oil immersion: greyish with weak bluish shade, and a very weak brownish tone. On rotation, the brown tone increases somewhat, the mineral turns black and extinguishes almost completely. The dark positions are stronger than with crossed nicols.

Colours with crossed nicols are light brownish — dark greyish. The mineral shows a perfect parallel extinction with darkest positions when its long axis is parallel to the N—S and E—W directions of the microscope and maximum illumination in all 45° positions in between. The mineral is probably somewhat harder than galena. Its small size and its position on the grain boundary between galena and pyrite complicate its identification with the help of the microprobe analyzer. It has not been possible to discriminate on the X-ray photos the small area occupied by this mineral from the adjacent species.

### METALLIC OXIDES

Metallic oxides are generally very scarce in the Stekenjokk deposit. Hematite and magnetite are found in a few cases in the outskirts of thin massive pyrite ore bands. They accompany each other and have simple contacts. Zoning or intimate intergrowths are not seen. In one locality minute euhedral magnetite crystals were seen. Ilmenite is sporadically found in small amounts. Rutile has only occasionally been identified.

### OTHER UNIDENTIFIED CONSTITUENTS

In spite of detailed work with the help of various quantitative methods such as microprobe investigations and reflectance and microhardness measurements, several minor constituents still remain partly or wholly unidentified.

Some of the localized unknown minerals occur in too small quantities to be satisfactorily characterized even with the help of these tools. Some of them may however be fully characterized, but their description was left incomplete. Types of minerals or mineral groups which exist in minor amounts and whose identity is still unknown are:

Fahlore-like compounds containing copper, zinc, antimony but without sulphur and iron.

Fahlore-like lead compound without sulphur.

Galena-like lead compounds, not containing sulphur or selenium.

Stannite with variable qualities is probably localized in several places, but its identity has not been ascertained through microprobe work.

Noble metal tellurides are represented by more varieties than the one described (hessite).

Described and partly well-known mineral groups which demand further work to be fully characterized are: sulphosalts, arsenopyrite-gudmundite, gold-silver alloys, antimonides and various bismuth compounds.

## ASPECTS OF THE GEOCHEMISTRY OF THE ORE MINERALS

Through different quantitative and qualitative methods of analysis, information about the distribution of some elements in the ore-forming minerals has been acquired. The investigations have been performed on isolated powder concentrates of minerals and on polished sections. Methods include:

1. Optical spectrography: *a.* emission spectrography with registration on photo plate, Hilger quartz spectrograph with palladium as internal standard, *b.* tape machine, direct photo-electric registration and computerized evaluation.
2. Microprobe analyzer.
3. X-ray Debye — Scherrer powder method.
4. Wet chemical analysis.
5. Atomic absorption.

See also Appendix p. 156.

The separation of the main sulphides (pyrite, pyrrhotite, sphalerite, chalcopyrite, galena) was done by means of crushing, heavy liquids, magnetic separator and hand-picking. Three flotation concentrates of pyrite, chalcopyrite and sphalerite, respectively, produced by Boliden AB from 925 tons of ore are included in the investigated material (Tables 5, 7 and 9).

The other minerals were either hand-picked directly from uncrushed specimens or studied in polished sections with the help of the microprobe. The methods of investigation have different degrees of accuracy. By a combination of different methods, however, it has in many cases been possible to increase the reliability. The greatest limitation of the data lies in the character of the material itself. Due to fine grain size, intimate intergrowth and frequent mutual inclusions the mineral concentrates produced by the heavy liquid method do not have the ideal and desired purity, but are generally contaminated by one or several of the other minerals.

Another weakness is that for a number of elements the lower limit of sensitivity is not exactly known for all methods. Several trace constituents are not sufficiently studied to be satisfactorily characterized. Their amount and the size of the minerals often lie below the limit of correct discrimination of the microprobe, optical spectrography or microscopy methods.

The methods are mostly the same as have been used for studies of other sulphide deposits (Oftedal 1941, Fleischer 1955, Rouhunkoski 1968). Comparisons with results from other investigations are meaningful also because the great number of data improve the understanding of the degree of accuracy, even if the sources of error can not be eliminated.

Regarding the size of the deposit, the extent of the sampling varies. The samples of the main sulphides have a representative distribution. They are hand

specimens, drill core samples and flotation concentrates. In the case of some rarer minerals, e.g. the fahlore, sampling probably is too concentrated to be representative of the whole occurrence.

Interpretation of the results regarding formational theories is here left at a strict minimum.

Elements investigated in the respective minerals are: Cu, Ag, Au, Zn, Cd, Hg, Ga, In, Tl, Ge, Sn, Pb, Ti, As, Sb, Bi, V, Se, Te, Cr, Mo, Mn, Co, Ni, Os, Ir and Pt. They are listed according to increasing atomic number within each period of the periodic system.

*Cu.* Dominant mineral is chalcopyrite, minor and trace minerals are bornite, covellite, cubanite, valleriite, fahlore, bournonite.

Cu as a trace element in the concentrates of the main sulphides: pyrite 600—4500 ppm, sphalerite 3200—10 000 ppm, galena 100—1000 ppm, pyrrhotite 2000—10 000 ppm (Tables 5—8).

These contents appear to be due, to a large extent, to inclusions and impurities in the minerals. Pyrrhotite and sphalerite also show regular intergrowth with chalcopyrite (cf. Oftedal 1941, p. 71; Carstens 1941a, 1941c, 1942a; Fleischer 1955, p. 988 and p. 1005; Keith and Degens 1959; Mitchell 1968).

*Ag.* Independent trace minerals are acanthite (silver glance), tellurides and Bi compounds. Native silver has not been identified with certainty. Small droplets of Au-Ag alloys probably contain about 20 % Ag, according to reflectance and semi-quantitative microprobe analyses.

2.5 % Ag in fahlore (tetrahedrite) is the highest value found in any of the host minerals but may probably be higher. The highest reported Ag content for a Swedish fahlore (tetrahedrite) is 23.5 % from the Rakkejaur pyrite deposit in the Skellefte district (K. Vesterberg, personal communication).

The content of silver in some minerals from Stekenjokk is shown in Table 15. The registered contents seem to confirm Goldschmidt's (1954, p. 194) sequence of host minerals of silver according to increasing effectiveness, namely: pyrite, sphalerite, chalcopyrite, galena, tetrahedrite.

*Au.* The whole deposit contains 0.2—0.3 ppm Au as a mean value. Apart from native gold, an alloy, probably with 20—30 % Ag, has been identified with the microprobe. Au occurs as a trace element in most of the silver-rich compounds. The presence of gold tellurides is probable, but has not been proved.

*Zn.* Sphalerite is the main Zn mineral. Minor Zn contents are found in fahlore (max. 4.59 % determined). Microscope inspection suggests that a low zinc content in chalcopyrite is probably lodged in this mineral's lattice, and that a high content of zinc in other major sulphides represents impurities.

TABLE 15. Silver analyses of single minerals. Values in ppm if not marked otherwise. Analyses by emission spectrography on photo plate or microprobe.

Mineral	Number of samples	Maximum	Minimum	Mean value
Chalcopyrite separated	5	240	60	120
"    flot. conc.	1			410
Sphalerite separated	7	150	25	105
"    flot. conc.	1			136
Galena separated	3	1000	100	550
Galena in specimen by microprobe analysis	1			1000
Pyrite separated	10	55	10	25
"    flot. conc.	3	35	31	33
Pyrrhotite separated	9	120	30	36
Fahlöre by microprobe analysis	6	2.57 %	0.9 %	1.76 %
Boulangerite by microprobe analysis	4	0.1 %	traces	
Cubanite by microprobe analysis	1	traces		

*Cd.* No independent minerals have been identified. The most important host mineral of Cd is sphalerite. In the few runs, made by emission spectrography on photo plate, contents between 0.07 and 0.23 % were registered. Two samples of flotation concentrates of sphalerite were run on atomic absorption. They both had 0.33 % Cd.

*Hg.* Detected in one sample of tetrahedrite (70 ppm) by emission spectrography on photo plate. The best Hg line (2536, 52 Å) coincides with a weak Co line and is considered to be not sensitive enough even for qualitative appraisals of the small amounts in the other minerals.

*Ga.* A content of 25 ppm was determined in sphalerite. Traces in pyrrhotite (< 10 ppm) and in pyrite (< 10 ppm). Not seen in galena. All determinations with emission spectrography on photo plate.

*In.* Trace amounts (<10 ppm) in galena. Emission spectrography on photo plate.

*Tl.* Trace amounts (< 10 ppm) in sphalerite and in chalcopyrite. Emission spectrography on photo plate.

*Ge.* Trace amounts (< 100 ppm) in chalcopyrite, pyrrhotite, and pyrite. Emission spectrography on photo plate.

*Sn.* Stannite (identified with uncertainty) is the only tin mineral observed. Trace amounts are ~ 50 ppm in chalcopyrite and < 10 ppm in sphalerite, galena and pyrite. Emission spectrography on photo plate. Cf. data by Gavelin and Gabrielson (1947), Fleischer (1955), Vokes (1960, 1963). In spite of the small number of galena and sphalerite spectrograms available from Stekenjokk it is clear that sphalerite is richer in Sn than galena. Stannite, sphalerite and chalcopyrite belong to the same "tetrahedral" group. Their structural affiliation is much closer than that of stannite and galena.

*Pb.* The main mineral is galena. Trace minerals are the sulphosalts and clausthalite. Pb does not seem to enter the fahlore, not even in trace amounts, cf. p. 66. The high contents of Pb in the main sulphides (sphalerite 145—3300 ppm, chalcopyrite 100—800 ppm, pyrite 90—3000 ppm, pyrrhotite 110—1000 ppm, emission spectrography on photo plate) must be considered mainly as inclusions and otherwise locked galena grains in the respective concentrates.

*Ti.* The minerals ilmenite and rutile are present in trace amounts. The content of Ti is 20—120 ppm in pyrite, 100—400 ppm in pyrrhotite, 50—150 ppm in sphalerite, < 30 ppm in chalcopyrite, < 10 ppm in boulangerite and not detected in galena. Emission spectrography on photo plate.

*As.* The main mineral is arsenopyrite. Trace minerals are fahlore and rare accessory glaucodote. As determined as trace element in galena is 100—1000 ppm. Emission spectrography on photo plate. Presence in the main sulphides pyrite and pyrrhotite has not been determined quantitatively.

*Sb.* Microprobe analyses gave Sb contents of gudmundite, tetrahedrite (max. 29.5 %), boulangerite (max. 26.5 %), and bournonite. The Ni-antimonide breithauptite may possibly be a widespread, but very minor trace mineral. Trace element in pyrite (< 100 ppm), sphalerite (50—300 ppm), pyrrhotite (< 100 ppm), chalcopyrite (2 samples < 100 ppm, 3 samples < 300 ppm, flotation conc. 310 ppm). Emission spectrography on photo plate. Gudmundite and tetrahedrite are most probably the dominating Sb carriers of the deposit.

*Bi.* Bismuthinite and native bismuth are possible trace constituents, but have not been determined with certainty (reflected light microscopy only). Bi occurs in a trace compound with silver and in an unidentified Bi telluride. Trace element in the main sulphides: pyrite (< 30 ppm), chalcopyrite/pyrrhotite (~ 100 ppm), galena (10—100 ppm). Bi was not detected in sphalerite. It also occurs as a hardly detectable trace element in clausthalite, and as much as 1000 ppm in

boulangerite. Bi always accompanies galena. This is qualitatively determinable with the help of the microprobe. The amount lies however at the limit of detection.

V. No discrete V mineral was identified. Investigation with the help of emission spectrography on photo plate gave trace element contents in pyrite (< 20 ppm), pyrrhotite (< 30 ppm), sphalerite (< 30 ppm), chalcopyrite (< 30 ppm), but V was not detected in galena. Carstens (1943) reported the presence of V in pyrites of sedimentary origin and absence in those of "hydrothermal" origin. In order to draw any conclusions from the contents of V in the major Stekenjokk sulphides, additional data are needed.

Se. The only Se mineral identified is clausthalite. Se occurs as a minor trace element in minerals which are high in Pb (qualitative analyses on microprobe). Possibly there is a submicroscopic distribution of clausthalite, ex. in galena and boulangerite. Because of the position of the Se lines, Se was considered too difficult to determine on the available quartz spectrograph. Therefore eight pyrite specimens were analyzed by fluorescence spectrography (method developed by K. Börjesson, SGU).

The content of Se is 20—90 ppm in 7 samples. One sample contains as much as 210 ppm Se and comes from a volume of brecciated ore. It is possible that mobilized selenides were concentrated here during the metamorphism. However, no Se minerals were observed during the microscopy of six polished sections from the same volume.

According to Carstens (1943) pyrites of sedimentary origin should have no, or only traces of Se. In the 115 Se analyses reported by Fleischer (1955) the majority (83 samples) have 10—99 ppm. Edwards and Carlos (1954) also report very low Se contents in sedimentary pyrite. Mitchell maintains that marine pyrite has a higher Se content than fresh water pyrite, but does not give any absolute values (1968, p. 76). The Se content of Stekenjokk pyrites seems to be within the normal limits for the metamorphic pyritic base metal deposits of the Scandinavian Caledonides.

Te. Tellurides with Ag occur as trace minerals of widespread distribution. Bi-tellurides of unknown distribution are occasionally found. Te accompanies as a trace element all higher Ag concentrations. Further it is detected in galena (< 10 ppm) by emission spectrography on photo plate and is qualitatively determined in boulangerite with the help of the microprobe. It is known that altaite, PbTe, however not identified as a proper mineral in this paragenesis, can occur in solid solution with galena (Goldschmidt 1954, p. 406). This can possibly explain the registration of Te in galena. Its occurrence in boulangerite remains a problem.

*Cr.* No discrete Cr mineral was identified. Trace element in pyrite (<10 ppm) and in pyrrhotite, chalcopyrite and sphalerite (< 30 ppm). Not detected in galena. Emission spectrography on photo plate.

*Mo.* The only mineral identified is molybdenite which occurs in trace amounts. Investigation done only by emission spectrography on photo plates gives trace element content in pyrite, chalcopyrite, pyrrhotite and sphalerite of about 10—20 ppm. Exceptionally high contents of Mo are registered in all the flotation concentrates: pyrite 150—160 ppm, chalcopyrite 120 ppm and sphalerite 220 ppm.

*Mn.* No discrete Mn mineral was identified. The element has only been investigated by emission spectrography on photo plate and occurs as trace element in pyrite (20—40 ppm), pyrrhotite (10—40 ppm), chalcopyrite (~ 20 ppm), sphalerite (260—320 ppm) and galena (100—1000 ppm, impurity?). The chalcopyrite flotation concentrate shows an exceptionally high value (120 ppm), while the other flotation concentrates have the same contents as the respective hand-picked samples.

*Co.* Glauco-dot, the only Co-mineral identified, was found in one single locality. Trace element investigated by emission spectrography on photo plate in pyrite (65—310 ppm), pyrrhotite (40—370 ppm). Only two chalcopyrite samples were investigated for cobalt. The one had < 10 ppm Co, the other 140 ppm Co. The latter result probably must be attributed to impurities. Cobalt was detected neither in galena nor in sphalerite.

According to Carstens' studies at Løkken (1948), the cobalt content of the bulk ore is, like selenium, proportional to the copper content, but is considered to be mainly contained in pyrite. The "eksportkis" from Løkken with 41.5 % S, 2.0 % Cu and 2.12 % Zn should contain around 900 ppm Co (Ni content is 50 ppm). Hegemann (1943) gives 330 ppm Co as a mean value for pyrites from different parts of the Løkken ore bodies.

Five analyses of ore with keratophyric gangue from Stekenjokk show as a comparison the following mean values: 32 % S, 2.7 % Cu, 3.5 % Zn and only 108 ppm Co (Ni content 47 ppm). The flotation concentrate of pyrite gave 110 ppm (Ni content 25 ppm), while the separated pyrites gave from 65—310 ppm Co (Ni content < 10 ppm).

The sympathetic covariance between Cu and Co at Løkken is probably a simple indication that the best copper ores are those with high content of pyrite.

In Stekenjokk, there is no consequent proportionality between Co and Cu. The reason is probably that the good copper ores have very variable contents of pyrite.

Ni. Breithauptite is the only discrete Ni mineral identified (microprobe)\*. Trace element investigated by emission spectrography on photo plate in pyrite (< 10 ppm in hand-picked samples and 25 ppm in flotation concentrate), pyrrhotite, chalcopyrite and sphalerite (< 30 ppm), not detected in galena.

*Co versus Ni.* Carstens (1941 a, b, c; 1942 a, b, c) and Hegemann (1943) used the Co and Ni proportions as indicators of genetic relationships in sulphide deposits. It therefore merits special consideration. Carstens found that pyrite of sedimentary origin was characterized by a content of less than 100 ppm Co and  $Co < Ni$  in all samples analyzed. This has been confirmed by the work of Hegemann (1943) and Talluri (1951). In so-called "hydrothermal" deposits there is a great variation in analytical results. The content of Co reported ranges from traces to more than 1 %. Although most samples have  $Co > Ni$ , the reverse relationship is not uncommon (Fleischer 1955, p. 1004). Hegemann considered the Co-Ni relationships in hydrothermal deposits to be too irregular to be exploited as genetic indicators, thus only deposits of sedimentary origin should be taken into consideration. Pyrites from metamorphic, primary sedimentary deposits should have similar Co and Ni contents within one and the same deposit. Hegemann found that with increasing metamorphic grade, the Co content of pyrite increases while its Ni content diminishes. His interpretation is that Co enters the pyrite lattice more readily and that Ni enters the lattice of pyrrhotite which is formed during the metamorphism.

Neumann (1950), investigated the Co-Ni ratio of pyrite and of pyrrhotite pseudomorphs after pyrite in the contact metamorphic slates at Ballachulish, Scotland. He found, however, that the thermo-metamorphism which transformed pyrite to pyrrhotite had been unable to disturb the content of Co and Ni.

Saager who studied the Co-Ni ratio in the Mofjell deposit, Norway, (1966, p. 122—124) has made a comparison with other sulphide deposits of the Caledonian milieu and the German deposits Meggen and Rammelsberg. He divided them into three groups:

Co-Ni ratio	0—10: Meggen, Rammelsberg, Løkken
"-	25—60: Mofjell, Bleikvassli, Sulitjelma, Røros, Follidal
"-	> 100: Sølvgruva, Hauknestind, Heselia, Bosmo

Saager also states that "Verschiedene grosse Co/Ni Quotienten können daher nur dann ein Beweis für unterschiedlich starke metamorphe Beanspruchung von Erzlagern sein wenn Anzeichen bestehen, dass der Magnetkies bei der Metamorphose sicher aus dem Pyrit gebildet wurde — der Magnetkieshalt also mit dem Metamorphosegrad des Erzes in Zusammenhang steht — und kein primärer Magnetkies vorhanden war".

\*Added in proof: Small pentlandite grains are found in some massive pyrite samples.

The Norwegian Løkken deposit, situated SE of Trondheim has a ratio of 11 (Hegemann 1943). Løkken and the Grong area deposits are all fine-grained pyritic deposits associated with volcanic, tuffitic and sedimentary sequences in an environment of low grade metamorphism. According to Mitchell's data (1968; relative numbers produced on a spark source mass spectrograph) the Joma deposit has a Co-Ni ratio of 0.7—1 and the Skorovas deposit approximately 4—5.

Stekenjokk has many traits in common with the Løkken—Grong deposits. We do not know how much of the pyrrhotite is primary and how much is of metamorphic origin. It is found that the Co-Ni ratios of pyrite and pyrrhotite are quite similar in Stekenjokk. The order of magnitude of the Co-Ni ratio of the pyrite is 7—30 (bulk ore ratio of Co-Ni ca 5), and places the occurrence in the upper part of Saager's scheme. It neither expresses clearly any particular genetic relationship nor a distinct metamorphic grade.

In accordance with the investigations of Carstens, Hegemann and Fleischer this would class Stekenjokk with the so-called "hydrothermal" deposits, but as seen from this review, the Co-Ni relations are complex in the group of massive pyritic deposits. Genetic conclusions may appear premature.

*Os, Ir, Pt.* No discrete minerals are identified. With the help of the microprobe the three elements are seen to occur in alloys of Au and Ag and in Ag telluride.

## ORE TYPES

### INTRODUCTION

The main primary ore types of the Stekenjokk deposit are few and their mineralogy relatively simple. They are strictly *stratiform* and concordant with the primary compositional banding of the host rocks. The same common sulphides are represented in all of them: pyrite, pyrrhotite, sphalerite, chalcopyrite and minor galena — however in highly variable proportions. Generally, the mineralizations exhibit a well developed banding. Some spectacular and important exceptions to this are met with. One of these is the brecciated or "durchbewegte" pyrrhotite-chalcopyrite ore (cf. terminology of Vokes, 1969). It contains rounded and crushed fragments of the ore minerals, particularly pyrite, wall rock and gangue material and has locally broken into clearly discordant positions. Volumetrically this breccia ore type is not very significant, but has been of great importance for the understanding of the metamorphic development of the deposit.

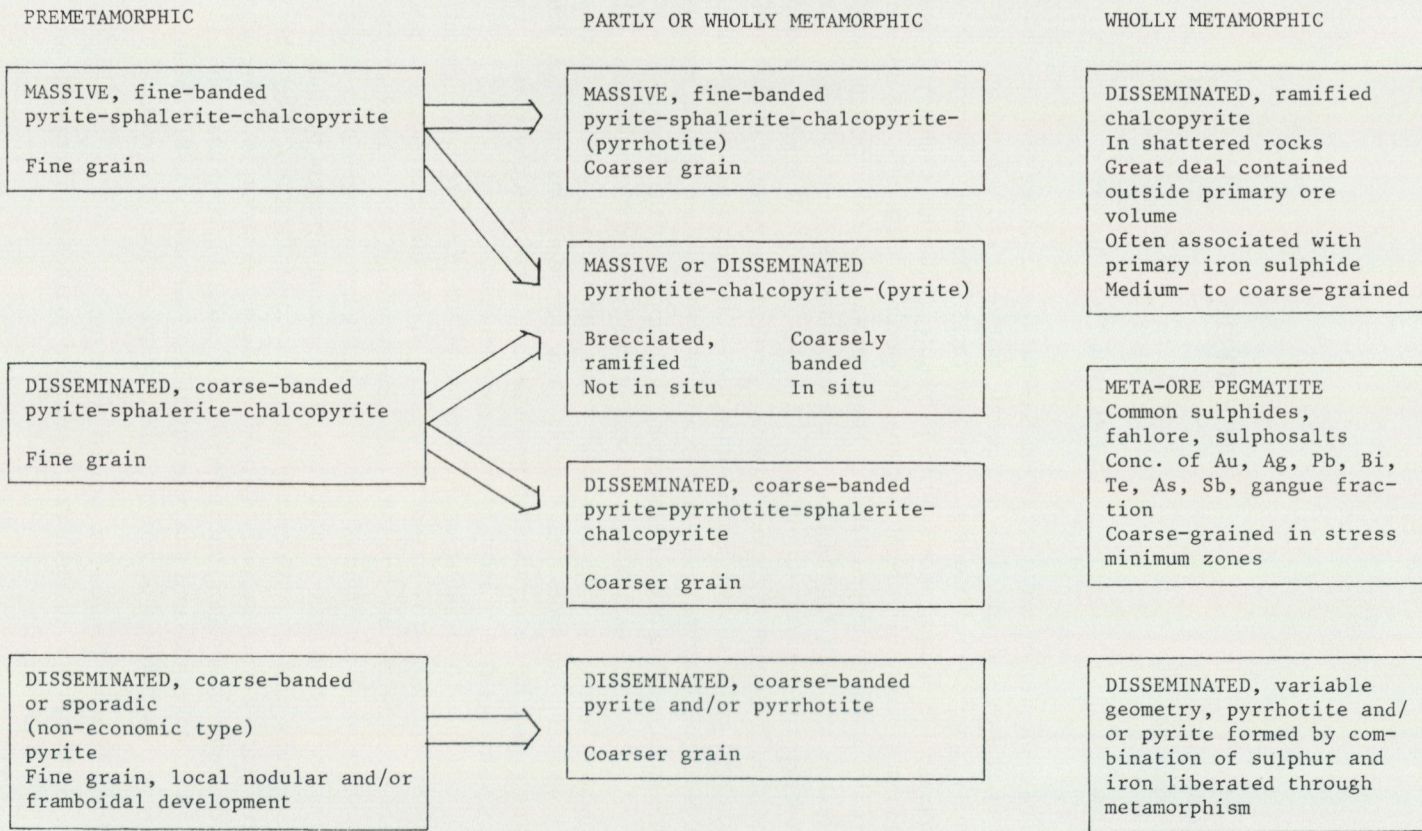
Another non-banded type consists of chalcopyrite disseminations, where the mineral is mainly lodged in small veins and cracks. The host rock and accompanying sulphides are variable, and disseminations in black schist and tuffite may be distinguished from those in quartz-keratophyric rock. Economically this ore type is partly of great importance.

In Table 16 an interpretative scheme of the main ore type nomenclature is given. The deposit is considered to be a wholly metamorphosed complex. The pre-metamorphic ore types are only known through very rare observations. The vestiges which are found of these types justify however their place in the scheme. The ore types in the central column of the scheme represent the bulk of the volumetrically and/or economically important mineralizations. The wholly metamorphic ore types (secondarily produced during metamorphism) are all of minor volumetric importance, but are partly of considerable economic value.

The Stekenjokk ores can be grouped into four main classes. The disseminated types are subdivided according to the character of their host rocks:

- 1 A. Massive, banded fine-grained pyritic ore.
- 1 B. Massive to disseminated, brecciated pyrrhotite-chalcopyrite ore, with or without pyrite.

TABLE 16. Interpretative scheme of main ore type nomenclature



- 2 A. Disseminations in light-coloured rocks.
- 2 B. Other disseminated ores, in black phyllites, often adjacent to the massive ores, or in tuffitic rocks.

A great number of subdivisions and transitional ore types may be recognized, emphasizing different theoretical and practical aspects. A very detailed subdivision has been presented by Helfrich (1969). For a general description the division given above is a practical one, and the different modifications and varieties will be described under these four headings.

#### 1 A. MASSIVE, BANDED FINE-GRAINED PYRITIC ORE

When the sum total of the sulphide volume in an ore specimen exceeds 50 %, it is characterized as massive ore. Both the texture and the composition of the banded fine-grained ore type is totally dominated by the content of pyrite. Sphalerite and chalcopyrite are common and important matrix sulphides. The content of pyrrhotite is highly variable. Galena is a constant, but very minor constituent, generally not visible to the naked eye. Due to variable content and alternations in the rhythm of intercalated bands of gangue minerals, the massivity is variable. For 54 ore samples with a sulphur content of 35—41 %, the mean massivity is 69.45 %. The banded appearance and the grain-size variation patterns of the ore are distinctly influenced by the degree of admixture of matrix sulphides and gangue minerals. The gangue is mostly of chlorite-sericitic keratophyre type, but is often tuffitic and even graphitic.

Frequently these massive ore bands form border mineralizations with (for instance) keratophyric rocks on one side and black phyllite on the other. The limit between the two wall rock units may be impossible to determine with accuracy. The gangue of the ore may consist of both. Common types of contact between pyrite-dominated massive ores and wall rocks are schematically illustrated in Fig. 44. See also Figs. 45 and 46.

It is typical that even the most massive varieties have a well banded texture, expressed by changes in the proportions of the main sulphide minerals.

There is a clear compositional banding due to mutually parallel sulphide and silicate bands.

The banded texture is further emphasized by variations in the grain-size distribution pattern of pyrite. Parallel bands, each with grains of similar size are as a rule arranged strictly concordant to the sedimentary layering of the host rock. This is well illustrated both in hand specimen and under the microscope. In the case of the relatively undeformed ore bands the pyrite grain-size variation is first of all seen as a direct result of the so-called "matrix effect". The softer the

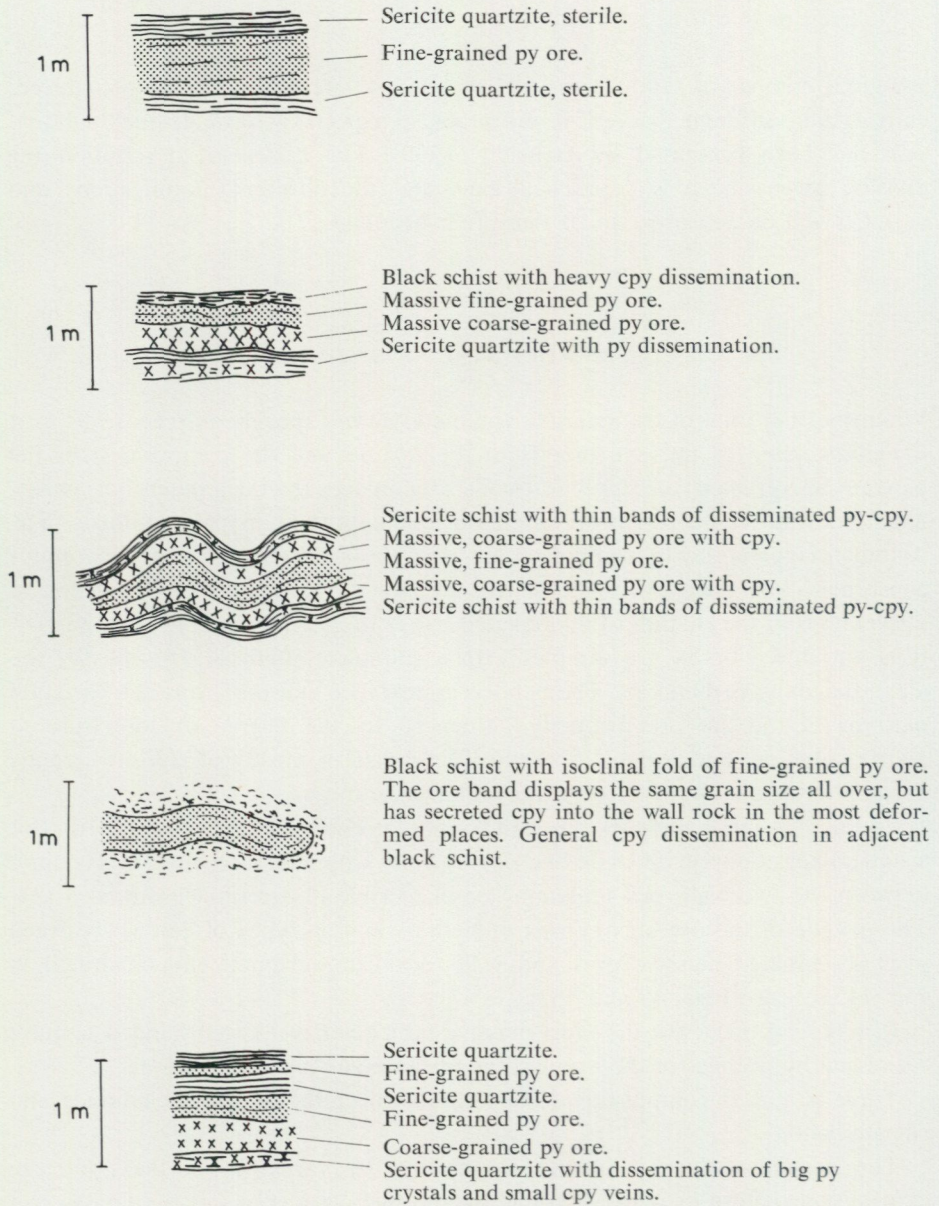


Fig. 44. Types of contacts between massive pyrite ore and wall rock.



Fig. 45. *Two-phase folding of graphitic phyllite band in massive pyritic ore. Immediate hanging wall rock is a thin strip of graphitic phyllite. Above this sericitic quartzite. The nearest 10—15 cm above the hanging wall limit of the massive ore are densely impregnated by chalcopyrite.*

surrounding matrix, the more rapid is the growth of the pyrite crystal, and the general grain size is proportional to the admixture of matrix minerals, i.e. the distance between growing pyrite grains. Comparative studies of the histograms (Fig. 47) of grain-size distribution show that the form of the curves are very similar from one locality to another, although the location of the frequency peaks varies. The frequency maximum in the majority of cases is centred around grain sizes of 0.8—1.2 mm as is also shown in a compilation of grain-size distribution from 34 different massive ore samples (Fig. 10). Another peak is often localized in the interval 0.2—0.5 mm, which suggests the existence of another generation of smaller individuals. Maxima in the very finest size classes are also frequent. It is quite probable that the lower grain-size classes are due either to grain growth or to fragmentation by cataclasis, and in many cases to a combination of these two processes. Grain growth alone may give rise to a variety of grain-size distributions, and, if proceeding undisturbed, would ultimately often result in the prevalence of a single size. If the ore undergoes brecciation or other fragmentation after the growth of all grains, the curve moves to the left, and its form is usually modified. The usual maximum around 0.8—1.2 mm is reduced, and the smaller grain-size classes increase. The beginning of fragmentation is illustrated in Fig. 47 e. Intense fragmentation leads to transitions to other ore types and is illustrated by two histograms from brecciated ore samples (see Fig. 51).

The two histograms show how an increasing degree of reworking of the ore volume changes the grain-size distribution patterns towards smaller grain-size

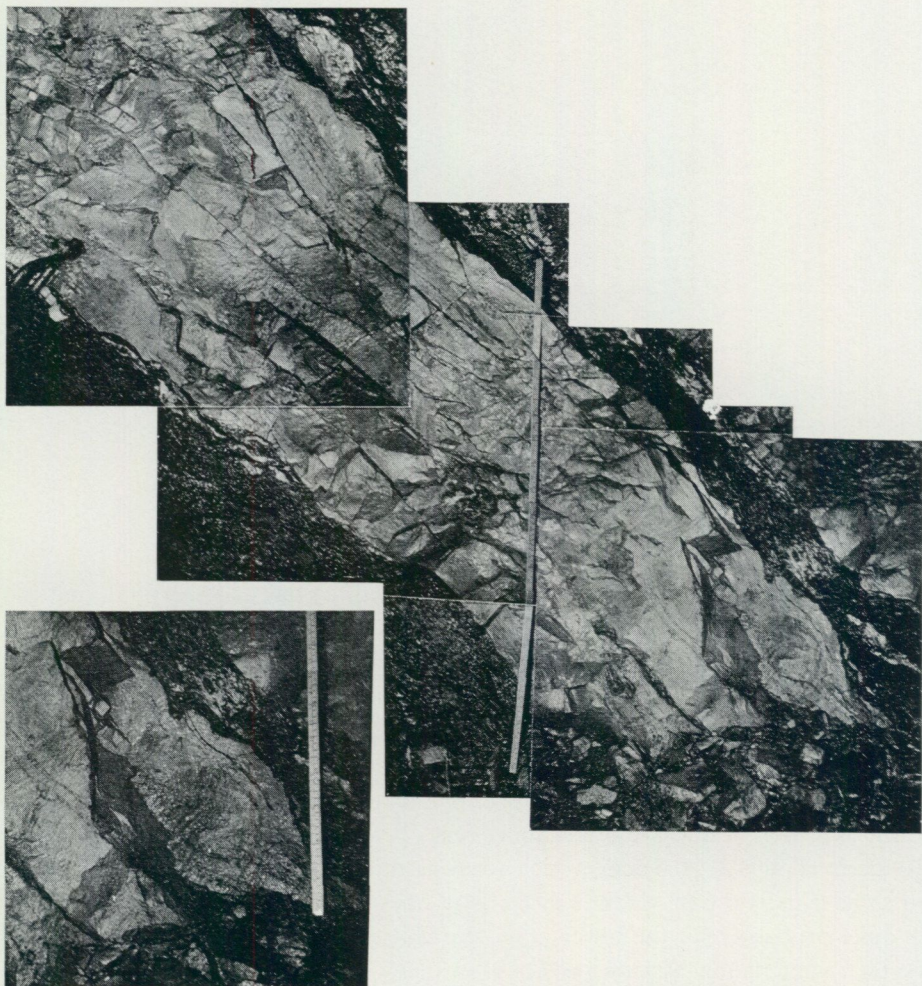


Fig. 46. Massive pyrite ore in graphitic tuffite. Layered primary sphalerite distribution. Carbonate bands and nodules. The ore bed is isoclinally folded during the first fold phase ( $F_1$ ). The second phase ( $F_2$ ) is hardly visible here. The degree of mobilization of the sulphides is low. Scale: the metre stick is 100 cm long. Detail: Tight fold nose in the massive ore marked by the shadowy distribution of a folded sphalerite layer.

classes. But also the "matrix effect" is of prime importance. The disturbance of the form of the distribution curves is probably also due to additional factors which have inhibited growth in one locality and favoured it in others. Such factors are for instance the metamorphic mobilization of minerals and elements which may increase the availability of sulphide material in one locality and correspondingly decrease it elsewhere.

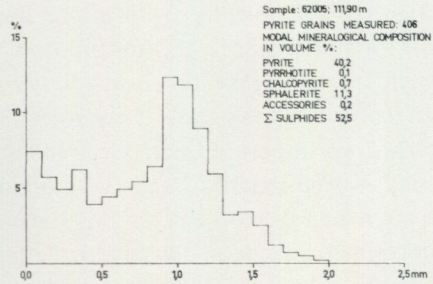
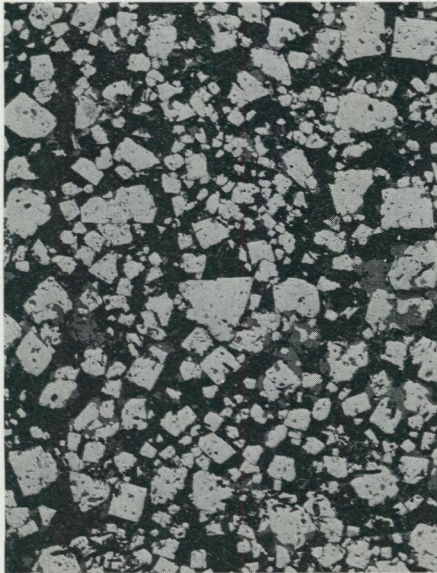
The two important matrix sulphides, sphalerite and chalcopyrite, are concentrated in well marked bands with good continuity along the strike. The sphalerite-rich bands have nearly the same geometry as the pyrite-rich ones or the intercalated silicate bands (that is with plane parallel top and bottom limitations, but with a ragged outline fitting into the interstitial space between the pyrite grains of the adjacent layer). If one compares sphalerite- and chalcopyrite-rich bands of similar thicknesses, the latter have more flamy or shadowy outlines and are much more difficult to follow continuously along the strike. A relevant and frequent observation is that the sphalerite-rich bands, which may have thicknesses of 2—50 mm, are far narrower than the chalcopyrite-rich bands. Sphalerite occurs more concentrated (purer). Chalcopyrite is often distributed in bands, 5—10 cm thick, with less apparent, ragged borders. The frequency of single sphalerite-rich bands in the massive ores is, however, distinctly higher than that of chalcopyrite bands. In an ore layer of 40—80 cm one may find up to 6—7 sphalerite-rich layers while more than 3—4 chalcopyrite bands are rare.

Based on the material collected during the present investigation it has not been possible to discern any fixed primary pattern for the vertical metal distribution of each individual ore layer. One layer may be zinc-rich at the base, another one in the middle, and so on. It is also difficult to discriminate between one single *unfolded* stratum and one which is *isoclinally folded*. The amplitudes of the tight, isoclinal  $F_1$ -folds are highly variable, and therefore the observed banded alternations may often represent repetitions due to folding.

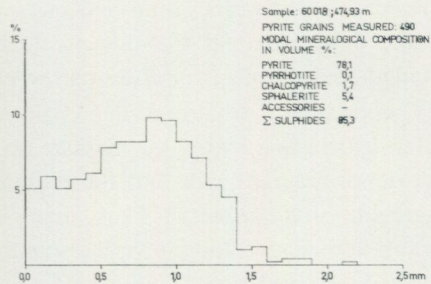
Compared to sphalerite and chalcopyrite, pyrrhotite has a much more irregular distribution within the massive ore volumes. First of all, continuous pyrrhotite-rich bands are rare, but the flattened lens-form prevails for each individual aggregate of the mineral. Thus, many such aggregates within one and the same stratigraphic layer, though very discontinuous, give a banded impression.

Pyrrhotite is nearly always present as a minor constituent even in the purer pyrite ores. As it is often "hidden" as inclusions or in intricate intergrowths with the other matrix sulphides, the mineral is not very conspicuous in the massive banded ores and in small quantities may easily be overlooked. In sections more than a foot thick, pyrrhotite-richer bands may as a rule be encountered. The sympathetic co-existence between pyrrhotite and chalcopyrite is not so prominent in the massive pyrite-dominated ores as in disseminated types described below, but in cases of gradually increasing copper content (both across and along the strata), it is repeatedly seen that the admixture of pyrrhotite increases

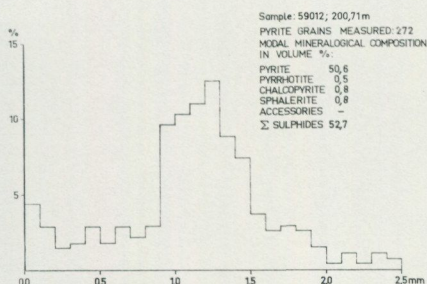
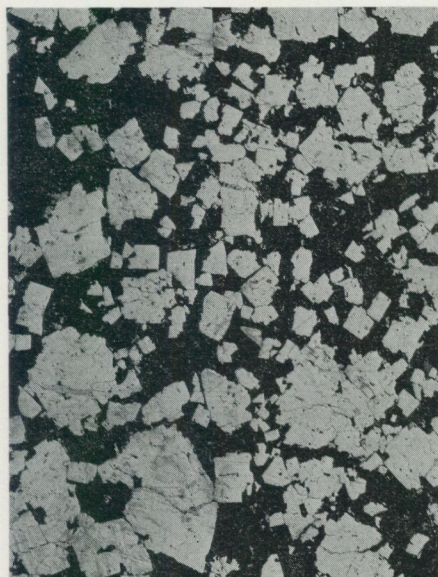
Fig. 47. a—e. Grain-size distribution diagrams and detailed photos on the scale 8:1 from five polished sections of massive pyrite ore.



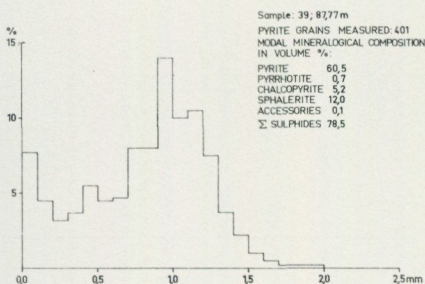
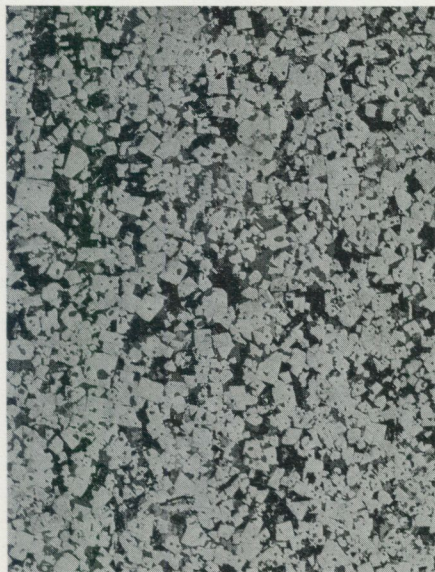
a) Banded pyrite-sphalerite ore. Mixed grain sizes in each band, but distinctly larger sizes in bands with much gangue material.



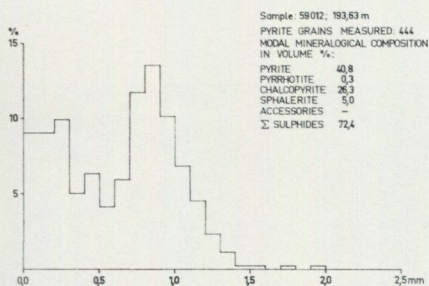
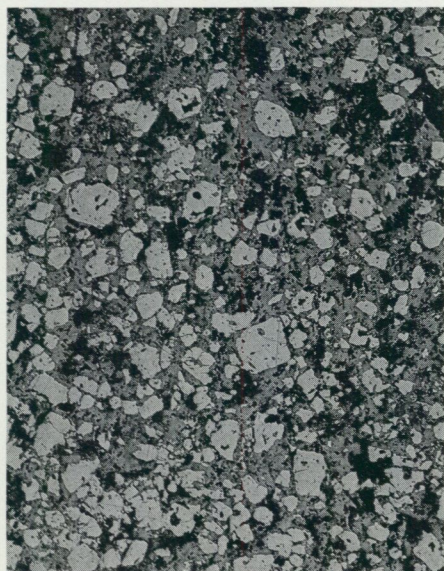
b) Pyrite-sphalerite-chalcopryrite ore. Patch-wise fine-grained island-like aggregates with irregular outlines "floating" in areas with more gangue and somewhat coarser pyrite. No banding visible on the scale of the polished section.



c) Pure pyrite ore with large, irregular aggregates and smaller more perfect individuals "floating" in an important gangue fraction. A weak cataclasis has produced a certain amount of minute grains. No banding visible on the scale of the polished section.



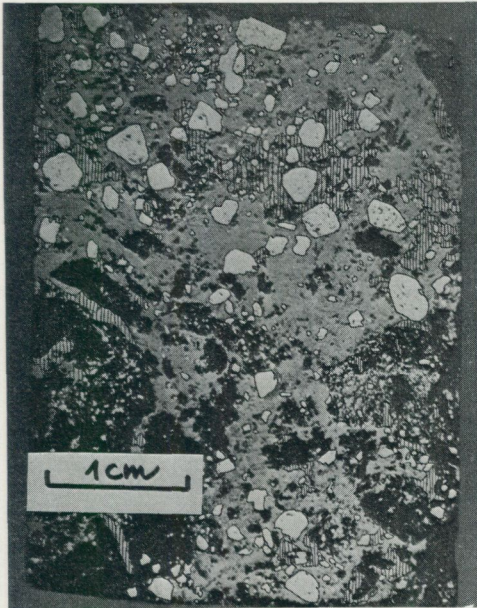
d) Pyrite-sphalerite-chalcopyrite ore consisting of irregular, but densely packed agglomerations, 2—5 mm across. The photo shows how the smaller grain size classes (under 0.5 mm) occur in an irregular constellation of aggregates with little gangue admixture. The grain size increases gradually with the content of gangue material. Only a vague banding, no cataclastic effects visible on the scale of the polished section.



e) Incipient corrosion and fragmentation has reduced the importance of the larger grain-size class and created a considerable class of minute grains in this chalcopyrite-rich pyritic ore. Compare histograms for brecciated chalcopyrite-pyrrhotite ore, Fig. 51.

Fig. 48. Two samples of "durchbewegt" pyrrhotite-chalcopyrite ore taken within a 10 cm drill-core section, illustrating rapid changes in composition. The "Durchbewegung" not only gives a disordered texture in each mineralogically determined ore type, but often results in intimate mixtures of different types over short distances. White and lighter grey, corroded—pyrite. Striped—chalcopyrite. Matrix sulphides: medium grey—pyrrhotite; somewhat darker, sporadic—sphalerite. Large gangue inclusions—mainly quartz; ragged smaller assemblages—schist fragments.

Fig. 49. Typical transition from massive, banded pyrite ore (bottom of picture) through a movement zone to lenticular dissemination of pyrrhotite-chalcopyrite.



correspondingly. There are ores which can be considered as mixtures between pyrite-sphalerite ore and a pyrrhotite-chalcopyrite type. These massive sub-types are also well banded. Pyrrhotite and chalcopyrite are commonly in intimate intergrowth, and the aggregates exhibit two types of distribution:

- a. pyrrhotite-chalcopyrite assemblages randomly spread.
- b. microscale alternations between thin bands rich in pyrite-sphalerite-(chalcopyrite) and pyrrhotite-chalcopyrite, respectively.

The content of galena, which on the whole is a moderate constituent (mean value for the whole deposit: 0.3 weight % Pb) varies sympathetically with the content of sphalerite. However, as observed under the microscope there is sometimes a noticeable reduction of galena when the content of chalcopyrite increases.

The scarcity of the mineral and the fineness of its intergrowths, makes the study of its geometrical distribution a tedious task.

#### 1 B. MASSIVE TO DISSEMINATED, BRECCIATED PYRRHOTITE-CHALCOPYRITE ORE

Texturally and compositionally this is a very variable ore type. But all varieties have many distinct characteristics in common. The mineralogical constituents both of sulphide and gangue material are the same as generally met with in the deposit, but their relative amounts are different. Pyrrhotite and chalcopyrite are quantitatively dominant. They are intimately intergrown and mutually include each other. Variable amounts of gangue and wall rock fragments are always present. The pyrite content is very different from place to place. The gangue is richer in free quartz than is generally the case in the other mineralization types of the deposit. Illustrations are given in Figs. 48, 49 and 50.

The ore type shows much evidence of brecciation or "Durchbewegung", and the grain-size distribution pattern also reflects an advanced fragmentation (Fig. 51). Characteristic features are angular to rounded fragments of wall rock and gangue, and especially of pyrite. The harder constituents have been rolled, bent and cracked. Even the softer sulphides pyrrhotite and chalcopyrite locally bear traces of deformation. The twin lamellae of chalcopyrite are in places deformed. This is not observed in pyrrhotite, but here a formation of "subparallel lensoid discs" may be interpreted as an effect of deformation. The cataclastic effects on the pyrite may however in some cases be astonishingly small. While the exterior of the individuals may be intensively attacked and often well rounded, cracks in the interior are rarer.



Fig. 50. Detail of breccia ore containing much chalcopyrite and a large quantity of rounded pyrite individuals. Small sphalerite areas visible near pyrite grains. The sample is unusually low in pyrrhotite. Host rock—tuffite. Drawing after microphoto mozaic, M. Bergman.

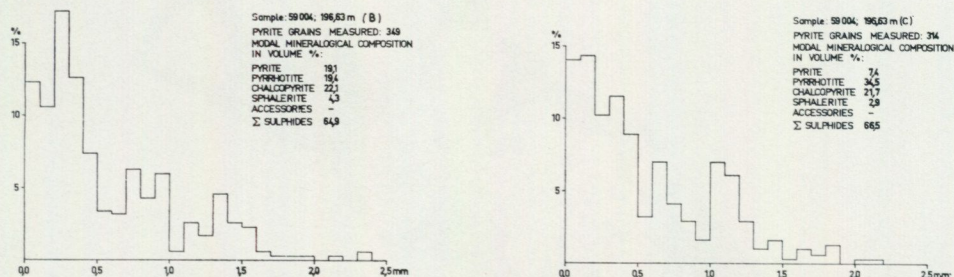


Fig. 51. Grain-size distribution patterns of pyrite from two consecutive drill-core samples of massive brecciated chalcopyrite-pyrrhotite-dominated ore. The pyrite content is respectively 19.1 vol %, and 7.4 vol %. The importance of the grain-size classes 0.0—0.5 mm is due to intense cataclastic fragmentation.

The possibility that pyrrhotite and chalcopyrite have etched pyrite is indicated by repeatedly observed embayments in deformed pyrite crystals, filled by these minerals.

The gangue fragments are often well rounded. Their exterior may be polished, or have a scratchy, striated surface, an observation which is similar to that seen on single tectonically deformed pyrite crystals in a silicate matrix. Small balls of quartz are in some localities very frequent. The softer matrix minerals are sometimes seen to have been smeared out on the surface of the rounded fragments. These are frequently covered with thin films of carbonaceous material or chalcopyrite. This ore type occupies only a small part of the total ore volume of the deposit, however it is seen, especially under the microscope, to be a more or less integrated part of many other ore types. There are graded transitions into other less extreme developments, both regarding the exclusive mineralogy and the tectonic development.

As was mentioned under the description of pyrrhotite's different modes of occurrence (p. 42), there is a gradual transition between small veins of pyrrhotite-chalcopyrite as lateral secretions from massive pyrite-dominated ore and the massive pyrrhotite-chalcopyrite breccia ore. Even if the ore type may not be massive all through an economically exploitable volume, it is seen under the microscope, that the type is identical, whether it is contained as a pocket in disseminated ore or part of a thicker, massive volume.

The exterior morphology of the brecciated ore is irregular in the sense that it does not necessarily follow the common bedding structure of the host. On the contrary, its volumetric distribution is tectonically controlled. It is found where movements may have taken place, or where tectonic voids have been created by these movements.

In principle, its position is parallel to the primary layering only where the dynamic forces have been released along concordant zones. The localization of this

ore type to tectonic zones of weakness equals in many respects that of the individual sulphides as they are seen to have been mobilized and redeposited during metamorphism. But, while the minerals are selectively rearranged, the "durchbewegte" ore seems mainly to have been moved *en bloc*. Further it seems as if the brecciated ore as a whole was not of particularly high mobility. It is especially difficult to imagine the pyrite and some of the gangue and wall rocks fragments as subject to transport over larger distance. The following factors seem to influence the type and quantity of minerals entering the composition: 1. Primary mineralization present within the actual ore volume and in its near surroundings, 2. relative mobility of sulphides and gangue minerals, and 3. metamorphic transformation of pyrite to pyrrhotite.

The availability of different minerals and their relative mobility primarily dictate the composition. There is a marked relative enrichment in chalcopyrite relative to sphalerite, and quartz is much more frequent here than in the common types of gangue in other mineralizations. With particularly sphalerite-rich surroundings, the breccia ore is also relatively rich in this mineral. However, pyrrhotite may be nearly absent in the surroundings, and it seems logical to connect the enormous concentration of this mineral in the breccia ore with the metamorphic transformation of pyrite to pyrrhotite. Because of the textural irregularity and rapid variations in modal mineralogical composition, it has not been possible to check quantitatively if the other more mobile sulphides, galena and fahlore, are correspondingly enriched.

## 2. GENERAL ASPECTS OF THE DISSEMINATED MINERALIZATIONS

The study of the sparse mineralizations, the economically important disseminations of chalcopyrite as well as the economically less interesting parts of the deposit is indispensable for the understanding of the ore bodies. It reveals in a more accentuated form many important features both of the host rock — sulphide relationships and of the metamorphic development of the sulphide assemblages. The metamorphic grain growth, the tectonic deformation during and after the growth of the minerals, the sympathetic relationship between chalcopyrite and pyrrhotite during recrystallization are all features which are best observed in sparsely mineralized volumes.

Also the study of the mineralogical composition of gangue and host rock is often more rewarding in the disseminated ores than in the massive ones. It was emphasized elsewhere (p. 21) that the main economic ore horizons at Stekenjokk were emplaced near a border between different host rock members — generally units of quartz-keratophyre — tuffite and black phyllite. The whole ore deposit as such may be characterized as a border mineralization, and this is especially obvious for the economically exploitable part of it.

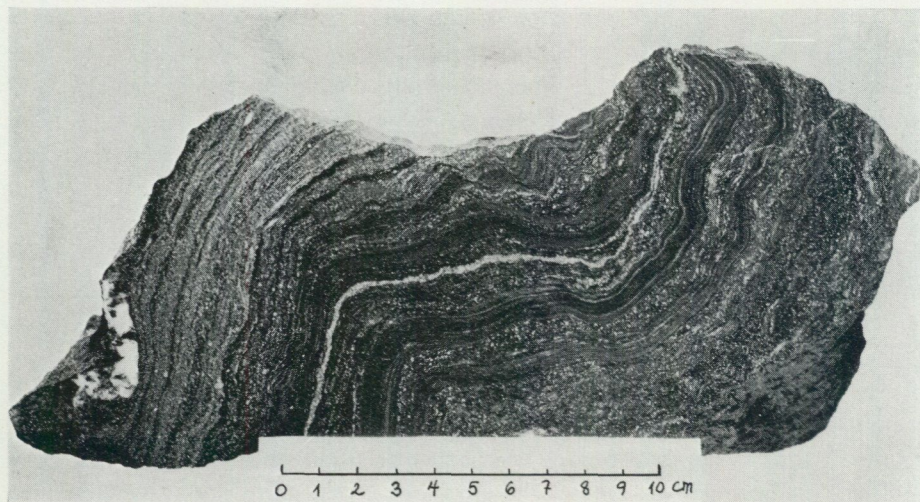


Fig. 52. *Weak pyrite mineralization in fine-banded graphitic tuffite. A few thin sulphide bands are rather massive. Within some of the thicker individual layers pyrite occurs as isotropic disseminations. The mineralized layers alternate with sterile silicate layers of which some are rich in quartz.*

Detailed study shows that the occurrence in fact consists of a multitude of horizons which on the micro-scale both compositionally and texturally repeat the patterns of the main massive layers.

In view of the small thicknesses often exhibited by each individual dissemination it would seem normal that the host rock should be identical all through each such mineralized horizon. However, in a very high proportion of cases, the individual layers of the disseminated ores are in fact localized near a zone of change of composition (depositional facies) of the general host rock type. Sometimes it is localized exclusively within a thin intercalation whose composition is slightly different from the hanging wall and foot wall rocks. The disseminations are in many cases transgressional in the sense that they may occur with identical composition on both sides of a host rock border. This is similar to observations in the thick, more massive ores where radical differences in silicate matrix may occur on variable levels between the hanging wall side and foot wall side of an ore layer. Apparently, the thin mineralized horizons are thus small scale replicas of the thicker massive ores also with respect to their localization in the stratigraphic sequence. There is little or no consequent preference for any particular host rock. The same metal concentrations in the form of disseminations may thus occur in the light quartz-keratophytic rocks as well as in green tuffites and black phyllites.

Texturally the disseminated ores represent a continuous transitional series. The two extremes of this series are:

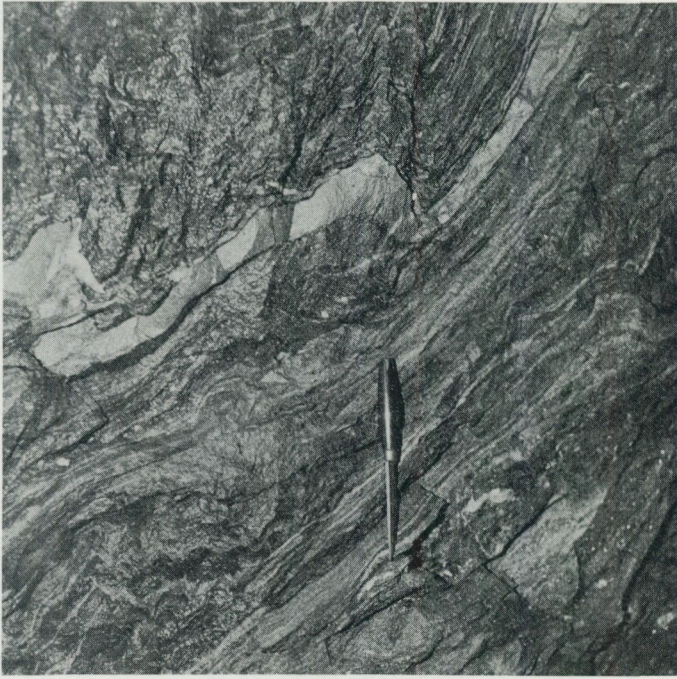


Fig. 53. *Pyritic ore layers in black phyllite of swiftly changing quartz and carbon content. Visible fold phase is  $F_2$  with vertical axial plane. The sum of these mineralized layers is called a "dissemination", but it is obvious that many of the layers in fact consist of massive banded ores of highly variable thicknesses.*

1. "Anisotropic disseminations". Thin, concordant trains of sulphide aggregates or sulphide bands, alternating with important silicate bands. Individually the sulphide bands can often be considered as micro-editions of the massive, banded ores.
2. "Isotropic disseminations". Isolated, small sulphide aggregates, distributed with equal density in all directions, but generally with concordant main hanging wall and foot wall borders.

The disseminated mineralizations at Stekenjokk are as a rule "anisotropic". Wholly "isotropic" sulphide distributions are exceptions, but are locally of great importance. The generally well banded host rock dictates the distribution geometry of the sulphides, even in the more sparse disseminations. With gradually increasing sulphide content, the development can be followed stage by stage from "sterile" host rock to massive banded ores.

The most important difference between a dissemination and a massive, banded ore is in fact the increased vertical distance between the individual mineralized bands. On the other hand, the individual sulphide bands in themselves can



Fig. 54. *Recumbent first phase (F<sub>1</sub>) fold with parasitic structures in light-coloured rocks with thin bands of pyritic mineralization. The host rocks consist of alternating layers of sericitic quartz-keratophyre and tuffitic rocks. The mineralization is made up of millimetre-thick massive or densely disseminated ore layers which are perfectly concordant to the compositional banding of the host rocks. The borders towards the sterile silicate layers are neat and abrupt. Pyrite is the main sulphide, but some thin layers are dominated by pyrrhotite. Chalcopyrite and sphalerite are subordinate. The thickness and the rhythmic repetition of the different types of layers are the same for the mineralized strata as for the sterile host rock strata.*

show differing degrees of dilution. Instead of continuous bands, there are then trains of single individuals of one species or of aggregates of pyrite, pyrrhotite, chalcopyrite and sphalerite (Figs. 52, 53 and 54).

Mineralizations which on the basis of drill-core inspection are reported as disseminations without other geometrical specifications are often real micro-editions of the massive, banded ore types. Millimetre thick layers may be followed more than ten metres (in some cases 20 metres or more, all depending upon the observation possibilities in the mine) and in a perfectly concordant position. There are transitions to discontinuous pyrite bands, and also thin stringers where the thickness of the band may equal the grain size, in other words trains of pyrite individuals in a perfectly concordant position.

The frequency of perfect pyrite cubes is relatively higher in the disseminated than in the massive ores. Crystal faces may be well developed in all grain-size classes contained within one and the same volume. However, the general rule that the smaller the crystal, the more perfect its outline, is not invalidated. This rule is applicable when the crystal form is due to near-saturation growth and not for instance to cataclasis.

The minerals contained in the disseminations are the same as in the massive ores. Pyrite and pyrrhotite occur however locally in sensibly different proportions. Relatively, the disseminations are richer in pyrrhotite than are the massive, banded ores. The relative frequency of pyrrhotite is somewhat lower in the pure albite-quartz rocks than in the green tuffites, containing iron-rich chlorites, or in black phyllites. Altogether this suggests a connection with the metamorphic transition of pyrite to pyrrhotite, which would be favoured by the greater reaction surface in the disseminated ores and the availability of iron in the host rock.

Chalcopyrite, sphalerite and galena occur on an average with similar spread and in similar proportions in all the varieties of sulphide concentrations, their mean relative importance is nearly identical in the disseminations and in the massive banded ores, as shown in Table 10, Figs. 64 and 66—70, giving respectively contents and proportions of metals and minerals according to increasing S-content. It is remarkable that the "sterile" wall and country rocks (with less than 0.5 % sulphur) contain sensibly the same spread and mean proportions of copper, zinc and lead as do the mineralizations which are highest in sulphur. It is further most probable that the average proportions between the major minerals and minor constituents such as fahlore and sulphosalts are also similar in all degrees of mineralization density. This relationship has only been studied qualitatively under the microscope, but is substantially supported by the chemical analyses. It is improbable that antimony, arsenic, silver and gold etc. should enter other minerals in the disseminations than they do in more concentrated mineralizations.

The banded alternating rhythm between copper, zinc and iron sulphides is apparently the same in the disseminations as in the massive bands. As exclusive

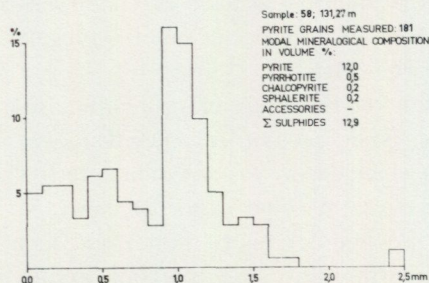


Fig. 55. Grain-size distribution pattern of pyrite in a banded dissemination in quartz keratophyre.

(single) sulphides in disseminated mineralizations both pyrite and pyrrhotite may locally not only make up single beds, but can attain decimetre — or metre — thicknesses, — mostly with less than 5 vol. % sulphides in the rock. (These types are not in any respect considered to be economic ores.)

Pyrrhotite as a single sulphide is rarer in the light rocks than in the black phyllite, where it mostly occurs as discontinuous trains of flattened aggregates.

Isolated disseminations of sphalerite are rare. When occurring, they are always well stratiform, with constant thickness along the strike. Pyrite is the most conspicuous iron sulphide in their neighbourhood. Chalcopyrite as single sulphide is rare also in the disseminations, though more frequent than sphalerite. Chalcopyrite occurs in two geometrical varieties which are both transitional into types of intimate coexistence with other main sulphides. The one is as trains of flattened grains or thin, flamy stringers parallel to the compositional banding of the host. The other is an irregular vein filling in small cracks and fissures, mainly the result of mobilization and redeposition in shattered rocks.

Chalcopyrite and sphalerite exhibit as a rule a layered, alternating distribution pattern in the banded, disseminated ores. They are interrelated in exactly the same manner as are the bands of the massive ores. It is only the rhythm of the silicate/sulphide distribution which is different. There is a greater vertical spacing between the banded metal concentrations, and single individual bands of dissemination can appear as consisting of only chalcopyrite + iron sulphides or of only sphalerite + iron sulphides.

In the greater part of the volume of the disseminations a banded, concordant distribution of bands rich in each of the respective sulphides is to an astonishing degree kept intact even after intense folding. Therefore it may be suggested that the greater part of the disseminated mineralizations in their content and distribution of metals are formed prior to folding. Disseminated ores which do not reflect this pattern are as a rule marginal to the massive, banded ores (which repre-

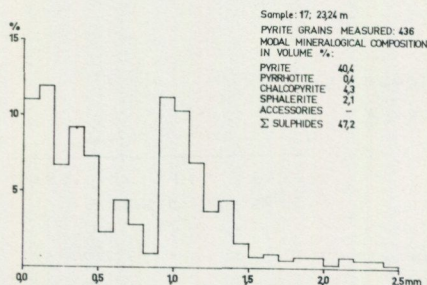


Fig. 56. Grain-size distribution pattern of pyrite in a transitional zone dissemination — massive ore. The two main peaks of the histogram are expressions of two possible growth generations of pyrite.

sent a high metal concentration, capable of producing lateral secretion of mobile sulphides) and are mostly composed of chalcopyrite, the more mobile of the main sulphides. The host rock may be light keratophyric as well as black phyllite or intermediate tuffitic types.

By virtue of the brittle nature of the keratophyric rocks, the mobilized chalcopyrite has, in favourable localities, moved further into this rock type than into any other. The resulting impregnation, which as a rule consists of small-scale, irregular vein-like fillings, constitutes in many places good economic ores.

A few grain-size distribution patterns (histograms) have been established for ores with less than 50 vol. % sulphides (Figs. 55 and 56). They support the impression that the general mean grain size in the disseminated mineralizations is slightly greater than that of the massive banded ores. Locally, however, there are multitudes of small individuals which considerably reduce the mean grain size.

These small crystals are considered to represent "new" metamorphic products, and they do not affect the rule that the crystal growth has been most intense in a mixed silicate/sulphide milieu where the contact surface between the two phases is at a maximum.

In strongly deformed rock volumes with disseminated mineralization, the cataclasis and fragmentation of pyrite have sometimes gone much further than in the massive ores. Extreme disintegration of pyrite into the finest fragments may locally be seen in the soft graphitic phyllites as well as in the brittle keratophyres. No particular grain-size class attributable to metamorphic grain growth can then be discerned. The phenomenon may be illustrated by a generalized grain-size distribution curve as shown in Fig. 57. See also Fig. 51. The pyrite individuals are mostly isotropically distributed. The concentrations of fragmented pyrite in black phyllite have a general disordered exterior geometry. In brittle rocks they are mostly connected with visible dislocations, often irregularly ramified in the rock volume.

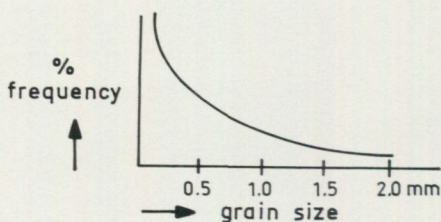


Fig. 57. Generalized grain-size distribution curve of tectonically fragmented pyrite ore.

It is clear that cataclasis and fragmentation have taken place repeatedly. In some cases cataclasis can be shown to have taken place simultaneously with the strong fold phase  $F_1$ . In other cases it is part of the latest events in the development of the deposit. The irregular chalcopyrite-pyrite disseminations in light rocks, the brecciated chalcopyrite-pyrrhotite-pyrite assemblages and certain pyrite disseminations consisting of fine, fragmental pyrite "gravel" together with big, coarse crystals, have all a genetic development which is intimately linked to these fragmentation processes.

## 2 A. DISSEMINATIONS IN LIGHT-COLOURED ROCKS

The most common type in this subgroup is the more or less banded pyrite-dominated disseminations containing sphalerite and chalcopyrite and variable amounts of pyrrhotite.

It is typical that if the host rock shows rhythmic alternations between millimetre to centimetre thick layers of slightly different compositional types, there is a corresponding alternation in the development of the sulphide distribution, sterile layers alternating with layers of disseminated sulphide. If the sulphide-bearing layer is thick and homogeneous, the distribution of sulphides within it is more isotropic. The grain size is often concentrated about one major class; a majority of the pyrite grains having attained 1.0 mm and a few of them exceeding 1.2 — 1.5 mm.

According to the tectonic treatment undergone by the layers, large variations of individual crystals or aggregate geometry can be observed. The general picture is that if the crystals do not exhibit the isometric cube form, they have a weak, but widely observable tendency to be aligned more or less parallel to the  $F_1$  fold axis, within the  $S_1$  surfaces, the crystals having been deformed during their growth (Fig. 15). In weak disseminations, the chalcopyrite and sphalerite aggregates mostly appear randomly distributed in relation to the pyrite grains. Pyrrhotite behaves very much in the same way. All these "softer" sulphides occur in



Fig. 58. *Shattered quartz-keratophyre with very fine-grained, vein-like impregnations of chalcopyrite.*

aggregates flattened parallel to the prevailing schistosity. In denser disseminations and particularly in more intensively deformed parts it is seen how the softer sulphides have moved to the pressure shadows around the pyrite crystals. This feature is beautifully developed in volumes where the pyrite crystals are deformed to give lozenge-shaped sections, also partly after increase in volume had stopped (Fig. 16). When the relative pyrrhotite-content increases, it can be seen how chalcopyrite gradually prefers intergrowth with this mineral. Sphalerite seems to be more or less unaffected by this development. In more deformed host rock layers the pyrrhotite-chalcopyrite aggregates can gather into bigger veinlets entering discordant fractures and cracks. They may be interpreted as an initial stage in the formation of the brecciated pyrrhotite-chalcopyrite ore type.

A characteristic ore type in the light rocks is the generally coarse, irregularly ramified dissemination of pyrite and chalcopyrite. It always occurs in more or less deformed host rocks. Compared to pyrite and chalcopyrite, pyrrhotite and sphalerite are as a rule quantitatively subordinate. The pyrite individuals which may attain very coarse sizes are nearly always somewhat shattered and physically corroded. Perfect cubes are rare. The distribution is often ramified according to visible irregular dislocations in the brittle host rock. The type may as a rule be interpreted as a combination of a primary (pre-tectonic) pyrite-dominated dissemination which has been mechanically and chemically mobilized and rede-

posited nearly *in situ*, combined with chalcopyrite mobilized from adjacent volumes.

Where the primary pyrite is lacking, chalcopyrite is often the only sulphide visible (Fig. 58). However, trace amounts of other more mobile sulphides such as galena and fahlore are locally seen to accompany the chalcopyrite, and in favourable localities of minimum stress, the secretion has led to the formation of meta-ore pegmatites.

## 2 B. OTHER DISSEMINATED ORES

in black phyllites, often adjacent to massive ores, or in tuffitic rocks.

The majority of disseminated mineralizations in black phyllites or strongly tuffitic rocks are compositionally of the same type as those most frequently met with in the light rocks, which means that the pyrite-dominated chalcopyrite-sphalerite-bearing type is relatively abundant even here. However, the relative admixture of pyrrhotite is generally more pronounced (Fig. 59). Many occurrences appear as more or less intimate mixtures of pyrite and pyrrhotite-chalcopyrite aggregates. In addition to the general mineral associations, isolated, deformed nodules of extremely fine-grained pyrite are found with apparently random distribution or weak banding in certain horizons of the black phyllite. Some of the nodules exhibit zoned textural features and may be interpreted as vestiges of framboids (cf. Figs. 8 and 9).

Iron sulphides are normal constituents of all black shales and can therefore not be interpreted as an indication of a general ore formation, but in Stekenjokk gradual transitions, both texturally and compositionally, occur from monomineralic pyrite nodule mineralizations to base metal — iron sulphide assemblages. In some cases the pyrite nodules are an integral part of fine-banded disseminated copper-zinc ores, and intimate intergrowths occur between all sulphides, indicating contemporaneity for all sulphide constituents. This again indicates that the host rocks and their total sulphide content were formed at the same time.

Disseminations consisting exclusively of one of the iron sulphides are more frequent in black phyllites and dark tuffites than in the light-coloured rocks. Pyrrhotite disseminations of this type may locally attain 1—4 metres' thickness. The aggregate distribution is then sometimes quite irregular, consisting of flattened grains without particular concentration along any horizon. Pyrite disseminations may also exhibit this irregular geometry, but are as a rule more banded. One particular pyrite grain-size pattern which is rather common in certain disseminations of the black phyllites consists of bigger crystals of quite even size (1.0 — 1.5 mm) and with relatively well developed outlines, which are inter-

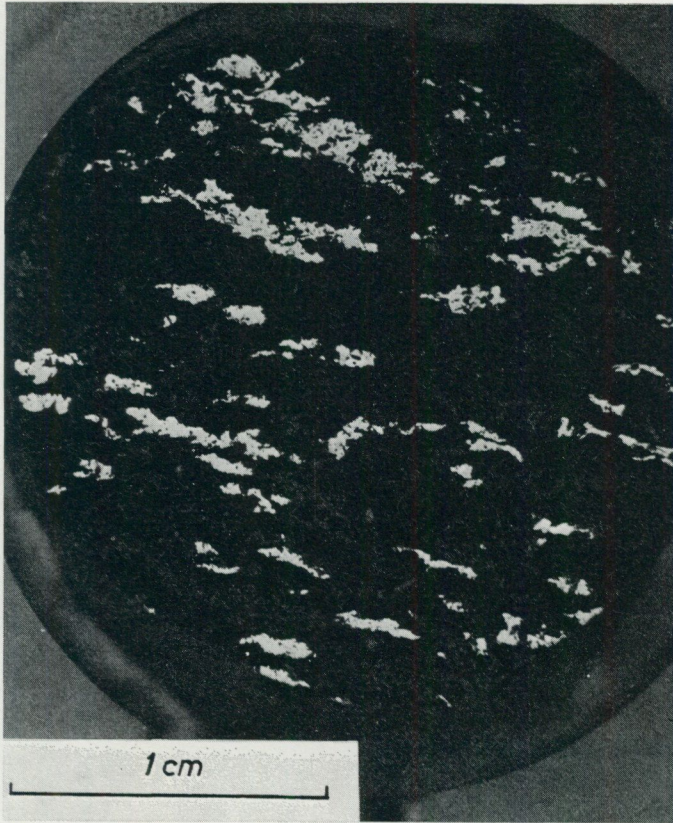


Fig. 59. Dissemination of flattened aggregates of pyrrhotite-chalcocopyrite. A sparse content of pyrite is mostly made up of small grains isolated from the other sulphides.

mingled with multitudes of small individuals with variable perfection (Fig. 60). Sometimes sharply angular, irregular outlines are seen, sometimes a high degree of euhedralism.

The small individuals are in some cases undoubtedly the result of a physical fragmentation. The bigger ones seem to carry only small traces of cataclasis as cracks and some missing corners. In other cases an overlapping grain growth has masked every possible trace of a physical fragmentation.

It has not been possible in an unequivocal manner to correlate these features with different degrees of deformation of the host rock. When pyrite is combined with pyrrhotite-chalcocopyrite, the preferential intergrowth between the latter minerals is often so well developed in the black phyllite that the pyrite grains only rarely are in contact with the two others. Sphalerite is mostly equally distributed between pyrite and pyrrhotite-chalcocopyrite contacts. It is sometimes temp-

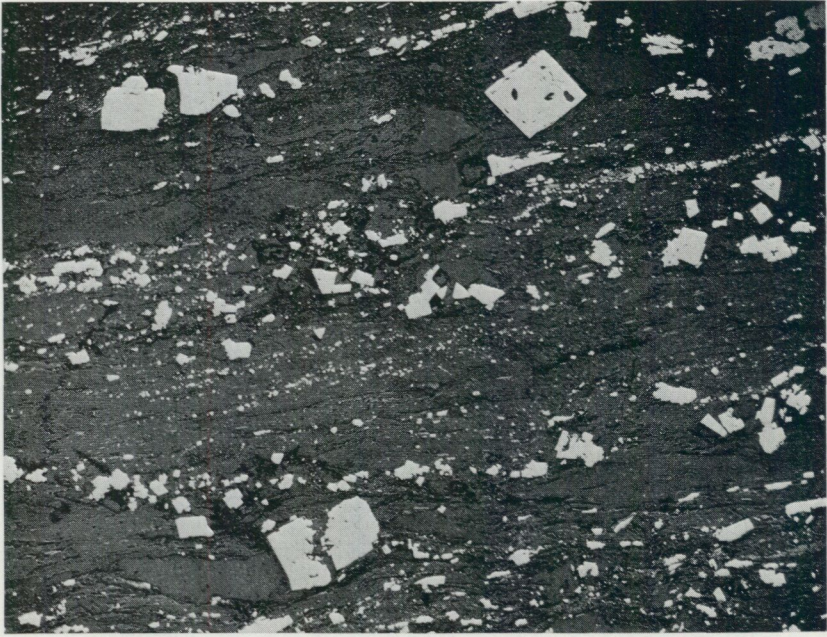


Fig. 60. Pyrite dissemination in black phyllite exhibiting three main grain-size groupings. All the bigger individuals are zoned. The uneven lamination of the host rock indicates an irregular deformation. Deformation both during the growth (flattening, elongation) and after the growth (ruptures and fragmentation) can be seen in all the size classes of pyrite. 6.5 X.

ting to regard this particular distribution as a metamorphic segregation phenomenon connected with the mobilization in the actual locality. The more deformed the host rock is, the more accentuated are the accumulations of pyrrhorite-chalcopyrite versus pyrite. These features therefore appear to be initial stages in the formation of the independent, massive, brecciated pyrrhotite-chalcopyrite ores.

The generally fine-grained and incompetent black phyllite may contain much mobilized and redeposited chalcopyrite, often as conspicuous rims along the contact with the massive ores. These rims or zones are as a rule narrower than those observed in the brittle keratophytic wall rocks, but are often spectacular by their richness. There are examples of such marginal impregnations in black phyllite where the "receiver" is stuffed with secreted chalcopyrite in an approximate amount of 15 vol. % chalcopyrite, several metres along the contact and with a thickness of 20—40 cm. However, the secretional impregnations usually fade out after a few centimetres into their new host. They are clearly tectonically conditioned, and occur in zones which have been strongly affected by the folding, and preferentially parallel to the contact with rocks of greater competence.

Small, often disconnected veinlets and irregular patches of chalcopyrite, with or without other accompanying sulphides, usually fade out after some centimetres or a couple of decimetres. Many of the irregular chalcopyrite patches appear in places to be completely isolated islands within their host which may be a firmly cemented breccia of black phyllite. This indicates that locally the lateral secretion was at its maximum or even completed before the end of the folding and shattering movements.

Meta-ore pegmatites are found in stress minimum zones in the black phyllite, thus occurring in the same way as in the light rocks. Some of the best concentrations of coarse-grained fahlore and gudmundite are located in small pockets and crack fillings in black phyllite adjacent to big recumbent folds of massive banded pyrite-chalcopyrite-sphalerite ore.

#### ASPECTS OF CHALCOPYRITE ENRICHMENTS IN WALL ROCK LAYERS ADJACENT TO MASSIVE BANDED ORES

On the basis of observations in the mine and microscope studies a few simple rules have been established regarding the localization and intensity of chalcopyrite impregnations which locally are found in marginal positions to massive banded ores (Figs. 61, 62 and 63).

1. The more intense the deformation, the broader the impregnated zone. This particularly refers to shattering or small-scale fracturing of competent rocks, where mobilized chalcopyrite has invaded the dislocations.
2. Generally, the impregnation (secretion) goes further into quartz-keratophyric rocks than into black phyllites.
3. The best developed low-pressure zones contain the strongest concentrations of mobile minerals, particularly chalcopyrite. This mainly applies to the hinge zones and drag structures of the ore folds where increased volumes correspond to an influx of mobile sulphides, and generally of gangue minerals such as quartz and carbonate. A corresponding relative increase in grain size, particularly of pyrite, is observed.
4. In otherwise structurally comparable sites the richer copper impregnations are found adjacent to those massive pyrite ores, which in less deformed localities also show relatively high contents of copper.

The quartz-keratophyre has a more uniform and coarser grain size than the black phyllite. This gives a higher porosity and permeability whether deformation

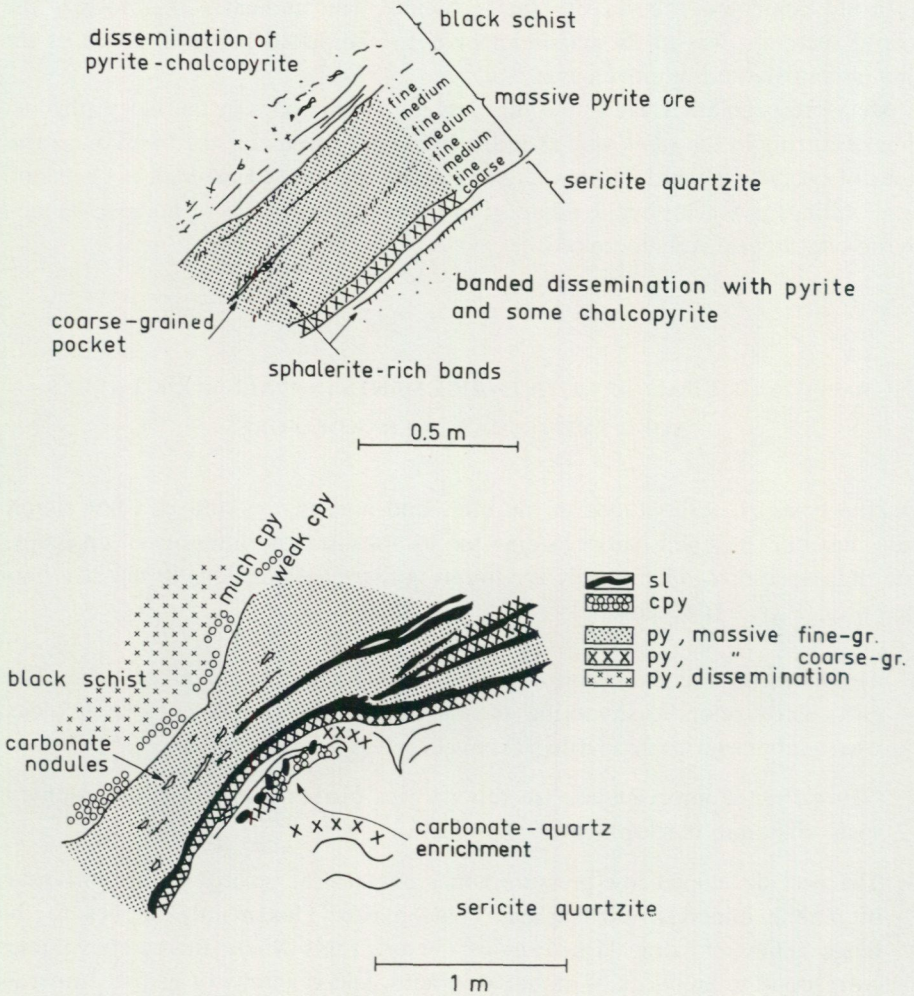


Fig. 61. Diary sketches showing two examples of bilateral metamorphic secretion of chalcopyrite. In the upper example the foot wall layers had already a primary copper content to which the secreted chalcopyrite was added on tiny cracks. In the lower example the mobile gangue minerals quartz and calcite have accompanied the secreted chalcopyrite.

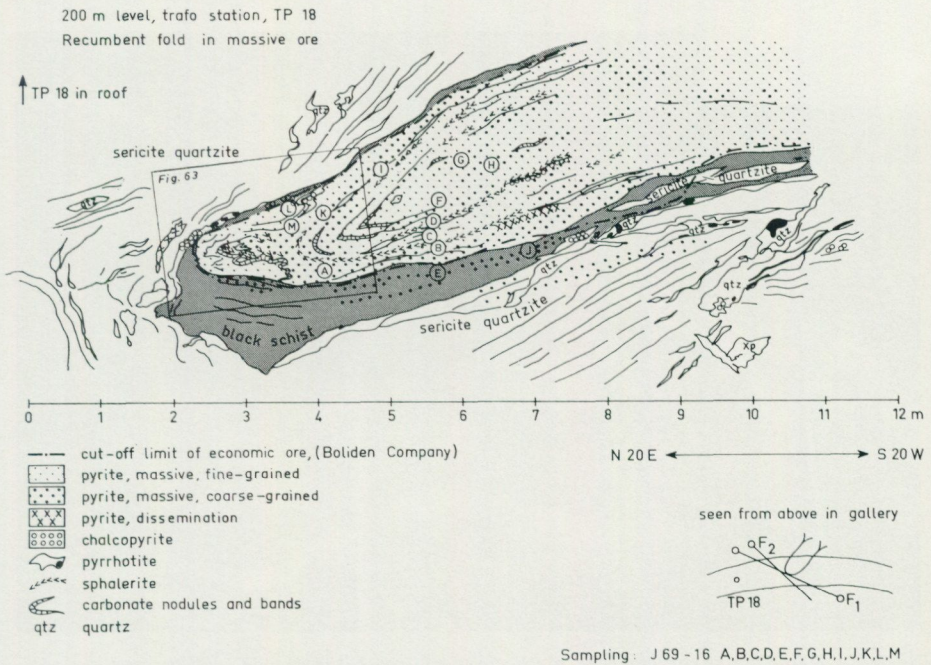


Fig. 62. Hinge of tight, recumbent  $F_1$  fold in massive, pyritic ore, showing:  
 1. Thickening of rock layers in hinge zone, stretching (thinning) along limbs. A layer of black phyllite is adjacent to the ore fold all the way round, but is tectonically reduced to a few centimetres' thickness on the hanging wall side.  
 2. Mobilization and redeposition of minerals in tectonic weakness zones.  
 3. Coarsening of grain size in thickened zones, particularly where pyrite meets mobilized calcite and quartz (matrix effect).

has taken place or not. Generally a finer grain size and probably also a more inhomogeneous grain-size distribution of the black phyllite, which allows the finer grains to slip in between the larger ones, produces a more impermeable rock. Deformation has created more and coarser cracks in the brittle keratophytic rocks than in the black phyllites, and here the largest accumulations of chalcocopyrite veinlets are found.

RELATIONSHIP BETWEEN ORES AND REGIONAL METAMORPHISM

On structural grounds it may be concluded (p. 28) that the Stekenjokk mineralizations are of pre-tectonic origin. Important ore thickening and thinning patterns control the exterior morphology of the ore bodies.

The ores are of pre-metamorphic origin and have undergone the same greenschist facies metamorphism as their enclosing wall and country rocks. The presence of retrograde common hornblende is restricted to the gabbro sills and represents remnants of an intrusive paragenesis.



Fig. 63. Detail photo of the nose of the fold shown in Fig. 62. A well-formed drag-fold and thickening zone with strongly increased pyrite grain size. Thickened limestone and sphalerite bands are seen. Small pockets with quartz, chalcopyrite, in some places minor fahlore and galena are found both along the wall-rock contact and within the massive ore.

The mineralizations consist of several parallel, stratiform layers of relatively homogeneous and similar mean composition. Individually some of these layers are isolated from each other by important intercalations of silicate rocks. Within each of these ore layers the intergrowths between the ore minerals reveal that they were all present when their recrystallization (diagenetic and/or metamorphic) started. Their mutual geometric relationships seem to exclude the possibility that any particular one of them was introduced at a later stage than the others.

On the contrary, at each mineralized stratigraphic level all the ore constituents were assembled within the primary depositional volume at the same time.

This is particularly true for the common base metal sulphides sphalerite and chalcopyrite. Some metamorphic neoformations of minerals occur, but their geometry and accompanying minerals always indicate that they were formed *in situ* or a short distance away (millimetres to some metres) from their original place of deposition. The transformation of pyrite to pyrrhotite is the most important metamorphic effect on the ore mineralogy of Stekenjokk. The effect is stronger in the disseminated mineralizations than in the massive ones, thus giving rise to a zoned pattern visible in different cross-sections, — pyrite-dominance in the central, massive zone and increasing relative pyrrhotite content outwards to the weakest disseminations.

Sulphides and gangue minerals were mobilized and at places selectively redeposited at variable distances from their original site (internal and lateral secretion). A sequence of mobilization ability of ore and gangue minerals can be established. Relatively mobile minerals were fahlore, galena and chalcopyrite, pyrite being the most inert of the common sulphides. A sequence of redeposition of the minerals is also clearly seen. It has the opposite order of the mobility sequence and is identical with the minerals' relative "strength of crystallization".

Most ore mineral textures are of metamorphic origin.

The apparent depositional sequences of the ore minerals are the results of grain growth and selective mobilization and redeposition during the metamorphism.

The "oldest" minerals are those which possess the greatest crystallization strength and have a low mobility: pyrite and arsenopyrite. The "youngest" minerals are mobile and exert a relatively low crystallization force: chalcopyrite and the minor galena and fahlore.

Local sulphide pegmatites are coarse-grained concentrations of more rare constituents in certain pressure minimum zones created by the fold movements. The softer minerals such as galena and fahlore have given the common sulphides the possibility to develop very coarse crystals. These concentrations, generated by the metamorphism, are called meta-ore pegmatites (cf. Lawrence 1967). The fillings of cracks and fissures parallel to the axial plane of the second fold phase ( $F_2$ ) were deposited by low-temperature aqueous solutions. A more or less constant depositional sequence is observed — quartz, carbonate, iron sulphide, zeolite (?), irregular distribution of chalcopyrite. The mineralization density of the fissures can in places be demonstrated to be proportional to the sulphide content of the rocks they cross.

The fissures and their subsequent filling were generated in a folded, well consolidated and rigid rock complex. They are epigenetic in relation to their surroundings and are wholly generated by the metamorphism. They may be called meta-deuteric (or "meta-hydrothermal") fissure deposits.

Discordant, irregular sulphide masses have in places grain sizes indicative of abrupt chilling of a highly mobile sulphide "mush" at the contact with a cold wall rock. Such "magmas" are considered to have been generated during folding and metamorphism by a rough squeezing of primary banded ore. They are an exceptional example of non-selective metamorphic mobilization and may be called "metamorphic sulphide neomagmas". Their extension and their total volume are relatively unimportant.

To judge from the intergrowths of silicates and sulphides and their correlation with the tectonic development, it appears clear that metamorphism reached its maximum during the first fold phase ( $F_1$ ). Subsequent regressive metamorphism found its last spectacular manifestation in the form of fissuring and fissure-filling on zones parallel to the axial plane of the second fold phase ( $F_2$ ).

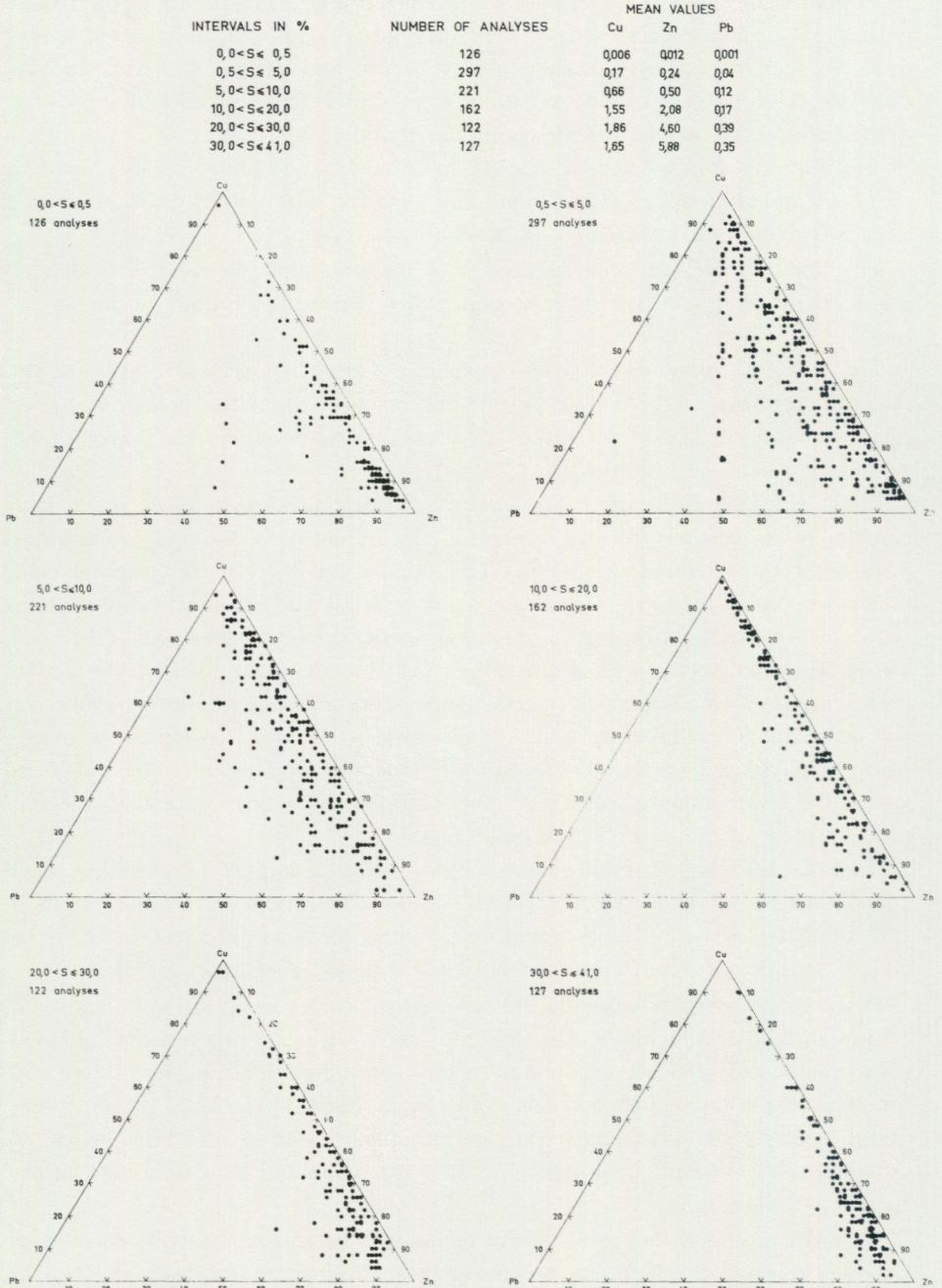


Fig. 64. Weight proportions of Cu, Zn and Pb from 1055 ore analyses. Triangular plots at intervals with increasing sulphur content.

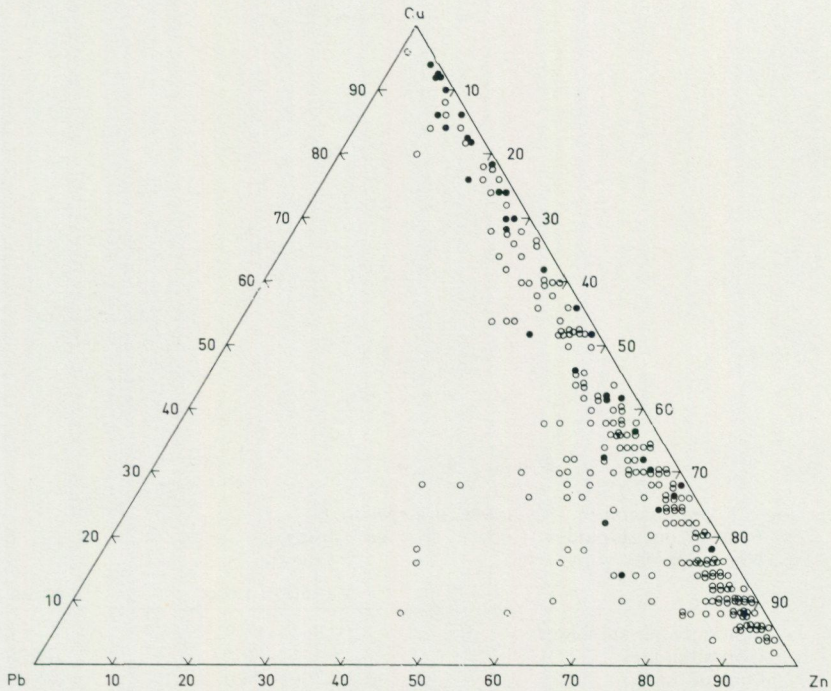
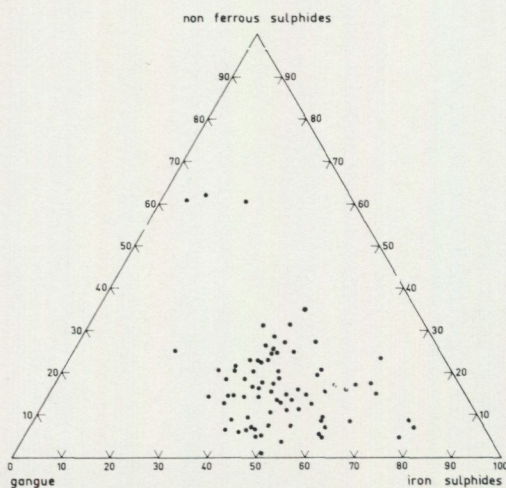


Fig. 65. Weight proportions of Cu, Zn and Pb from 257 ore and wall-rock analyses. Plot on one triangular diagram of 222 analyses containing  $<0.3\%$  Cu (rings) and 35 analyses containing  $\geq 0.3\%$  Cu (black spots).

#### CHEMICAL AND MINERALOGICAL CHARACTERISTICS OF THE MINERALIZATIONS

In the following section some of the main mineralogical and chemical characteristics of the ores will be presented. Figures and tables are based upon the chemical analyses of the ore elements Cu, Zn, Pb, Fe, S and Ag. Mineralogical mode calculations through manual point-counting (Figs. 66 and 67) under the microscope and computerized calculations and plots (Figs. 68, 69 and 70) from chemical analyses (KISMOD) are presented.

The spread of the base metal proportions is very similar regardless of variations of the mineralization intensity (Figs. 64 and 65). The "sterile" wall and country rocks (with less than 0.5 % sulphur) contain a similar spread of the relative proportions of copper, zinc and lead as do the ores with up to 41 % sulphur. Lead shows a weak relative "enrichment" in some low-sulphur samples. Not only the spread, but also the average values of these proportions are fairly similar all through the progressive increase of the sulphur-content. The silver



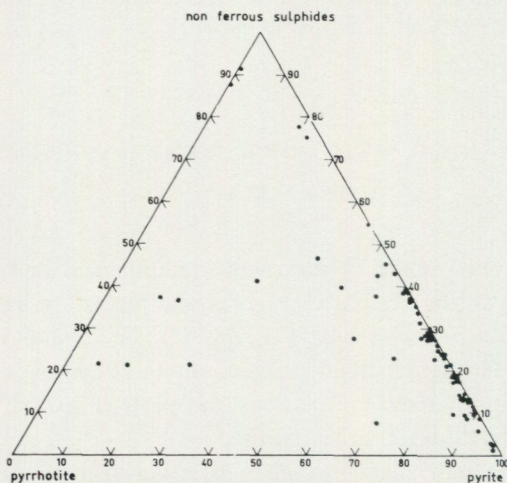
Mineralogical composition of 79 massive, ore specimens

Non ferrous sulphides = cpy + sl + gn + aspy

Iron sulphides = py + po

	Variation range	Mean value
Non ferrous sulphides	0.85 — 61.95 %	17.67 %
Iron sulphides	5.51 — 78.14 "	46.26 "
Gangue	12.76 — 54.07 "	36.09 "

Fig. 66. Triangular plot non Fe sulphides—Fe sulphides—gangue. Manual point-count.



Mineralogical composition of 79 massive, gangue-free ore specimens

Non ferrous sulphides = cpy + sl + gn + aspy

	Variation range	Mean value
Non ferrous sulphides	1.62 — 91.83 %	26.83 %
Pyrite	0.55 — 97.39 "	64.87 "
Pyrrhotite	0.42 — 72.28 "	6.06 "

Fig. 67. Triangular plot pyrite—pyrrhotite—non Fe sulphides. Manual point-count.

TABLE 17. Volume percentage of sulphide related to sulphur and base metal contents. 686 ore analyses calculated by the KISMOD program.

Sulphur content w. %	Number of samples	Mean values weight %			M. v. volume % of sulphide
		Cu	Zn	Pb	
0.0 < S < 5.0	45	0.14	0.36	0.08	5.05
5.0 ≤ S < 10.0	171	0.58	0.76	0.12	11.28
10.0 ≤ S < 15.0	97	1.48	1.55	0.10	20.64
15.0 ≤ S < 20.0	81	1.76	2.38	0.17	29.21
20.0 ≤ S < 25.0	74	1.92	3.55	0.28	39.52
25.0 ≤ S < 30.0	71	1.92	4.73	0.34	49.69
30.0 ≤ S < 35.0	93	1.60	5.82	0.32	59.60
35.0 ≤ S < 40.0	50	1.75	5.88	0.27	68.86
40.0 ≤ S < 41.0	4	1.06	5.12	0.11	75.80
0.0 < S < 41.0	686	1.33	2.84	0.20	32.52

686 samples analyzed

685 " contain Cu

686 " Zn

561 " Pb

Mean value of the 25 highest sulphur assays is 38.23 %.

TABLE 18. Average contents of Cu, Zn, Pb and Ag in four groups of analyses with variable S-content. Plot points shown in Fig. 74 C and D.

Samples	Sulphur content w. %	Metals	Cu %	Zn %	Pb %	Ag ppm	Plot points
70	0—0.99		0.009	0.018	0.002	0.48	I
44	1—4.99		0.046	0.079	0.060	1.32	II
15	≥ 5		1.372	2.416	0.356	42.8	III
Total ore	20.1		1.46	3.03	0.3	53	T

Fig. 68. *Triangular plots non Fe sulphides—Fe sulphides—gangue illustrating the variations with increasing sulphur content. Note the rectilinear development towards a massive ore composition of 70—80 % iron sulphides in a theoretically gangue-free sample. KISMOD calculation and plot.*

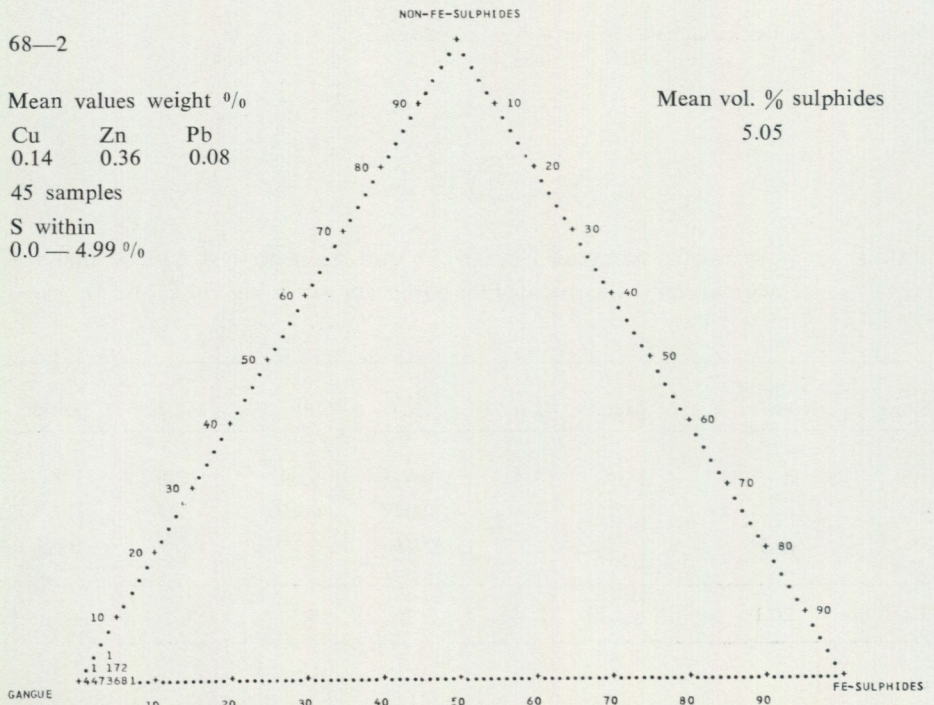
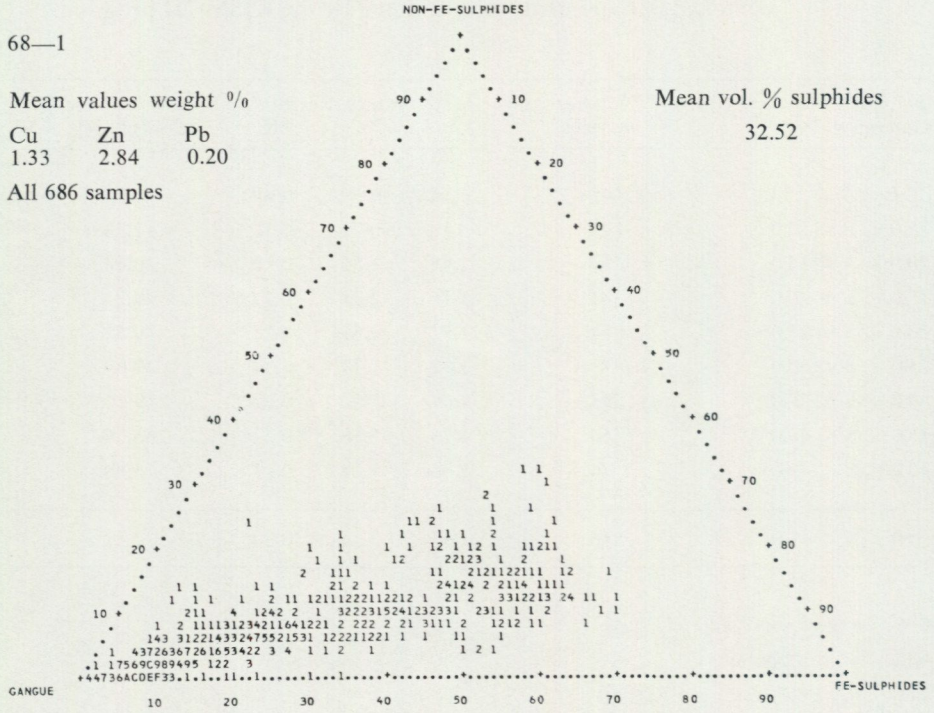










Fig. 69. *Triangular plots pyrite—(sphalerite+galena)—(chalcopyrite+pyrrhotite) weakly illustrating the sympathetic co-variance of sphalerite and pyrite. KISMOD calculation and plot.*

69—1

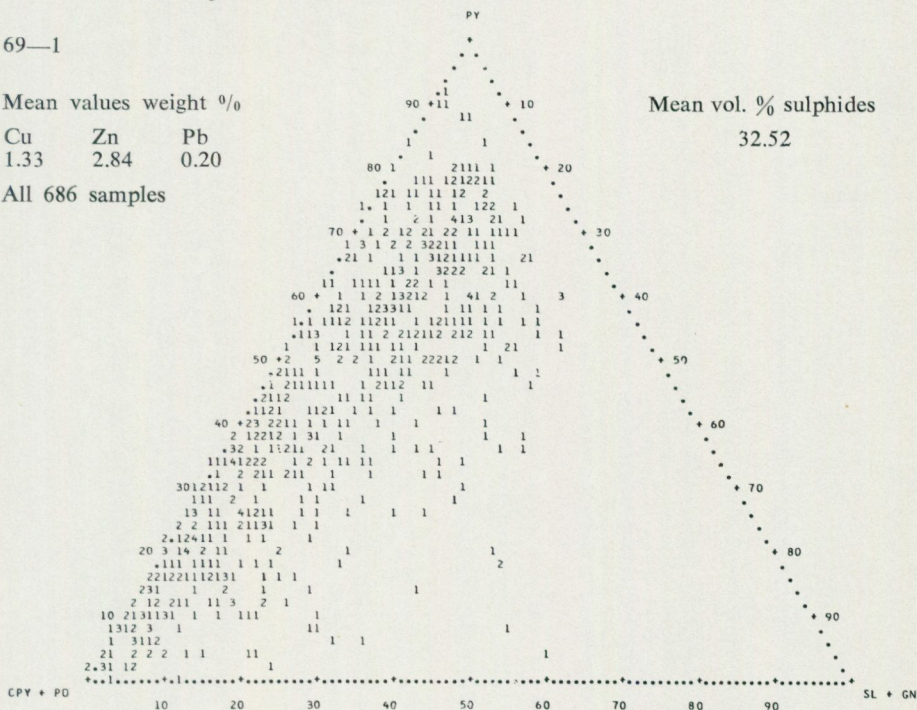
Mean values weight %

Cu	Zn	Pb
1.33	2.84	0.20

All 686 samples

Mean vol. % sulphides

32.52



69—2

Mean values weight %

Cu	Zn	Pb
0.14	0.36	0.08

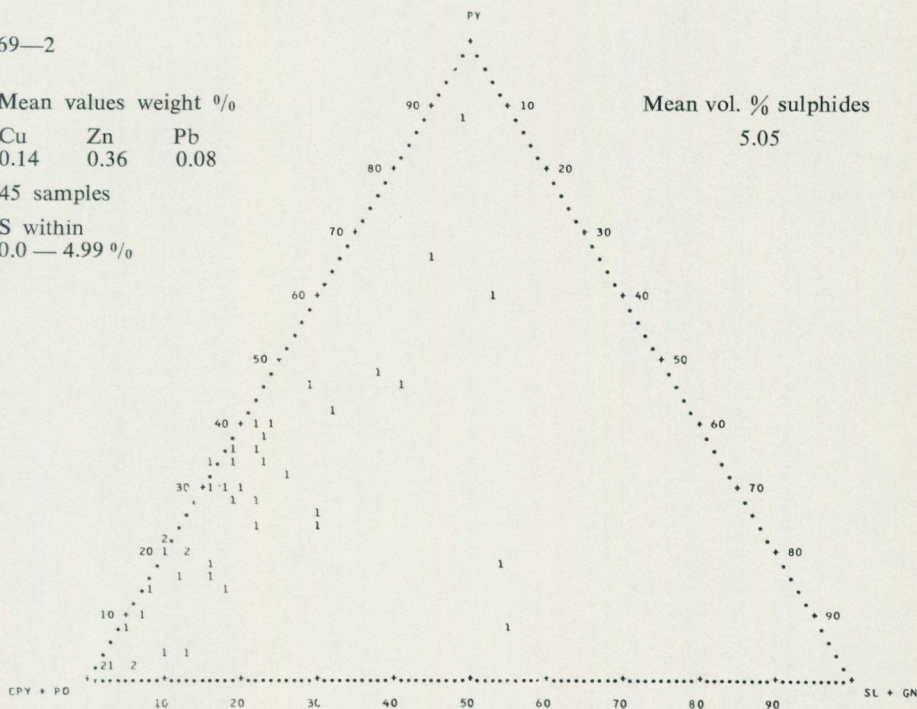
45 samples

S within

0.0 — 4.99 %

Mean vol. % sulphides

5.05



69—3

Mean values weight %/o

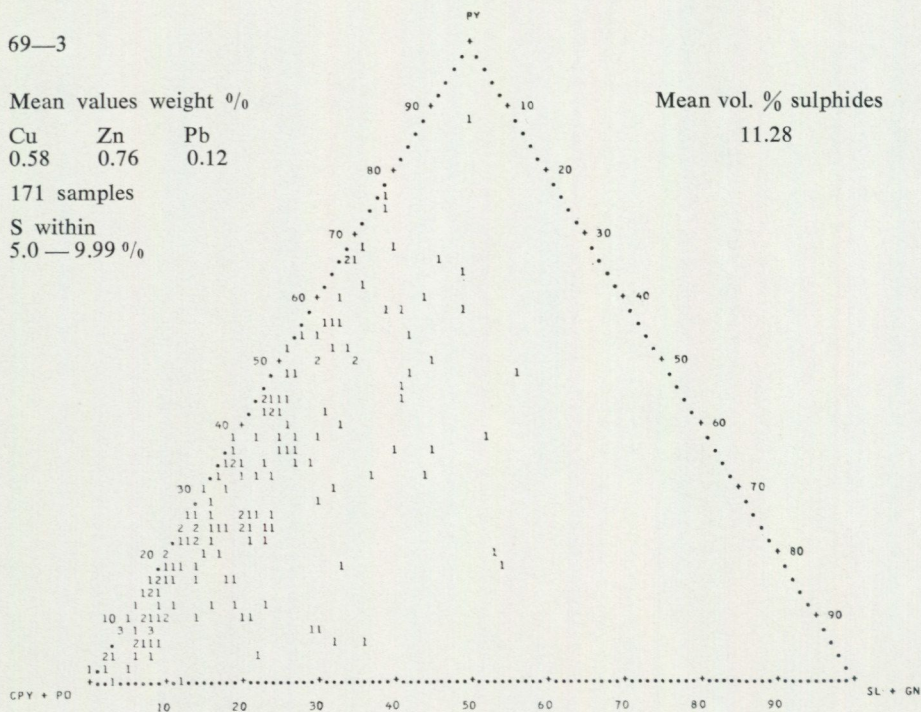
Cu    Zn    Pb  
0.58 0.76 0.12

171 samples

S within  
5.0—9.99 %/o

Mean vol. % sulphides

11.28



69—4

Mean values weight %/o

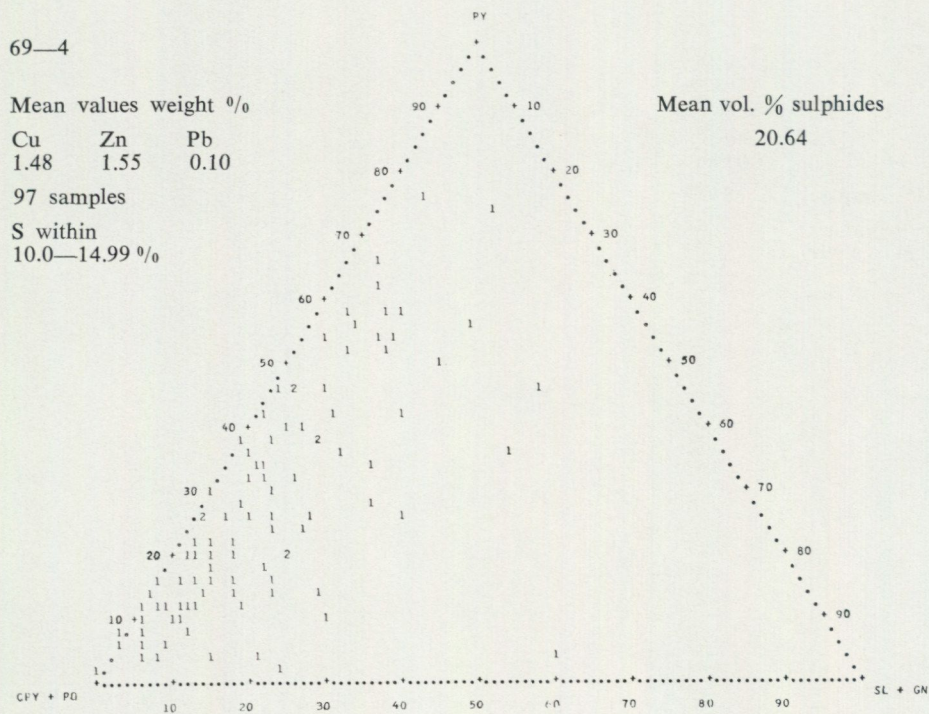
Cu    Zn    Pb  
1.48 1.55 0.10

97 samples

S within  
10.0—14.99 %/o

Mean vol. % sulphides

20.64



69-5

Mean values weight %

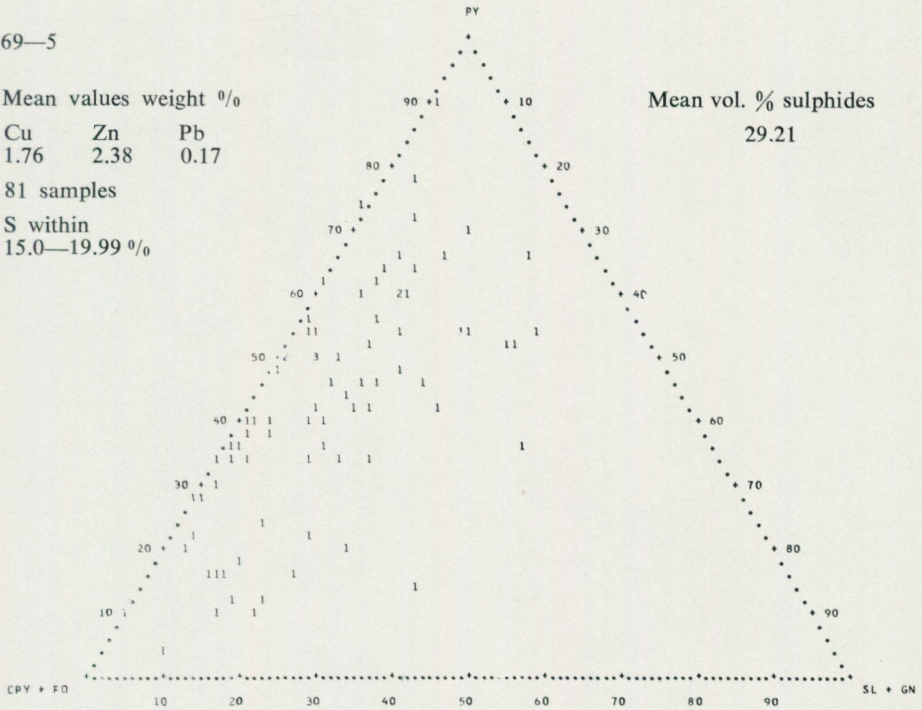
Cu	Zn	Pb
1.76	2.38	0.17

81 samples

S within  
15.0-19.99 %

Mean vol. % sulphides

29.21



69-6

Mean values weight %

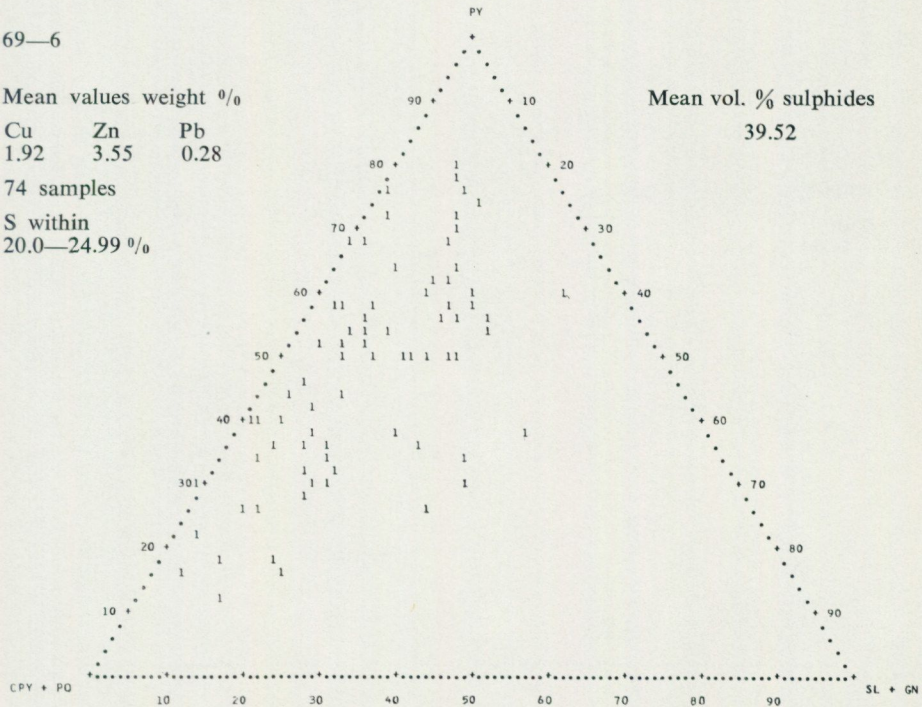
Cu	Zn	Pb
1.92	3.55	0.28

74 samples

S within  
20.0-24.99 %

Mean vol. % sulphides

39.52



69—7

Mean values weight %

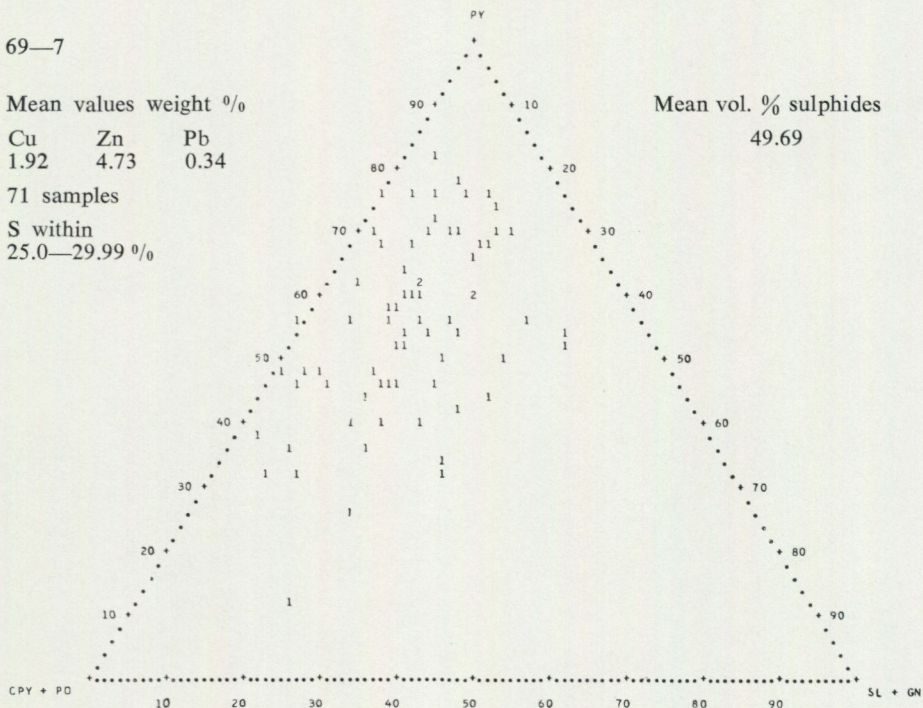
Cu	Zn	Pb
1.92	4.73	0.34

71 samples

S within  
25.0—29.99 %

Mean vol. % sulphides

49.69



69—8

Mean values weight %

Cu	Zn	Pb
1.60	5.82	0.32

93 samples

S within  
30.0—34.99 %

Mean vol. % sulphides

59.60

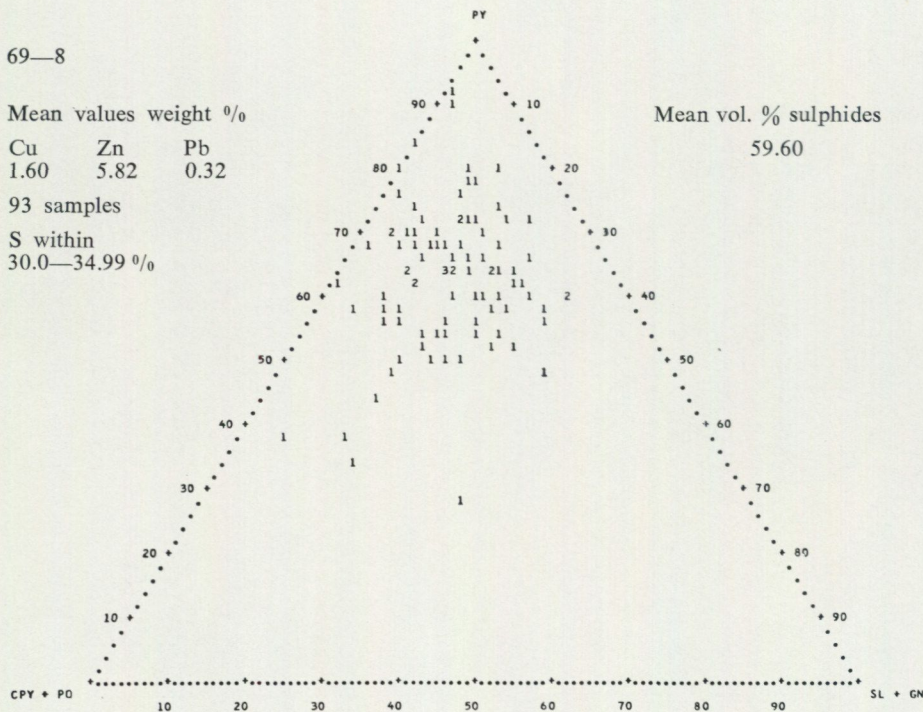


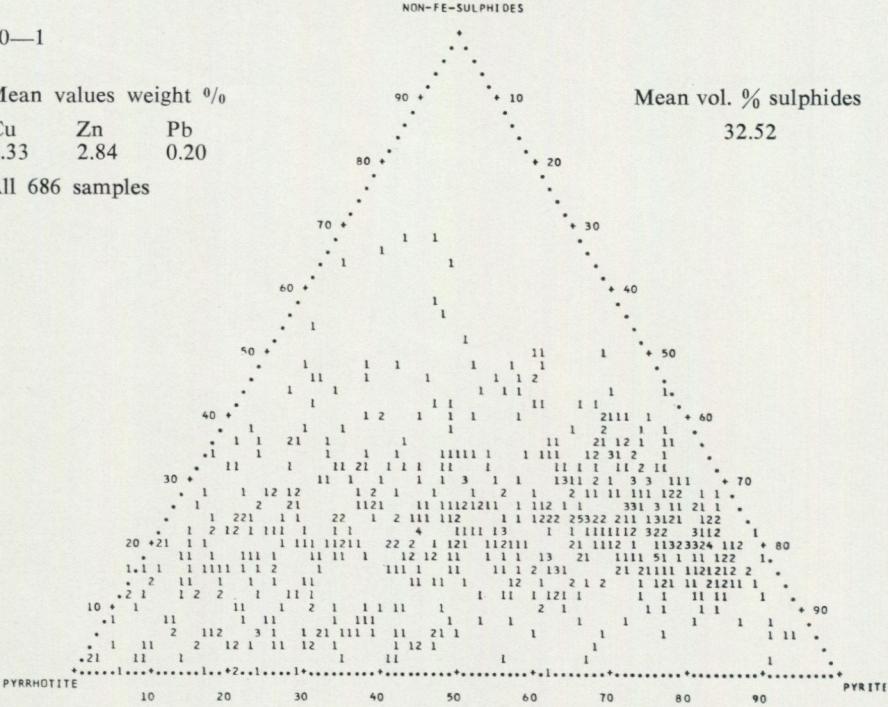


Fig. 70. *Triangular plots nonFe sulphides—pyrite—pyrrhotite illustrating the dominance of pyrrhotite in the sulphur-poor mineralizations (disseminations) and that of pyrite in the sulphur-rich mineralizations (massive ores). KISMOD calculation and plot.*

70—1

Mean values weight %  
 Cu    Zn    Pb  
 1.33  2.84  0.20  
 All 686 samples

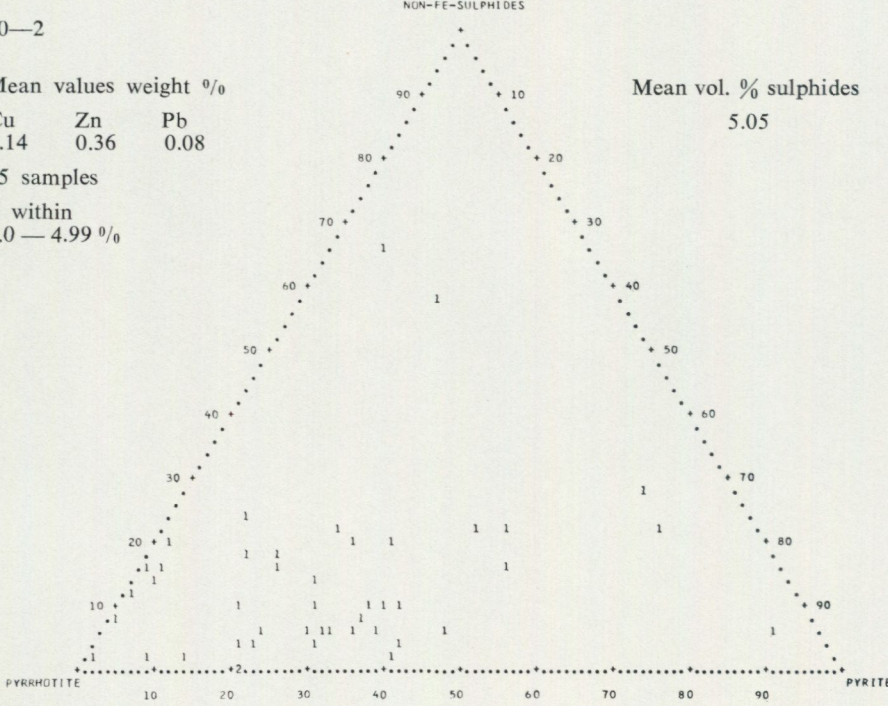
Mean vol. % sulphides  
 32.52



70—2

Mean values weight %  
 Cu    Zn    Pb  
 0.14  0.36  0.08  
 45 samples  
 S within  
 0.0 — 4.99 %

Mean vol. % sulphides  
 5.05



70—3

Mean values weight %

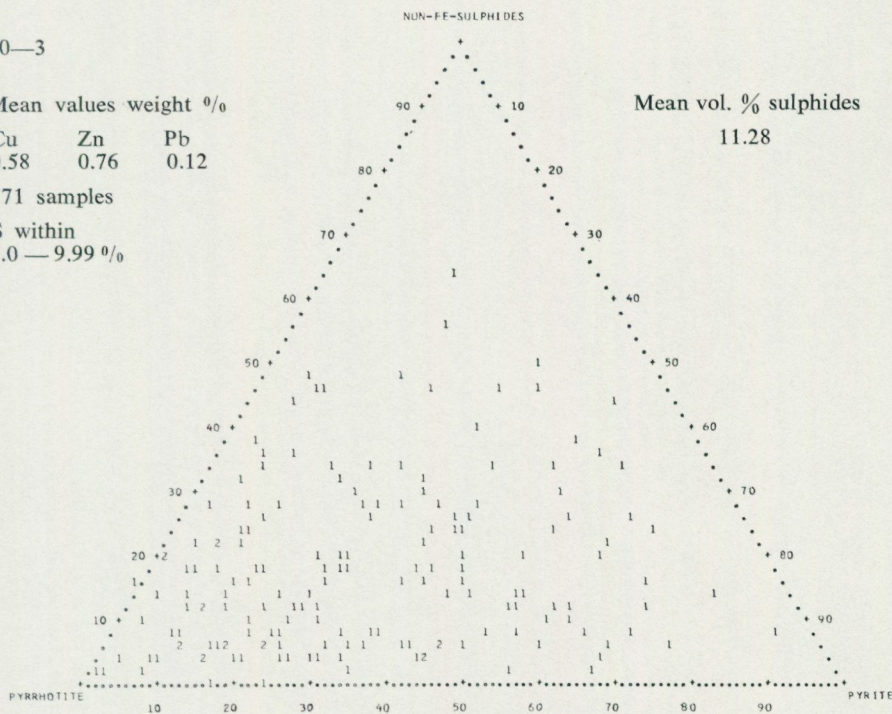
Cu	Zn	Pb
0.58	0.76	0.12

171 samples

S within  
5.0 — 9.99 %

Mean vol. % sulphides

11.28



70—4

Mean values weight %

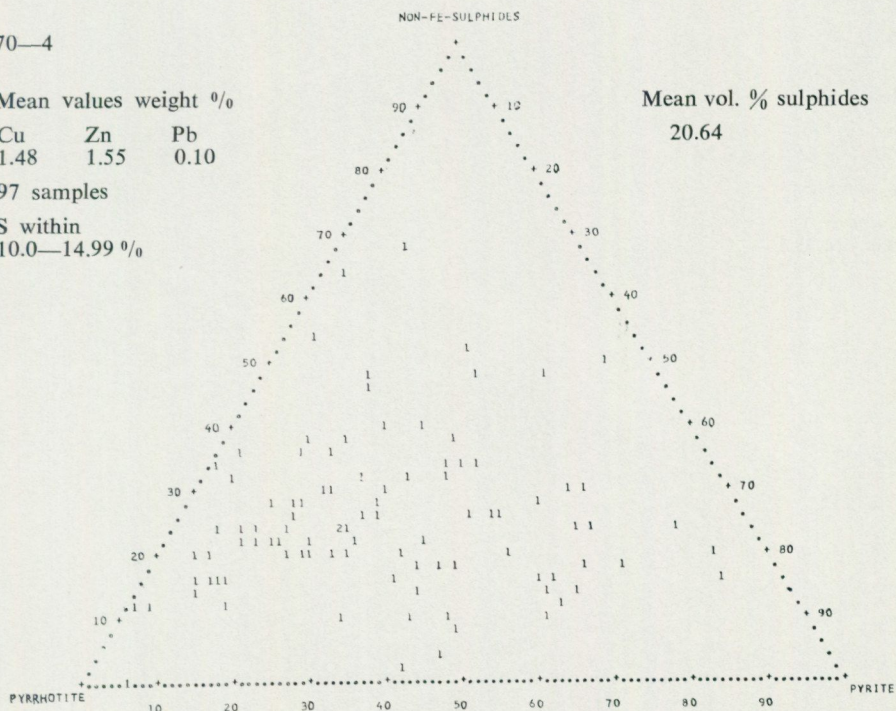
Cu	Zn	Pb
1.48	1.55	0.10

97 samples

S within  
10.0—14.99 %

Mean vol. % sulphides

20.64



70—5

Mean values weight %/o

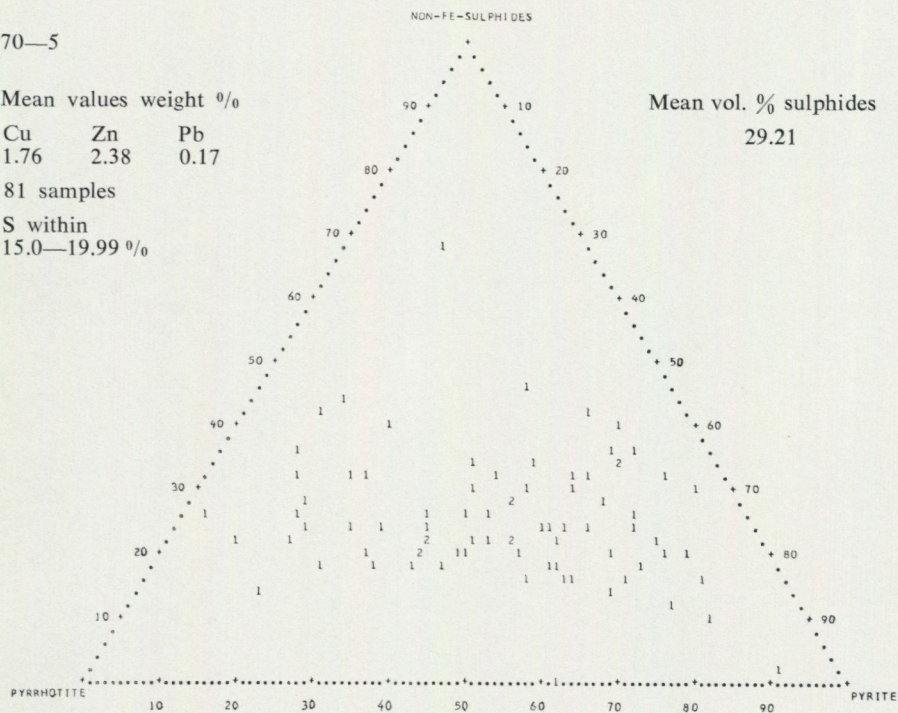
Cu	Zn	Pb
1.76	2.38	0.17

81 samples

S within  
15.0—19.99 %/o

Mean vol. % sulphides

29.21



70—6

Mean values weight %/o

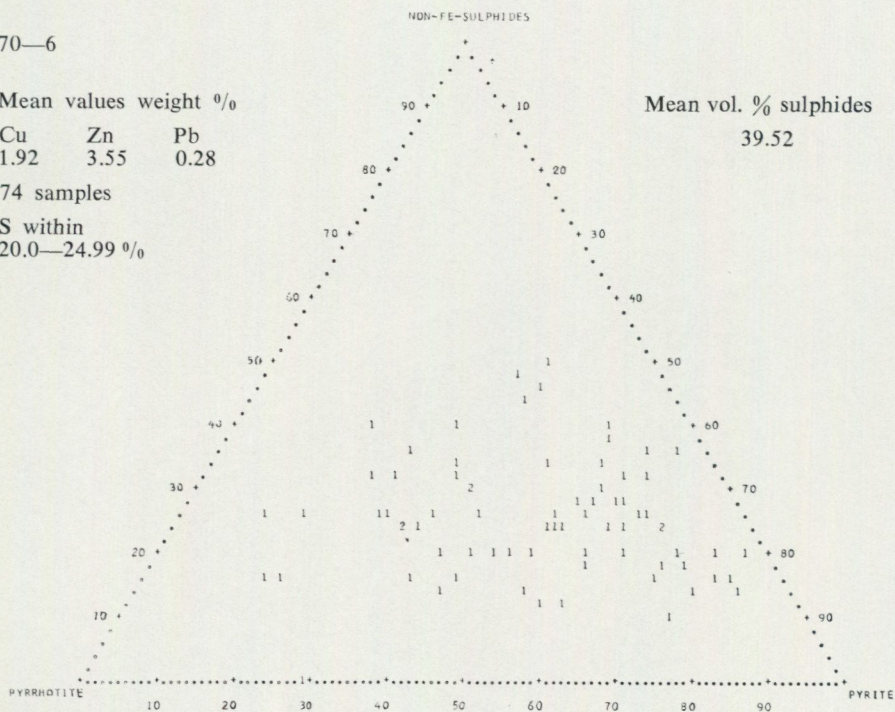
Cu	Zn	Pb
1.92	3.55	0.28

74 samples

S within  
20.0—24.99 %/o

Mean vol. % sulphides

39.52





70—9

Mean values weight %

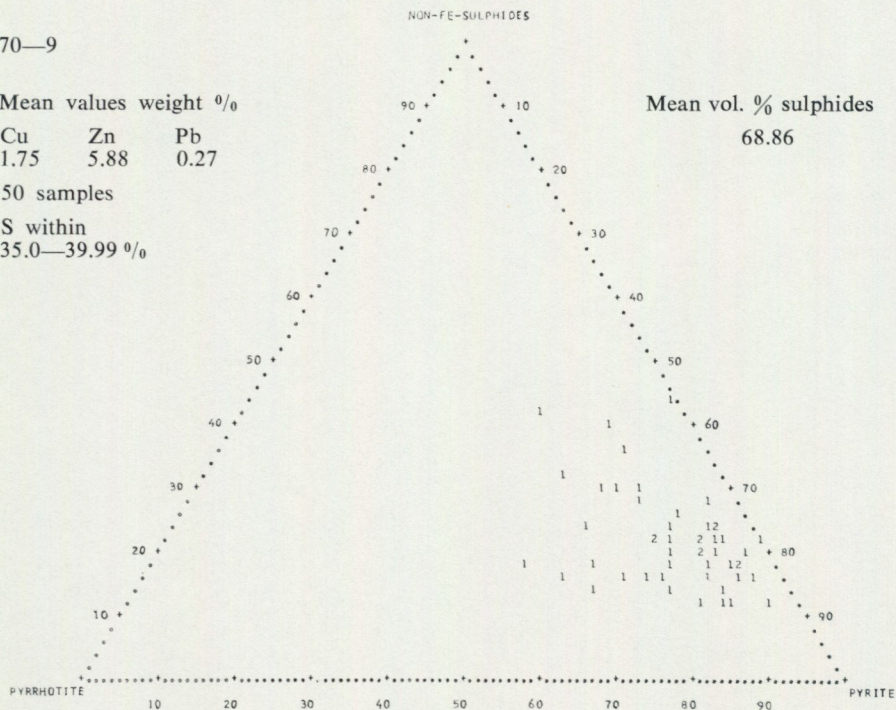
Cu	Zn	Pb
1.75	5.88	0.27

50 samples

S within  
35.0—39.99 %

Mean vol. % sulphides

68.86



70—10

Mean values weight %

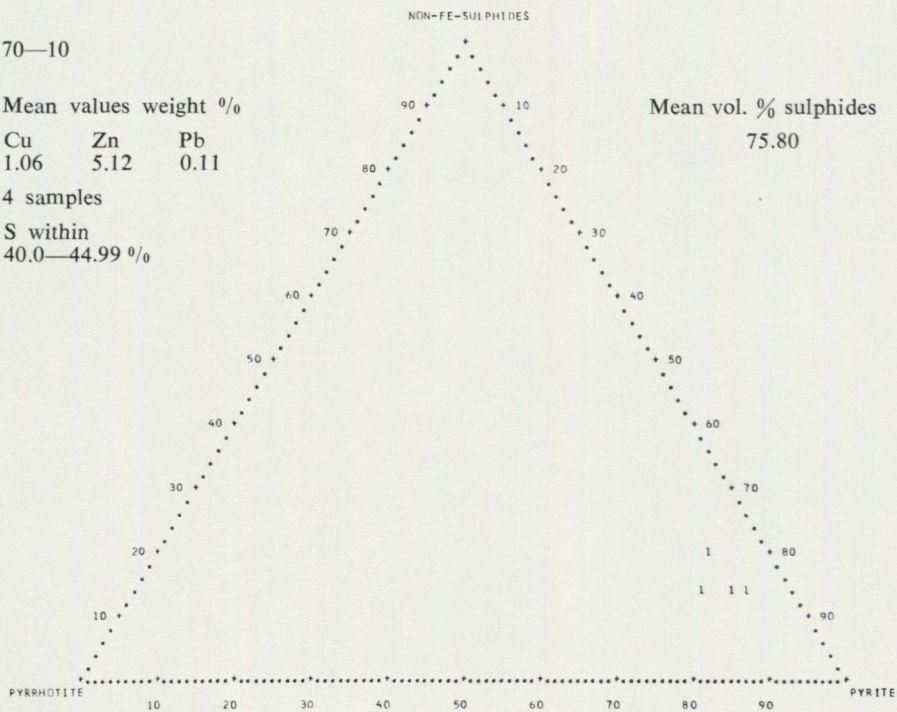
Cu	Zn	Pb
1.06	5.12	0.11

4 samples

S within  
40.0—44.99 %

Mean vol. % sulphides

75.80



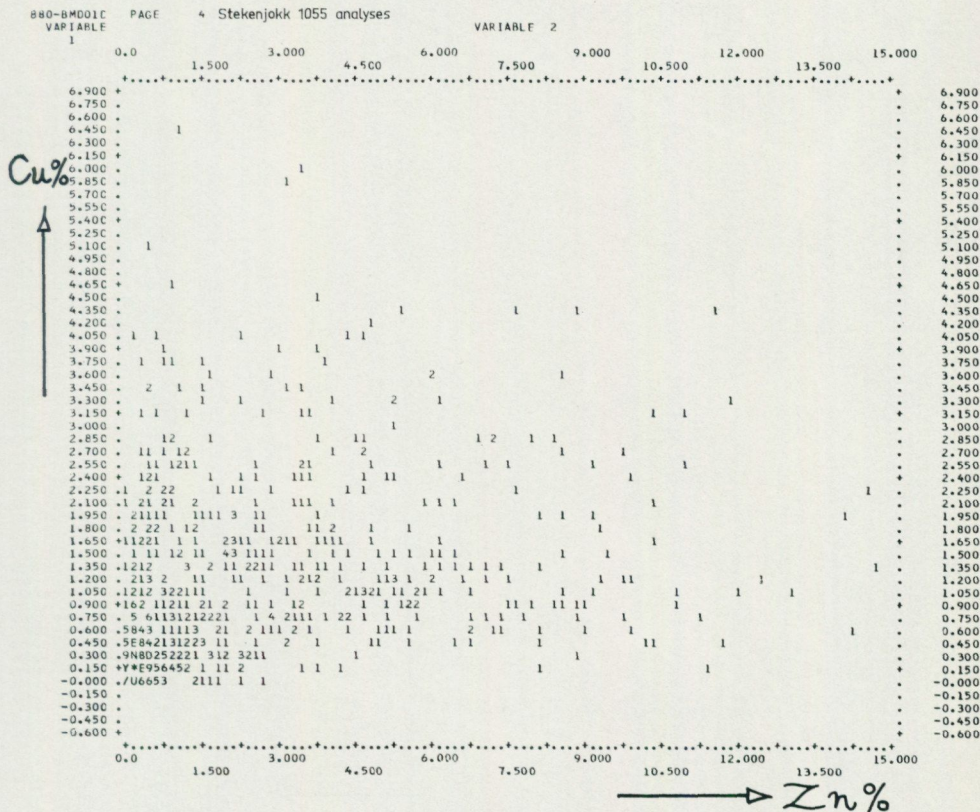


Fig. 71. Two-dimensional frequency distribution diagram. Correlated plot of Cu and Zn content in 1055 analyses.\*

\*Note concerning the two-dimensional frequency distribution diagrams (Figs. 71, 72, 73):

Material: With computer's claim of  $Pb \neq 0$  in all samples, the 1055 analyses were selected from a total of 1302.

Cu content  $\neq 0$  in 1054 samples  
 Zn " " 1055 "

Significance of plot symbols:

1—9 = direct number of coinciding Cu-Zn assays pr interval.

A, B, C, . . . . . Z = 10, 11, 12, . . . . . 35 ditto.

— = 36—41

+ = 42—47

\* = 48—54

Å = 55—62

/ = 63

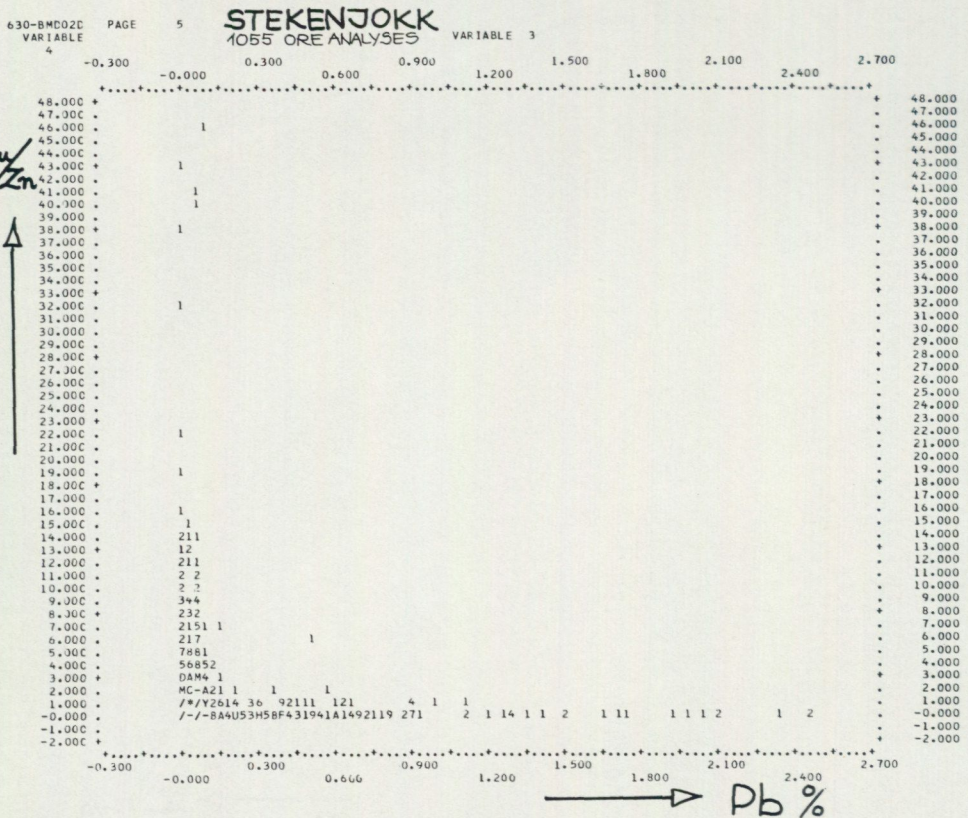


Fig. 72. Two-dimensional frequency distribution diagram. Correlated plot of Cu/Zn ratio and Pb content in 1055 analyses. All the high lead values imply low Cu/Zn ratios. The 21 Pb values > 1% have Cu/Zn ratios < 1. Relatively as well as absolutely, the higher copper values, which are considered independent of the zinc content, are obviously also independent of the lead content. See Fig. 71, foot note.

contents are intimately related to those of the base metals. A mutual, sympathetic co-variation is shown in Figs. 74 and 75 and Table 18.

The same common sulphides, pyrite, pyrrhotite, sphalerite, chalcopyrite and galena are present all over the mineralized volume. Accordingly the spread of the proportions of the base metal sulphides also show a high degree of similarity. The iron sulphides, however, differ in mutual proportions from a total dominance of pyrite in the massive banded ores towards important pyrrhotite fractions in the massive brecciated ore and even pyrrhotite dominance in some of the weaker disseminations (Figs. 66—70). The increase of the relative pyrrhotite content in the disseminations is interpreted as a metamorphic effect. Partly it is due to the direct transformation pyrite — pyrrhotite, partly to the combination of the

liberated (mobilized) sulphur with iron leached from the surrounding silicates. The occurrence of pyrrhotite seems to be proportional to the availability of such leachable iron. Sparse sulphide disseminations in an iron-rich silicate matrix have as a rule the highest pyrrhotite/pyrite proportions.

Regarding the mutual relations of the metal contents of all the individual samples, it is seen that:

1. Copper and zinc have no distinct correlation (Fig. 71).
2. Copper and lead have probably no distinct correlation (Fig. 72).
3. Zinc and lead show a positive co-variation (Fig. 73).
4. Silver and lead show a clear positive co-variation (Figs. 74 and 75).
5. Silver and copper show a positive co-variation (Figs. 74 and 75).
6. Silver and zinc show a weak positive co-variation which probably is connected with sphalerite's intimate relationship with galena (Figs. 74 and 75).

The proportional relationships of silver, copper, zinc and lead in the ore and country rocks are illustrated by the triangular diagrams of Fig. 74. The lower limit of an analytically reliable silver content to be used in the comparative study was estimated to 0.3 ppm. In order to obtain a better resolution of the plot crowd the lead assays are multiplied by 10, and the silver assays by 1000. The copper and zinc assays are given with their real values.

The three components are recalculated to 100 % and the results plotted automatically by the computer. Of the total of 256 samples, 154 contain  $\geq$  0.3 ppm silver. 81 of them contain  $\geq$  1 % sulphur, and 40 samples contain  $\geq$  5 % sulphur. In Figs. 74 A and B these 40 samples are marked with a ring around the plot point. A small square marks the position of the average proportions of the metals of the whole economic ore volume (15 M.t. with 1.46 % Cu, 3.03 % Zn, 0.3 % Pb, 53 ppm Ag). The average values of groups of analyses according to different sulphur contents are given in Figs. 74 C and D. Of the 154 samples (Table 18) containing  $\geq$  0.3 ppm Ag, 70 contain 0—0.99 % S, 44 contain 1.0—4.99 % S and 40 samples contain  $\geq$  5 % S.

Of the 40 samples with high sulphur content, 15 could be considered to represent well banded mineralizations, relatively undisturbed, though metamorphosed. The plot of the average proportional relationships of the four metals in these 15 samples is given separately. The other 25 samples with  $\geq$  5 % S represent less regular, deformed mineralizations and are incorporated in the plot of the average proportions for the whole economic ore volume (point "T" in Figs. 74 C and D).

High silver assays usually accompany high contents of lead or copper, or a combination of the two.

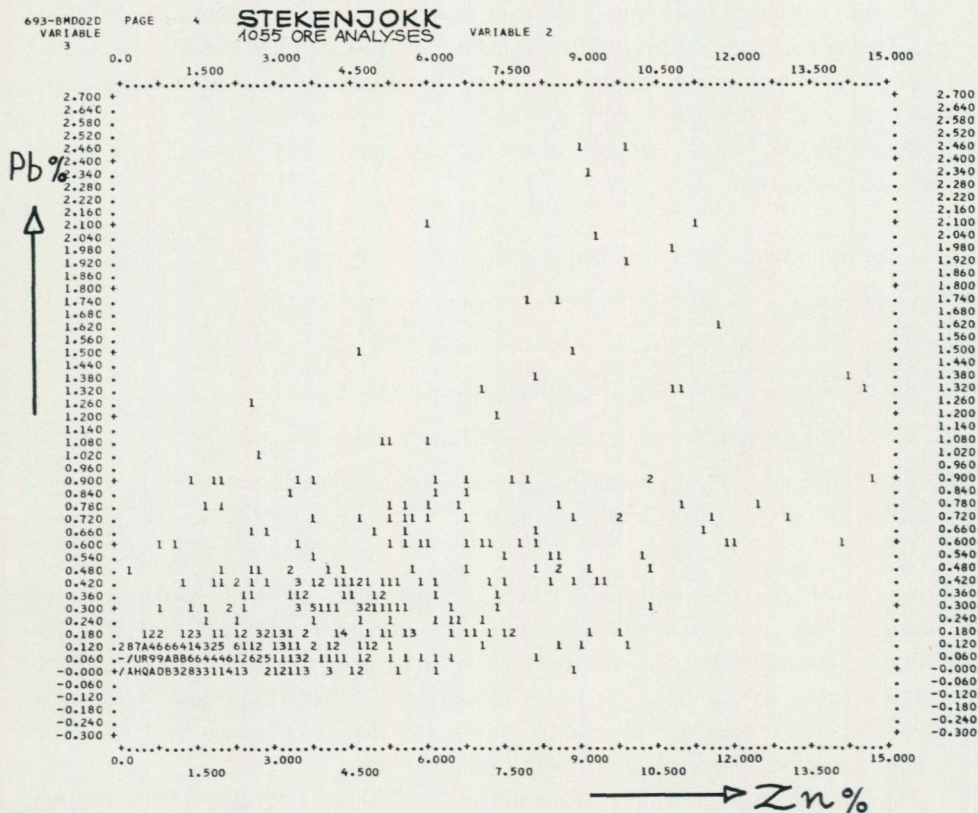


Fig. 73. Two-dimensional frequency distribution diagram. Correlated plot of Pb and Zn content in 1055 analyses. A somewhat irregular, but distinct correlation exists between Zn and Pb. All higher Pb values are connected with high Zn values. However, some very high Zn values imply only moderate content of Pb. See Fig. 71, foot note.

The above triangular diagrams (Fig. 74) indicate that high relative contents of silver do not claim any particular proportional combination of the other metals, — respectively Cu-Pb and Zn-Pb.

Low relative silver contents are in some cases induced by either high zinc or high lead contents, but seldom by high copper contents.

This indicates that much of the Stekenjokk silver has a sympathetic co-variance with copper. That means again that the silver content partly varies independently of the lead and zinc assays. It can be concluded that the proportional relationships between silver and the base metals are stable within wide ranges of mineralization densities.

However there is a weak tendency towards higher relative contents of silver

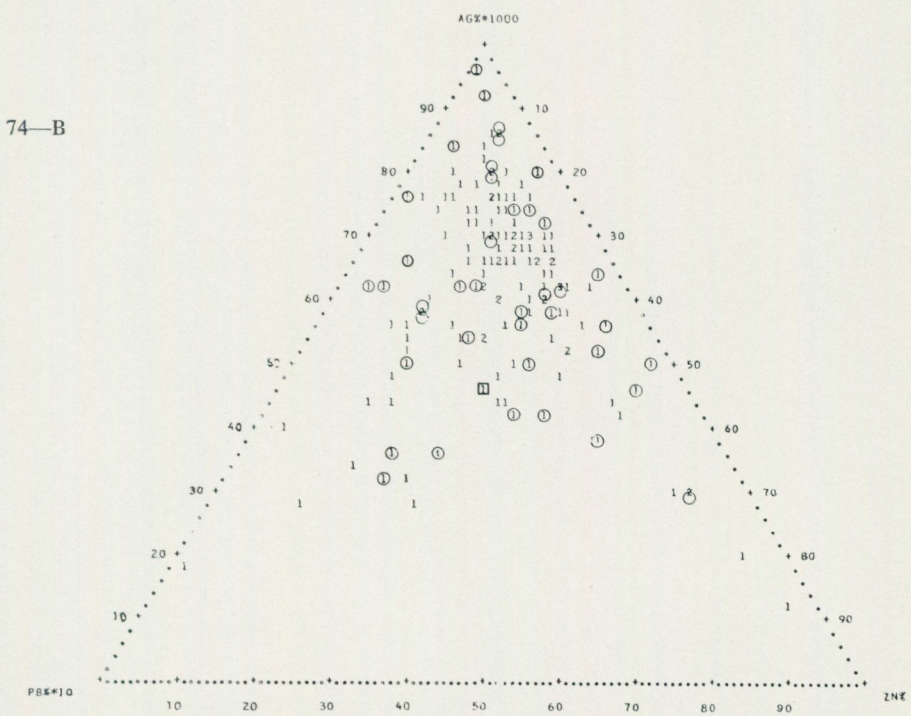
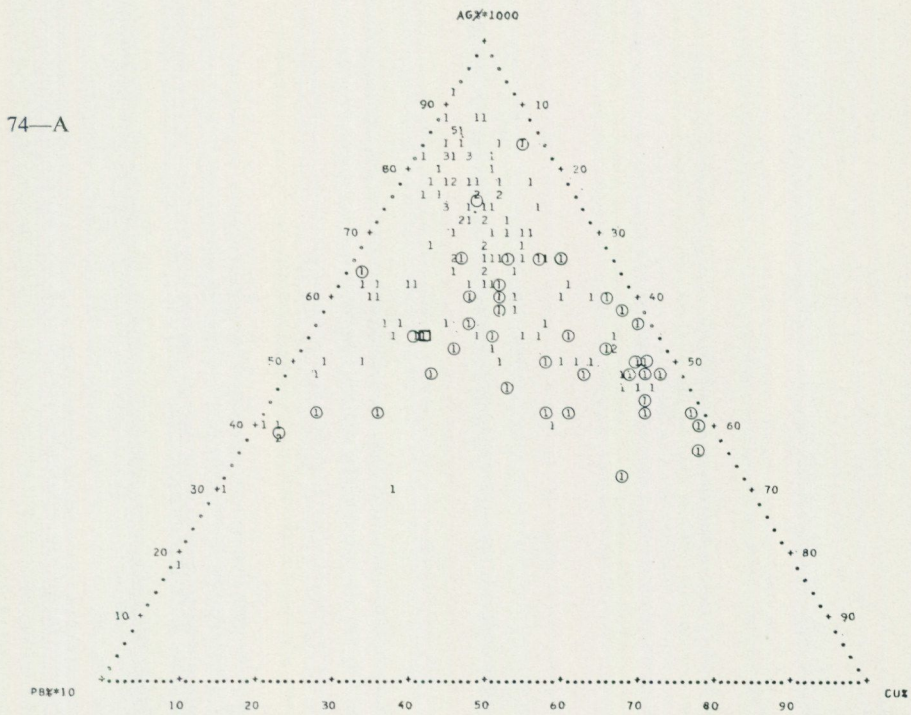
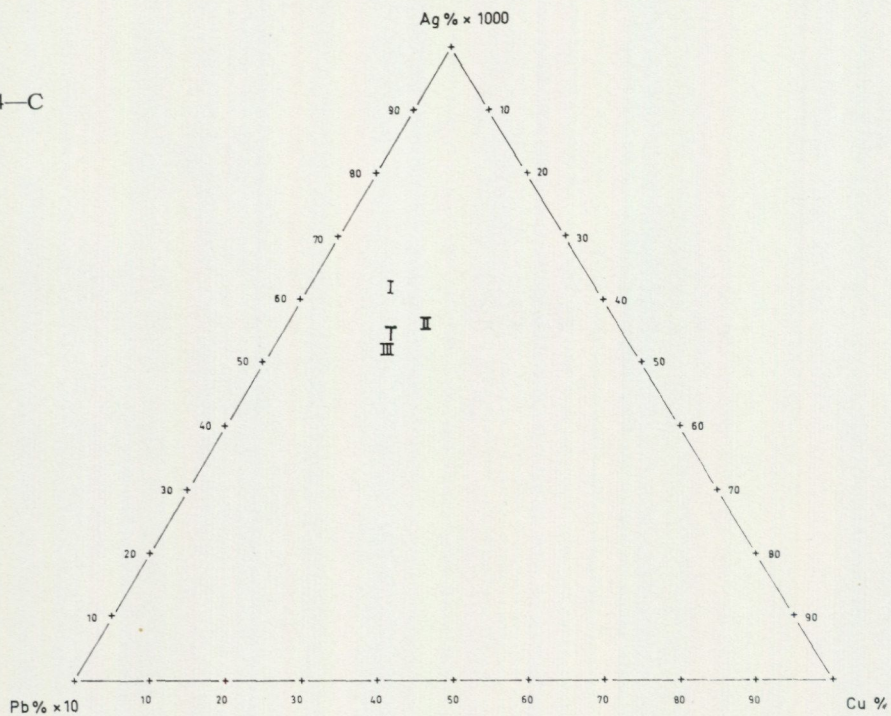
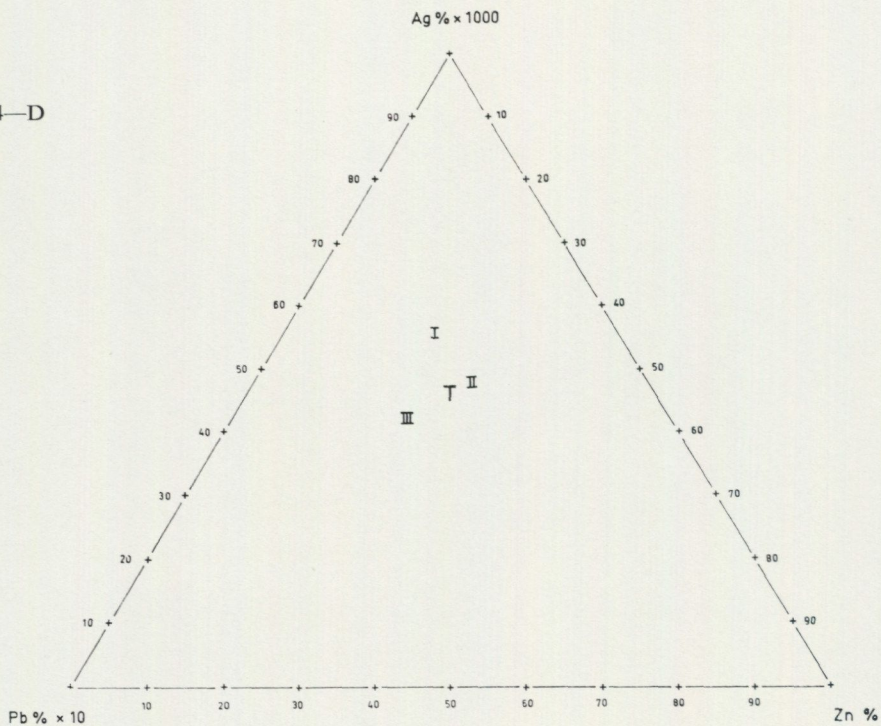


Fig. 74. Four triangular plots of ore and country rock analyses showing the relationship Ag-Cu-Pb- and Ag-Zn-Pb.

74—C



74—D



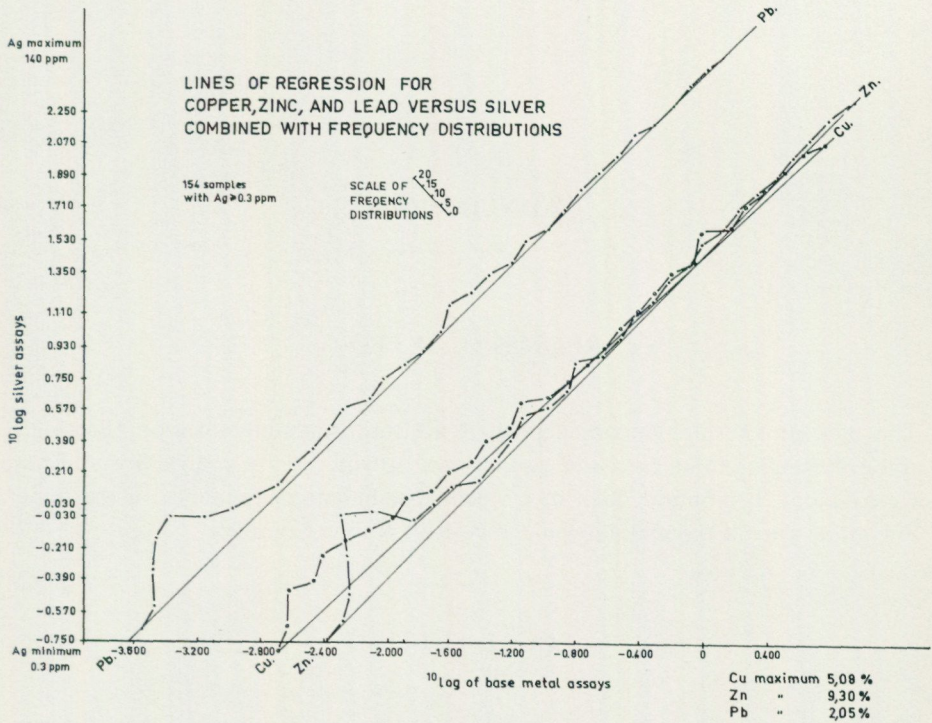


Fig. 75. Scattergram with logarithmic co-ordinates showing co-variance of silver, respectively with copper, zinc and lead in 154 ore- and country-rock analyses.

in the sterile country rocks than in the ores. The tendency is so weak that no reasonable explanation is at hand for the time being. The problem may reside in the analytical procedure. The low metal concentrations in the sterile silicate rocks may for instance partly be bound to minerals other than sulphides, and this may have given a small bias in the analytical results.

Silver has a clear sympathetic co-variance both with lead and copper, these two metals being apparently independent of each other. Silver also shows an indirect sympathetic co-variance with zinc. This is probably caused by the intimate relationship between galena and sphalerite.

The co-variance of silver versus copper, zinc and lead is demonstrated in Fig. 75. The diagram shows the lines of regression and frequencies obtained by summation perpendicular to the regression lines. An arbitrary class width was used. The frequency scale is indicated on the diagram. The regression lines can practically be considered as parallel. The respective frequency maxima occur on the whole at the same intervals on the regression lines.

## CONCLUSIONS

### REGIONAL SETTING

The Stekenjokk sulphide ore deposit is a stratiform mineralization (Kieslagerstätte) belonging to an extensive copper-zinc province of the central Scandinavian Caledonides. It is interbedded in a volcanic-sedimentary sequence of the upper, low-grade part of the metamorphic Seve-Köli Nappe Complex.

### LOCAL SETTING

The main ore horizon is located on or near the border between acid volcanic tuffs and fine-grained carbonaceous phyllites. Several minor sulphide horizons occur within the stratigraphic column. The mineralization density fades out in the hanging wall and foot wall directions by a decrease in the frequency and thickness of the sulphide layers. The sulphides are found in host rocks of highly variable character. The mineralizations do not have any absolute preference for any one particular host rock composition.

The tendency to be located on borders or transitions between different host rock types is maintained even for the thinnest sulphide strata.

The primary mineralization is considered to be independent of the gabbro sills which have intruded the series. Larger intrusive massifs which can be connected with the mineralizations are not found.

The ore bodies are considered to be of pre-tectonic age. Accordingly, the sulphide masses are metamorphosed in the same metamorphic mineral facies as are their enclosing host rocks and the surrounding country rocks. The ore textures are metamorphic, and the morphology of the ore bodies is on all scales controlled by a two-phase fold system. The first isoclinal fold phase created important patterns of thickening and thinning of the ore bodies. The second phase remodelled them by an open folding but had little influence on further relocalization of the sulphides. The important thrust zones of the area as well as the local dislocations seem all to be of post-ore-formational age.

## ORE MINERALS

In analogy with other Caledonian stratiform sulphide deposits (Ramdohr 1938, Vokes 1957 and 1963, Jøsang 1964, Saager 1966) the total number of ore minerals in Stekenjokk is considerable ( $> 30$ ), but the number of conspicuous minerals in the ores is small. The iron sulphides pyrite and pyrrhotite and the base metal sulphides sphalerite and chalcopyrite totally dominate quantitatively. Galena is subordinate. Arsenopyrite is a very minor constituent. Trace minerals like sulphosalts and tellurides are of a certain economic importance, primarily as silver carriers. Pyrite, which is present in dominating proportions practically all over the mineralized volume, is considered to be a mainly primary mineral, while pyrrhotite is a metamorphic transformation product from pyrite as well as a primary mineral.

## PARAGENESIS

At each stratigraphic level the mineral textures strongly indicate that all the constituents were deposited at the same time. Apparent age sequences are due to the minerals' different crystallization forces which they have exerted during an almost complete recrystallization generated by the regional metamorphism. Real age sequences of mineral deposition are however seen in lateral and internal secretions from the massive ore bodies. They represent metamorphic mobilizations where selective enrichments and impoverishments of the sulphides have taken place according to a consistent sequence of mobility. The minerals of low crystallization strength, like the sulphosalts, galena and chalcopyrite are those which exhibited the greatest mobility. Pyrite, which is the only main sulphide to have formed crystal faces all over the deposit, was very inert vis-à-vis the mobilizing forces.

## ORE TYPES

The ores are grouped into four main classes:

- 1 A. *Massive, banded fine-grained pyritic ore.*
- 1 B. *Massive to disseminated, brecciated pyrrhotite-chalcopyrite ore, with or without pyrite.*
- 2 A. *Disseminations in light-coloured rocks.*
- 2 B. *Other disseminated ores, in black phyllites, often adjacent to massive ores, or in tuffitic rocks.*

The massive, banded fine-grained pyritic ore is volumetrically and economically the most important type of the deposit. The brecciated pyrrhotite-chalcopyrite ore is quantitatively of minor importance.

It is concluded that the larger part of the disseminated ores occurs as compositional and structural small-scale replicas of the massive ores.

Important features are that the relative pyrrhotite content increases along with the admixture of gangue minerals ("dilution" of sulphide by silicate) and that the grain sizes are generally greater in the disseminated ores than in the banded, massive ones. Particular ore types, which locally are of economic importance, are the irregularly textured disseminations (impregnations), marginal to the greater massive ores.

#### CHEMICAL CHARACTERISTICS OF THE SULPHIDE VOLUME

The spread of the base metal proportions is large across the layers. However, both the spread and the average proportions are remarkably similar regardless of variations in the intensity of mineralization. This similarity is even maintained in the sterile country rocks surrounding the deposit.

The proportion of iron to base metals and sulphur increases, however, as the sulphide content decreases. Pyrite is gradually substituted by pyrrhotite as the admixture of gangue minerals increases. But apart from the variable relationships of iron and sulphur, therefore, both the spread and the average proportions of the metals are very uniform throughout the deposit. They suggest a homogeneous source of mineralization during the whole period of primary deposition.

A more complex picture appears regarding the mutual relationship of pairs of the respective metals in all the individual samples:

1. Copper and zinc — no distinct correlation.
2. Copper and lead — probably no distinct correlation.
3. Zinc and lead — clear positive co-variation.
4. Silver and lead — clear positive co-variation.
5. Silver and copper — positive co-variation.
6. Silver and zinc — weak positive co-variation (probably connected with sphalerite's intimate relationship with galena).

The irregularities in metal distribution which are interpreted in the above scheme of sympathetic and antipathetic correlations between the metals may partly be explained by the metamorphic features observed — first of all the differences in mobility between the minerals. The subdivision of samples into characteristic types before analysis has contributed to the revelation of these variegated patterns. It is concluded that the metamorphic rearrangements of the base metals are relatively local, so that the gain of an element in one locality is compensated by a loss of the same element in another. The dilution of the sulphide material with iron in the disseminated parts of the deposit is probably

also a result of chemical adjustments which have taken place during metamorphism.

Silver is of particular interest, whose sympathetic co-variance with the three base metals indicates that it may be lodged in most types of sulphide assemblages — without any distinctly preferred host.

In spite of the chemical homogeneity of the ores as a whole, the attempt to understand the local variations has necessitated a considerable number of samples.

#### GENETICAL CONSIDERATIONS

Conclusions about the primary genesis of the ores are premature here as long as a full description of the metamorphic features and the chemical relationships between the sulphide and silicate volumes is not given (paper in preparation). The problem, however, is made evident from the field observations, mineralogical work and certain chemical aspects which are expressed in the present paper. The ores are of pre-tectonic age. They are interbedded in a water-lain series of acid volcanic tuffs, tuffaceous sediments and fine, often carbon-rich detrital and chemical sediments. A possible connection between intrusives and ore formation must be discarded as improbable.

The ores occur as a series of border mineralizations without absolute preference for any one particular host rock composition. They do not appear to have substituted for any of the host rock constituents, but seem to make up a pure addition to the stratigraphical column. Their average compositional homogeneity indicates a constant and common source for the whole sulphide volume, where all constituents have been deposited contemporaneously at every single locality. The geometry of the sulphide layers show great similarity with extension and thicknesses observed in the host rocks. As they are apparently an integrated part of the water-lain metamorphosed host rock sequence, the assumption that the Stekenjokkk sulphides are themselves meta-sediments may be advanced.

#### ACKNOWLEDGEMENTS

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## APPENDIX

### LABORATORY METHODS

#### MICROSCOPY

Microscope descriptions and reflectance measurements were made using a Leitz Ortholux-Pol microscope equipped with a Leitz MPV microphotometer.

Reflectance standards used were: 1. SrTiO<sub>3</sub> (Leitz) R = 17.5 % at a wavelength of 546 nm; 2. Silicium metal (NIRKM, Technical University of Denmark, Lyngby) R = 36.9 + 0.1 % at 546 nm; 3. Pyrite (Stekenjokk) R = 53.5 — 55.0 % in white light; 4. Native copper with 3 % As (Porsanger) R = 75 — 83 % in white light.

For microhardness measurements a Leitz Durimet-Pol microscope was used.

#### MICROPROBE

Mineralogical analyses were done on an ARL-AMX microprobe housed in the SGU geochemical laboratory. Operating conditions were variable, but generally an accelerating voltage of 30 kV and a specimen current of 0.02  $\mu$  A were used. The primary values obtained were corrected for effects of absorption, atomic number and fluorescence with the help of a computer program particularly prepared for sulphides (Springer 1967).

#### PHOTOGRAPHY

The microphotographs were taken on a Zeiss Ultraphot II instrument, using either 9 x 12 cm glass plates or Polaroid film, or 36 mm roll film. The microprobe photographs were all taken on Polaroid film.

For larger specimens a Linhof "bellows" camera was used.

For reflected light photographs of large polished surfaces, a glass plate 50 x 50 cm was used as a mirror/transmitter (on the same principle as that of the ore

microscope) with incident light at  $90^\circ$  to the axis of the camera and the glass plate in a  $45^\circ$  position over the object.

### CHEMICAL ANALYSES

The procedure used in the SGU laboratory for the analysis of the Stekenjokk samples is a combination of spectrochemical and other instrumental methods (Danielsson 1968), and suitable wet chemical methods (Asklund, Grundulis and Rönholm 1966).

Most of the elements were analyzed using a direct reading spectrograph equipped with a tape machine.

The trace elements were also analyzed using a Hilger quartz spectrograph with registration on a photo plate.

Iron was analyzed both spectrographically and by different wet chemical methods.

Potassium and sodium were determined by atomic absorption.

Particular methods used for individual elements are otherwise mentioned in the text.

### PRESENTATION OF ANALYTICAL DATA

The results from the whole rock analyses are subdivided into three fractions for further treatment (computer etc.): silicate fraction, ore fraction, trace element fraction.

The *silicate fraction* is the sum of the following radicles or elements (framed in Table 3, p. 14):  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{TiO}_2$ ,  $\text{CaO}$ ,  $\text{MnO}$ ,  $\text{BaO}$ ,  $\text{CO}_2$ ,  $\text{C}$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ ,  $\text{H}_2\text{O} > 105^\circ$ ,  $\text{FeO}$ ,  $\text{Fe}_2\text{O}_3$ .

When the sulphur content is under  $\sim 1\%$  the summing is performed directly from the laboratory transcript. When the sulphur content is  $\sim 1\%$  or above, new values for  $\text{FeO}$  and  $\text{Fe}_2\text{O}_3$  of the silicate fraction are calculated. Then the silicate radicles are recalculated to 100%.

Silicate-bound iron as  $\text{Fe}_2\text{O}_3$  is the only iron value used for the 100% recalculation itself. The value is given by  $(\text{total Fe} \div \text{sulphide-bound Fe}) \times 1.43 = \text{silicate-bound Fe (as Fe}_2\text{O}_3)$ .

An additional correction is introduced in order to subdivide the silicate-bound iron into  $\text{FeO}$  and  $\text{Fe}_2\text{O}_3$  values. The separately analyzed (all samples by titration)  $\text{FeO}$  value is reduced by the iron bound to sulphide. The rest of the silicate-iron is given as  $\text{Fe}_2\text{O}_3$ .

This additional correction has been done for all the analyses presented in Table 3, also for those with  $\text{S} < 1\%$ . The sums may thus deviate from 100%.

The remaining parts of the analyses,  $H_2O < 105^\circ$ , the auxiliary iron values, necessary for the calculation of the sulphide-bound iron, the other elements included in the *ore fraction* (Cu, Zn, Pb, As, S) and the *trace element fraction* (Bi, Mo, Sn, Ag, Co, Ni, V) are presented directly as arithmetic mean values of the laboratory transcripts. The mean values only take into account the samples where the respective element has been detected. However, the number of "blind" samples is relatively small, and the bias due to this is neglected.

## COMPUTER PROGRAMS

### PROGRAM ANALIN

ANALIN is programmed in FORTRAN IV for the computer IBM 360/75. ANALIN lists and presents the laboratory transcripts of the full chemical analyses. If desired the program proceeds through the following operations.

Mean values and sums of series of analyses are calculated. Each analysis is subdivided into three parts, *silicate fraction*, *ore fraction* and *trace element fraction*. Calculations of 100 % sums of each fraction, proportions of selected elements, mineralogical mode and automatic plots in different diagrams are performed.

The program ANALIN was used for calculating the chemical composition of the country rocks, wall rocks and gangue (silicate fraction).

### PROGRAM KISMOD

KISMOD is programmed in FORTRAN IV for the computer IBM 360/75. KISMOD calculates the mineralogical composition of the sulphide ores. Input data are analyses of Cu, Zn, Pb, As, Fe and S. The specific weights for chalcopyrite, sphalerite, galena, arsenopyrite, pyrite, pyrrhotite and gangue/host rock are given as variables. The weight percentage of FeS in ZnS is also given, as well as the composition of pyrrhotite i.e.  $Fe_9S_{10}$ ,  $Fe_8S_9$  or FeS. The program consecutively calculates the weight percentage for the above given sulphides in five steps:

1. The calculation of  $CuFeS_2$  is carried out if Cu, Fe and S  $> 0$ . If Cu = 0, then  $CuFeS_2 = 0$ . If Fe or S = 0, Cu is given as rest. The program proceeds to step 2.
2. ZnS (with a prefixed amount of FeS) is calculated if Zn, Fe and S  $> 0$  after step 1. If Zn = 0, then ZnS = 0. If S (and Fe) = 0 or if the amounts of Fe and

S are not sufficient to form  $Zn(Fe)S$  from the available Zn-atoms, Zn is given as rest. The program proceeds to step 3.

3.  $PbS$  is calculated in a similar way. If the amount of S after step 2 is not sufficient to calculate  $PbS$ , Pb is given as rest. The program proceeds to step 4.

4.  $FeAsS$  is calculated in a similar way. If Fe, or S are not sufficient for calculating  $FeAsS$ , As is given as rest. The program proceeds to step 5.

5. Remaining amounts of Fe and S after step 1—4 are calculated as pyrite and pyrrhotite according to the following setup:

Remaining Fe = X

Remaining S = Y

$k_1$  and  $k_2$  are the coefficients of pyrrhotite  $Fe_{k_1} S_{k_2}$ .

The general equation can be written:

$$XFe + YS = \frac{Y - 2X}{k_2 - 2k_1} Fe_{k_1} S_{k_2} + \frac{k_2X - k_1Y}{k_2 - 2k_1} FeS_2$$

Depending upon the proportions, S and Fe can be given as rests. The volume percentages of each mineral and of all the sulphides together are calculated from the weight percentages, whereby it is supposed that the gangue will make up the ore body to 100 %.

For every sample the calculated specific weight is noted.

The calculated data may, apart from being listed, also be punched onto data cards for further treatment. If any sample has been left out from any of the above calculations, no card will be punched (even if this has been asked for).

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