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Tittel

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Sammendrag

Forfatteren presenterer sitt mineralogiske arbeid om zink-kis fra gruvene i Sulitjelma. Ogsa spor-element innhold av zink-kis er diskutert (MN, CD, GA, CO, NI, PB). Zink-malmer er klassifisert i 3-typer. Engelsk tekst. Mineralogi.

SULITJELMA BERGVERK AS

Tlf: (081) 40500
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Ref.nr:	Krt.nr:	Prj.nr:	År: 1978

Forfatter: KISHANLAL RAI			Ant:

Tittel: MICRO MINERALOGY AND GEOCHEMISTRY
OF SPHALERITES FROM SULITJELMA
MINING DISTRICT, NORWAY
NORSK GEOL. TIDSSKR. 58 17-31

Fordeling
Sulitjelma:

Ngo.koord:

X1:	Y1:	Z:
X2:	Y2:	

Sulis koord:

X3:	Y3:	Z:
X4:	Y4:	

Resyme:

FORFATTEREN PRESENTERER SIN
MINERALOGISK ARBEID OM ZINK-KIS
FRA GRUBER I SULITJELMA.
OGSÅ, SPORE-ELEMENT INNHOLD AV
ZINK-KIS ER DISKUSERT (MN, CD, GA,
CO, NI, PB)
ZINK-MALMER ER KLASSIFIKERT IN
I 3- TYPER.

(ENGELSK TEKST)

Andre:

Kommentar:

Micromineralogy and geochemistry of sphalerites from Sulitjelma mining district, Norway

KISHANLAL RAI

A wide range of zinc-rich to zinc-poor ore bodies characterizes the famous Caledonian pyritic copper-zinc ore deposit of Sulitjelma. It is, however, observed that, in general, the sphalerites from the two main assemblage types of ores in different ore bodies display remarkably analogous minor- and trace-element geochemistry marked with comparable concentrations of individual elements. The distribution of certain common minor elements between sphalerite and co-existing iron-sulphide minerals tends to be regular. On the crystal scale too, the sphalerites show no evidence of physical or chemical heterogeneity. The implications of the study in deciphering equilibration or re-equilibration of ores during regional metamorphism and the probable optimum geobarometric conditions have been considered.

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The Sulitjelma mining district, located at ca. 67° N. lat. in northern Norway, constitutes a small yet important subprovince of the great Caledonian metallogenetic province of Scandinavia. It owes its economic significance to the occurrences of several pyritic copper-zinc ore bodies that have sustained a mining and smelting industry in this part of the country since the turn of this century. By 1975, the district had already produced more than 19 million tons of raw ore, the annual production in recent years having been about 360,000 tons of ore that yields about 20,000 tons of copper concentrates, 2000 tons of zinc concentrates and 80,000 tons of pyrite (1968 figures).

The present study on sphalerites from this important, and in many respects, representative deposit of its type in the Scandinavian Caledonides, was undertaken as a part of a larger project dealing with detailed mineralogical and geochemical studies of Sulitjelma ores. The primary objective of this study is to evaluate and assess the physical, mineralogical, and geochemical characteristics of sphalerites belonging to various types of ores and the ore bodies represented in this deposit. No such study seems to have been carried out so far. Limited information based on the analyses of a few sphalerite samples from this deposit has, of course, been available in certain earlier publications dealing with broad-scale studies on sphalerites from the Norwegian/Scandinavian sulphide deposits (Oftedal 1940, Kullerud, Padget & Vokes 1953).

The ore geology of the Sulitjelma district

The Sulitjelma deposit lies in the central section of the 1,500 km long Caledonian mountain belt within a sequence of eugeosynclinal volcanic-sedimentary rocks that constitute the 'western facies' of the Caledonian geosyncline. Tectonically, these rocks belong to the lower of the two nappe units that have been distinguished in Sulitjelma region. The rocks have, in general, undergone a complex tectonic, structural, and metamorphic history, principally during Caledonian orogeny. Exhaustive accounts of all these and various other aspects of regional geology and tectonics are already available in the published literature (Sjögren 1900, Vogt 1927, Kautsky 1953, Mason 1967, Nicholson & Rutland 1969, Henley 1970, Wilson 1973).

Sulphide mineralization in the region consists of a series of strata-bound, elongated lenticular ore bodies that often lie en-echelon with their longer axes running parallel to the preferred orientation of the minor fold axes and linear structures of the country rocks. These ore bodies occur well within a single structural unit of the area (Wilson 1973) at or near the lower junction of the Sulitjelma amphibolites with the underlying Furulund Group metasediments (Fig. 1). The exact nature of the geologic setting of sulphide mineralization has received varied interpretations from earlier workers (J. H. L. Vogt 1894, Th. Vogt 1927, Kautsky 1953, Wilson 1973).
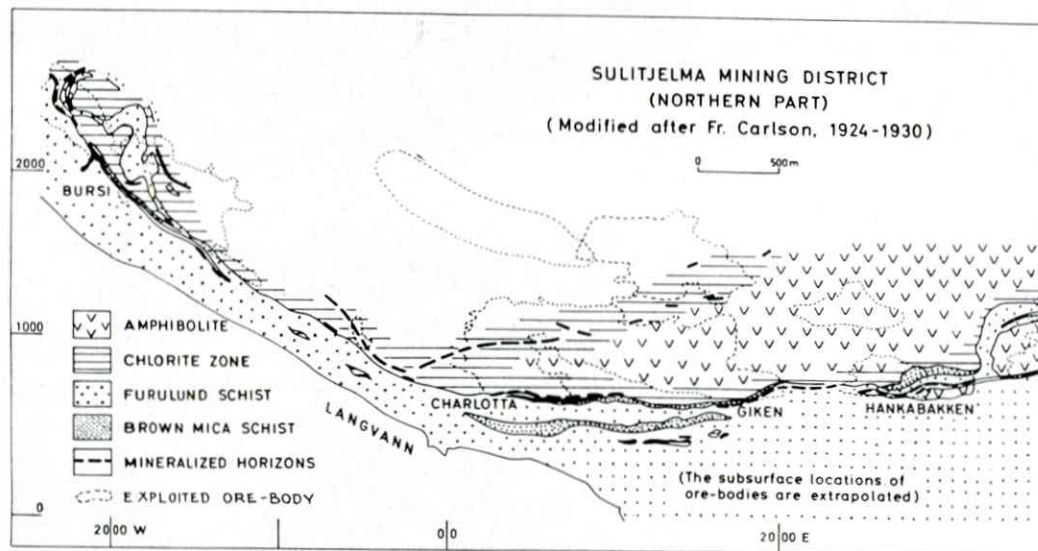
Fig. 1. Geological map of northern part of Sulitjelma mining district, Norway.

Two common paragenetical types of massive ores, namely pyritic and pyrrhotitic types, whose general occurrence in the massive sulphide deposits of Norwegian Caledonides has been highlighted by Vokes (1962), are also observed in the Sulitjelma deposit in close association and with widely variable proportions in its different ore bodies. The pyrrhotitic ores represent distinctly a younger mineralization as they clearly cut across the massive stratiform pyritic ores at several places.

Mineralogically, the ores comprise principally pyrite, pyrrhotite, chalcopyrite, and sphalerite that often constitute over 95 % of the ore mass. Quantitative differences in the mineralogy of various ores relate largely to the two iron-sulphide minerals and to a lesser extent, to the two matrix base-metal sulphides. Other minerals occurring in minor- to trace amounts and rarely exceeding 2 or 3 percent of the ore mass include galena, arsenopyrite, tetrahedrite, molybdenite, achinawite, bournonite, and many other sulphosalts. The occurrence of a multitude of Cu-, Pb-, Ag-, As-, and Sb-sulphides and sulphosalts and silver, gold, and antimony as native metals was reported by Ramdohr (1938) from an antimony-rich paragenesis at Jakobsbakken mine, that had been abandoned about 30 years ago. The common gangue minerals observed in the ores are quartz, calcite, hornblende, kyanite,

feldspar, and anhydrite. The observed textures and microstructures show that the ores have, in general, undergone varied effects of high-grade regional metamorphism.

Classification and micromineralogy of sphalerites

Sphalerite occurs as a common and important matrix sulphide next only to chalcopyrite in the Sulitjelma ores. Considerable variations, both of qualitative as well as quantitative nature, however, characterize its occurrence in the different ore types and ore bodies constituting the deposit.

Variations in quantitative proportion of sphalerite to other base-metal sulphides in different ores and ore bodies of the deposit seemingly find best expression in the average base-metal composition of the ores. Relevant data in this connection, assembled and depicted in triangular diagram in Fig. 2, shows that a wide range of zinc-rich to zinc-poor ore bodies is represented in the deposit. No systematic trend in the geographic distribution of such ore bodies, however, seems discernible. Abnormally high zinc content of Jakobsbakken ores, for example, prominently contrasts with the zinc-poor ores of Sagmo ore body which lies in an exactly similar

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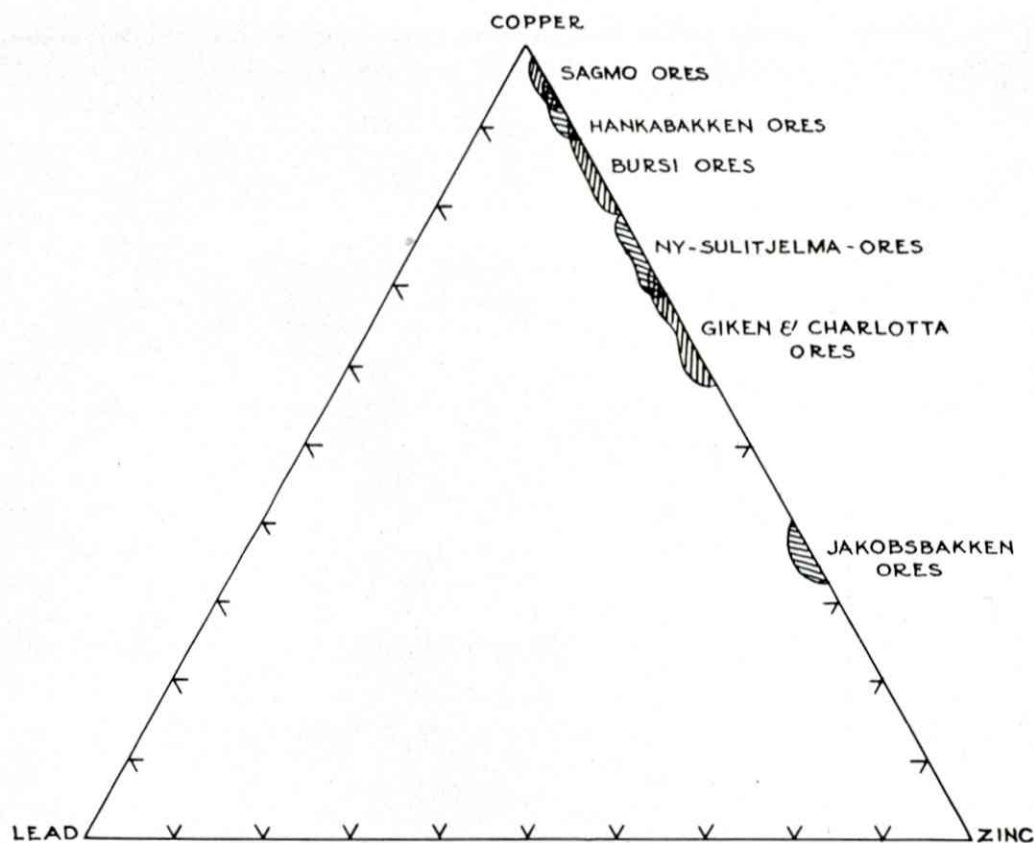namely Gi
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Fig. 2. Triangular diagram showing base-metal composition of ores from different ore bodies of Sulitjelma deposit.

geologic environment only about a kilometer north of Jakobsbakken Mine. On the scale of an individual ore body, however, the variability of the average base-metal composition of ores seems to be relatively much less, and often restricted between characteristically narrow limits.

In the light of the observations made as above, it was considered desirable to study the differences, if any, in the sphalerites belonging to different ore types and ore bodies of the deposit and subsequently evaluate their probable significance. With this in view, detailed studies were planned on about 120 samples of sphalerite-bearing ores collected according to definite sampling schemes, principally from four ore bodies of the deposit under active exploitation, namely Giken, Hankabakken, Charlotta, and Bursi. Detailed megascopic and microscopic studies of these samples helped to evolve the following classification on the basis of characteristic mineral assemblages:

Group A: Pyrite-sphalerite assemblage (with no visible pyrrhotite).
Group B: Pyrrhotite-sphalerite assemblage (with or without pyrite).
Group C: Sphalerite-galena assemblage.

Chalcopyrite occurs as a common constituent of all the assemblages mentioned above.

Group A and B assemblages represent the two most common types of sphalerite-bearing ores, although gradations between them are also present in the deposit. Typical megascopic and morphologic characteristics of these ores are depicted through representative specimen photographs in Figs. 3A and 3B. Studies on chalcopyrite-sphalerite ore show that it can be remobilized equivalent to one or the other of the two principal ore types. Such ore, found usually
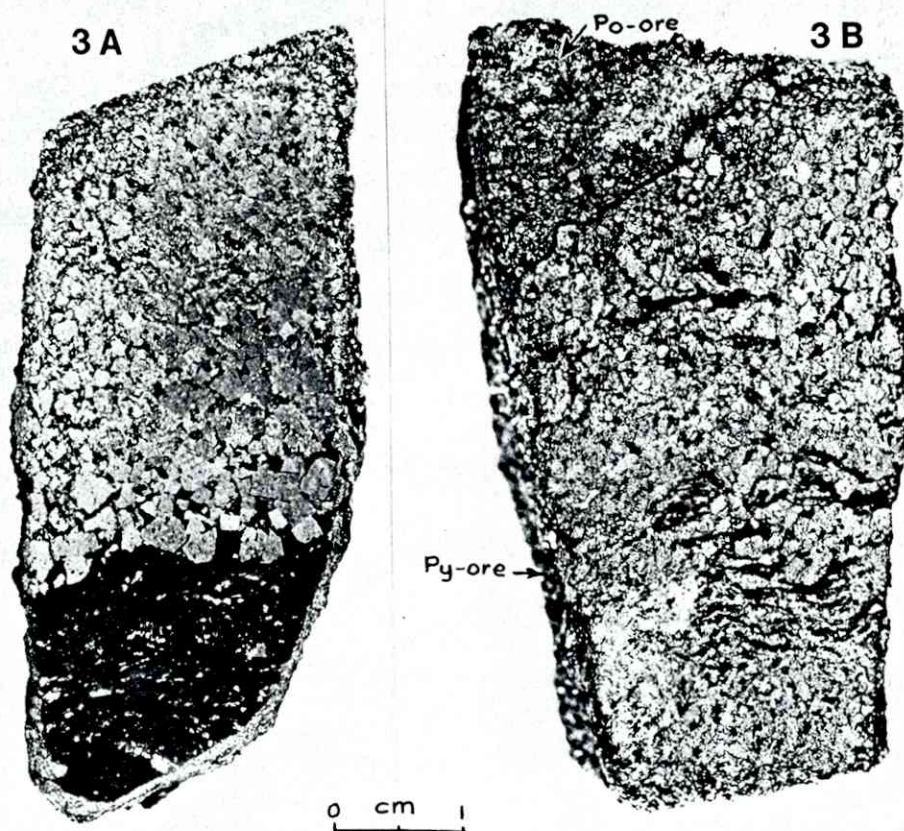
3 A

3 B

Po-ore

Py-ore →

0   cm   1

Fig. 3A. Representative specimen photograph of massive pyritic ore at its contact with the wall rock. Sphalerite may be seen infilling the interspaces of the pyrite crystal aggregates.

Fig. 3B. Specimen photograph displaying the contact of pyrrhotitic ore (Po-ore) with massive pyritic ore (Py ore).

4A

Fig. 4A (right
Magnification
Fig. 4A (left).
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5A

Fig. 5A. Pho
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Fig. 5B. Pho
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in association with pyrrhotitic ore, however, seems to be of limited occurrence in the deposit.

Mineralogic and textural characteristics of different types of sphalerite-bearing ores and the essential aspects of the micromineralogy of their sphalerites are briefly described below.

Group A: Pyrite-sphalerite assemblage

Sphalerite in samples of this group occurs commonly as the principal matrix mineral occupying the interstitial spaces of the interlocked mosaic aggregates of pyrite crystals (Fig. 4A). It is often fine- to medium-grained, the diameter of grains commonly ranging from 0.05 mm to 2 mm or even more.

The mineral generally appears light grey in colour and sometimes shows a little birefringence, possibly due to strain effects. It commonly shows yellowish and reddish internal reflections. Lamellar twinning is exhibited by the mineral in some of the sections (Fig. 4B).

Sphalerite commonly shows mutual boundary relations with pyrite (Fig. 5A). Fracturing due to cataclasis, so commonly observed in the pyrite crystals of this paragenesis, is also noted sometimes in the interstitial sphalerite mass (Fig. 5B). Chalcopyrite, though most commonly associated with sphalerite of this group, is never seen exsolved or intergrown in it.

Group B:

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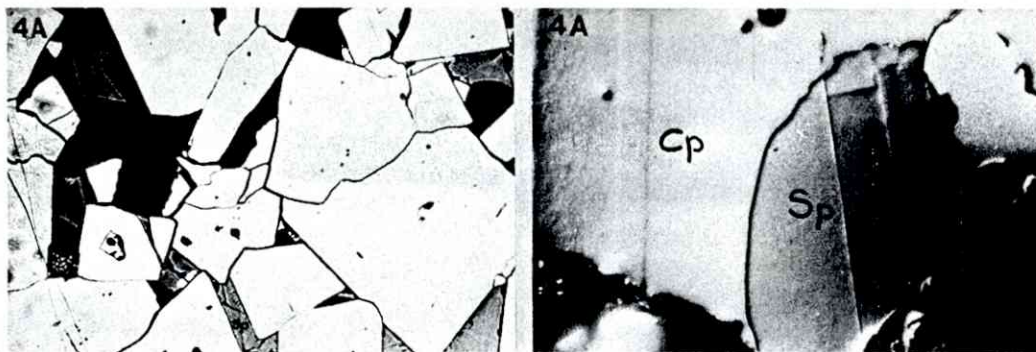some of th
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Fig. 4 A (right). Sphalerite (Sp) occurring as the infilling of the interspaces of pyrite crystal aggregates in massive pyritic ore. Magnification ×50.
Fig. 4 A (left). Sphalerite (Sp) showing lamellar twinning. Associated chalcopyrite (Cp) also exhibits similar twinning. Magnification × 100.
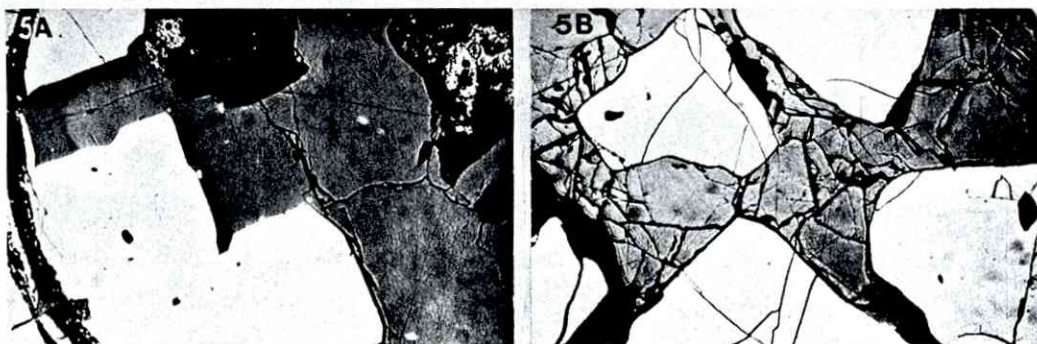

Fig. 5A. Photomicrograph displaying typical mutual boundary relations between sphalerite and pyrite of sphalerite-pyrite assemblage. Magnification × 100.
Fig. 5B. Photomicrograph exhibiting large-scale fracturing of groundmass sphalerite and to a lesser extent of pyrite, both belonging to sphalerite-pyrite assemblage. Magnification ×50.

Group B: Pyrrhotite-sphalerite assemblage

Sphalerite of this assemblage commonly occurs as aggregates, patches or crude bands within the pyrrhotite or chalcopyrite rich ore mass. It is also frequently seen infilling the fractures of the cataclastically-deformed pyrite porphyroblasts. Lamellar twinning possibly caused by shearing stresses during crystallization is more commonly seen in sphalerites of this paragenesis.

Under the microscope, the mineral appears grey to dark-grey in colour and shows deep-reddish or reddish-brown internal reflections. In some of the sections, it shows weak to distinct anisotropism. Under high magnification, some of the sphalerite grains are seen containing numerous blebs or shreds of chalcopyrite in random or vague orientation.

The mineral commonly replaces earlier generation (usually porphyroblastic) pyrite often along its fractures and cracks (Fig. 6A). The latter has to be distinguished from pyrite of sphalerite-pyrrhotite assemblage which is often characterized by perfect euhedral shape and freedom from effects of cataclasis (Fig. 6B). The textural relations between various minerals of this assemblage, by and large, indicate contemporaneity of their crystallization/recrystallisation (Figs. 7A and 7B).

Sphalerite belonging to remobilized-type chalcopyrite-sphalerite ore, which is occasionally found associated with pyrrhotitic ores, shows coarse unmixing of chalcopyrite (Fig. 8A). The unusual shape and distribution of chalcopyrite bodies in and around (particularly near the grain boundaries of) sphalerite of this ore, possibly
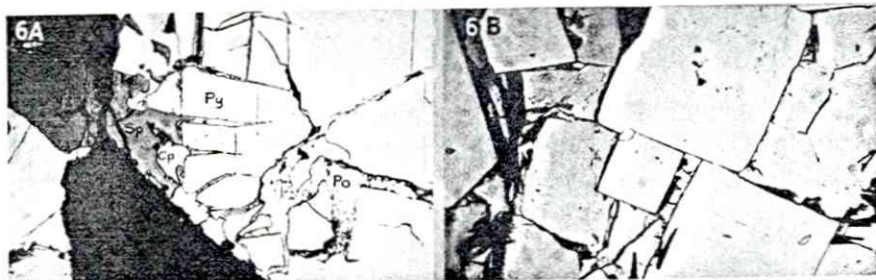
Fig. 6A. Sphalerite (Sp), chalcopyrite (Cp), and pyrrhotite (Po) replacing earlier generation porphyroblastic pyrite (Py) along its fractures and cracks. Magnification ×50.
Fig. 6B. Euhedral and undeformed crystals of pyrite belonging to sphalerite-pyrrhotite assemblage, floating in pyrrhotite groundmass. Magnification ×50.
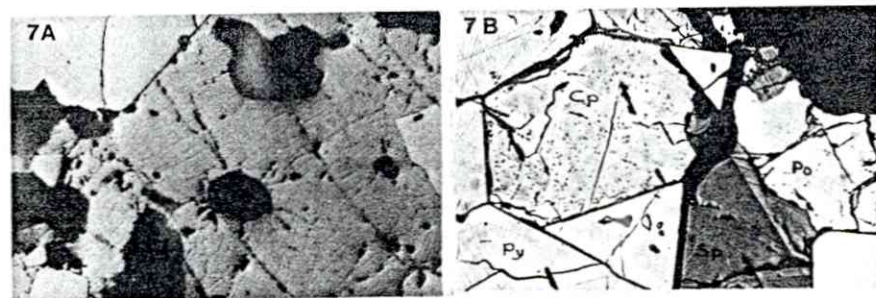

Fig. 7A. Photomicrograph exhibiting mutual boundary relationship of pyrrhotite and pyrite in sphalerite-pyrrhotite assemblage. Pyrrhotite contains exsolved lamellae of troilite. Magnification ×100.
Fig. 7B. Photomicrograph displaying common textural relations of sphalerite (Sp), pyrrhotite (Po), pyrite (Py) and chalcopyrite (Cp) in ores having sphalerite-pyrrhotite assemblage. Magnification ×50.
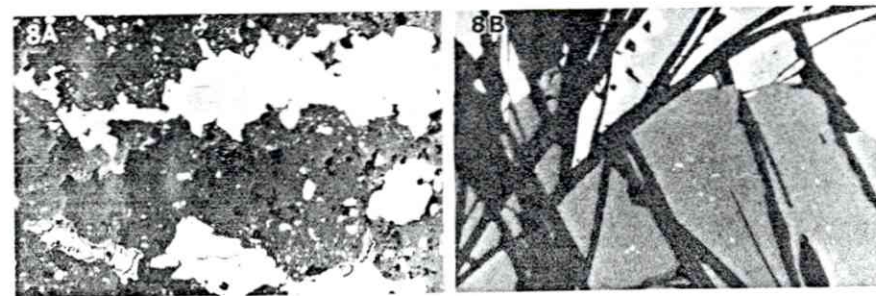

Fig. 8A. Sphalerite from remobilized-type chalcopyrite-sphalerite ore exhibiting coarse unmixing of chalcopyrite which occurs as minute blebs or spherical droplets of varying shape and size in sphalerite-bearing layers. The concentration of chalcopyrite droplets all along the grain-boundaries of sphalerite seems specifically notable. Magnification ×50.
Fig. 8B. Photomicrograph exhibiting cuspate intergrowth of silicates with ore minerals of sphalerite-chalcopyrite assemblage. Minute blebs and shreds of chalcopyrite exsolved randomly in sphalerite may be seen. Magnification ×100.

points to its complicated history. Ramdohr (1969) has noted that he has not observed chalcopyrite bodies of the type mentioned above in high-temperature sphalerites which, according to him, are best exemplified by sphalerites from the Boliden and Sulitjelma deposits. The present observation seems quite significant and may need consideration in this connection. The chalcopyrite-sphalerite ore of this type at times shows intimate intergrowth of lath-shaped hornblende crystals in sulphide ore mass displaying cuspate texture which is typical of the metamorphic nature of the ore (Fig. 8B). Thin bands of magnetite ore are sometimes found associated with massive sulphide ores of this type.

Group C: Sphalerite-galena assemblage

This assemblage seems to be of limited occurrence in the deposit. It has been observed along or near the contact of the main ore mass with the wall rocks, particularly in the Hankabakken and Giken ore bodies.

Sphalerite of this assemblage is characterized by its light-grey colour and yellowish to yellowish-brown internal reflections. It is further characterized by the occurrence of numerous minute inclusions as shreds or lamellae of chalcopyrite in crystallographic orientation along its dodecahedral cleavage planes, thus representing typical exsolution texture.

Sphalerite composition

Material studied

Field relationships of various ore types, megascopic studies of their hand specimens, and microscopic investigations on mineral associations, texture, inclusions, and paragenetic relations were integratedly considered in selecting 50 most representative samples of various types of sphalerite-bearing ores for detailed mineral-chemical investigations. These samples were subjected to a series of mineral-separating operations in order to obtain purest possible concentrates of sphalerites and associated iron-sulphide minerals. Final checks on the purity of concentrates were effected through the microscopic studies of their polished grain-mounts and chemical analyses of the final concentrates for copper and lead. All possible attempts were thus made to obtain up to about 98 % purity of the concentrates and the samples for which this could not be achieved, were simply rejected. Ultimately only 30 sphalerite concentrates belonging principally to the three main ore bodies – Giken, Charlotta, and Bursi – could be taken up for the desired analytical studies. A larger data base, although desirable, was not possible under the then existing constraints of time.

Analytical methods

Combinations of atomic absorption, electron probe and X-ray diffraction techniques were employed to determine the minor- and trace-element composition of sphalerites. About a dozen selected samples were analysed by all the three techniques for certain elements, and the analytical data so obtained have been assembled in Table 1 to facilitate comparative study of the results. The procedures and results of analytical work by the three methods have been as follows:

Atomic absorption spectrophotometric analyses. This method was employed for the quantitative determination of minor elements, namely Fe, Mn, Cd, Pb & Cu and some trace elements, e.g. Ga, Co and Ni in the sphalerite samples of this study. The analytical work was carried out in F. J. Langmyhr's atomic absorption spectrophotometric laboratory at Kjemisk institutt, Universitetet i Oslo.

Sphalerite concentrates were subjected to dissolution in acids by decomposition bomb technique. The detailed procedure described by Langmyhr & Paus (1968, 1970) was in general adopted for sample preparation and for analytical work that was carried out on Perkin Elmer AAS Model-303 in the laboratory of Kjemisk institutt, Oslo.

The results of analyses of sphalerites of the two principal groups are presented in Tables 2 and 3 respectively and are discussed in detail later on. The analysis of a sphalerite sample (sp.no. H/13) representing Group C, i.e. sphalerite-galena assemblage, has been included only in Table 1. It was extremely difficult to get adequately pure sphalerite concentrate from this ore; it was therefore considered futile to take up any more samples of this group for chemical analyses by this method.

Electron probe microanalyses. – Electron probe microanalyses of sphalerites from 12 selected samples of different ore types from different ore

Table.1. Comparison of atomic absorption spectrophotometric, electron microprobe, and X-ray diffraction data on selected sphalerites from Sulitjelma mining district, Norway.

Ore body	Speci-men No.	Atomic absorption spectrophotometric Results (in mole percent)				Electron Microprobe Results (in Mole %)		X-ray diffraction results		
		FeS	MnS	CdS	Total	FeS	MnS	Measured cell edge (A)	Apparent mole % FeS	Calculated cell edge (A)
Giken	G/111	12.3	0.38	0.31	12.99	13.0	0.35	5.4180	16.4	5.4174
Giken	G/107	17.3	0.14	0.15	17.59	13.5	0.14	5.4164	14.1	5.4165
Giken	G/37	15.8	0.04	0.14	15.88	13.3	0.02	5.4170	15.6	5.4158
Giken	G/39	13.7	0.10	0.19	13.99	16.3	0.08	5.4165	14.3	5.4157
Giken	G/57	12.0	0.06	0.25	12.31	12.0	0.05	5.4165	14.3	5.4157
Giken	G/51	9.9	0.12	0.16	10.18	11.5	0.09	5.4160	13.5	5.4154
Giken	G/48	13.3	0.13	0.14	13.57	16.0	0.09	5.4175	16.3	5.4176
Charlotta	G/102	12.9	0.14	0.21	13.25	14.0	0.13	5.4172	15.8	5.4176
Charlotta	C/94	16.5	0.16	0.15	16.80	14.1	0.14	5.4170	15.6	5.4165
Bursi	B/7	16.2	0.12	0.17	16.49	13.9	0.17	5.4165	14.3	5.4167
Bursi	B/21	14.5	0.09	0.20	14.79	13.4	0.09	5.4176	16.5	5.4170
Hankabakken	H/13	3.6	0.10	0.51	4.21	1.9	0.09	5.4116	4.3	5.4126

bodies were carried out principally to detect and study the microchemical zoning, or the iron-rich patches in sphalerite, if present. The samples were also analysed for their iron- and manganese content as a measure of cross-check on the results of atomic absorption spectrophotometric analyses. In addition, zinc- and sulphur content of samples were also determined to provide a check on the correction procedure.

The analytical work was carried out at Sentral-instituttet for industriell forskning in Oslo, with the kind cooperation of Dr. W. L. Griffin, on an A. R. L. EMX-Model Electron probe microana-lyser at 20 KV with an effective specimen current of 0.05 MA. Standards used were ZnO, natural pyrite, natural sphalerite and manganese sulphide of well-established composition kindly provided to the author by Dr. Otteman of the University in Heidelberg. Instrumental corrections for absorption (Philibert 1963), fluorescence (Read 1965), dead-time, and atomic number effect were calculated using the Springer Programme on the computer. Under the analytical conditions employed, detection limits were 0.02 % for iron and 0.01 % for manganese determination. In the iron-concentration range commonly encountered, analytical precision was usually better than ± 2 % of the amount present.

The results of analyses by this method have been presented in Tables 1 and 4.

Unit-cell measurements of sphalerite. – Cell dimensions of sphalerite from the above-mentioned 12 selected samples were determined by the X-ray diffractometric method of Smith (1955) as revised by Short & Steward (1959). Extrapolation of these measurements on the X-ray determinative curve of Barton & Toulmin (1965) was then adopted to estimate the iron content of the corresponding sphalerite samples. For purposes of comparison, these results expressed as apparent FeS content are incorporated in Table 1 side by side with the results of atomic absorption spectrophotometric and microprobe analyses.

Comparative study of the analytical results

Comparative study of analytical results on the 12 selected samples which were analysed by all the three methods mentioned above (Table 1) brings out a fairly good agreement of the electron-probe and atomic absorption spectrophotometric results for both the FeS and MnS content of the sphalerites. X-ray diffraction results on the mole percent FeS content of sphalerites, as obtained from the measured cell dimensions, on the other hand, appear to be generally on the high side as compared to the corresponding electron probe or AAS results. This is presumably attributable to the expansion of unit-cell dimensions of sphalerites by their manganese- and cadmium contents. In order to check this, the unit-cell dimensions of the sphalerite samples were calculated, using the atomic absorption spectrophoto-

Table 2. Com

Ore body and
mine level

Giken(+100)
Giken(-106)
Giken(-142)
Giken(-233)
Giken(-233)
Giken(-233)
Giken(-256)
Giken(-283)
Giken(-351)
Charlotta(-2
Hankabakken
Bursi

Average (of
Standard dev

Table 3. Com

Ore body and
mine level

Giken(+127)
Giken(+61)
Giken(+61)
Giken(-111)
Giken(-233)
Giken(-396)
Charlotta(+1
Charlotta(-2
Charlotta(-2
Charlotta(-2
Charlotta-3.
Bursi(+80R)
Bursi(+60R)
Bursi(-5R)
Jakobsbakken
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Table 2. Composition of Group-A sphalerites associated with pyrite only (pyrrhotite being absent).

Ore body and mine level	Speci-men No.	FeS mole %	MnS mole %	CdS mole %	Ga ppm	Co ppm	Ni ppm	Pb %
Giken(+100)	G/109	13.9	0.08	0.18	7	60	20	0.11
Giken(−106)	G/37	15.7	0.04	0.14	8	50	15	0.08
Giken(−142)	G/38	13.4	0.09	0.15	6	55	20	0.01
Giken(−233)	G/41	16.2	0.06	0.23	8	25	15	0.11
Giken(−233)	G/57	12.0	0.06	0.25	5	25	20	0.01
Giken(−233)	G/24	13.7	0.06	0.14	5	40	15	0.02
Giken(−256)	G/42	13.9	0.09	0.15	10	50	20	0.02
Giken(−283)	G/43	14.1	0.10	0.19	15	35	20	0.03
Giken(−351)	G/46	9.5	0.06	0.22	5	40	25	0.03
Charlotta(−233)	C/55	15.7	0.09	0.15	15	120	35	0.02
Hankabakken	H/20	11.2	0.06	0.23	10	25	20	0.20
Bursi	B/7	16.2	0.12	0.17	12	130	15	0.02
Average (of 12 samples)		13.8	0.08	0.18	9	54	20	0.05
Standard deviation		1.9	0.02	0.04	3	33	5	0.03

Table 3. Composition of Group-B sphalerites associated pyrrhotite (with or without pyrite).

Ore body and mine level	Speci-men No.	FeS mole %	MnS mole %	CdS mole %	Ga ppm	Co ppm	Ni ppm	Pb %
Giken(+ 127)	G/110	13.4	0.06	0.17	10	70	22	0.15
Giken(+61)	G/108	12.9	0.09	0.16	6	50	20	0.03
Giken(+61)	G/107	17.3	0.14	0.15	15	75	30	0.05
Giken(−111)	G/39	13.7	0.10	0.19	7	40	25	0.10
Giken(−233)	G/51	9.9	0.11	0.17	5	75	25	0.01
Giken(−396)	G/74	14.5	0.16	0.15	12	60	12	0.01
Charlotta(+17)	G/102	12.9	0.14	0.21	10	110	15	0.01
Charlotta(−233)	C/94	16.5	0.16	0.15	8	75	30	0.01
Charlotta(−289)	C/74	14.6	0.19	0.15	18	95	30	0.01
Charlotta(−289)	C/9	17.1	0.08	0.19	10	65	20	0.01
Charlotta(−325)	C/78	19.9	0.06	0.13	15	200	40	0.01
Bursi(+80R)	B/3	14.5	0.10	0.17	10	75	20	0.14
Bursi(+60R)	B/4	18.2	0.06	0.20	10	120	12	0.01
Bursi(−5R)	B/13	12.4	0.06	0.20	10	120	12	0.01
Jakobsbakken	J/1	12.7	0.31	0.22	8	65	18	0.04
Jakobsbakken	J/2	15.7	0.21	0.19	15	70	15	0.05
Average (of 16 samples)		14.7	0.12	0.17	11	80	22	0.04
Standard deviation		2.4	0.06	0.02	4	38	7	0.04

metric results, from the following function after Barton & Skinner (1967):

$$a_0 = 5.4093 + 0.000456\ x + 0.00424\ y + 0.00202\ z$$

were x, y, and z represent the mole percent FeS, CdS, and MnS respectively. The results so obtained from calculations are placed side by side with those of actual measurements in Table 1 for comparative observations. As may be seen, there is generally a good agreement between the measured and calculated cell dimensions, the differences (often ± 0.0003) being well within the limits of tolerable error in the measurement.

The observed agreement confirms that the iron, manganese, and cadmium are the principal elements affecting the cell dimensions of sphalerite. It also confirms that the contents of these elements, as detected by atomic absorption technique, largely represent their amount fixed within the lattice of the respective sphalerites.
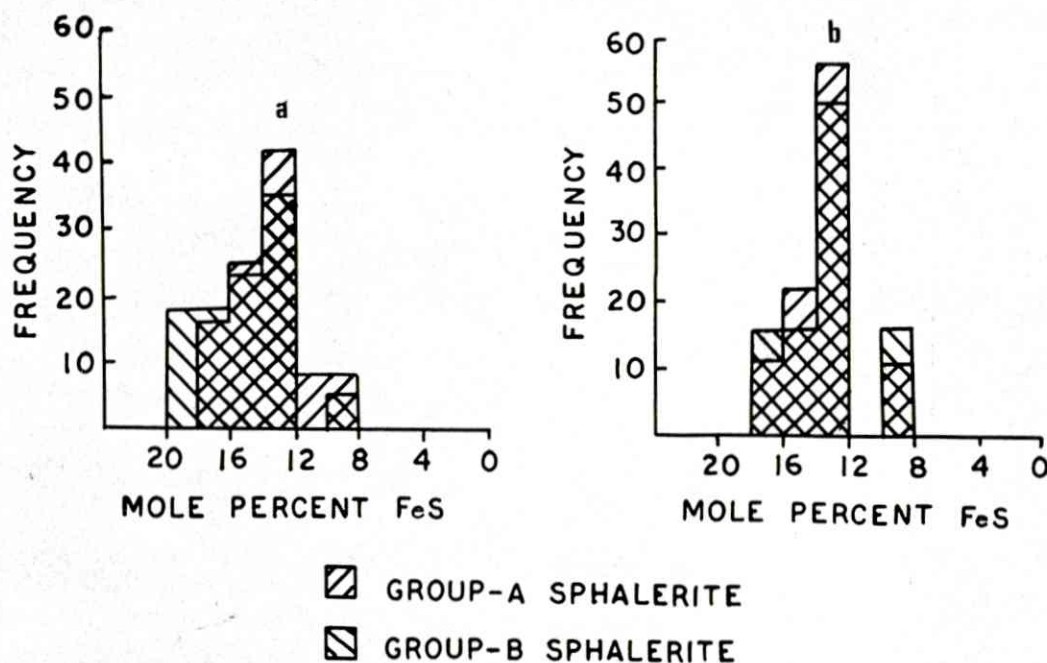
Fig. 9. Composite histograms showing the distribution of analyses of (a) Sulitjelma sphalerites and (b) Giken sphalerites.

Results

Iron content of sphalerites

The FeS-content of sphalerites belonging to two principal groups of ores in Sulitjelma deposit varies, in general, from 9.5 to 19.9 mole percent, the ranges of variation for the two groups overlapping each other for the major part of their spreads (Fig. 9a). The range from 12 to 17 mole % FeS covers nearly 90 % of Group-A and 75 % of Group-B sphalerites and, therefore, largely represents the composition of sphalerites of the deposit in general.

The pattern and trend of variation of iron content in sphalerites of the two groups of ores may be best studied on the scale of an individual ore body. Accordingly, a study of the analysed samples from Giken ore body, the biggest and most representative of the deposit (Fig. 9b), leads to the following interesting and significant observations.

Group-A sphalerites show a variation in mole % FeS from 9.5 to 16.2 with an average of 13.6 and a mode of 13.9 while those while those belonging to Group-B exhibit a range from 9.9 to 17.3 mole % FeS with an average of 13.6 and a

mode of 12.2. Group-A sphalerites thus tend to show relatively higher FeS-content than their Group-B counterparts.

The pattern of distribution of iron analyses in either group is unimodal with pronounced mode in 12 to 14 mole % FeS range. In either group, over 65 % of the analysed samples have their iron analyses clustered closely within or around the mode.

The spread of analyses is comparatively larger for sphalerites of the pyrrhotitic assemblage.

Manganese content

The two paragenetical groups of sphalerites exhibit fairly distinctive and rather characteristic ranges of their manganese content. Group-A sphalerites seem to have generally low and relatively more consistent manganese content in the narrow range of 0.02 % to 0.07 %. Group-B sphalerites, on the other hand, exhibit higher manganese content in a wider range of 0.04 % to 0.22 %. Sphalerites from the Jakobsbakken ore body show abnormally high manganese content, usually exceeding 0.2 %.

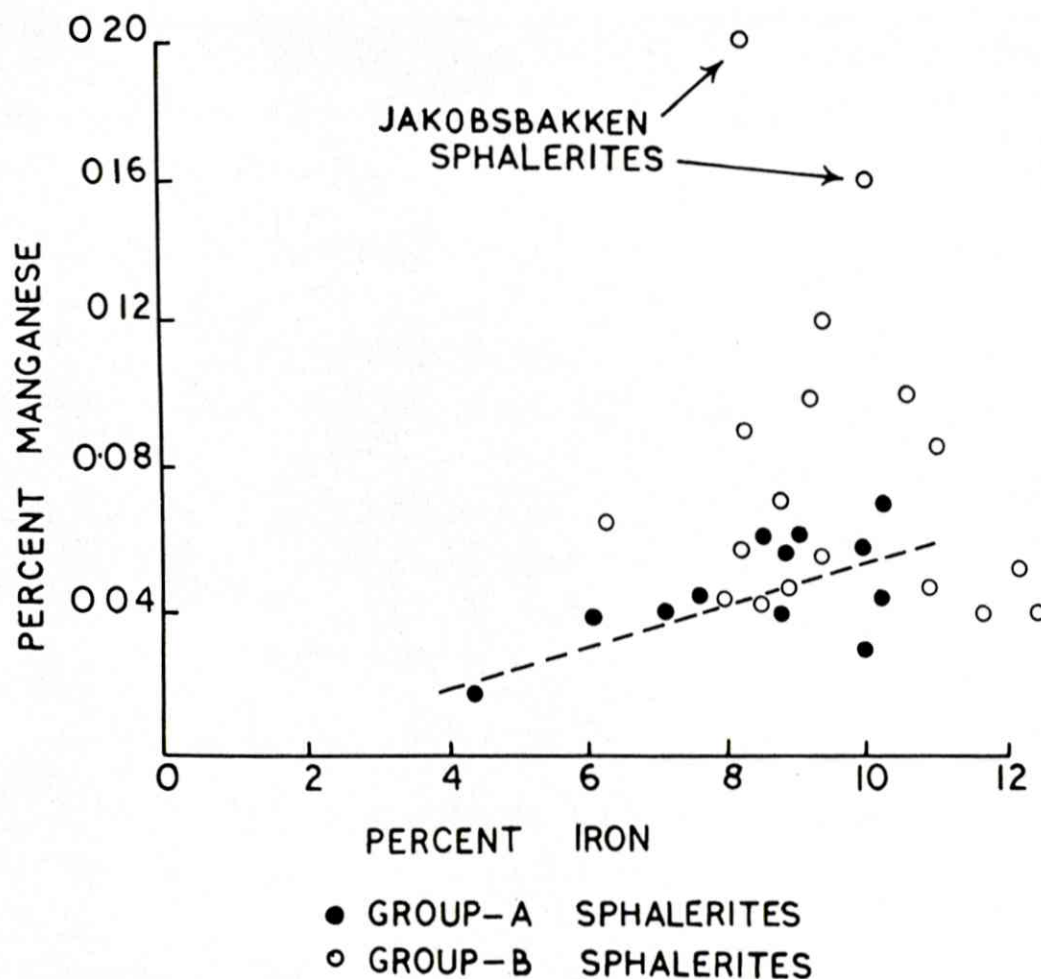The graphic evaluation of the iron-manganese

Fig. 10. Graph showing relationship of iron- and manganese-contents in Group-A and Group-B sphalerites.

relationship in Fig. 10 brings out clearly discernible sympathetic correlation between the iron and manganese content of Group-A sphalerites. No such relationship, however, is visible in Group-B sphalerites.

Cadmium content

The cadmium content of the two principal groups of sphalerites varies over a characteristically narrow range of 0.11 % to 0.19 % with a prominent modal concentration around 0.14 %. Ranges of cadmium content pertaining to the two principal groups of sphalerites appear to be overlapping for the large part of their spreads. The cadmium content of sphalerite from the

sphalerite-galena assemblage, on the other hand, appears strikingly high, being about 0.37 % in its analysed sample.

There is no discernible linear nor logarithmic correlation between the iron- and cadmium content of Group-A or Group-B sphalerites of the deposit.

Other trace elements

Elements detected in trace amounts in almost all the sphalerite samples of this study include gallium, cobalt, nickel, silver, arsenic, and antimony. The abundances of the first three of them, determined quantitatively, appear in Tables 2 and 3. It is difficult to say how much of the
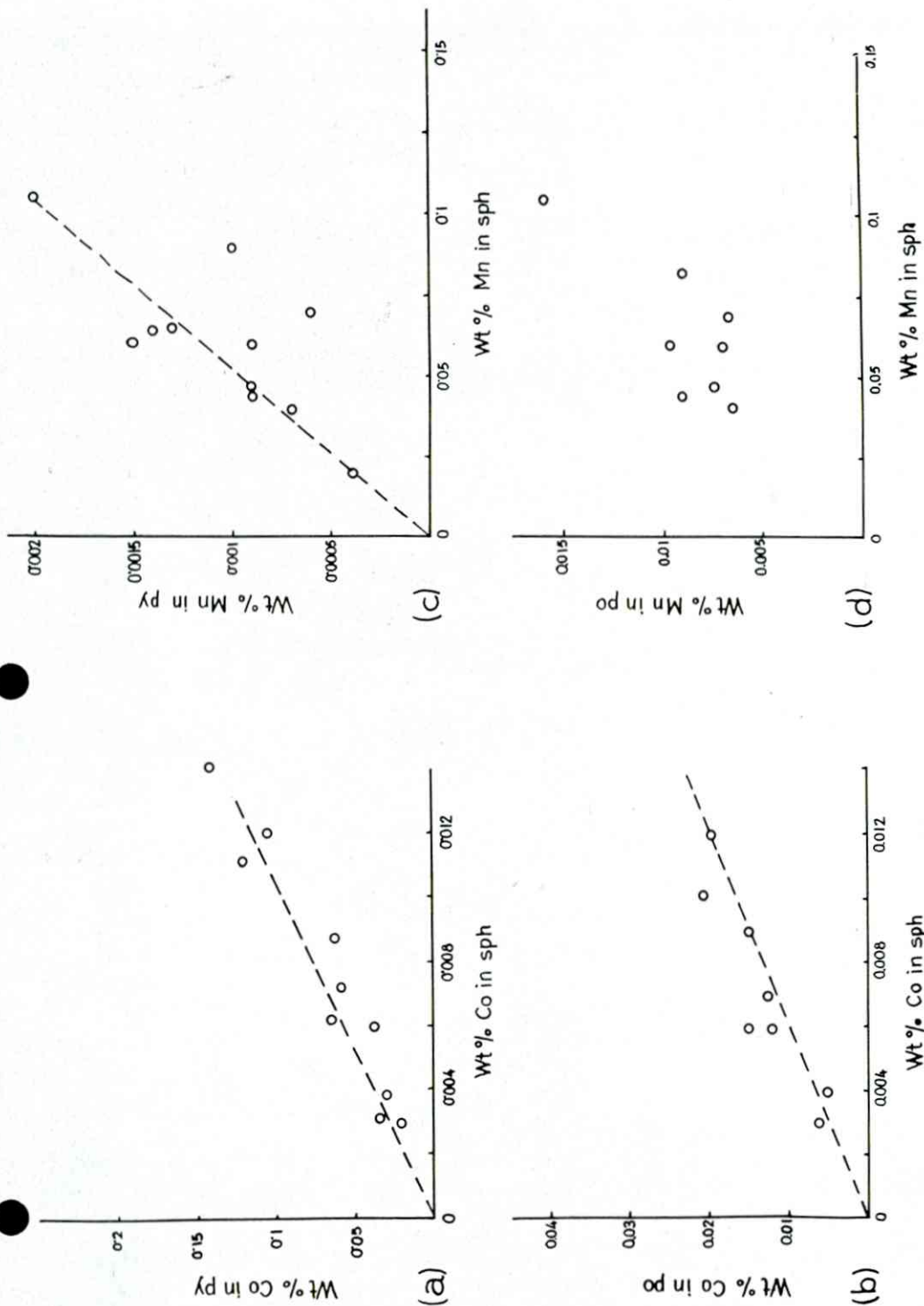
Fig. 11. (a) and (b): Roozeboom diagrams showing the distribution of cobalt between (a) pyrite and sphalerite, and (b) pyrrhotite and sphalerite in Sulitjelma ores.

Fig. 11. (c) and (d): Roozeboom diagram showing the distribution of manganese between (c) pyrite and sphalerite and (d) pyrrhotite and sphalerite in Sulitjelma ores.

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Table 4. Chemical composition of different parts of selected sphalerite crystals.

Sample No.	Part of the crystal		Zn %	Fe %	Mn %	S %
G/107	Central part (core)	(1)	57.02	8.79	0.13	34.74
	Marginal part	(2)	56.14	8.37	0.11	35.18
		(1a)	0.86	0.16	0.00	1.00
		(2a)	0.85	0.15	0.00	1.00
G/57	Central part (core)	(1)	58.00	7.49	0.03	33.99
	Marginal part	(2)	58.15	7.77	0.03	34.22
		(1b)	0.87	0.13	0.00	1.00
		(2b)	0.88	0.14	0.00	1.00

1(a) and 2(a) and 1(b) and 2(b) represent no. of atoms calculated from the analyses 1 and 2 on the basis of 1(S).

observed abundances of these elements in the analysed sphalerite samples should be ascribed to the microcrystalline particles or grains of chalcopyrite, galena etc. that may be occurring as minute, invisible, and inseparable inclusions in sphalerite, or to the copper possibly present in solid solution with zinc. In this connection, two important facts have to be taken into account:

The analytical results show fairly low concentration of both copper and lead in the analysed sphalerite samples, thus indicating minimal contamination.

The abundances of the above-mentioned microelements in the analysed sphalerites, in general, fall within appreciably narrow ranges.

It is, therefore, surmised that the observed abundances of the trace elements by and large represent the amount fixed within the lattice of sphalerite itself, and the contributions of the impurities, if any, are almost negligible.

Unlike iron, manganese, and cadmium, none of the trace elements mentioned above exhibit any dependence upon the paragenetic grouping of sphalerites. The ranges of abundance of the various trace elements corresponding to the two paragenetic groups of sphalerites are found to be characteristically narrow and almost overlapping for the whole or the large part of their spreads.

Sphalerite composition on a crystal scale

Microprobe analyses of numerous spots representing central (core) and marginal (rim) portions of several sphalerite crystals in about a dozen selected samples of the two principal types of ores were carried out to examine the homogeneity/heterogeneity of sphalerite composition

on the crystal scale. Representative results of this study referring to two typical samples, summarised in Table 4, exhibit nearly identical composition in the core and rim portions of the crystals thereby indicating total absence of zoning in them and almost homogeneous chemical constitution of the sphalerites.

Following suggestions of Scott & Barnes (1971), microprobe traverses across a few sphalerite grains in three polished sections of typical ores belonging to sphalerite-pyrrhotite assemblage were also undertaken in order to detect the presence of iron-rich patches, if any. No such patch, however, could be detected in the analysed sphalerites.

Element distribution between sphalerite and associated iron-sulphide minerals

The partitioning of some common minor elements, particularly manganese and cobalt between sphalerite and pyrite of pyritic ores on the one hand, and sphalerite and pyrrhotite of pyrrhotitic ores on the other, was studied on a limited scale. The results of this study are presented graphically as 'Roozeboom diagrams' in Fig. 11. As may be seen the study brings out fairly distinct and meaningful distribution patterns. The distribution of cobalt between sphalerite and pyrite, as well as between sphalerite and pyrrhotite, shows remarkably little scatter of points on the diagrams. The distribution of manganese in both the mineral pairs, on the other hand, exhibits less distinct, yet still delineable trend towards consistency of distributional relationship. The magnitude of deviations, of course, appears relatively more but is still within reasonable limit of error.

While it may be desirable to have many more analytical results to study partitioning of elements, the aforesaid study possibly succeeds within its limitations to focus upon the discernible trend towards regularity of element partitioning in the typomorphic mineral pairs representing the two ore-types.

Synthesis and discussion

The overall observations of the present study confirm the classification of sphalerite-bearing ores of Sulitjelma deposit into three typomorphic groups that have distinguishable modes of occurrence, mineral associations, and micro-mineralogic and geochemical characteristics of sphalerites. This fact is, in itself, suggestive of the polycyclic nature and complicated history of sulphide mineralization in the region.

The first two groups of sphalerite-bearing ores, represented by pyrite-chalcopyrite-sphalerite and pyrrhotite-chalcopyrite-sphalerite assemblages, constitute over 90 % of the ore mass in the deposit. They vary considerably not only in their own relative proportion in the average ore mass, but also in their average chemical composition from one ore body to another. A big range of zinc-rich to zinc-poor ore bodies having no definite pattern in their setting is consequently represented in the deposit. This observation has a significant bearing on the problem of ore genesis in the region (Rai 1972, 1977).

In contrast to the above-mentioned picture regarding their average chemical composition, the two groups of ores exhibit only minor differences, essentially of quantitative nature, in the minor- and trace-element geochemistry of their sphalerites. The ranges of variation in the content of an element in sphalerites of the two groups of ores are overlapping for the large part of their spreads in the case of minor elements like iron and manganese and cadmium and are generally quite narrow and indistinguishable for trace elements like gallium, cobalt, nickel, etc. Similarities in the pattern and trend of distribution of analytical results of iron in the two groups of sphalerites are also striking and significant. All these observations seem to be suggestive of final crystallization or recrystallization of the two groups of sphalerites and related ores under almost identical physico-chemical conditions corresponding possibly to the isofacial high-grade metamorphism of ores and the country rocks.

In the Giken ore body, the sphalerites of pyritic assemblage exhibit a tendency to be slightly richer in iron as compared to the sphalerites of the pyrrhotitic assemblage. While this significant observation needs to be strengthened with a larger data base covering the entire deposit, it may be mentioned that a similar pattern and trend of sphalerite composition has been observed recently in the massive lead-zinc deposit of Sullivan in British Columbia, Canada (Barton pers. comm. 1975). It is difficult to say if observations of this sort can be explained simply by high (total) pressures during crystallization or by the equilibration at low temperatures or even both. As suggested by Barton, a better explanation might well be multiple mineralization or limited re-equilibration wherein the pyrite was inert. The possibility of interactions between some phases while others remained inert or sluggish as temperatures and pressures fell has, accordingly, to be considered. The modifying role of lower temperature phenomena which are capable of clouding or even destroying the records of metastable stages also needs proper evaluation in this connection.

The present study on sphalerites also has an important bearing on the problem related to equilibrium control of ore formation in the deposit. The observed textural relations of sphalerite and associated iron-sulphide minerals in the two ore types indicate essentially the co-existing nature of the sulphide minerals concerned. The homogeneity of sphalerite composition on the crystal scale, as brought out by the microprobe studies, seems to be suggestive of effective equilibration even on the micro scale in the ore mass of the two ore-types. This is further substantiated by the observed regularity in the partitioning of certain minor elements, particularly manganese and cobalt, between sphalerite and associated iron-sulphide minerals in the two ore-types. The study on minor- and trace-element composition of sphalerites further brings out a close approach to compositional uniformity of sphalerites of each group on the scale of an ore body as well as the ore deposit in general. All these micro-, macro- and mega-scale observations suggest a good degree of equilibrium control of ore formation in the deposit under study.

As shown by Scott & Barnes (1971) and Scott (1973), sphalerite co-existing with pyrrhotite and pyrite may be used confidently as a geobarometer in most of the geologic environments. In

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regionally metamorphosed sulphide deposits, according to them, this geobarometer is most likely to succeed because the duration and extent of the metamorphic event offers optimum conditions for equilibration and homogenization of mineral assemblages. Accordingly, in the Sulitjelma deposit, where the equilibration of mineral assemblages on all scales has already been surmised and is presumably an effect of the regional metamorphism, the sphalerite geobarometer seems to be best-suited for deciphering the pressure conditions of deposition and metamorphism of ores. Paucity of adequate data regarding the temperature conditions of ore formation, however, circumscribes the effective application of this geobarometer. Meanwhile, some provisional estimates regarding the pressure conditions may be made on the basis of the following available data:

Henley's (1970b) estimates regarding the upper limit of temperature of recrystallization of country rocks at 550°C–600°C, this being presumably applicable also to the ores in the light of isofacial nature of regional metamorphism of country rocks and the ore deposit.

The estimates of minimum temperatures in 375°–425°C range, as obtained from the application of pyrrhotite geothermometer.

The composition of sphalerites co-existing with pyrrhotite and pyrite commonly in the range of 12 to 17 mole % FeS, as observed in this study.

The extrapolation of the above data on the geobarometric curves of Scott & Barnes (1971) indicates the pressures of 4.0 ± 1 Kb in the deposit. While presenting this estimate tentatively, it may be emphasized that the existing composition of sphalerites in both the major paragenetical groups of ores represents at best the optimum conditions undergone by them during regional metamorphism and not necessarily the primary conditions of ore-formation in the deposit.

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