SVERIGES GEOLOGISKA UNDERSÖKNING

SER. C. Avhandlingar och uppsatser. N:O 438.

ÅRSBOK 35 (1941) N:O 1.

GEOLOGY AND ORES OF THE BOLIDEN DEPOSIT, SWEDEN

BY

OLOF H. ÖDMAN

WITH 48 PLATES

Pris 8 kronor

STOCKHOLM 1941
KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER
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Page 17. Table 1, Analysis No. 2: Fe read F.
Page 23. Fourth passage, line 1: al, read all.
line 2: alterationl read alteration.
Page 48. Sixth passage, line 3: Pyrrhotite is older read Pyrrhotite is later.
Page 49. Fifth passage, line 1: *e. g.* should be left out.
Page 53. Line 7: apatite ore read apatite rock.
Page 59. Fig. 8: 10 m (in the scale) read 2 m.
Page 65. Table 18: Sp. gr. = 5.903 refers to Analysis No. 25.
Page 68. Sixth passage, line 4: jaspilitic read jasperoid.
Page 142. Line 6 from below: Western read western.
Page 189. 87. Schmidt, W. R. read 87. Schmidt, W. E.

410630—S. G. U., Ser. C, 438.

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Contents.

Page.

Preface 7
Introduction 9
General Geological Survey of the Boliden Area 11
General Geological Survey of the Deposit 13
Description of the Rocks 15
A. Unaltered Rocks 15
General 15
Quartz Porphyry 15
Keratophyre and Quartz Keratophyre 16
Dacite 18
Pyroclastic Rocks 19
Black Phyllite 20
B. Altered Volcanic Rocks with Basic Plagioclase, Hornblende, and Biotite 20
C. Altered Rocks 23
1. Sericitic Rocks 24
Terminology 24
Normal Sericite Schist 24
Quartz-porphyritic Sericite Schist 25
Chloritic Sericite Schist 27
Pyritic Sericite Schist 28
Pyroclastic Sericite Schist 29
Sericite Rock 29
Chemical Composition of the Sericitic Rocks 31
2. Andalusite Rocks 32
General 32
Normal Andalusite Rock 34
Quartz-bearing Andalusite Rock 38
Chemical Composition of the Andalusite Rocks 39
Description of the Ores 40
Types of Ore 40
Arsenopyrite Ore 41
Distribution 41
Contact Relations 41
Description of the Arsenopyrite Ore 42
Normal arsenopyrite ore 42
Dense arsenopyrite ore 44
Apatite-banded arsenopyrite ore 44
Quartz-banded arsenopyrite ore 45
Cobaltite-bearing arsenopyrite ore 46

Page.

Paragenesis of the Arsenopyrite Ore 47
General 47
Ore minerals 47
Gangue minerals 51
Chemical Composition of the Arsenopyrite Ore 55
Mineral Associations connected with the Arsenopyrite Ore:
A. Rutile Rock 55
B. Pyrite-Apatite Ore 57
C. Apophysis in Stope 20 (90 m Level) 62
D. Felspathization and Felspar Veins 66
Disseminated Ore 68
Summary; Order of Crystallization 68
Lamprophyric Dykes with Quartz-Tourmaline and Sulphide Ores 71
A. Lamprophyres 71
General 71
Relations to the Arsenopyrite Ore 72
Petrographic Description 73
Hornblende lamprophyre 74
Chloritic lamprophyre 75
Chemical Composition of the Lamprophyres 77
B. Quartz-Tourmaline and Sulphide Ores 78
General 78
Description of the Quartz-Tourmaline Ore 80
Vein-shaped ores 80
Lens-shaped quartz-tourmaline bodies 82
Paragenesis of the Quartz-Tourmaline Ore 83
Ore minerals 83
Gangue minerals 93
Chemical Composition of the Quartz-Tourmaline Ore 96
Copper-Pyrrhotite Ore in connection with the Quartz-Tourmaline Ore 97
Inclusions of Tourmaline Ore in the Sulphide Ore 99
Relation of the Quartz-Tourmaline Ore to the Arsenopyrite Ore 99
Relation of the Quartz-Tourmaline Ore to the Andalusite Rock .. 100
Concentrations of Bi-tellurides 101
Bi-tellurides in Stope 28 (250 m level) 102
Bi-tellurides on the 210 m level 104
Impregnations of Gangue and Ore Minerals (Disseminated Ores) 106
Summary; Order of Crystallization 107
Pyrite Ore 108
Distribution 108
Relation to the Wallrock 108
Relation to the Arsenopyrite Ore 109
Relation to the Lamprophyre Dykes 109
Description of the Pyrite Ore 110
Paragenesis of the Pyrite Ore 111
Ore minerals 111
Gangue minerals 113
Chemical Composition of the Pyrite Ore 116
Apophyses 117
General 117
Paragenesis 120

Page.
Sulphide-bearing Quartz-Plagioclase Veins 121
Felspathization and Disseminated Ores 123
Inclusions of Wallrock 124
Apophyllite-bearing Fissures 125
Summary; Order of Crystallization 127
Description of the Ore Bodies 128
Arsenopyrite Ore Bodies 128
General 128
The a-d-lens 128
The k-lens 131
The b- and h-lenses 132
The e-lens 132
Quartz-Tourmaline Ore Bodies 133
General 133
Quartz-Tourmaline Ore in Stope 23 (170 m Level) 133
Quartz-Tourmaline Ore on the 330 m level (Section 15) 133
Quartz-Tourmaline Veins in Stope 26 (250 m Level) 133
Tourmaline Vein between Sections 14 and 15 (250 m Level) 134
Pyrite Ore Bodies 135
General 135
Western Ore 136
Eastern Ore 137
Structure 138
Folding 138
Faults 142
Origin of the Altered Rocks 143
Origin of the Sericitic and Chloritic Rocks 143
Age of Sericitization 143
Original Composition of the Sericitic Rocks 144
Chemistry of the Sericitization 145
Origin of the Chlorite-bearing Schists 148
Origin of the Andalusite Rocks 149
Age of the Andalusite Rocks 149
Chemical Relations of the Formation of the Andalusite Rocks 149
Comparison with Other Occurrences of Andalusite-bearing Rocks 151
Origin of the Hornblende-Plagioclase Rocks 153
Summary 154
Origin of the Ores 155
Origin of the Arsenopyrite Ore and its Differentiates 155
Evidence of the Contacts 155
Evidence of Structures and Textures 156
Mise en Place of the Ore Bodies by Displacement 157
Nature of the Ore Solution 159
Differentiation of the Ore Solution:
A. Origin of the Various Types of Arsenopyrite Ore 160
B. Origin of the Various Mineral Associations Related to the Arsenopyrite Ore 160
The Lamprophyres and the Origin of the Quartz-Tourmaline Ores 162
Original Composition of the Lamprophyres 162
Chloritization of the Lamprophyre 162

Page.
Mise en Place of the Lamprophyres and the Quartz-Tourmaline Ores ... 163
Nature of the Ore Solution ... 164
Differentiation of the Ore Solution ... 165
Sericitization of the Andalusite Rock ... 165
Origin of Mariposite and the Source of Chrome ... 166
Relations between the Lamprophyres and the Accompanying Ores ... 167
Origin of the Pyrite Ore ... 168
Mise en Place of the Ore ... 168
Nature of the Ore Solution ... 170
Differentiation of the Ore Solution ... 171
Origin of the Spinel-bearing Inclusions ... 172
Origin of the Apophyllite Fissures ... 172
Comparison between the Boliden Ores and Similar Ores ... 173
The Arsenopyrite Ore ... 173
The Quartz-Tourmaline Ore ... 174
The Pyrite Ore ... 175
Source of the Ore Solutions ... 177
Formation of Ore Deposits by Displacement — A General Discussion ... 178
Summary ... 180
List of Minerals in the Boliden Ores (Table 42) ... 184
Bibliography ... 186
Explanatory Notes to the Maps (Pl. 1—8) ... 190

Preface.

This description of the geology of the Boliden Deposit was originally intended to be a company report on the investigations I carried out as a mining geologist of the Boliden Mining Company during the years 1935—1940. Thanks to the courtesy of the company it has been possible for me to publish the report and to give it the shape of a detailed geological description.

I owe a great debt of gratitude to Mr. O. Falkman, President of the Boliden Mining Company, for all the interest he has shown in my work and for his kindness in permitting the publication. I am very much indebted to Dr A. Lindblad, Vice President of the company, for the large number of analyses carried out at the company's laboratories. I also wish to express my gratitude to the Board of Directors for the funds placed at my disposal for the printing.

Mr. E. Wesslau, the Manager at Boliden, and my friends and colleagues among the officials of the company at Boliden and in Stockholm have all rendered me very great assistance for which I here wish to convey my sincere thanks. My co-operation with Mr. G. Lindgren, who served as my assistant, has been most fruitful. His keen eye and his great interest in the work have yielded many observations of value.

I also wish to thank Prof. P. Geijer, Consulting Geologist to the company, for very pleasant co-operation and for many inspiring discussions. The principles followed in preparing the mine plans accompanying the paper were originally suggested by Prof. Geijer.

To Prof. P. Quensel, of the University of Stockholm, I wish to convey my thanks for his great support and interest ever since the day fifteen years ago when as his pupil I began my studies at the University.

Finally, I wish to express my gratitude to my present chief, Dr A. Gavelin, Chief Director of the Geological Survey, for the aid he has given me in my work and for allowing the paper to be published in the Series of the Survey.

Stockholm, January, 1941

Geological Survey of Sweden.

Olof H. Ödman.

Introduction.

The Boliden deposit is situated in the province of Västerbotten in northern Sweden at about latitude 64° N and approximately 630 km north of Stockholm (Fig. 1). The mine is connected by a local branch with the line Bastuträsk—Skelleftehamn of the Swedish State Railways. The smelter is at Skellefte-hamn.

Boliden is so far the most valuable of the deposits found within the Skellefte Mining District in Västerbotten during the extensive prospecting campaign of the last twenty years.

The deposit was covered with up to 19 m of glacial drift and the ore never outcropped. Some boulders of ore found in the drift were the first indications of a mineralization in the area. Extensive electrical prospecting was carried out during the years 1921—1924 and a large number of electrical indications were obtained. Most of them were due to graphitic and pyrrhotite-bearing phyllites, but in December 1924 a drill hole located solid sulphide ore in a series of indications which further drilling disclosed to be caused by the ore bodies. Mining operations were then started in 1925.

Up to the present time very little has been published on the geology of the deposit. The late Chief Geologist of the Boliden Mining Company, Dr O. Bæckström, in 1930 gave a short account of the main geological features of the deposit (1)[1] and in 1935 the late Dr A. Högbom, of the Geological Survey, published a general survey of the mine (38, pp. 80 and 115). In a paper by Mörtsell (58) the problem of the occurrence of gold in the arsenopyrite ore is discussed. Otherwise only short, and sometimes incorrect communications on the geological conditions of the deposit have from time to time appeared in various mining and geological journals.

[1] The numbers refer to the bibliography on p. 186.

In April 1935 the present author was engaged by the Boliden Mining Company to make a thorough geological survey of the mine. First of all a detailed mapping in scale 1 : 200 of the main levels was carried out. The maps served as a basis for the official mine plans in scale 1 : 800, here reproduced in Pl. 1—7. The intricate geologic and paragenetic relations of the deposit and the selective mining of various types of ores necessitated, however, a detailed mapping also of the stopes and up to the present time the author and his assistant, Mr. G. Lindgren, have mapped the sublevels at each three metres in the stopes in scale 1 : 200, by means of which a detailed picture of the deposit has been obtained.

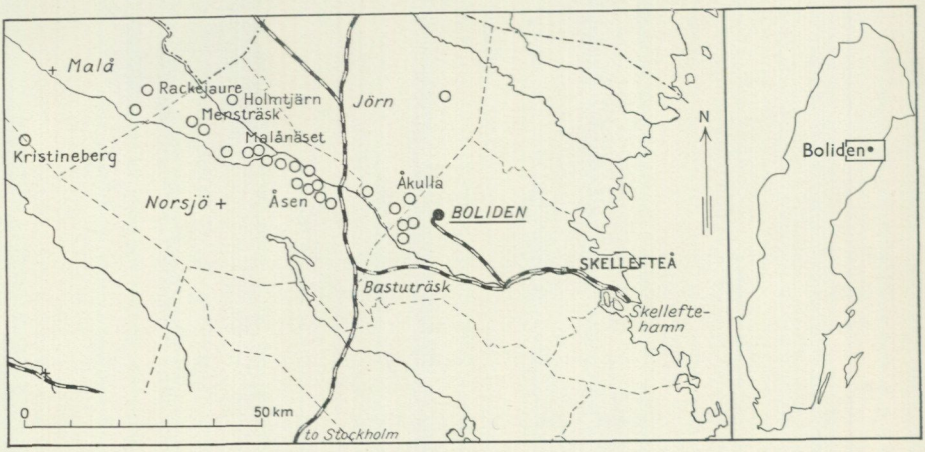

Fig. 1.

An extensive material of rock and ore specimens was collected during the work and was subjected to a thorough microscopic study. Also a large number of chemical analyses were made at the company's laboratories at Stockholm and Boliden.

In 1937 most of the work was completed and the main features of the geology ascertained. A paper on the results was read before the Swedish Mineralogical Society in November 1937 and an excerpt was published in 1938 (65).

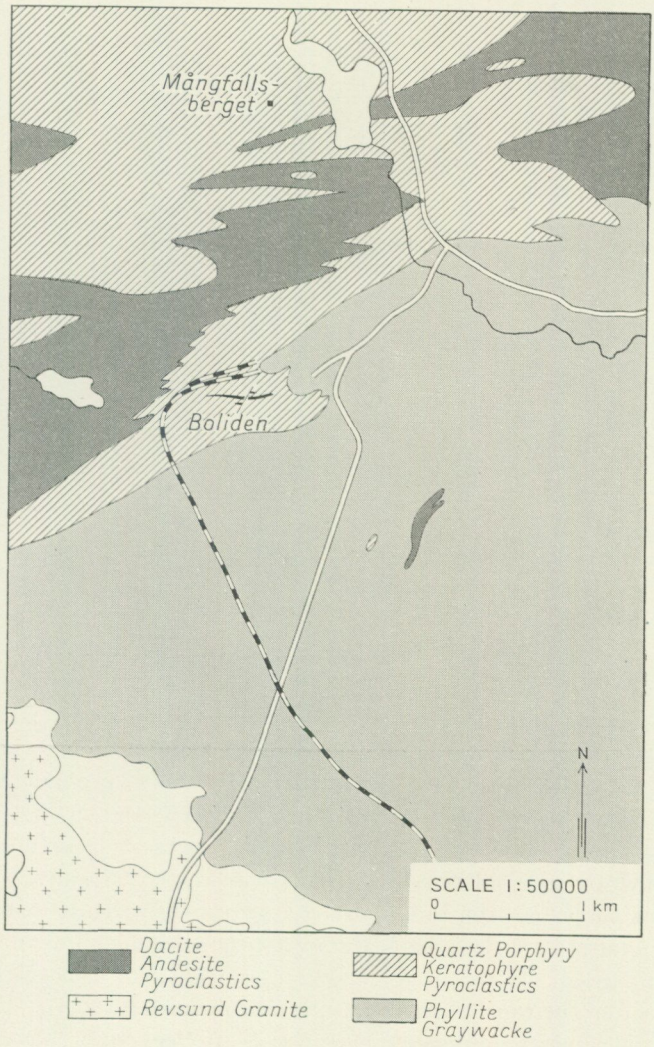

Fig. 2. Geological sketch map of the Boliden area (after Grip).

General Geological Survey of the Boliden Area.

Before entering upon a detailed description of the deposit, a general survey of the geology of the Boliden area will be given. This survey is entirely based on unpublished maps and reports compiled by Grip.

Fig. 2, copied from Grip's map in scale 1 : 50,000, shows the position of the deposit in relation to the main features of the general geology. The bedrock around the deposit is mainly composed of quartz porphyries, tuffs, and agglomerates. Several large beds of dacite and andesite are intercalated in this series,

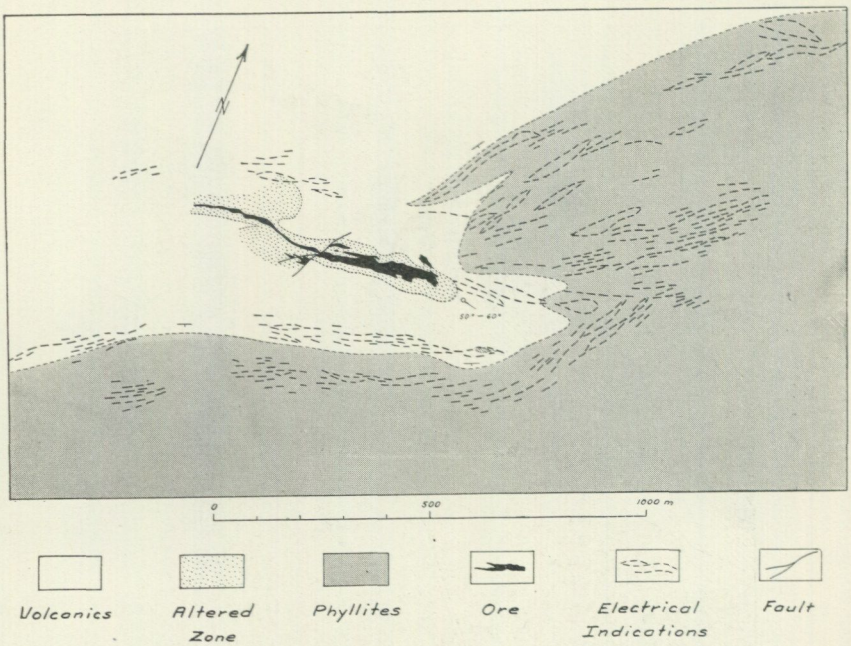

Fig. 3. Position of the Boliden deposit in the dragfold. (Fig. 1 in 65.)

also accompanied by pyroclastics. Keratophyric and quartz-keratophyric rocks also intermingle with the quartz porphyries and are observed in several places within the deposit where the alteration is not so prominent.

To the south the volcanics are overlain by black and gray phyllites and graywackes, a very thick series which forms the youngest division of the supercrustal rocks of the area. The boundary between the volcanics and the sediments is not very sharp, however, the change taking place successively.

The youngest rock in the area is a granite forming a massif about 3 km SSW of Boliden (Fig. 2). The gray and medium-grained rock constitutes an oligoclase-rich variety of the Revsund granite (38, pp. 31 and 100).

All the supercrustal rocks belong to the oldest Pre-Cambrian and form the so-called porphyry-leptite formation, so widely distributed in this part of Sweden. The granite belongs to the younger Archaean period of intrusion.

The supercrustal rocks are strongly folded. The direction of strike is generally ENE—WSW and the dip is steeply south. The tectonic feature that dominates the geology round the mine, and which played an important part when the ores were deposited, is a dragfold in the generally smooth contact between the volcanics and the sediments. Figs. 3 and 4 give a closer view of this dragfold.

Outcrops are rare in the area and the outline of the dragfold has been constructed by Grip from the electrical indications of the conductive sediments and from drill records. Some underground observations have been added by the present author. The electrical indications show that the dragfold is fairly irregular and that thrusting and shearing evidently took place within it. The

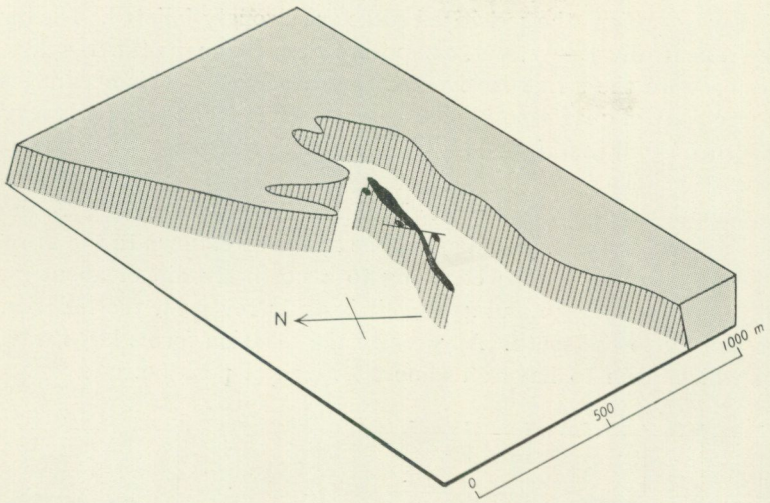

Fig. 4. Perspective sketch of the Boliden dragfold viewed from the west (volcanics removed, sediments gray).

axis of the dragfold pitches about 55—60° to the east, a direction which evidently exercised a strong structural control on the deposition of the ores. The general axis of folding in the area usually has a very gentle dip.

General Geological Survey of the Deposit.

The dragfold constitutes a frame within which the deposit is situated. Owing to the scarcity of exposures on the surface and underground outside the main ore-bearing area, the detailed maps (Pl. 1—7) show only the ore zone and its immediate neighbourhood.

A study of Plates 1—7 shows that a central part is occupied by the ore bodies, surrounded by a zone of altered rocks of various kinds.

The ore bodies in the upper parts of the deposit are mainly two, the Eastern and the Western, which are brought into contact with each other by a fault. The reconstructed picture of the deposit, with the two faulted blocks moved back to their original positions (Fig. 5), shows two bodies, overlapping to the right. The total length of the faulted ore bodies is 590 m on the surface. On deeper levels a number of additional ore bodies appear (cf. p. 128).

The zone of altered rocks surrounds the ore bodies as a hood of varying width. The limits of the altered zone have on the whole been reliably established in the north and south, but not in the west and east. Judging from some drill-holes east of the ore, the altered rocks soon cease in the dragfold. To the west, however, they continue beyond the area mapped.

Several different types of altered rocks occur. Common to all of them is the almost complete disappearance of primary minerals and structures and the development of a large number of hydrothermal alteration products, mainly sericite but also chlorite, andalusite, and others.

With few exceptions the sericitized rocks are strongly foliated. The direction of strike is generally E—W, but, as appears from the maps (Pl. 1—7), towards the Western Ore the strike is diverted towards WSW. This occurs just east of the large body of quartz-porphyritic sericite schist (Pl. 2—7). It is very likely that this rock acted as a rigid body against which the schists were pressed and diverted.

In the upper parts of the deposit the dip of foliation is 70—85° S, in exceptional cases even vertical. From about the 170 m level down to the 210 m level the foliation is vertical, then changing to a northerly dip of about 70—85°. At still deeper levels (330 and 410 m) it is again reversed, the foliation there dipping steeply to the south. Apparently the foliation forms large waves, the axes of which seem to have an almost horizontal position.

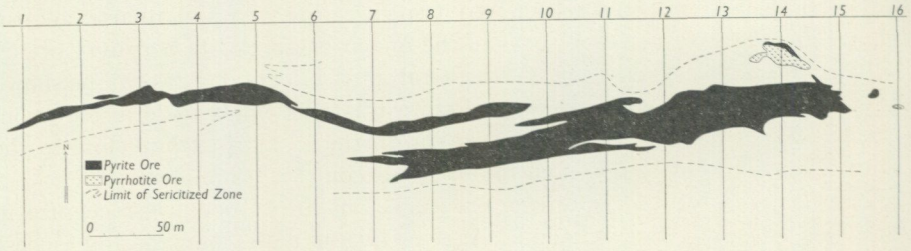

Fig. 5. Reconstructed picture of the deposit at the surface, showing its appearance before the faulting (arsenopyrite bodies not shown.)

In the altered rocks the linear structure is often distinctly visible, pitching 50—60° to the east. Owing to the varying dip of the foliation, the direction of the linear structure oscillates somewhat. The linear structure is well developed in the eastern part of the open pit, where the foliation is less distinct (Fig. a, Pl. 9). It is, however, noticeable also in many other parts of the mine.

Outside the altered zone follow the »unaltered» rocks which have to a certain degree retained primary minerals and structures. They are »unaltered» only in a relative sense of the word, in comparison with the extremely altered, mainly sericitized rocks of the inner zone, and are metamorphosed in several respects, as most of the other pre-Cambrian rocks of the area.

As mentioned above, Grip has established the presence of several beds of different lavas and pyroclastic rocks in the area around the deposit. On account of the lack of exposures the mine itself is not particularly well suited to a study of these rocks. It has been established, however, that quartz porphyry, keratophyre, quartz keratophyre, and dacite, including some pyroclastics, constitute the predominant rock types of the deposit.

These rocks have in many places been subjected to a metamorphism, manifested in recrystallization and in the formation of certain minerals, such as basic plagioclase, hornblende, and biotite. The resulting rocks are widely distributed not only in the mine but also in the surrounding area (personal communication by Grip). This kind of alteration is accentuated towards the

sericitized zone and there is evidently a genetic connection between the two kinds of metamorphism (cf. p. 153).

The contact between the rocks with basic plagioclase and hornblende and the sericitized rocks is not sharp but is characterized by a transitional zone about 5—10 m wide, within which the amounts of sericite, quartz, and Fe-sulphides continuously increase at the cost of plagioclase, hornblende, and biotite in the former rocks.

Description of the Rocks.

A. Unaltered Rocks.

General.

The mapping underground showed that keratophyres and quartz keratophyres are the most common rocks in the mine. Fresh quartz porphyry occurs only as insignificent masses within the keratophyric rocks, but, as will be shown later (p. 25), in a thoroughly altered state this rock has a wide distribution. Dacite is chiefly present in a narrow band in the main crosscuts, close to the shaft (Pl. 1—3), but has been encountered also on the 410 m level.

Pyroclastic rocks appear among the lavas but are difficult to recognize in the fresh exposures underground. Agglomerate is most common and is best visible in the sericitized rocks (p. 29). Tuffs are scarcer and have been observed only in the north-easterly crosscut on the 90 m level (Pl. 3, section 16). Finally a small exposure in black phyllite is found in the south-east on the 50 m level (not shown on the map).

Quartz Porphyry.

The quartz porphyry differs from the keratophyric rocks mainly by the occurrence of quartz phenocrysts. Phenocrysts of felspar do not seem to be present. The rock is fine-grained, has a brownish gray colour and contains faintly bluish quartz eyes, a couple of mm in diameter.

The groundmass is recrystallized and is composed of polygonal quartz grains and irregular masses of fine-grained plagioclase. In polarized light this mineral is rather irregular and diffuse, which makes an accurate determination of its composition almost impossible. A comparison with the indices of refraction of the quartz shows that the plagioclase probably is an andesine, a rather surprising fact in view of the quartz-porphyritic nature of the rock. As will be shown later (p. 20), this abnormally basic plagioclase is typical of some of the less altered volcanics in the deposit.

Among the accessory constituents of the rock we note biotite, chlorite, and some apatite.

Quartz-porphyritic sericite schist occupies large areas in the western part of the deposit (Pl. 2—7). Originally the rock was a normal quartz porphyry, but with the exception of the quartz phenocrysts the rock is now totally devoid of any primary features. The main body of quartz-porphyritic

schist has been sectioned by some drill-holes on the 50 and 410 m levels and it was then found that in the north the rock finally changed to a less altered type still containing appreciable amounts of plagioclase. This plagioclase was still richer in anorthite than in the above case.

Keratophyre and Quartz Keratophyre.

These rocks are the least altered ones in the mine. Some good examples are found in the south-eastern crosscut on the 50 m level,[1] in the southern crosscut in section 11 on the 250 m level[1], and in the eastern part of the 130 m level (Pl. 4, section 17).

As a rule the rock is gray, although brown to green shades are sometimes noticed. This is particularly true close to the sericitic rocks and is due to the development of biotite and chlorite, a circumstance which is connected with the alteration of the keratophyre to a rock rich in basic plagioclase (p. 20).

The keratophyric rocks are fine-grained and sometimes dense. They lack foliation, although they are often fissured, the fissures sometimes being healed by epidote. Phenocrysts of felspar, a few mm long, are common, especially in the fresh rocks at the above localities (Fig. b, Pl. 9). A weak impregnation of pyrite and/or pyrrhotite is commonly present, even in the freshest types.

Schlieren and spots of calcite are occasionally noticed. The mineral also occurs with quartz in veins. The lime was probably carried in during the formation of the sericitic rocks (p. 154).

The groundmass is generally recrystallized and is composed of a fine-grained mass of quartz and alkali felspar. In the fresher rocks some primary features are still intact and the groundmass is pilotaxitic with tiny laths of felspar, or microgranitic. In the latter cases the grain size is about 0.01—0.03 mm.

The felspar phenocrysts are tabular (Fig. b, Pl. 9) but they are often granulated and filled with calcite, sericite, quartz, and other minerals. The felspar is an albite with 5—10 % An.[2] Twinning according to the Albite and Carlsbad laws was noticed.

The felspar of the groundmass has probably the same composition but in some cases a higher An-content was observed. This is presumably due to a beginning alteration of the same kind as noted in the quartz porphyry (see above) and which finally results in the formation of rocks with basic plagioclase, hornblende, biotite, etc.

Microcline is very rare but has been noticed for instance in the analysed keratophyre from the 250 m level. It occurs here in the granulated albitic phenocrysts.

Biotite, chlorite, sericite, calcite, clinozoisite, epidote, apatite, rutile, titanite, and zircon are accessory minerals. The micas are fairly common in the groundmass, where they form small scales. Calcite is sometimes quite common, for

[1] Not shown on the map.

[2] The determinations of plagioclases and of optic angles and extinctions in this paper have been carried out on the universal stage.

instance in the analysed rock from the 250 m level (Analysis No. 2 below), in which it amounts to about 3.3 %.

No quartz phenocrysts are present in the keratophyres and all quartz is associated with the groundmass or the granulated albite. In some fresh types the amount of quartz is insignificant but in other cases it is so high, that postulating it to be primary, the rocks must be termed quartz keratophyres. It is, however, difficult to decide whether all quartz is primary or if some of it has been carried in during the metamorphism. There does seem to exist a transition from normal keratophyres over quartz-rich types to normal quartz porphyries. Similar observations have been made by Grip in other parts of the area.

Table 1.

Chemical composition of the keratophyres.

Analyst: Th. Berggren.

Analysis No. 1.				Analysis No. 2.			
	%	Mol. prop. × 1000	Norm		%	Mol. prop. × 1000	Norm
SiO_2	65.93	1 098	Q 12.55	SiO_2	66.61	1 109	Q 26.88
TiO_2	0.55	7	Or 1.95	TiO_2	0.51	6	Or 12.24
Al_2O_3	15.27	150	Ab 71.15	Al_2O_3	14.74	145	Ab 34.60
Fe_2O_3	0.05	—	An 1.95	Fe_2O_3	0.57	4	An 10.85
FeO	2.83	39	C 0.31	FeO	2.59	36	C 1.73
MnO	0.02	—	sal = 87.91	MnO	0.07	1	sal = 86.30
CaO	0.90	16		CaO	4.22	75	
MgO	0.07	2	Hy 4.55	MgO	1.17	29	Hy 6.47
Na_2O	8.41	136	Il 1.06	Na_2O	4.10	66	Mt 0.93
K_2O	0.33	4	Ap 0.34	K_2O	2.11	22	Il 0.91
$H_2O^{-105°}$	0.01	—	FeS 0.68	$H_2O^{-105°}$	0.12	—	Ap 0.34
$H_2O^{+105°}$	0.59	—	FeS_2 3.87	$H_2O^{+105°}$	0.56	—	FeS_2 0.66
P_2O_5	0.13	1	fem = 10.50	P_2O_5	0.12	1	fem = 9.35
CO_2	0.24	6	$H_2O^{+105°}$ 0.59	CO_2	1.47	33	$H_2O^{+105°}$ 0.56
F	0.01	—	Cc 0.55	Fe	0.01	—	Cc 3.30
FeS	0.68	—	99.55	FeS_2	0.66	—	99.51
FeS_2	3.87	—	I; 4 (5); 1; 5—Noyangose		99.63		I; 4; 2; 4—Lassenose
	99.89		Or : Ab : An = 2.60 : 94.81 : 2.59	Sp. gr = 2.636			Or : Ab : An = 21.30 : 59.20 : 19.50
Sp. gr = 2.720							

1. Keratophyre from northern crosscut, section 17, 130 m level.
2. Keratophyre from southern crosscut, section 11, 250 m level.

In some places, for instance in the southern crosscut in section 11 on the 250 m level, amygdules occur in a rock which in spite of a slight alteration primarily had a keratophyric composition. As a rule the amygdules are small, about 0.5—1.0 cm long, and are filled with epidote, hornblende, chlorite, cal-

cite, and quartz. They are arranged parallel to the strike and dip of the rock. Occasionally amygdules 20—30 cm long occur, but as their contours are rather uneven and as they are unusually narrow considering their length, they should very likely be interpreted not as amygdules, but as fissures which were formed as a result of tectonic disturbances in the rock.

Two types of the keratophyre have been analysed (Table 1 above), the fresh rocks from the 130 and 250 m levels (cf. above). The rock of Analysis No. 1 displays a well preserved pilotaxitic texture and contains phenocrysts of a fairly pure albite. But for the notable amount of sulphides, the rock is unusually free from products of alteration and is a very fresh representative of the keratophyres in the mine. The rock of the other analysis contains intact phenocrysts of albite but its groundmass is recrystallized and it carries fairly abundant quantities of new minerals, such as calcite, micas, titanite, and clinozoisite. The calcite amounts to about 3.3 %. The normative An-content is surprisingly high, which probably depends on the occurrence of titanite and clinozoisite. Also some microcline is present. The norm indicates that the rock is not a typical keratophyre and that it forms a transition to the quartz porphyries.

Dacite.

As mentioned above, dacite occurs in a restricted area south of the main shaft and to some extent also on the 410 m level.

The dacite is a massive, dark greenish gray rock with schlieren and tufts of a dark hornblende visible to the naked eye. It is sometimes amygdaloidal, the amygdules being filled with hornblende, calcite or quartz and arranged in zones parallel to the strike. Some large, irregular »amygdules» remind of similar features in the keratophyre. They were probably formed as fissures.

Under the microscope the dacite is disclosed to be composed of a fine-grained groundmass in which are enclosed abundant tufts and needles of hornblende and rare, microscopic phenocrysts of plagioclase. It also contains a number of alteration products and accessory minerals.

The texture of the groundmass is generally microgranoblastic and it is made up of plagioclase and quartz. The grain size varies from 0.02—0.2 mm. The plagioclase is an andesine with 30—40 % An.

A surprisingly well preserved texture is found in a dacite from the main crosscut south of the shaft on the 170 m level. The rock consists of a pilotaxitic felt of about 0.15 mm long laths of a basic oligoclase (c. 30 % An) (Fig. a, Pl. 10) together with abundant hornblende in green tufts and needles. This mineral also forms veinlets, indicating that some transport of material has occurred in spite of the fresh nature of the rock. This type of dacite has been analysed (Table 2). The composition of the rock is rather basic, this depending on the large amount of hornblende present.

Phenocrysts of plagioclase are rare in the dacite. When they do occur, they are often granulated and contain some alteration products. The composition varies between 30 and 44 % An.

Table 2.

Chemical composition of the dacite.

Analysis No. 3.

Analyst: Th. Berggren.

	%	Mol. prop. × 1000	Norm	
SiO_2	56.50	936	Or	2.00
TiO_2	1.10	14	Ab	58.00
Al_2O_3	17.67	173	An	16.13
Fe_2O_3	0.13	1	sal =	76.13
FeO	6.81	95		
MnO	0.10	1	Di	5.11
CaO	5.01	89	Hy	4.42
MgO	3.01	75	Ol	8.54
Na_2O	6.86	111	Mt	0.23
K_2O	0.34	4	Il	2.12
$H_2O^{-105°}$	0.24	—	Ap	0.67
$H_2O^{+105°}$	1.11	—	Cc	0.20
P_2O_5	0.22	2	FeS	0.55
CO_2	0.09	2	FeS_2	0.49
FeS	0.55	—	fem =	22.33
FeS_2	0.49	—	H_2O	1.11
	99.93			99.57
Sp. gr = 2.818			II; 5; 2; 5—Grenadose Or : Ab : An = 2.6 : 76.2 : 21.2	

3. Dacite. Main south crosscut, S of the shaft, 170 m level.

The hornblende present in the dacite has the pleochroism α = yellowish green, β = grass green, and γ = bluish green. The extinction angle $c : \gamma$ = 17—20° and the optic angle $-2V$ = c. 72°. The same kind of hornblende occurs in the amygdules.

Biotite is sometimes rather abundant but chlorite and sericite are scarcer. Calcite is found in the groundmass but most of it occurs in the amygdules. Among the accessory minerals we note epidote, apatite, titanite, and rutile.

Pyroclastic Rocks.

Tuffs and agglomerates are difficult to recognize underground in the fresh rocks but are easily discernible in the sericitized rocks (p. 29). An unmistakable agglomerate occurs north of the main shaft on the 90 m level. Inclusions of quartz porphyry were here noted in a rock of keratophyric composition.

Bedded, fine-grained to dense tuffs are met with in the north-eastern crosscut in section 17 on the 90 m level (Pl. 3). They strike north-east and dip about 45° south-east, which indicates that the rocks are situated in the large lobe in the

northern, synclinal part of the dragfold (Fig. 3). The dark gray to black rocks are composed of a biotite-bearing mass of quartz and plagioclase. The texture of the rock is rather indistinct and it has evidently been recrystallized. The plagioclase has an intermediate to basic composition. Some of the rocks contain schlieren of an extremely fine-grained and opaque mineral, probably graphite. Pyrrhotite is also present.

Black Phyllite.

Finally the occurrence of a black, graphite-bearing phyllite in a south-eastern crosscut in section 18 on the 50 m level should be mentioned[1]. The rock has the same qualities as the black phyllites from other parts of the Skellefte District, as described by A. Högbom (38, pp. 22 and 97).

B. Altered Volcanic Rocks with Basic Plagioclase, Hornblende, and Biotite.

Some of the rocks described above have experienced a fairly extensive structural and chemical metamorphism. These metamorphosed rocks are irregularly distributed, and as they generally cannot be recognized without a microscopic study, it has not been possible to indicate them on the maps. As a rule they seem to be particularly well developed immediately outside the zone of sericitized rocks, and as will be discussed later (p. 153), they probably stand in a genetic connection with the latter.

The rocks in question are as a rule massive and fine-grained and have a brown to dark gray or dark green colour. They are generally strongly fissured, the fissures often being healed by epidote. An impregnation of pyrite or pyrrhotite is almost always noticeable. Aggregates of a coarse hornblende are also observed. Irregular veinlets with calcite and quartz occur in some instances.

Some of the rocks have an appearance divergent from the above. Some are very light-coloured as, for instance, a rock close to the main shaft on the 170 m level, which contains large amounts of epidote. Others are comparatively coarse-grained and are composed of needle-shaped amphiboles, 2—3 mm long, in radiant groups, surrounded by a fine-grained groundmass of quartz and plagioclase. The coarse types are sometimes irregularly banded, the amphiboles being arranged in bands a couple of mm broad. The amphibole may also be arranged in diffuse patches. The coarse types have been observed particularly in the west drift on the 90 m level, between sections 4 and 6, and in the east drift on the 170 m level.

Under the microscope these rocks are characterized by an intense recrystallization and the formation of several secondary minerals, such as basic plagioclases, amphibole, biotite, sericite, chlorite, epidote, clinozoisite, calcite, garnet, titanite, rutile, and Fe-sulphides (Fig. b, Pl. 10; Fig. a, Pl. 11).

The rocks generally lack distinct textural features and the components are

[1] Not shown on the map.

irregularly intermixed. Mosaic or leptitic texture has been observed in some cases and occasionally the rocks are foliated, due to the development of subparallel scales of mica. In some cases a quartz-porphyritic texture is noted.

The most outstanding components of the present rocks are quartz and plagioclase, the latter mineral as a rule being the most plentiful. In the darker types hornblende and biotite are also very important constituents.

The quartz is fine-grained and granoblastic. In zones with impregnated sulphides the size of the quartz grains increases and they are intergrown with coarse scales of chlorite and sericite.

The shape of the plagioclase is rather irregular and no large individual grains occur. The small grains accumulate to larger aggregates which in polarized light show a very indistinct and irregular pattern. The grains are twinned according to the Albite law but the twin lamellae are extremely thin and irregular. Furthermore, the extinction is undulatory and the mineral often contains plenty of submicroscopic alteration products. These circumstances render an accurate determination of the composition of the plagioclase quite difficult. It can also be suspected that the composition is not uniform within the same aggregate or even within the same grain. Repeated measurements on a large number of grains gave a composition varying from 60—84 % An.

There is a great contrast between the composition of the plagioclase in these rocks and in the keratophyres and the dacite. In the latter rocks the plagioclase is of a primary nature and consists of albite or, in the dacite, of an andesine with a maximum An-content of 44 %. The plagioclase of the present rocks is considerably richer in An-molecule and must be looked upon as extreme, considering the acid composition of the primary rocks. This holds true not only in the cases where the primary rock was a keratophyre or a quartz porphyry but also where it was a dacite. The plagioclase of the altered rocks must consequently be considered to be of secondary origin, formed by the addition of lime to the plagioclase of the primary rocks.

Hornblende is a very prominent constituent in some types. Under the microscope the mineral forms irregular bundles of varying shape and size. The pleochroism is generally α = pale yellow, β = grass green, and γ = pale bluish green. The extinction $c : \gamma$ = c. 20°. Lighter to colourless varieties also occur. The mineral is optically negative and the optic angle varies from 72—82°. During the metamorphism some amphibole was most likely formed in the keratophyric rocks by the addition of lime and iron but in many cases the amphibole-rich types derive from the primarily amphibole-bearing dacitic rocks by a recrystallization and re-arrangement of the mineral without any addition from the outside.

Biotite occurs in single scales or in schlieren. It is generally faintly coloured and has the pleochroism: α = colourless, β and γ = yellowish brown. Besides this type of biotite there is also another mica, probably of a phlogopitic composition. It is colourless, has a very small optic angle and a birefringence slightly less than that of biotite. In many cases it is intimately intergrown with the biotite.

Table 3.
Chemical composition of altered keratophyre with basic plagioclase.

Analysis No. 4.

Analyst: Th. Berggren.

	%	Mol. prop. × 1000	Norm	
SiO_2	54.71	911	Q	18.44
TiO_2	0.85	11	Or	17.36
Al_2O_3	10.37	151	Ab	4.72
Fe_2O_3	0.54	3	An	20.86
FeO	5.40	75	C	3.67
MnO	0.23	3	sal =	65.05
CaO	6.55	117		
MgO	6.04	150	Hy	23.50
Na_2O	0.56	9	Mt	0.70
K_2O	2.94	31	Il	1.67
$H_2O^{-105°}$	0.10	—	Ap	0.67
$H_2O^{+105°}$	1.38	—	FeS	2.64
P_2O_5	0.22	2	FeS_2	0.79
CO_2	1.54	35	fem =	29.97
FeS	2.64	—	H_2O	1.38
FeS_2	0.79	—	Cc	3.50
	99.86			99.90
Sp. gr. = 2.70			II; 4; 4; 4—Bandose Or : Ab : An = 39.50 : 11.16 : 49.34	

4. Altered keratophyre with basic plagioclase. Southern crosscut, section 11, 250 m level.

Sericite is not a typical mineral in this kind of altered rock. Chlorite is more common and occurs in the same manner as the biotite. It is sometimes intergrown with biotite and phlogopite(?). The chlorite is generally colourless, although it occasionally shows a faint pleochroism in grayish green colours. It is optically positive and the birefringence is very low.

Clinozoisite and epidote are as a rule rather scarce and form only small grains. As mentioned above, epidote is abundantly present in a rock from the 170 m level where it occurs in prismatic and faintly yellowish green grains, not less than 2 mm long.

Calcite would generally appear to be one of the minerals formed during the metamorphism. In a coarse, hornblende-rich rock from the west drift on the 90 m level it occurs in coarse-grained spots together with chlorite and sericite. In this case it is probably of primary origin, having been formed by the recrystallization of calcareous inlayers in the rock. Calcareous zones have in some instances been observed by Grip in the volcanic rocks of the area.

Garnet, apatite, titanite, and rutile are of an accessory nature. Garnet is on the whole a very rare constituent of the rocks in the deposit. It has been encountered in a few places as insignificant brownish red aggregates. Titanite is generally fine-grained but in the coarse, hornblende- and epidote-bearing rocks it sometimes forms large idiomorphic crystals. Rutile, which is so common in the sericitic rocks, is only sporadically present in these rocks, where it forms fine-grained, undulating schlieren.

As mentioned above (p. 14), similar rocks with abnormally basic plagioclase, hornblende, etc., are found in other places in the Boliden area. From the Bjurliden deposit in the Malånäs District, S. Gavelin (29, p. 100) has described a quartz porphyry which has gone through a metamorphism similar to the one that overtook the rocks just described. Hornblende has thus been formed and the plagioclase has an extremely basic composition (90 % An).

A typical representative of the rocks in question, exposed in the southern crosscut in section 11 on the 250 m level, has been analysed (Table 3[1]). The rock does not carry any hornblende and differs in that respect from certain types of similarly altered rocks in the deposit. However, it constitutes a metamorphic derivative of the keratophyre described and analysed above (Analysis No. 2, p. 17) and occurring further to the south in the same crosscut.

C. Altered Rocks.

This group comprises the rocks forming the wallrocks of the ore bodies, al, of which are characterized by profound mechanical and chemical alterationl resulting in a destruction of primary minerals and textures. They are generally strongly foliated and are composed of such minerals as quartz, sericite, chlorite, andalusite, and rutile. Occasionally andalusite is so predominant that an almost mono-mineralic, massive andalusite rock is formed. The altered rocks derive from the volcanic rocks described above, having been subjected to a hydrothermal process of alteration. It is often possible to trace a transition from the fresh rocks to the altered ones, and furthermore some primary features such as quartz phenocrysts and agglomeratic structure are still recognizable, in spite of the strong alteration, thanks to which certain conclusions can be drawn as to the primary nature of the rocks.

A number of different types of altered rocks have been recognized and mapped, *viz.* normal sericite schist, quartz-porphyritic sericite schist, chloritic sericite schist, pyritic sericite schist, sericite rock, and andalusite rock. A study of the maps (Pl. 1—7) shows the distribution of these rocks.

The contact between the sericitized rocks and the more or less altered volcanic rocks is generally characterized by a transitional zone 5—10 m wide. A pyritic sericite schist is frequently developed next to the contact.

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[1] For a discussion of the analysis see p. 153.

The contacts between the different types of altered rocks are often sharply defined and easy to map, but in many cases the contact is also here a transitional one.

1. Sericitic Rocks.

Terminology.

In the present paper these rocks have been termed schists with a prefix to indicate the main mineralogical feature of the individual types. In one case, sericite being the predominant mineral, the rock has simply been called »sericite rock».

In Scandinavian literature metasomatically altered rocks occurring in association with ore deposits and characterized by such minerals as quartz, biotite, sericite, chlorite, cordierite, andalusite, and others, have been called »quartzites», *e. g.* cordierite-quartzite, chlorite-quartzite, etc. Sometimes »ore-quartzites» are mentioned. The term has been used also in modern Russian literature on ore deposits (61, 68). The word is a direct translation of the Swedish word »kvartsit». The use of the term »quartzite» when referring to a metasomatically altered rock, is likely to involve misunderstandings and the author has found it most suitable to use the conventional English term »schist» in the present paper. The altered, sericitic rocks at Boliden seem to be well in accordance with this term as defined by Holmes (40) and Grout (36).

Normal Sericite Schist.

This rock is the most abundant one in the altered zone where it often forms the immediate wallrock. Petrographically it is fairly homogeneous, although it sometimes grades into the other types.

The sericite schist is generally gray to grayish white and very distinctly foliated. The rock cleaves along the foliation planes in thin plates. The linear structure is well marked in many places. Particularly at the contacts to the ores, the sericite schist is often corrugated and sharp, Z-shaped folds have been developed (Fig. b, Pl. II).

The rock is composed of the following minerals: quartz, sericite, rutile, and apatite, and sporadically also andalusite, kaolin, tourmaline, and sulphides. No traces remain of primary minerals (except possibly some quartz) or textures.

Quartz is the predominant mineral, sometimes amounting to 70—75 per cent. of weight. The grains are even, their size generally ranging from 0.2—0.4 mm. They are somewhat elongate parallel to the foliation but are only slightly undulatory.

Second to quartz, sericite is the most common mineral, making up about 20—25 per cent. of weight of the rock. The quartz grains are interwoven with sub-parallel streaks of sericite foliae of about the same size as the quartz grains, giving the rock its distinct foliation. Some of the sericite streaks are continuous and regular, others are more irregular and form a network among the quartz

grains. Tiny scales of sericite are also scattered among the quartz grains (Figs. a and b, Pl. 12). The sericitic zones have registered movements in the rock and are often folded.

Rutile is a fairly common constituent of this rock. The analysed sample (p. 30) of the sericite schist thus contains 0.59 % TiO_2, but the actual amount is probably close to 1 % as some FeO is most likely combined with TiO_2. The grains of rutile are very small and rod-shaped and are arranged parallel to the foliation.

Apatite is almost always present but only in minor amounts.

Single crystals of andalusite are fairly common. They are generally 1—2 cm long but occasionally crystals 10—12 cm long are met with. The mineral has a pink colour and is often quite clear. Under the microscope the andalusite is often found to be traversed by veinlets of sericite or kaolin, which minerals in the final stage of alteration completely consume the host mineral. The kaolin occurs in extremely fine scales. Its refractive index is abt. 1.56 and the birefringence abt. 0.006. The optic character of the mineral is negative and the optic angle large.

Tourmaline is often present in the shape of microscopic needles. It is colourless or faintly yellowish green. During the quartz-tourmaline stage of mineralization tourmaline was concentrated locally in the sericite schist (cf. p. 106).

The normal sericite schist does not contain any sulphides. In certain places at the ore contacts and in the large areas of disseminated ore, impregnations of mainly pyrite, but also arsenopyrite, chalcopyrite, pyrrhotite, and other minerals, are encountered. Gold is sometimes present as thin coatings on the planes of foliation.

Due to variations in the amount of quartz and sericite, the sericite schist grades into other types. There is thus a gradation into sericite rock, or to an extremely quartzose schist, which is locally developed at some of the ore contacts by silicification during the mineralization. An increase in the impregnation of pyrite leads to the development of a pyritic sericite schist.

Quartz-porphyritic Sericite Schist.

This type is mainly found in the western part of the mine, north and northwest of the Western Ore. Here it forms a lobe-shaped body which can be followed from the 50 m level (the rock is not exposed on the surface) down to the 410 m level. Its limit in the north is not exposed in the mine. On the surface the same rock, although somewhat less altered, still outcrops about 200 m north of the Western Ore. Small areas of the same rock are also found within the normal sericite schist.

Two types of quartz-porphyritic sericite schist have been observed, one light-coloured and purely sericitic, and the other dark and chlorite-bearing. The latter type occurs in the former as tongue-shaped bands, particularly on the 410 m level.

The light-coloured schist is very similar to the normal sericite schist and differs from it mainly by its quartz-porphyritic texture. The chlorite-bearing schist is dark green in colour but has otherwise the same qualities as the sericitic quartz-porphyritic schist.

The most characteristic feature of these two types of schist is the appearance of abundant quartz phenocrysts of a faint blue or gray colour. The general rule seems to be that the larger grains are blue and the smaller ones gray. The phenocrysts are rounded or elliptic and vary in size from 1 to 4 mm. The influence of the shearing on the phenocrysts is remarkably slight and under the microscope they are generally quite intact, still showing corrosive embayments and optical uniformity (Fig. a, Pl. 13). Granulation is noticed but seldom and undulatory extinction is insignificant. The sericitic streaks of the groundmass smoothly follow the outline of the grains. Small scales of sericite are found growing into the quartz at the ends of the grains.

It is difficult to conceive how the quartz grains could survive the development of the foliation without being crushed. Their primary nature is indisputable and is proved by the corrosive embayments and by the fact (see below) that andalusite porphyroblasts grow around the quartz phenocrysts, replacing the groundmass. Intact phenocrysts of quartz in metasomatically altered quartz-porphyry have been described from the Malånäs District (29, p. 88) and from Flin Flon in Manitoba (10, p. 261).

The quartz-porphyritic sericite schist has the same mineralogical composition as the normal type. In the chloritic variety chlorite appears, partly replacing the sericite. No primary minerals or textures are preserved.

Quartz and sericite have the same mode of appearance as in the normal schist and occur in the same amounts. In some cases, especially noticeable on the 410 m level, the percentage of quartz is very considerable, amounting to approximately 90—95 %.

In spite of the dark colour of the chloritic type, indicating a high percentage of chlorite, the quantity of this mineral is not very large (cf. Analysis No. 9 on p. 30). It is accumulated to bands which occasionally may cut the schistosity at a small angle. It is interwoven with the sericite or occurs in separate foils. The chlorite is only faintly coloured under the microscope.

Andalusite occurs in separate crystals but on the 330 m and 410 m levels it is also found in streaks, the rock thus grading into the quartz-bearing andalusite rock (p. 38). The chloritic type sometimes carries pink porphyroblasts of andalusite, about 2—3 cm long. Under the microscope they are micro-poikilitic and replace the groundmass but leave the quartz phenocrysts intact. The blue quartz stands out sharply against the surrounding pink andalusite.

Tourmaline occurs in the same manner as in the normal sericite schist and was probably introduced during the quartz-tourmaline stage. Rutile is found in rounded grains, max. 0.1 mm large, sometimes aggregated to cloudy formations. It is semi-opaque with a brownish violet colour.

There can be no doubt but that this rock primarily was a quartz porphyry. The quartz phenocrysts prove this and, what is more, the rock sometimes grades

into a less altered rock, which in spite of its abnormal plagioclase (p. 15) still retains its character of quartz porphyry.

Another question is whether the rock should be interpreted as a lava, as most of the other rocks in the area, or if it is of an intrusive nature. The volcanic rocks of the area generally form elongate subparallel zones, but as far as can be judged from the scanty exposures the quartz-porphyritic sericite schist rather seems to have the shape of an intrusive body. However, no chilled contacts or other indications of an intrusive mode of formation have been observed in the highly altered rock. Although it cannot be proved at present, the author nevertheless holds the opinion that this type of sericite schist very likely derives from an intrusive quartz-porphyry. In any case the rock is certainly closely connected with the volcanic rocks in the vicinity.

Corresponding rocks are known from other parts of the Skellefte District. S. Gavelin, for instance, describes from Malånäset (29, p. 24) a rock which has some qualities in common with the less altered type of the quartz-porphyritic sericite schist. Gavelin interprets the rock from Malånäset as a lava but believes that it partly may be of an intrusive nature.

A certain resemblance also exists to the intrusive quartz-porphyries of the Porcupine District in Ontario (11, p. 223), *e. g.* the Pearl Lake and Miller Lake porphyries.

Chloritic Sericite Schist.

As is evident from the maps (Pl. 1—7) this rock has a restricted distribution and is particularly present in the western and central parts of the deposit where it can be traced in some fairly continuous zones between the 90 and 210 m levels. Chloritic schists also occur sporadically along the ore contacts.

The rock differs from the other schists mainly by the dark green colour, depending on its content of chlorite. The boundaries to the normal sericite schist are generally easy to follow, but between the chloritic type and the pyritic schist (see below) some gradational forms occur which are difficult to classify. The chloritic schist is well foliated, like the foregoing types.

The rock is composed of the following minerals: chlorite, sericite, quartz, and occasionally rutile, apatite, andalusite, tourmaline, and sulphides.

Chlorite and sericite predominate and amount to about 50—60 per cent. of weight. They are intimately intergrown to bands or streaks, almost devoid of other minerals. Only some elongate grains of quartz and rutile are present in the micaceous bands. The bands alternate with other bands or lenticular zones within which quartz is the predominant mineral and where only scattered foils of mica occur. Chlorite is generally more plentiful than sericite. The chlorite is quite colourless under the microscope, uniaxial, and optically positive.

The quartz grains are elongate but are not very distinctly undulatory.

Pyritic Sericite Schist.

This type of schist is widely distributed and is often localized to the outer portions of the sericitic zone. It also occurs around the Western Ore on the surface and on the 50 m level.

On the whole the pyritic schist is easily distinguished from the other schists but sometimes gradational types are met with.

The rock has many qualities in common with the other schists. It is thus strongly foliated and often corrugated. Its colour is gray but darker than in the other sericitic rocks. The most characteristic feature is the occurrence of thin streaks of sulphides, mainly pyrite and pyrrhotite.

Also from a microscopic point of view the resemblance is well marked (Fig. b, Pl. 13). Here, too, the characteristic minerals are quartz and sericite, the latter occurring in streaks and bands. The sericite also forms a network in the groundmass of quartz.

Among the other, more or less accessory minerals we note chlorite, andalusite, kaolin, plagioclase, calcite, apatite, and rutile.

Chlorite in small foils is not uncommon and in some darker varieties of the rock it may occur in large quantities. In some rare cases chlorite predominates over sericite and a transition to the chloritic sericite schist is formed. The chlorite is practically colourless under the microscope and is optically positive; the optic angle is very small. The birefringence is sometimes unusually high. The mineral is probably a clinochlorite.

The andalusite occurs in small irregular grains which are sometimes decomposed to kaolin. Thin veinlets of kaolin are also found cutting grains of sulphides, indicating that the mineral was formed by late hydrothermal solutions.

The pyritic sericite schist occasionally still contains remnants of plagioclase, particularly towards the surrounding volcanics. The plagioclase is very turbid and the grains are filled with alteration products. A determination of the composition is consequently difficult but the content of An seems in general to be 25—30 %. Considering the basic composition of the neighbouring rocks a more basic plagioclase would be expected. The mineral is, however, highly altered and a decalcification has probably taken place.

The most typical feature of the rock is the impregnation of pyrrhotite and pyrite. Locally also arsenopyrite and chalcopyrite are encountered. The sulphides generally form narrow bands or streaks (Fig. b, Pl. 13) but sometimes the impregnation is more uniformly distributed. The pyrite grains are often idiomorphic. In the impregnated zones the quartz is often rather coarse-grained and the foils of chlorite or sericite enclosed in the quartz are much coarser than usual. The solution which brought in the sulphides evidently also caused a local recrystallization of the rock, a fact which proves the later age of the impregnation in relation to the sericitization (p. 148).

Pyroclastic Sericite Schist.

In some of the intensely sericitized rocks agglomeratic structure is occasionally well discernible, as Fig. a (Pl. 14) exemplifies. The figure shows a number of inclusions of different shades of gray in a groundmass of normal sericite schist. Some inclusions are quartz-porphyritic but most of them are composed of normal sericite schist, although of varying colour.

Agglomeratic rocks are frequently met with in the altered zone. These rocks, which are more inhomogeneous than the massive lavas, were particularly liable to the formation of ducts transmissible to the altering solutions that ascended in this zone.

Sericite Rock.

The sericite rock is a locally developed variety of the normal sericite schist and is generally confined to the lower parts of the ore bodies and to the bodies of andalusite rock. The rock is mainly present on the 210 and 250 m levels and to some extent also on the 330 and 410 m levels (Pl. 6—7). The contacts to the normal sericite schist are gradational and consequently no boundary lines have been marked on the maps.

The most characteristic feature of the sericite rock is the complete absence of quartz and the absolute predominance of sericite. Other constituents are only of an accessory nature. The rock has a gray or greenish gray colour. In rutile-rich varieties the colour is darker. The rock is well foliated but not to the same degree as *e. g.* the normal sericite schist. It is often intensely corrugated, sharp Z-shaped folds being developed. The rock has a soapy consistency and is frequently traversed by slips and small faults which make the rock a rather treacherous one in open stopes.

Besides sericite, the rock normally contains rutile and apatite, the latter two always being present in small quantities. In less typical cases also quartz, andalusite, kaolin, tourmaline, zircon, and sulphides are found in insignificant quantities.

The sericite forms a felt of very fine scales, showing a well developed parallel structure under the microscope. The sericite mass is very ductile and microscopic folds are often developed in it (Fig. b, Pl. 14).

Rutile occurs in rounded grains which often accumulate to aggregates. Locally the rutile is concentrated to streaks or even to compact lenticular bodies, containing besides rutile a great number of ore minerals (cf. p. 55). In thin sections the rutile is almost opaque. In condensed light it is translucent and has a brownish to violet colour.

Apatite occurs only in small grains.

As mentioned above, quartz is not present in the typical sericite rock. Where the rock grades into sericite schist, quartz gradually appears. Andalusite is present in the sericite rock on the contacts to the andalusite rock and then forms idiomorphic crystals often decomposed to sericite or kaolin. Tourmaline

is rare and is only found in small needle-shaped crystals, particularly in the vicinity of quartz-tourmaline veins. It may sometimes accumulate to radiate groups of larger needles. Sporadically, small rounded grains of a colourless and uniaxial positive mineral of strong refringence and birefringence have been observed. The mineral has been interpreted as zircon.

As a rule the sericite rock does not contain any sulphides, but occasionally weak impregnations of mainly pyrite and pyrrhotite have been noticed. On a few occasions also Bi-tellurides and gold have been observed. Of interest is the occurrence of small scales of molybdenite in a sericite rock from the 330 m level. It is the only molybdenite found in the deposit.

Table 4.

Chemical composition of the sericitic rocks.

Analyst: Th. Berggren.

Analysis No.	5		6		7		8		9		10	
	%	Mol. prop. × 1000	%	Mol. prop. × 1000	%	Mol. prop. × 1000	%	Mol. prop. × 1000	%	Mol. prop. × 1000	%	Mol. prop. × 1000
SiO_2 . . .	78.95	1 314	83.58	1 392	60.86	1 013	58.43	973	75.38	1 255	44.19	736
TiO_2 . . .	0.59	9	0.20	3	0.66	8	1.09	17	0.25	3	2.20	28
Al_2O_3 . .	13.39	131	11.32	111	15.39	151	17.58	173	13.14	129	37.68	370
Fe_2O_3 . .	0.25	2	0.06	—	1.11	7	2.38	15	0.53	3	0.45	3
FeO . . .	0.59	8	0.46	6	2.47	34	4.42	61	2.87	40	0.03	—
MnO . .	tr.	—	0.06	1	0.03	—	0.08	1	0.02	—	nil	—
CaO . . .	0.25	5	0.05	1	0.25	5	0.65	11	nil	—	0.65	12
MgO . .	nil	—	nil	—	3.56	88	7.62	180	1.94	48	0.04	1
Na_2O . .	1.33	22	0.54	9	0.99	16	0.65	10	0.82	13	2.04	33
K_2O . . .	2.64	28	2.58	27	2.61	28	2.51	27	2.51	27	8.71	93
$H_2O^{-105°}$.	0.09	—	0.04	—	0.08	—	0.12	—	0.11	—	0.05	—
$H_2O^{+105°}$.	1.60	89	1.31	73	2.94	163	4.13	229	2.15	119	4.00	222
P_2O_5 . . .	0.16	1	nil	—	0.24	2	0.41	3	0.03	—	0.20	1
CO_2 . . .	nil	—	nil	—	0.09	2	—	—	—	—	0.05	1
F	0.03	2	0.03	2	nil	—	0.09	5	nil	—	0.13	7
B	—	—	nil	—	—	—	—	—	—	—	—	—
S	0.01	—	0.03	—	4.50	—	0.04	—	0.02	—	0.03	—
As	0.01	—	0.03	—	0.03	—	0.12	—	—	—	0.01	—
	99.89		100.29		[1] 99.85		99.96		99.77		100.46	
Sp. gr. . .	2.642		2.593		2.76		2.64		2.689		2.792	

5. Normal sericite schist. Main east drift, 210 m level.
6. Quartz-porphyritic sericite schist. Crosscut to stope, section 2—3, 90 m level.
7. Pyritic sericite schist. Main west drift, section 7, 250 m level.
8. Chloritic sericite schist. Main west drift, section 9, 130 m level,
9. Quartz-porphyritic sericite schist, chloritic. Underground shaft, section 11, 410 m level.
10. Sericite rock. Main east drift, section 14, 250 m level.

[1] Incl. 4.04 % Fe in sulphides.

Chemical Composition of the Sericitic Rocks.

Several analyses of the sericitic rocks have been carried out. In order to facilitate a comparison they have been put together in one table (Table 4). The corresponding Niggli values are found in Table 5.

Table 5.

al-fm-c-alk-values of Analyses 5—10 (recalculated to 100).

Analysis No.	al	fm	c	alk
5.	66.2	6.1	2.5	25.2
6.	71.6	4.5	0.7	23.2
7.	44.9	40.5	1.5	13.1
8.	35.2	55.0	2.2	7.6
9.	49.1	35.7	—	15.2
10.	71.8	1.4	2.3	24.5

Analyses Nos. 5 and 6 represent normal sericite schist and quartz-porphyritic sericite schist and may be considered representative of the typical quartz- and sericite-bearing altered rocks of the deposit. SiO_2, Al_2O_3, K_2O, and H_2O are the only oxides present in appreciable quantities, whereas the femic oxides, as Fe_2O_3, FeO, CaO, and MgO, occur in insignificant amounts only or are completely lacking. The latter oxides are entirely confined to the sulphides, rutile or apatite. MgO is altogether lacking in the present rocks.

A calculation of the modal composition of the rocks in Analyses Nos. 5 and 6 yields the approximate values in Table 6. When calculating the amount of sericite, the approximate formula $K_2O \cdot 2H_2O \cdot 3Al_2O_3 \cdot 6SiO_2$ was applied. The amount of Na_2O was added to that of K_2O. In No. 6 there is a good agreement between the sericite-forming oxides but in No. 5 there is a deficit in Al_2O_3 and H_2O in proportion to the alkalis. The amount of rutile has been obtained by adding the amounts of FeO and Fe_2O_3 to TiO_2, assuming that these oxides combine with the latter oxide in rutile. The calculation involves certain errors but the values obtained may be considered approximate.

Table 6.

Modal composition of sericite schist and quartz-porphyritic sericite schist.

	Analysis No. 5	Analysis No. 6
Quartz	61.3	70.6
Sericite	36.6	28.4
Rutile	1.4	0.7
Apatite	0.3	—
	99.6 %	99.7 %

Analysis No. 7 is of a pyritic sericite schist, composed of quartz, sericite, chlorite, sulphides, apatite, and rutile. The amount of chlorite is here unusually

high. A little calcite was also present. There was no plagioclase in the rock. Making a comparison with the foregoing analyses, the high amount of FeO, MgO, and Fe_2O_3 is at once noticeable, evidently depending on the presence of chlorite. K_2O occurs in about the same quantity as in the above cases.

The modal composition of the rock cannot very well be measured under the microscope owing to the intimate intergrowth of sericite and chlorite. A calculation on the basis of the analysis is in this case not possible on account of the composition of the chlorite not being known. A calculation of the contents of sericite and sulphides gives 34.5 and 8.6 %, respectively.

The next two analyses, Nos. 8 and 9, represent chloritic sericite schist and chlorite-bearing quartz-porphyritic sericite schist. Common to both is, as in the above case, the comparatively large percentage of MgO, FeO, and Fe_2O_3, owing to the presence of chlorite. In No. 8 the amount of this mineral is fairly considerable, but it is evident from the microscopic study of several thin sections of the rock that the amount of chlorite varies from case to case and even within the same section. In both analyses K_2O predominates over Na_2O and occurs in about the same percentage as in the other analysed rocks. A calculation shows that the rocks carry about 29.2 and 30.6 % sericite, respectively. Also the foregoing rocks contained a corresponding amount of sericite.

Analysis No. 10 shows the composition of the sericite rock. Alkalis and water predominate and besides those only TiO_2 occurs in any quantity. Fe_2O_3 and FeO probably combine with TiO_2 in rutile. Part of the CaO is combined in apatite (and in the exceedingly small quantity of calcite, indicated by the presence of 0.05 % CO_2). There ensues a small surplus of CaO (0.45 %) which possibly may enter into the sericite molecule.

The calculation of the content of sericite, using the approximate formula, discloses a small deficit of H_2O and SiO_2. If, instead, the accessory minerals rutile, apatite, and calcite are deducted, the sericite forming the rest, the following mode (Table 7) is arrived at. Although the figures are approximate, they may still be considered fairly accurate as no other minerals but those mentioned above occur in the rock.

Table 7.

Modal composition of sericite rock.

Sericite	96.9
Apatite, rutile, calcite	3.1
	100.0 %

2. Andalusite Rocks.

General.

The andalusite rocks have a restricted occurrence and are mainly present on the deeper levels, where, however, they can form rather large bodies. Some small lenses have been met with in drill holes on the 50 m level[1]. On the 210 m level (Pl. 6) small lenses occur around section 11 and N of the a-d-lens. Most

[1] Outside the map.

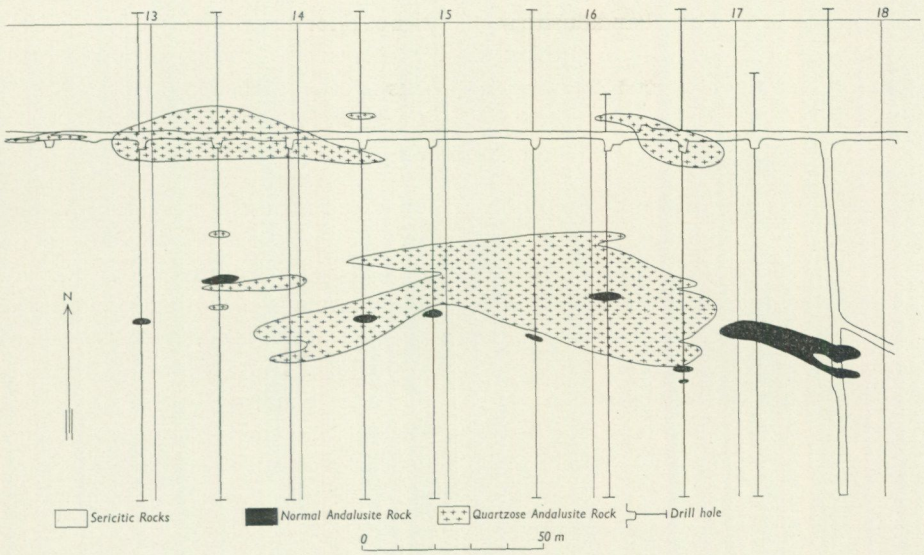

Fig. 6. Distribution of andalusite rocks. 410 m level.

wide-spread are the andalusite rocks on the 250, 330, and 410 m levels (Pl. 7 and Fig. 6).

As the figures show, the rocks generally appear within the central part of the altered zone in the vicinity of the ore bodies. Even this circumstance indicates that the rocks were formed by the same hydrothermal processes which led to the formation of the other altered rocks (cf. p. 149).

The andalusite rocks occur in lenses which often have rather irregular outlines. In size they vary from only a few dm in length and width up to lenses 170 m long and 35 m thick. Our knowledge of their extension in space is so far rather incomplete, but judging from the smaller lenses, which could be studied in some detail, they form elongate bodies with their axes pitching east, parallel to the pitch of the dragfold and the ore bodies.

The underground mapping showed that the andalusite rocks appear in two separate types, a normal, quartz-free type and a quartz-rich one seemingly restricted to the 330 and 410 m levels (Fig. 6). From a mineralogical and chemical point of view the two types of andalusite rock differ quite considerably from one another.

The normal andalusite rock is generally enclosed within the sericite rock. In many cases the hood of sericite rock is too thin to be mapped. More seldom is this variety of the rock found in the sericite schist. The quartz-bearing type, on the other hand, is almost always confined to the normal sericite schist, or to the quartz-porphyritic variety.

The contact with the sericite rock is generally fairly well marked but in many cases there is a gradational zone with an abundance of andalusite crystals in the sericite rock, indicating a replacement of the latter by the andalusite. The andalusite crystals disappear, however, after a few metres. Generally the

mapping of the normal andalusite rock does not offer any difficulty. The quartz-rich variety presents some difficulties in that respect — particularly in drill-holes — as the contact to the sericitic rocks is often rather indistinct.

Normal Andalusite Rock.

The normal andalusite rock is quite massive and is megascopically composed of a coarse- to medium-grained mass of andalusite with a varying amount of sericite. The grains of andalusite sometimes attain a length of 0.5—1.0 cm. The colour is gray in the fresh varieties but somewhat yellowish gray when the rock is sericitized. Occasionally darker gray spots are noticed, evidently caused by the presence of aggregates of rutile or corundum. In its fresh state the rock is very hard; the sericitized portions, on the other hand, are softer.

The rock is often intensely sericitized, the sericite occurring in irregular spots and streaks or in veins. Some of the veins carry crystals of fresh andalusite, about one or two cm large. There also occur later veins of fresh andalusite in the rock. A further description is given on page 36.

The microscopic study of the normal andalusite rock reveals a number of minerals besides andalusite and sericite, namely corundum, diasporite, cyanite,[1] kaolin, chlorite, apatite, rutile, zircon, tourmaline, rarely ore minerals, and an unknown graphitic mineral.

Andalusite is the most characteristic component and predominates over the other minerals. In the analysed sample (Analysis No. 14, p. 39), the amount is only 38 %, corundum here being unusually abundant. In normal cases, where corundum is sparser, the amount of andalusite is 50—75 per cent. of the weight or even more. In the massive types of andalusite rock the mineral occurs in aggregates of hypidiomorphic grains (Fig. a, Pl. 15), but in the sericite-bearing portions of the rock, *e. g.* on the contact to the replaced sericite rock, andalusite occurs in idiomorphic grains of a prismatic form (Fig. b, Pl. 15). In the fresh state the mineral is colourless and clear. It is, however, quite often decomposed and such minerals as sericite, corundum, diasporite, and kaolin have been formed. The grains are then turbid and have a brownish gray colour. Sometimes only the marginal portions of the grains are thus coloured. The optic axis of the andalusite was determined in a number of cases and was found to vary between 82° and 84° around a.

Sericite is often plentiful, the amount increasing with the alteration. The microscopic study indicates two generations of sericite, one older than the formation of the andalusite and one younger.

The sericite of the older generation occurs as a fine-grained groundmass between the grains of andalusite and particularly in the portions of the rock that border on the sericite rock. The andalusite here replaces the sericite and the sericitic groundmass represents replacement remnants of the sericite rock. In those cases the andalusite is generally idiomorphic.

[1] In later veins, see p. 37.

The sericite of the second generation occurs in streaks or veinlets which clearly replace the andalusite. Under the microscope the borders of the andalusite grains are seen to be eaten into by the sericite, which also traverses the host mineral along cracks and cleavage planes. This later sericite is often rather coarse-grained, particularly when it occurs in megascopic veins. As will be shown later (pp. 94 and 100), the mineral was formed during the quartz-tourmaline stage of the ore deposition.

Corundum must also be looked upon as an alteration product of andalusite. It is fairly common but in most cases the amount is small. In the analysed sample (p. 39) corundum is unusually plentiful, amounting to 35 per cent. of weight. The mineral as a rule occurs in small rounded grains or aggregates in the andalusite grains, sometimes resembling pseudomorphs (Fig. b, Pl. 16). In such cases the aggregates of corundum are a few mm across and are visible to the naked eye as dark spots. The mineral may also occur as separate grains in the sericitic groundmass. Under the microscope the corundum is colourless or faintly brownish gray. The refringence is very strong and the grains stand out well due to their high relief. The birefringence is weak and the optic character is uniaxial negative.

The diasporite presents an analogous appearance. It is often present but always in small amounts. The colourless grains are lath-shaped or elongate tabular, attaining a size of 0.2—0.3 mm. The refringence and birefringence are very strong; the optic character is positive and the optic angle 83°. The optic plane is parallel to the cleavage.

Another product of alteration is kaolin. The appearance of the mineral is similar to that of sericite. It forms symmetric veinlets which cut the andalusite. The interior of the veinlets is composed of a fine-grained, colourless felt and separate larger scales of kaolin. The mineral has a weak refringence and birefringence and the optic angle is of medium size. The optic character is negative. In the interior portions of the veinlets also coarse scales of sericite occur, growing at right angles to the walls. Towards the margins the kaolin veinlets become more and more fine-grained and finally the scaly felt appears to be isotropic in polarized light. Kaolin also forms pseudomorphs after andalusite, particularly when the replacement of the sericite rock is incomplete, and scattered crystals of andalusite occur in the fine sericitic groundmass.

Chlorite is extremely rare and has been observed only in two or three cases.

Rutile is a characteristic component of the rock and is always present in varying amounts. In some cases the colour of the andalusite rock is dark on account of the appearance of swarms of rounded or rod-shaped grains of almost opaque or dark violet rutile. The swarms are independent of the boundaries of the andalusite grains and the mineral has been introduced after the formation of the andalusite. The size of the individual rutile grains is about 0.1 mm.

Apatite occurs but rarely and is difficult to recognize because of its resemblance to andalusite under the microscope.

Occasionally there are found small grains of a mineral which has been inter-

preted as zircon. The refringence and birefringence are strong and the optic character is uniaxial positive.

Tourmaline is occasionally met with in the andalusite rock but as a rule only in small amounts. It was formed in connection with the quartz-tourmaline stage, as is evident from the fact that it appears close to tourmaline veins (p. 100).

Ore minerals are very rare in the andalusite rock and only Bi-tellurides and gold have been observed.

Of great interest is the occurrence of a graphitic matter, so far not identified, in the andalusite rock. It occurs as reniform or botryoidal pieces, about the size of a pea or a walnut, enclosed in the veinlets of coarse sericite (Fig. a, Pl. 16). A preliminary study of the substance has been made at the Boliden Research Laboratory at Stockholm and a closer study is being carried out by Prof. G. Aminoff of the Museum of Natural History at Stockholm.

The substance is jet black on the surface but on fractures it has a dull blackish colour. Its hardness is about 3 and its specific gravity 1.512. On heating, fumes are given off and finally the substance burns, leaving 9—10 % ash.

Prof. Aminoff communicates that by X-ray spectrographic methods he has been able to prove the presence of uranium, thorium, titanium, and lead, among other elements. The content of uranium is considerably higher than that of thorium. In an X-ray diffraction pattern of the substance graphite lines were visible. The substance is radioactive.

As already mentioned the andalusite rock is traversed by younger veins of sericite and andalusite.

The veins, or streaks, of sericite are generally irregular and diffuse. They are as a rule not more than about one m long and have a winding course. Two distinct types occur, one with coarse and one with fine-grained sericite. In the former case the gray or sometimes faintly greenish mineral grows in rosette-shaped tufts, the individual scales often having a diameter of 0.5—1.0 cm. Occasional clear crystals of andalusite and pieces of the graphitic substance are found in these veins. A partial determination of the indices of refraction of the sericite gave: $\beta = 1.586$ and $\gamma = 1.591$ ($\pm$ 0.002).[1] The chemical composition is given in Table 8 below.

In the fine-grained veins the sericite forms a massive, soapy felt, composed of scales only a few tenths of a mm in diameter. The colour is white or greenish yellow. In order to check the microscopic determination, a chemical analysis was carried out (Table 8) which proved the mineral to be sericite. The analysis shows a good agreement with the approximate formula $K_2O \cdot 2H_2O \cdot 3Al_2O_3 \cdot \cdot 6SiO_2$.

Both types of veins stand in close connection with the general sericitization of the andalusite rock and on some occasions also with quartz-tourmaline veins, and as will be discussed in a later chapter (pp. 94 and 100) they were formed in conjunction with the latter.

[1] The refractive indices published in this paper have kindly been determined (by the immersion method) by Dr. T. Krokström of Upsala.

Table 8.

Chemical composition of sericite.

Analyst: Th. Berggren.

Analysis No.	11	12	Analysis No.	11	12
SiO_2	45.10	45.95	Na_2O	2.27	1.99
TiO_2	0.16	0.06	K_2O	9.24	9.00
Al_2O_3	37.32	37.90	Li_2O	nil	nil
Fe_2O_3	0.40	0.21	$H_2O^{-105°}$	0.92	0.04
FeO	nil	nil	$H_2O^{+105°}$	4.39	4.48
MnO	tr.	nil	P_2O_5	nil	—
CaO	0.12	0.01	F	0.21	0.27
MgO	0.05	nil		100.18	99.91
			$-O=F$	0.09	0.12
Sp. gr. =	2.806	2.833		100.09	99.79

11. Coarse sericite. Section 13—14, 250 m level.
12. Fine-grained sericite. Section 15, 250 m level.

The veins of later andalusite are generally rare. Between sections 14 and 15 on the 250 m level they are fairly common and could be studied in detail. The veins are a few cm wide and 2—3 m long and run in various directions. They are often sharply delimited and give the impression of having been formed along fissures in the andalusite rock. Two generations of veins are present as shown in Fig. a (Pl. 17), where two systems of veins cut each other. The older veins are grayish white, the younger ones faintly pink.

The veins are mainly composed of hypidiomorphic grains of andalusite, about one centimetre long. Under the microscope the mineral is often turbid and shows a beginning decomposition. The formation of sericite, kaolin, and diasporite is noted. The refringence was determined in one case:

$$\alpha = 1.631;\ \beta = 1.637;\ \gamma = 1.643\ (\pm 0.002)$$
$$\gamma - \alpha = 0.012$$
$$-2V = 81—83° \text{ (measured)}$$

The chemical composition of the andalusite veins is shown in Table 9.

Sericite is noted already with the naked eye as large foliae between the andalusite individuals or along the margins of the veins. The amount of sericite increasing, a transition takes place to the sericite veins.

Kaolin in rosette-shaped aggregates, composed of scales max. 0.1 mm in diameter, replaces the andalusite in patches (Fig. b, Pl. 17). The kaolin is optically positive and the optic angle is approximately 67°. Small grains of diasporite occur in indistinct coronas around the patches of kaolin or appear within the grains of andalusite. The diasporite forms elongate grains, a few tenths of a millimetre long.

Coarsely crystalline cyanite has been found in one case in the andalusite rock between sections 14 and 15 on the 250 m level. It forms a long-columnar mass

of grayish white crystals about 15—20 cm long. Together with the cyanite there occurred some coarse sericite, replacing the former. The cyanite appeared as an irregular streak in the andalusite rock and should probably be looked upon as a later formation of the same kind as the later veins of andalusite.

Table 9.

Chemical composition of andalusite vein.

Analysis No. 13.

Analyst: Th. Berggren.

	%		%
SiO_2	35.92	CaO	tr.
TiO_2	nil	MgO	nil
Al_2O_3	61.14	Na_2O	0.16
Fe_2O_3	0.12	K_2O	0.11
FeO	0.07	$H_2O^{-105°}$	0.09
MnO	nil	$H_2O^{+105°}$	2.69
Sp. gr. = 3.077			100.30

13. Andalusite vein. Section 14, 250 m level.

Quartz-bearing Andalusite Rock.

The quartz-bearing type of the andalusite rock is restricted to the deeper levels of the mine and Fig. 6 shows its distribution on the 410 m level. The wall-rock here is sericite schist or quartz-porphyritic sericite schist.

From a mineralogical point of view the main difference from the foregoing type lies in the abundant occurrence of quartz. The present rock is gray and very fine-grained, almost »leptitic», with a faintly developed parallel structure, caused by the streaks of andalusite. It is very hard and brittle.

The rock is often traversed by quartz-filled fissures, evidently caused by rupture in the brittle material. The fissures occur in two systems, one striking almost due N—S, the other having a horizontal position. The quartz is coarsely crystalline and of a milky white colour. Small aggregates of Bi-tellurides are occasionally met with and in a few cases also gold has been found. The occurrence of Bi-tellurides indicates that the fissures were formed during the quartz-tourmaline stage of mineralization (pp. 84 and 102).

Besides quartz and andalusite the rock contains some sericite, diasporite, rutile, apatite, and zircon. The modal composition of the rock is given on p. 40. However, the amounts of the minerals vary from place to place.

Under the microscope the rock is made up of a fine-grained mass of elongate and somewhat undulatory grains of quartz. The andalusite is concentrated in the quartz to irregular streaks which produce the faint parallel structure in the rock. Occasionally bluish phenocrysts of quartz are noted, clearly indicating that the rock was partly formed by the alteration of a quartz-porphyritic sericite schist.

The grains of andalusite are very irregular and often contain micropoikilitic grains of quartz. The average size of the andalusite grains is 0.2—0.4 mm. The mineral is colourless and almost completely unaltered. The average size of the optic angle is 85°.

The amount of sericite is only a few per cent. The mineral occurs in small foils within the andalusite or in the quartz. In contradistinction to the quartz-free andalusite rock, the sericitization is here very slight. Diasporite has been found only in one thin section. Rutile is a typical mineral, occurring in scattered grains or streaks.

Chemical Composition of the Andalusite Rocks.

One analysis has been made of each type of andalusite rock (Table 10).

Table 10.

Chemical composition of andalusite rocks.

Analyst: Th. Berggren.

Analysis No.	14	15	Analysis No.	14	15
SiO_2	21.73	68.89	Na_2O	0.36	0.39
TiO_2	1.05	1.20	K_2O	1.43	0.38
Al_2O_3	72.49	27.23	$H_2O^{-105°}$	0.16	0.08
Fe_2O_3	0.21	0.29	$H_2O^{+105°}$	2.04	0.53
FeO	0.41	0.48	P_2O_5	nil	0.31
MnO	nil	nil	F	0.03	nil
CaO	nil	0.40	CO_2	nil	—
MgO	0.01	nil	S	0.04	0.03
			As	—	nil
Sp. gr. =	3.046	2.687		99.96	100.21

14. Quartz-free andalusite rock. Crosscut in section 17—18, 410 m level.
15. Quartz-bearing andalusite rock. Main east drift, section 13, 410 m level.

Analysis No. 14 shows the composition of the quartz-free andalusite rock. It contains an unusually high amount of corundum and in that respect the analysis cannot be considered typical, for generally the andalusite rock contains far less of this mineral. The amount of sericite is less than usual. Normally the rock contains about 45—55 % Al_2O_3 and about 5—10 % of combined alkalis, as indicated by several analyses of samples taken at various localities in the mine.

Al_2O_3 and SiO_2 predominate, and, with the exception of TiO_2, K_2O, and H_2O, other oxides are present in insignificant quantities only, or are completely absent. In comparison with the sericitic rocks, Al_2O_3 shows a considerable increase while SiO_2 has considerably decreased. Also the alkalis have decreased.

The analysed rock is composed of andalusite, corundum, diasporite, sericite, and rutile. A calculation of the modal composition of the rock, founded on the

analysis, gives the following approximate figures (Table 11). Probably also some kaolin occurs but the quantity thereof could not be calculated. The small amount of S present has not been taken into account. The amount of rutile was obtained in the same manner as before (p. 31).

Table 11.

Modal composition of quartz-free andalusite rock.

Andalusite	38.2
Corundum	34.8
Diasporite	8.5
Sericite	16.5
Rutile	1.7
	99.7 %

Analysis No. 15 represents the quartz-bearing type. The high content of silica is at once conspicuous. The content of Al_2O_3 is still comparatively high but nevertheless considerably lower than in Analysis No. 14. The other oxides, excepting TiO_2 but including the alkalis, are here present only in insignificant amounts.

A calculation of the modal composition on the basis of the analysis give the following result (Table 12).

Table 12.

Modal composition of the quartz-bearing andalusite rock.

Quartz	51.1
Andalusite	38.4
Sericite	7.8
Rutile	2.0
Apatite	0.7
	100.0 %

Description of the Ores.

Types of Ore.

The geological survey of the mine shows that from a geological point of view the ores can be divided into three types, characterized by differences in appearance and mineralogical composition. These types are 1) arsenopyrite ore, 2) lamprophyric dykes with quartz-tourmaline and sulphide ores, and 3) pyrite ore. The survey also led to the important conclusion that these types represent three stages of mineralization, separated by intervals and appearing in the sequence given above.

Arsenopyrite Ore.

Distribution.

The arsenopyrite ore appears in a large number of ore bodies, irregularly scattered throughout the central part of the ore zone (Pl. 1—7). Most of them are enclosed in the pyrite ore but some occur in the sericite schists, particularly on the deeper levels. A detailed description of some of the more important ore bodies is given in a later chapter (p. 128).

In close relation to some of the ore bodies there appear a number of separate mineral associations, such as rutile rock, pyrite-apatite ore, and quartz-plagioclase veins, which are considered to be differentiation products of the arsenopyrite ore. They are described in detail below (p. 55).

Contact Relations.

The contacts and boundaries of an ore body are of particular interest as they disclose valuable information as to the mode of formation of the ore and its age relations. Particular attention was given these phenomena and several important observations were made.

The contacts between the arsenopyrite ore and the wallrocks are generally very sharp and the ore abuts against the schist without any transitional zone being developed. The ore does not generally contain any remnants of wallrock and often the adjoining sericite schist is free from impregnation. The ore is generally frozen to the walls.

Divergencies from the conditions now described are, however, not unusual. There are thus contacts that show a transitional zone of impregnated wallrock, often forming mineable portions of disseminated ore. Sometimes lateral lenses, varying from a few cm up to several m, occur in the wallrock at the contact. These lenses have the same composition as the main ore and may also have sharp boundaries towards the surrounding schist. They do, however, also contain replacement remnants of schist.

Replacement contacts are noticed particularly at the ends of the ore bodies. They peter out in an irregular fashion and are surrounded by a halo of impregnated wallrock. Separate small lenses also appear. Incomplete replacement is here a common condition.

The ore as a rule distinctly follows the foliation of the wallrock. This condition is very distinct in the gentle folds of the schist but in the sharp Z-shaped folds which sometimes form at the contact, it is less conspicuous. Also the lateral lenses follow the folds, without, however, being ruptured.

On some occasions the ore breaks through the wallrock, more or less sharply delimited apophyses being formed. A good example of such an apophysis is found in Stope 20 on the 90 m level (a closer description is found in (78) and on p. 62 of the present paper). The apophyses are sometimes wedge-shaped and cut sharply through the schist. The wedges can generally be followed a

length of a few dm only. They may be composed of arsenopyrite ore but they are occasionally composed of other minerals, *e. g.*, quartz or sulphominerals.[1] Gold is often concentrated in those places. Wedge-shaped apophyses from the arsenopyrite ore have been met with on several levels in the mine.

The contact relations of the arsenopyrite ore to the younger ores are also of great interest and they will be considered in following chapters.

Description of the Arsenopyrite Ore.

The study of the arsenopyrite ore shows that a number of different types occur. They differ quite considerably from one another and must be treated separately. These types are:

1) Normal arsenopyrite ore
2) Dense arsenopyrite ore
3) Apatite-banded arsenopyrite ore
4) Quartz-banded arsenopyrite ore
5) Cobaltite-bearing arsenopyrite ore.

The normal arsenopyrite ore is the type most widely distributed, the others being only locally developed.

Normal arsenopyrite ore. This type of ore is composed of a great number of minerals forming a compact sulphide mass. Most prominent is arsenopyrite, a mineral that gives the ore its typical aspect. The arsenopyrite is generally very fine-grained and the individual grains are not visible to the naked eye, their size varying from about 0.4 mm down to some μ. The average size is 0.01—0.04 mm. Larger grains, sometimes showing crystal forms, are occasionally developed where the ore is cut by later minerals. At least part of them were formed by the dissolution and recrystallization of earlier arsenopyrite.

The fine-grained arsenopyrite ore is steel-gray and in some cases whitish gray.

The ore has the nature of a breccia and the fine-grained arsenopyrite is cut by abundant fissures and veins with a large number of other minerals. Valuable information as to the sequence of mineralization is obtainable from these veins and it is evident that arsenopyrite is one of the oldest minerals.

Although the fine-grained arsenopyrite mass is the most conspicuous feature of the ore, it varies considerably in appearance according to the state of brecciation and depending on what minerals predominate in the brecciating veins.

The character of the breccia varies from case to case. Frequently a network of sharply delimited fissures cut the arsenopyrite ore to a breccia in which the individual inclusions still retain their original position and match each other. The brecciating fluid evidently had hardly any influence on the arsenopyrite and practically no replacement took place. This is a crush-breccia, into which the brecciating medium was forced in the manner of an intrusion.

[1] »Sulphominerals» is a term used in this paper to denote a number of lead-sulphantimonites and lead-sulphbismuthinites, *e. g.* jamesonite, boulangerite, »selenocosalite», etc.

From this type of breccia there is a transition to breccias where the inclusions are strongly replaced. The brecciating veins are very irregular and the inclusions are rounded and often more or less resorbed.

Also the small lateral lenses of arsenopyrite ore are brecciated in the same manner as the larger bodies.

The fissures and veins of the breccia as a rule have no definite direction. In some cases they tend to arrange themselves at right angles to the strike of the ore bodies.

Among the brecciating minerals we note practically all the ore and gangue minerals present in the ore. Several of them may occur together but it is also common to find breccias where one mineral, *e. g.* quartz, sphalerite, sulphominerals, or chalcopyrite, forms the sole constituent. Pyrite is particularly common at the contacts to the pyrite ore. A closer study of the arsenopyrite ore reveals that in some cases the minerals of the breccias belong to the arsenopyrite stage, whereas in others the brecciating minerals were introduced during one of the later stages of mineralization. It is, however, not always possible to determine the age of the brecciating minerals.

In Plates 18—19 and Fig. a, Pl. 20 some examples of brecciated arsenopyrite ore are illustrated.

The microscopic study of the ore yields the following data.

The arsenopyritic part of the ore is composed of a finely crystalline mass of arsenopyrite grains which may be said to be hypidiomorphic, as the individual grains, at least where their size permits a closer view, often have partly developed crystal outlines (Fig. b, Pl. 20). In the extremely fine-grained portions of the ore the arsenopyrite seems to lack crystal form. Where, on the other hand, the ore is coarser, the arsenopyrite is well crystallized.

The arsenopyrite seldom displays regular textures. In some cases a spherulitic growth of elongate crystals has been noted. Indistinctly concentric zones of chalcopyrite or quartz in rounded aggregates of arsenopyrite were found in one case. In another case the fine-grained arsenopyrite ore contained narrow fissures or cracks from which the arsenopyrite had grown out in small crystals, standing with their c-axes at right angles to the fissures (Fig. a, Pl. 21). Considering the great number of polished sections studied, these textural features are very rare.

Very common in the arsenopyrite ore is the occurrence of microscopic pores or »druses», filled with a large number of minerals. The pores have a rounded or elongate form with a diameter which in rare cases amounts to one mm. Generally the diameter is only some tenths of a mm. Towards the pores the fine-grained arsenopyrite gradually becomes coarser and tends to develop idiomorphic crystals. A ring of crystals is thus formed, pointing into the »druse» as shown in Fig. b, Pl. 21 and Figs. a and b, Pl. 22. By using an immersion system on the microscope, the walls and bottom of the pores, filled with *e. g.* quartz or calcite, are seen to be covered with idiomorphic crystals of arsenopyrite. Although it could not be proved, the »druses» would appear to form isolated and separated pores in the ore.

Larger and closely packed pores grade into veins which brecciate the ore, indicating that there is a connection between the pores and the brecciation.

With few exceptions all the mineral constituents of the arsenopyrite ore are found in the »druses». The filling may be composed of a mixture of several minerals but very often it consists of one mineral only.

The arsenopyrite ore often has a skeleton texture (Fig. c, Pl. 22), composed of a framework of fairly well crystallized arsenopyrite. The interstices in the framework are filled with the usual large number of later minerals. A similar texture was noted in the arsenopyrite ore from Holmtjärn (67). In the cases where the framework is dense there is a resemblance to the pores, and the texture is considered to have been formed in the same manner (p. 156). The framework is, however, also developed in the places where the arsenopyrite ore has been resorbed and replaced by minerals of the later stages. Here it was probably formed by the dissolution and recrystallization of the arsenopyrite.

Dense arsenopyrite ore. As stated above, the arsenopyrite is always very fine-grained but locally an ore is developed which is still more fine-grained and has the appearance of steel. It has been found in a lens at section 3 on the surface and together with normal arsenopyrite ore on the 130 and 210 m levels.

The size of the grains is less than the average of the normal ore and amounts to only 2 or 3 μ. The crystalline nature of the ore becomes evident in polarized light only.

In polished sections the ore is found to be inhomogeneous and indistinct inclusions occur in a slightly coarser crystalline groundmass.

In contradistinction to the foregoing type this ore is but rarely brecciated by later minerals and on the whole contains very few minerals except arsenopyrite. The ore from the lens on the surface was cut by some sharply delimited fissures, filled with a coarse mixture of sulphominerals, chalcopyrite, and quartz, and containing sharp-edged inclusions of arsenopyrite ore. Replacement was not noticed in this case.

This type of ore has been analysed and as is evident from the analysis, No. 17 in Table 14, p. 54, there is a good agreement with the theoretical composition of arsenopyrite.

Apatite-banded arsenopyrite ore. Apatite is one of the more common gangue minerals in the ore, but as a rule it occurs only as microscopic grains. In the e-lens on the 50 m level it occurred in larger quantities, however, forming an interesting variety of arsenopyrite ore. A similar ore has been found on two occasions as inclusions in pyrite ore.

The ore in the e-lens is very distinctly banded with alternate dark and light, about 1—2 cm wide bands with apatite and arsenopyrite, respectively, as predominant components. The bands are twisted and folded (Fig. a, Pl. 24; Fig. a, Pl. 23) and sometimes broken, the interstices then being filled with arsenopyrite ore of the normal type. They are occasionally cut by veins of chalcopyrite, pyrite,

cobaltite, and quartz. Sometimes the bands are sharply defined but they also grade into each other.

The general impression is that the ore has not been subjected to mechanical rupture, the folding rather having been developed by gentle movements in a plastic medium.

The arsenopyritic bands are composed of very fine-grained to dense arsenopyrite. »Druse»-like formations with apatite and quartz are developed on a small scale.

In the dark bands apatite generally predominates but occasionally small amounts of quartz are also present. The apatite grains are generally small, about 0.08—0.3 mm long, and comparatively well crystallized although they are corroded by arsenopyrite and chalcopyrite (Fig. b, Pl. 23). The grains do not show any directional arrangement and are surrounded by fine-grained arsenopyrite. Besides apatite and quartz, foils of sericite, some svanbergite (?; cf. p. 53), and occasional grains of cobaltite and chalcopyrite are met with.

Thin bands of pyrite, together with quartz, apatite, and cobaltite, are also noted. The pyrite is sometimes corroded and encrusted by the cobaltite.

Quartz-banded arsenopyrite ore. Also this type has a restricted occurrence and is found mainly in a lens at the hanging wall of the Eastern Ore at section 11 on the surface and in the footwall of the ore in Stope 28 on the 250 m level. A somewhat different but also quartz-banded ore occurs in some places, *e. g.* at the western end of the a-d-lens on the 210 m and 250 m levels.

The banding is not so distinct and is caused by irregularly alternate dark and light streaks or schlieren, rarely more than 1 or 2 dm long. The individual streaks are only a few mm wide. The banding is sometimes wavy and resembles flow-structure (Fig. b, Pl. 24). It does not resemble structures formed by the replacement of a foliated rock.

Occasionally the quartz-banded ore encloses small lenses of normal arsenopyrite ore which are then brecciated by the former, indicating the later age of the banded ore.

The mineralogical composition of the quartz-banded ore is very simple. Quartz and arsenopyrite are the predominant minerals in the dark and light bands, respectively. The arsenopyrite is intergrown to a fine-grained skeletal fabric, composed of often well crystallized individuals with fine-grained quartz filling the interstices. The quartz is frequently rather undulatory. It is somewhat more coarsely crystalline in the quartzous bands. The arsenopyrite occurring in the quartz-rich bands is accumulated to fluffy aggregates.

Apatite is sometimes common. It generally occurs in small corroded grains but is sometimes accumulated to streaks. Sericite, chlorite, calcite, and rutile are rare.

The banded ore at the western end of the a-d-lens differs from the normal banded type mainly by its content of remnants of sericite rock, and by the occurrence of andalusite and tourmaline.

Under the microscope the ore abounds in sericite and it is evident that it was here formed by an incomplete replacement of the wallrock. As mentioned above (p. 41) replacement on a large scale often took place in the terminal parts of the ore bodies.

Andalusite occurs in crystals about 2 or 3 cm long. They are brownish pink in colour and are generally clear. Some crystals are coated with thin foils of gold. Under the microscope the andalusite is found to be partly replaced by quartz, sericite, chlorite, arsenopyrite, and chalcopyrite (Fig. c, Pl. 24) and it is evident that the mineral was formed before the arsenopyrite ore. Andalusite is plentiful in the adjoining sericite rock and lenses of andalusite rock occur in the vicinity (Fig. 16, p. 101).

Tourmaline occurs in about 1 cm long, slender needles. They are often ruptured, the interstices being filled with various minerals. The mineral is particularly plentiful in the ore in the western part of Stope 25 (the a-d-lens on the 250 m level) and it increases towards a tourmaline vein which appears here. There are thus strong reasons for assuming that the mineral was introduced during the tourmaline stage and that it does not belong to the arsenopyrite stage. The interstices in the broken needles being filled with later minerals may depend on a partial mobilization, caused by solutions given off from the tourmaline veins.

Cobaltite-bearing arsenopyrite ore. Analyses of arsenopyrite ore normally show a certain content of Co (p. 54), without, however, any cobolt mineral having been found. In these cases Co probably enters into arsenopyrite.

The mineral cobaltite is, however, in some of the arsenopyrite ores known to occur in large amounts, forming a special type of ore. The cobaltite is especially enriched in the marginal and terminal portions of the ore bodies and also forms small lenses along the sides of the main ore bodies. Cobaltite-bearing ore has thus been found at the western end of the a-d-lens on the 170 m level and in the hanging wall of the same ore body between the 170 and 210 m levels. It also occurs at sections 10, 11, and 12 on the 210 m level, and in several other places. The cobaltite-bearing portions of the ore are generally only a few m long and one or two m wide. The sericite schist bordering on the cobaltite-bearing ore is sometimes impregnated with cobaltite.

In the above cases the cobaltite belongs to the arsenopyrite stage, but it should be emphasized that cobaltite was also introduced during the second stage (p. 85) and that in some cases it is difficult to decide during which stage it was formed.

The richest concentration of cobaltite is found in Stope 28 on the 250 m level where it occurs in connection with the pyrite-apatite ore of the arsenopyrite stage (p. 57).

The cobaltite-bearing ore is fine-grained and has a faint but distinct pink colour. It often shows a banding and occasionally contains small inclusions of a similar but somewhat more fine-grained ore.

The cobaltite occurs in rounded grains which only seldom present idiomorphic (cubic) forms. The size of the grains is about 0.2 mm. Some grains are atoll-shaped. The groundmass between the cobaltite grains is mainly composed of quartz.

A number of ore minerals are found in the ore, *e. g.* chalcopyrite, pyrrhotite, sphalerite, Bi-tellurides, and gold. Some of these minerals have probably been introduced during later stages of the mineralization. This is certainly true of the Bi-tellurides which were brought in during the tourmaline stage.

When cobaltite-bearing ore or sericite schist is subjected for some time to the influence of the moist air in the mine, the cobaltite oxidizes and a thin coating of erythrite ($Co_3As_2O_8 \cdot 8H_2O$) is formed.

Paragenesis of the Arsenopyrite Ore.

General. The mineral composition and paragenetic relations of the Boliden ores are extremely complicated, owing not only to the great number of minerals present (cf. Table 42 on p. 184) and the intimate intergrowths formed between them, but also to the fact that some minerals appear in two or more generations and in various associations within the same stage. These conditions are in particular true of the arsenopyrite ore which is indeed the most complicated of the ores in the deposit. It must also be borne in mind that the arsenopyrite ore has been affected by the solutions of two later mineralizing stages which have had a great influence on its mineral composition. Some minerals have been mobilized and recrystallized and new minerals have been added, which, although they apparently occur in the arsenopyrite ore, actually do not belong to its paragenesis. The latter circumstance often makes it very difficult and even impossible to decide whether a mineral actually belongs to the arsenopyrite ore or if it was brought in during one of the later stages.[1]

Because of their position fairly far away from the later ores, two arsenopyrite bodies, the a-d-lens and the lens in Stope 28 on the 250 m level, can, however, at least in part be considered still to have their paragenesis fairly intact.

Ore minerals. Bismuth. The amount of bismuth in the arsenopyrite ore is small in comparison with that in *e. g.* the tourmaline ores. Some of the complex sulphominerals in the arsenopyrite ore contain small amounts of bismuth, however, mostly in the form of a decomposition product. It is also met with as a late product of crystallization in some of the brecciating veins of chalcopyrite and galena.

Gold is megascopically visible in the arsenopyrite ore. It is generally found as thin sheets in quartz-filled fissures but may also occur directly in the arsenopyrite ore in the shape of wire gold. It has occasionally been observed on slickensides.

Under the microscope gold is rarely found as inclusions in arsenopyrite grains.

[1] According to the author's interpretation of the so-called »druses» (p. 156) in the arsenopyrite ore, minerals occurring in them are considered to belong to the paragenesis.

The individual grains are maximum a few hundredths of a mm in diameter and sometimes occur together with chalcopyrite. They have been found in zones intercalated parallel to the c-axis of the arsenopyrite. Gold may also occupy fissures in that mineral.

Most of the gold occurs in intimate connection with other minerals, mainly ore minerals. It has occasionally been seen, for instance, on »druses», either alone or together with quartz and other minerals. A description of this mode of occurrence, illustrated by figures, was first given by Mörtsell (58, Figs. 1—4). On the brecciating veins gold is still more common. It is here found with most of the other mineral constituents, mainly in the form of rounded inclusions. However, gold replaces and veins many of the minerals, *e. g.* quartz, sphalerite, pyrrhotite, and chalcopyrite, and it was probably formed rather late in the sequence of crystallization.

Some of the gold has been introduced by the ore solutions of the two later stages, but it is believed that the main part of it is a primary constituent of the paragenesis and that it was brought in together with the other components of the ore.

Bi-tellurides have sometimes been observed in the arsenopyrite ore. They were introduced during the second stage of mineralization and will be described in a later chapter (p. 101).

Sphalerite often fills »druses» and occurs on brecciating veins. It is closely associated with chalcopyrite and pyrrhotite and replaces arsenopyrite and pyrite.

Pyrrhotite has the same mode of occurrence as sphalerite. The arsenopyrite breccias with pyrrhotite as predominant constituent are among those best developed of their kind in the mine. Pyrrhotite is older than arsenopyrite and pyrite but is replaced by chalcopyrite, sulphominerals, gudmundite, and gold.

Only part of the pyrrhotite is a primary constituent of the paragenesis and large quantities of the mineral were brought in during the later stages. This is for instance true of the pyrrhotite that brecciates the k-lens on the 130 and 170 m levels.

The hardness of pyrrhotite in polished sections (»resistance to polish») is generally stated to be higher than that of chalcopyrite (88, p. 131). In the arsenopyrite ore, however, grains of pyrrhotite are in some crystallographic directions notably softer than chalcopyrite. The optical qualities of the mineral are in other respects quite normal and it cannot be doubted that the mineral really is pyrrhotite.

Niccolite (NiAs) has been found in a few grains in ore from the k-lens on the 130 m level. Together with chalcopyrite, sphalerite, gersdorffite, and gold it veins the arsenopyrite. It is also associated with pyrrhotite, in which it occurs in irregular grains. It is here often associated with gold. The k-lens is intensely brecciated by minerals of the second stage and it is quite likely that the niccolite was brought in during that stage.

Pyrite is not very common in the parts of the ore that have not been

influenced by the later pyrite solution. In samples from the a-d-lens on the 170 m level it has been found filling »druses» (Fig. a, Pl. 22). Pyrite occurs here also in veins, brecciating the arsenopyrite ore. The pyrite is well crystallized and is replaced by the groundmass which is composed of pyrrhotite and quartz. Pyrite has also been replaced by sphalerite, chalcopyrite, and sulphominerals, and is evidently an early crystallizing mineral.

Where the arsenopyrite ore has been brecciated and replaced by the pyrite ore, pyrite is one of the most common constituents of the ore.

Cobaltite (CoAsS) has already been mentioned as a constituent of the cobaltite-bearing ore. In the normal arsenopyrite ore it has never been observed.

Gersdorffite (NiAsS) is very rare and has only been seen on two occasions. The identification is not quite certain and it may be ullmannite or smaltite, two minerals similar to gersdorffite under the microscope. The mineral is younger than arsenopyrite and fills fissures in this mineral (cf. above). In an arsenopyrite ore from the 210 m level it occurred in veinlets together with Bi-tellurides, which makes it probable that it was carried in during the second stage of mineralization.

Marcasite is often formed, *e. g.* in pyrrhotite, by the influence of percolating meteoric waters. Marcasite of this origin has been found in arsenopyrite ore from the surface of the ore bodies. In arsenopyrite ore from the 210 m level there occurred, parallel with the basis of the pyrrhotite, thin lamellae of a hard, faintly yellow and anisotropic mineral; it is very likely marcasite. In this case the origin cannot be attributed to descending waters and the mineral was probably formed by residual solutions given off during the mineralization.

The occurrence of arsenopyrite has already been discussed. The idiomorphic crystals pointing into the »druses» and the crystals forming the framework in some types of arsenopyrite ore are elongate along the c-axis and show a striation or a cleavage along (110). Twinned crystals are rare but 4- and 6-pointed star-shaped aggregates representing penetration twins are occasionally seen. In polished sections the coarser, recrystallized arsenopyrite grains often display an irregular surface, some portions being harder than the surroundings. They sometimes take the shape of regular lamellae. The harder portions have the same optical orientation as the host mineral. The cause of the phenomena described is not known but they may depend on some irregularities in the lattice of the mineral.

Gudmundite (FeSbS) is typical of this paragenesis but it seldom occurs in large amounts. Descriptions of the qualities of this mineral are given in recent papers by S. Gavelin (28) and Ramdohr (74).[1] Gudmundite is closely associated particularly with Sb-bearing sulphominerals but is also found together with chalcopyrite, pyrrhotite, and sometimes also with galena. Gudmundite distinctly replaces pyrrhotite or grows out from the surface of pyrrhotite grains in clusters of crystals. Where the mineral is found associated with sulphominerals it is

[1] In Lehrbuch der Erzmikroskopie (88, p. 209) Ramdohr mentioned the presence of löllingite in arsenopyrite ore from Boliden. He found later, however, that it was gudmundite (76). Löllingite does not seem to occur in the deposit.

often the result of reactions and decomposition within these minerals, as is indicated by the fine-grained state of the mineral and the graphic intergrowths with the associated minerals. This implies that the mineral was formed comparatively late in the sequence of crystallization.

Safflorite ($CoAs_2$) has been observed in one case only, in arsenopyrite ore from the a-d-lens in the open pit. It occurs here partly as a star-shaped aggregate in a »druse» together with quartz, chalcopyrite, and sphalerite, and partly in veins with pyrite, cutting the arsenopyrite ore.

Dyscrasite (Ag_3Sb) has not been identified with certainty. A cream-coloured, soft and strongly reflecting mineral, thought to be dyscrasite, does occur, however, in chalcopyrite in the apatite- and pyrite-bearing arsenopyrite ore from Stope 28 on the 250 m level.

Galena is on the whole not very common in the arsenopyrite ore. Fairly large amounts are found in the veins and streaks of sulphominerals which here and there brecciate the arsenopyrite ore. It is then intimately intergrown with the sulphominerals and evidently belongs to the last minerals in the paragenesis.

Small, fine-grained aggregates of covellite were seen in chalcopyrite in arsenopyrite ore from the open pit. It is here formed by percolating surface waters. It may in this connection be mentioned that thin bluish crusts of a hydrous sulphate of copper are also found in the open pit.

Chalcopyrite is very widespread in the arsenopyrite ore. Part of it belongs to the paragenesis proper but large quantities were brought in during the later stages of mineralization. Chalcopyrite brecciates the arsenopyrite ore very distinctly and in some parts of the a-d-lens on the 210 m level and of the e-lens on the 50 m level it is practically the sole constituent of the brecciating veins. Chalcopyrite is also a very common mineral in the druses, in which case it belongs to the paragenesis. The mineral distinctly replaces arsenopyrite, pyrite, pyrrhotite, and sphalerite, but it is also replaced by several minerals, such as the sulphominerals, gold, galena, and others.

Cubanite ($CuFe_2S_3$) is exceptionally rare. It belongs to the paragenesis as shown by its occurrence in the »druses» (Fig. b, Pl. 22).

Valleriite ($Cu_3Fe_4S_7$) occurs as small grains in chalcopyrite or grows in fringes from the surface of pyrrhotite out into chalcopyrite.

Tetrahedrite may occur in concentrations the size of a head, from which brecciating veins cut the surrounding ore. Generally the mineral occurs in brecciating veins together with several other minerals, particularly sulphominerals, such as jamesonite, falkmanite, and boulangerite. It often forms complicated intergrowths with the latter minerals (cf. (78)). Tetrahedrite is also observed in »druses». Some of the mineral certainly belongs to the arsenopyrite ore but as Sb-minerals are common also in the pyrite ore, part of it was probably brought in during the third stage. A chemical analysis was made of microscopically pure material from an arsenopyrite lens in the open pit and gave the following result (Table 13).

The content of As is rather high for tetrahedrite, which is the Sb-bearing member of this group of minerals, and the analysed mineral must be regarded as

an intermediate member between tetrahedrite and tennantite, which is the arsenical equivalent to tetrahedrite. The comparatively high content of Hg in the mineral is of particular interest.

Sulphominerals is a collective name given to certain complex sulphosalts, chiefly containing Pb, Sb, and Bi, which are common in the Boliden ores. In the arsenopyrite ore mainly three sulphominerals have been identified, namely jamesonite, falkmanite (78), and boulangerite. The identification under the microscope is extremely difficult and often impossible. In the determination of the present sulphominerals the author received great and valuable help from Prof. Ramdohr and Dr. Hiller of the University of Berlin, where the ultimate identification of these minerals was carried out by X-ray methods.

Table 13.

Analysis of tetrahedrite.

Analysis No. 16.

	%		%
Cu	41.52	Fe	4.90
As	15.67	Zn	2.83
Sb	6.43	Mn	nil
Ag	0.49	Ni	nil
Au	nil	Co	nil
Bi	tr.	S	28.06
Pb	tr.	Hg	0.06
			99.96

Sp. gr. = 4.571

16. Tetrahedrite. Open pit.

Tetrahedrite, bournonite, gudmundite, galena, and several of the common sulphides also occur together with the above minerals, sometimes forming very intricate intergrowths. Some of them have been described in an earlier joint paper (78) with Ramdohr and in the present paper only a summary of their occurrence will be given in a later section of this chapter (p. 62).

The sulphominerals have the same appearance in the arsenopyrite ore as the other constituents and they brecciate and replace it in the same manner. They are evidently a late crystallizing fraction of the ore solution and often appear in apophyses. The best example is found in an apophysis in Stope 20 on the 90 m level, a description of which will be given later (p. 62).

Gangue minerals. Besides the ore minerals a large number of gangue minerals occur in the arsenopyrite ore. Some of them are found in the »druses» or in other positions which indicate that they were really formed during the arsenopyrite stage. In other cases the conditions are not so clear and it can be presumed that the minerals were introduced later. As was true of the ore minerals, it is

also here sometimes impossible to determine during which stage a mineral was formed.

Quartz is probably the most common gangue mineral in the ore and it is often found in brecciating veins and fissures and in »druses». In some parts of the ore bodies it forms practically the sole constituent of the breccias. The inclusions are often very sharp and match each other, but on the other hand they have in many places been partly resorbed by the quartz (Fig. a, Pl. 19).

Under the microscope the quartz is usually coarse-grained, but fine-grained quartz is not uncommon. The grains are often undulatory but they are only rarely granulated. In some cases the quartz appears in sub-parallel lamellae which are arranged in elongate zones in normal, faintly undulatory quartz (Fig. a, Pl. 25). The lamellae are not orientated parallel to the c-axis of the mineral. The phenomenon should probably be explained as a partial rupture of the mineral along translation planes.

A similar texture is presented by quartz around cubic grains of pyrite enclosed in quartz veins. The mineral forms radiate coronas of columnar grains, growing out at right angles from the faces of the pyrite (Fig. b, Pl. 25). The texture is very similar to the »pressure shadows» of feather quartz described by Mügge (60), Pabst (69), de Magnée (17), and others, from a number of localities. The texture is considered to have been created by the growth of quartz grains in openings around porphyroblasts in schists, formed during a process of stretching. This explanation is hardly acceptable in this case as other conditions certainly were ruling in the ore than in the schists in the cited papers. It is on the other hand difficult to produce another acceptable explanation, and the author only wishes to point out that the texture primarily must be interpreted as a phenomenon of crystallization, although stress action probably was a co-operative factor.

Rutile is a characteristic mineral in the paragenesis and is often present in large amounts. It is, however, irregularly distributed and in some samples of arsenopyrite ore the mineral is very rare. Analyses Nos. 17—21 (p. 54) are of material practically free from rutile but on the other hand many analyses made when sampling the mine show a content of TiO_2 amounting to as much as 2.0 %.

The mineral generally occurs in the »druses» but it may also occur directly enclosed in the arsenopyrite. It is very seldom met with in the later veins and is consequently one of the earlier minerals.

Zircon is very rare and has been observed in a few cases only.

Besides quartz, calcite is the most common gangue component of the ore. Its appearance is very similar to that of quartz and it is found in breccias or in »druses», sometimes associated with a number of other minerals. Calcite may also occur in concentrations in the arsenopyrite ore, having a diameter of about 2 or 3 cm. In connection with these, thin fissures with calcite are seen to cut the ore. In these cases the mineral is probably a later generation, formed by late, hydrothermal solutions.

Apatite is also a typical mineral of the arsenopyrite ore and as is shown

by the analyses (p. 54) it is often quite common. In three of the analyses the amount varies between about 1.3 and 6.5 %, but in the other two analyses the amount is insignificant. It generally occurs in the »druses» but it is also found in later veins with quartz and calcite. Exceptional concentrations of apatite occur in some places (cf. p. 57). The mineral sometimes forms grains which still show the prismatic form, although they are always more or less corroded. The analyses of the ore and the analysis of the apatite ore (Stope 28, 250 m level; p. 60), which belongs to this stage, show that the mineral is fluor-apatite.

S v a n b e r g i t e(?). In several thin sections of the arsenopyrite ore a mineral was found which could not be definitely identified but which has been preliminarily determined as s v a n b e r g i t e, a phosphate with the composition $AlPO_4 \cdot SrSO_4 \cdot Al_2(OH)_6$. The mineral occurs in microscopic grains in the quartz or in the arsenopyrite. They tend to show a prismatic crystal form with a cleavage parallel to the elongation. The mineral is colourless under the microscope but often contains cloudy formations of an extremely fine-grained matter. The refringence is strong and of the same magnitude as that of apatite (1.65). The birefringence is comparable to that of quartz, or somewhat stronger. The mineral is generally uniaxial positive but some grains are biaxial with a very small optic angle. The extinction is parallel to the cleavage. The optical qualities remind of those of svanbergite but they are not sufficiently known to allow an accurate identification. A further support for the assumption that the mineral is svanbergite is the presence of 0.03 % of Sr in the analysis of apatite rock (p. 60) in which the mineral also occurs. A test did, however, not show any SO_3.

The occurrence of a n d a l u s i t e in the banded ore from the western end of the a-d-lens has already been described. Otherwise the mineral is not found in the ore.

A m p h i b o l e s are found in brecciating veins with the other minerals or they may occur in rounded aggregates in the arsenopyrite ore. The latter are very irregular and have been replaced by arsenopyrite. Some of the amphibole is thus older than that mineral but a later generation is also present in the veins. In hand specimens the mineral is faintly coloured but under the microscope it is colourless. The optic angle $2V_\alpha$ varies from 70—87° and the extinction $c : \gamma = 15—18°$. A determination of the refringence gave the following result:

$$\alpha = 1.625;\ \beta = 1.641;\ \gamma = 1.648\ (\pm 0.002)$$
$$\gamma - \alpha = 0.023$$
$$c:\ \gamma = 17°$$

In the later veins the amphibole often occurs together with quartz and calcite and is then frequently replaced by the latter mineral.

S e r i c i t e is common at the ends of the arsenopyrite bodies where they replace the sericite schist. In the normal ore it is sometimes found in the »druses» and is there a primary constituent of the ore.

Table 14.

Chemical composition of arsenopyrite ores.

Analyst: Th. Berggren (No. 17) and A. G. Hybinette (Nos. 18—21).

Analysis No.	17	18	19	20	21	Analysis No.	17	18	19	20	21
SiO_2 . . .	0.30	3.13	1.53	13.93	13.55	S	19.67	18.60	21.64	17.07	17.22
TiO_2 . . .	0.03	0.02	0.03	0.18	0.03	As	44.99	40.40	33.30	37.10	37.01
Al_2O_3 . . .	—	0.05	0.19	0.10	0.22	Cu	0.06	0.12	2.11	0.13	0.20
Fe	33.76	30.50	28.80	28.88	29.40	Pb	0.27	0.24	1.10	tr.	0.15
MnO . . .	—	0.02	tr.	0.01	0.02	Bi	0.13	0.04	0.07	0.04	0.06
CaO . . .	—	2.00	4.05	1.06	0.45	Ag	0.01	tr.	0.01	tr.	tr.
SrO . . .	—	tr.	tr.	tr.	tr.	Au	tr.	tr.	tr.	tr.	tr.
MgO . . .	—	0.04	0.05	0.04	0.03	Hg	—	nil	tr.	tr.	tr.
Na_2O . . .	—	0.01	tr.	tr.	0.02	Sn	—	tr.	tr.	tr.	tr.
K_2O . . .	—	0.46	0.52	0.47	0.50	Sb	0.33	0.40	0.85	0.11	0.35
$H_2O^{-105°}$ . .	—	0.04	0.04	0.01	0.04	Se	0.28	0.18	0.19	0.19	0.20
$H_2O^{+105°}$ . .	—	0.11	0.11	0.04	0.15	Te	nil	nil	tr.	0.02	0.01
BaO . . .	—	tr.	tr.	tr.	tr.	Co	0.15	1.86	2.50	0.12	0.10
Cl	—	nil	nil	nil	nil	Ni	nil	0.08	0.10	nil	nil
F	—	0.10	0.18	0.08	nil	Zn	nil	tr.	0.15	tr.	tr.
P_2O_5 . . .	—	1.58	2.70	0.55	tr.		99.98	100.00	100.26	100.16	99.96
CO_2 . . .	—	0.02	0.04	0.03	0.25	— O = F .		0.04	0.08	0.03	
ZrO_2 . . .	—	nil	nil	nil	nil			99.96	100.18	100.13	
Sp. gr. = .	5.99	5.50	5.33	4.91	4.99						

17. Dense arsenopyrite ore. Section 3, open pit.
18. Normal arsenopyrite ore. The e-lens, 50 m level.
19. Normal arsenopyrite ore, with chalcopyrite. The e-lens, 50 m level.
20. Normal arsenopyrite ore. Stope 25, 250 m level.
21. Normal arsenopyrite ore. Stope 13, 210 m level.

A faintly brownish mica has sometimes been seen in brecciating quartz veins. It is probably of a phlogopitic composition.

Chlorite is present in small flakes, generally in the brecciating veins but sometimes also in the »druses». The mineral is as a rule colourless but has occasionally a faint grayish green colour.

Basic plagioclase is sometimes present in »druses» or in quartz veins (Fig. c, Pl. 25). In most of the cases it must be considered to be a primary constituent of the paragenesis. The grains are small and are only indistinctly twinned and undulatory which makes a determination of the composition difficult. A number of measurements have been carried out and the composition is generally found to vary between 45 and 65 % An. In a few cases the An-content amounted to 80 %.

Tourmaline has been met with on some occasions, *e. g.* in the a-d-lens in Stope 25 (250 m level). It is here considered to be a later mineral, brought

in during the second stage. It has also been found in the a-d-lens between the 130 and 170 m levels. It cannot be determined in this case whether the mineral is primary or if it is of a later origin. The a-d-lens is on the whole very little influenced by later mineralizations — particularly in its deeper parts — and the tourmaline may here belong to the paragenesis.

T i t a n i t e is rare and has only been seen on a few occasions in »druses» or in later quartz veins.

Chemical Composition of the Arsenopyrite Ore.

In order to illustrate the chemical composition of the arsenopyrite ore one specimen of the dense type of ore and four specimens of the normal type have been analysed (Table 14).

Analysis No. 17 represents the dense type of ore and as is evident from the analysis it is a very pure arsenopyrite ore with few other components. Analysis No. 18 is of a normal type, which, however, likewise contains but few other components except arsenopyrite. Only some apatite, quartz, and sericite are noted, together with minor amounts of sulphides. The following three analyses are more typical of the normal ore. The content of As is smaller than in the former cases and the ores contain various ore and gangue minerals in comparatively large quantities. Apatite is quite common in No. 19, which, as No. 18, comes from the apatite-rich e-lens. The content of TiO_2 is unusually low in all the analysed specimens.

Mineral Associations connected with the Arsenopyrite Ore:

A. Rutile Rock.

Concentrations of rutile are found in several places in the mine, particularly, however, close to some of the arsenopyrite bodies. The content of rutile in the concentrations is very high and they form separate bodies which have been given the name rutile rock.

The rutile rock is best developed around the western portion of the arsenopyrite lens in Stope 28 where it forms lenses which with some breaks have been followed from the 250 up to the 210 m level (Pl. 8, Stope 28). Small lenses of rutile rock have also been noted in Stope 23 (130—170 m levels) and around the western end and in the footwall of the a-d-lens between the 170 and 210 m levels.

As a rule the rutile lenses occur in close relationship to the arsenopyrite ores and they seem to accumulate to the western and deeper parts of the ore bodies. This circumstance as well as the common occurrence of rutile in the arsenopyrite ore indicate a genetic relationship between the two formations and leads to the conclusion that the rutile rock is a differentiate from the same solution as the arsenopyrite ore. The objection can be made that rutile is also a common constituent of the second mineralization (cf. p. 94) and that conse-

quently the rutile rock may have been formed during that stage. The ultimate proof of the older age of the rutile rock lies, however, in the fact that rutile lenses have been cut by lamprophyric dykes, *e. g.* in Stope 28.[1]

Rutile also occurs as impregnations in the sericitic rocks, particularly in the sericite rock generally forming the wallrock of the rutile lenses. The andalusite rock is also sometimes impregnated with rutile, this being a further indication of this rock being earlier than the arsenopyrite mineralization.

The rutile rock in Stope 28 is best studied and will be described below (cf. Pl. 8).

The lens-shaped bodies of rutile rock are sharply delimited from the sericite rock although the ends of the lenses are somewhat fringed and contain remnants of the latter. The size of the lenses varies from 3 m in length and 0.5 m in width down to lenses only a few cm long and wide. They have an elongate, cigar-shaped form and dip parallel to the general pitch of the deposit, *i. e.* 55—60° E. Along this direction the lenses may have a length of 5—6 m.

The rutile rock is gray with a characteristic shade of brown and violet. Occasionally the rock may be very light-coloured. It is very fine-grained and its components are not identifiable with the naked eye. The unique character of the rock was not disclosed until a microscopic study had been made.

Rutile is the predominant constituent of the rock and as is shown by the analysis in Table 15 the content of TiO_2 runs as high as 62.16 %. The analysed sample is, however, extraordinarily rich in rutile and generally the amount of TiO_2 lies around 50—60 %. The rutile occurs in rounded, seldom elongate grains of an average size of 0.05—0.07 mm. The largest grains are about 0.2 mm in diameter. They are densely packed as shown by the microphotograph in Fig. a (Pl. 26). As a rule the mineral is dark-coloured and in strong light translucent with a violet to brownish yellow colour. In polished sections the dark varieties of the mineral have the qualities of an opaque mineral.

Among the gangue minerals present in the rutile rock we further note quartz, sericite, chlorite, svanbergite(?), and apatite, and occasionally also andalusite and tourmaline.

The quartz may occur as a fine-grained groundmass to the rutile but it is also found in veinlets. In these the svanbergite is present in unusually large grains. It is replaced by chlorite and rutile. The occurrence of svanbergite, a mineral typical of the arsenopyrite paragenesis, indicates that the quartz veinlets were formed during the arsenopyrite stage. They also contain some Bi-tellurides and gold but these were in all probability introduced during the second stage (see below).

Sericite and chlorite are present only in small quantities. The sericite constitutes remnants of replaced sericite rock.

Apatite, andalusite, and tourmaline are rare. Of these, the last-mentioned does not belong to the paragenesis. The andalusite should probably be considered

[1] This important observation was first made by Prof. Geijer on a visit to the mine in 1935.

as a replacement remnant, as also the andalusite rock is impregnated by rutile. Apatite is only present in some cases.

Ore minerals are sometimes plentiful in the rutile rock but only cobaltite is considered to be a primary component of the paragenesis. In some rutile lenses it forms a strong impregnation of rounded, porous grains, evenly mixed with the rutile. In some cases, *e. g.* in the analysed sample, the amount of cobaltite is very insignificant.

Among the ore minerals present in the rutile rock but introduced during the second stage, we note large masses of Bi-tellurides, gold, and sulphominerals (cf. p. 101). These minerals occur in fissures in the rutile lenses and as they also appear in fissures cutting the lamprophyric dykes, their later age is definitely proved.

A sample of rutile rock from Stope 28 (250 m level) has been analysed and the result is given in Table 15 below.

Table 15.

Analysis of rutile rock.

Analysis No. 22.

Analyst: Th. Berggren.

	%		%
SiO_2	27.46	Pb	0.16
TiO_2	62.16	Cu	tr.
Al_2O_3	2.22	Bi	1.49
Fe_2O_3	0.13	Sn	0.12
FeO	2.09	As	0.03
MnO	tr.	Ni	tr.
CaO	0.34	Co	tr.
MgO	0.01	S	0.10
Na_2O	0.17	Se	0.12
K_2O	0.81	Te	1.30
$H_2O^{-105°}$	0.10	W	tr.
$H_2O^{+105°}$	0.82	V	tr.
CO_2	nil	Ag	0.04
P_2O_5	0.21	Au	0.19
Sp. gr. = 3.50			100.07

22. Rutile rock. Stope 28, 250 m level.

B. Pyrite-Apatite Ore.

In the lower portions of Stope 28 (250 m level) concentrations of apatite were found in the arsenopyrite ore and as separate lenses in the wallrock, here consisting of sericite rock.

During the mining of the stope the concentrations of apatite were found

to increase towards the 210 m level and large lenses of massive apatite rock appeared. At about the 230 m level a change was noted, and pyrite, which had been plentiful also on the lower levels in the stope, began to appear in large quantities. Finally on the 210 m level the apatite ore had almost completely given way to lenses of massive pyrite (Pl. 8 and Fig. 7).

Also the pyrite-apatite ore must be looked upon as a derivative from the same ore solution as the arsenopyrite ore. On several occasions there was noted a regular transition from arsenopyrite ore rich in apatite to apatite rock, or to pyrite-apatite ore.

Immediately north of the combined arsenopyrite-pyrite-apatite ore there appears in the upper portions of the stope a lens of pyrite ore, belonging to the

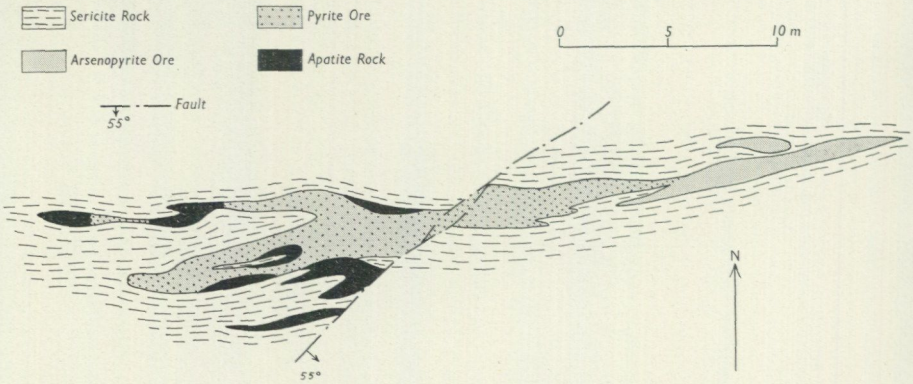

Fig. 7. Lenses of apatite rock and pyrite ore of the arsenopyrite stage. Stope 28, 225 m level.

t h i r d stage (Pl. 8). This ore penetrates into a pyritic apatite rock forming part of the main pyrite-apatite ore (Pl. 8) and is thus proved to be of a later age. The best proof is however supplied by the fact that this later pyrite ore contains brecciated remnants of lamprophyre of the second stage (Fig. 8). The pyrite-apatite ore is on the other hand cut by the same lamprophyre.

The illustrative but rather complicated conditions in Stope 28 thus show that the apatite rock belongs to the arsenopyrite stage of the ore deposition and that there is also a pyrite ore, with more or less apatite, belonging to the same stage.

It may finally be added that to the west the pyrite-apatite ore in the upper parts of the stope grades into an ore very rich in cobaltite. It has the same appearance both in specimens and under the microscope as the cobaltite-bearing arsenopyrite ore.

The lenses of apatite rock and pyrite-apatite ore have irregular outlines, as is evident from the maps (Pl. 8 and Fig. 7). In the upper parts of the stope, where the mainly pyritic ore occurs, the outlines of the ore body are smoother (Pl. 8, 213—215 m level). In spite of the irregularities in the outlines, the foliation of the sericite rock follows the ore very smoothly and the contacts are

on the whole sharp. Impregnations of apatite or pyrite are not seen in the wallrock.

The apatite rock is a massive, generally fine-grained, gray rock in which larger grains of apatite, quartz, and ore minerals are sometimes visible to the naked eye. The rock shows a striking resemblance to a gray leptite. In portions rich in pyrite a faint banding is noticeable. The apatite rock is cut by fissures filled with quartz, a brownish mica, Bi-tellurides, and a number of sulphominerals (including boulangerite). In most cases they belong to the second stage, as proved by the presence of Bi-tellurides.

Lenses and diffuse spots of apatite are mixed with the pyrite ore and the general impression obtained is that apatite crystallized earlier than pyrite.

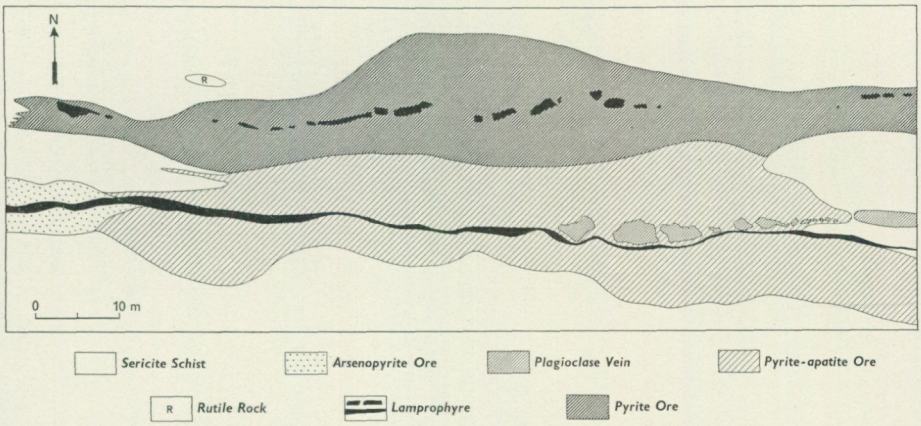

Fig. 8. Lens of pyrite-apatite ore of the arsenopyrite stage brecciating a plagioclase vein and cut by a lamprophyric dyke. The pyrite-apatite ore in the north borders on a pyrite ore of the third stage brecciating a lamprophyric dyke. Stope 28, abt. 210 m level.

Under the microscope the apatite rock is found to be composed of a dense mass of apatite grains (Fig. b, Pl. 26) some of which show crystal boundaries. As a rule the apatite crystals are better developed in the rock richer in quartz. They are corroded by the quartz and other minerals in the groundmass. Some of the grains have zonal inlayers of a submicroscopic dust. In exceptional cases the grains attain a size of 4—5 mm but the average size is only a few tenths of a mm. The content of apatite varies; the analysed sample contained about 78 %. A partial analysis of another sample showed only 52 %. The analyses further show that the mineral is a fluor-apatite.

Quartz makes up the main part of the groundmass between the apatite grains. Also sericite and chlorite occur in the groundmass and replace the apatite. A brownish mica has occasionally been found. Rutile is a rather common constituent of the groundmass but it is only rarely found in the apatite grains. Turbid grains of plagioclase were observed in some instances. An accurate determination could not be made because of its altered state but it seems to have an intermediate to basic composition. Zircon, titanite, svanbergite(?),

and tourmaline have been found in insignificant amounts. The latter mineral probably belongs to the second stage.

Polished sections of the apatite rock reveal a number of ore minerals probably belonging to the paragenesis (as mentioned above, those occurring in fissures were probably introduced during the second stage). Most common are arsenopyrite,[1] cobaltite, and pyrite. The two first-mentioned form good crystals which are enclosed both in the apatite and the groundmass. They may consequently be looked upon as early products of crystallization. Pyrite, on the other hand, does not seem to occur within the apatite and furthermore it grows around the two other minerals, indicating it to have been crystallized somewhat later. In addition some chalcopyrite, pyrrhotite, sphalerite, bournonite, and gold occur in the apatite rock. Gold is plentiful (cf. the analysis below with 0.12 % Au) and occurs as thin sheets on fissures in the rock or in microscopic grains interlocked in pyrrhotite and pyrite. In the former case the metal was probably introduced during a later stage.

Table 16.

Chemical composition of apatite rock.

Analysis No. 23.
Analyst: Th. Berggren.

	%		%
P_2O_5	33.15	Pb	1.74
SiO_2	15.67	Cu	0.22
TiO_2	0.15	Bi	0.24
Al_2O_3	0.26	As	0.40
Fe	0.94	Sb	0.69
MnO	0.05	Ni	tr.
CaO	42.85	Co	0.06
BaO	0.01	Zn	0.26
SrO	0.03	Mo	0.02
MgO	0.06	Se	0.14
Na_2O	0.15	Te	0.23
K_2O	0.06	S	0.97
$H_2O^{-105°}$	0.03	Ag	0.105
$H_2O^{+105°}$	0.10	Au	0.124
CO_2	0.08		101.44
Cl	tr.	$-O=F$	1.40
F	2.64		100.04
Sp. gr. = 3.13			

23. Apatite rock. Stope 28, 250 m level.

In the pyritic part of the ore the apatite is more seldom present and occurs mostly in the form of microscopic grains. In the transitional zone between the

[1] The statement in the preliminary paper on Boliden (65) that gudmundite occurred in this type of ore is erroneous, the mineral actually being arsenopyrite.

apatite rock and the pyritic ore, however, apatite is often found in spots or in schlieren. The pyritic ore is massive, rather fine-grained and sometimes slightly banded. It has a faint yellowish colour. When it occurs side by side with the pyrite ore of the third stage in the upper parts of the stope there is a notable difference as to shade of colour, structure, and mineral composition. The pyrite-apatite ore is lighter and on the whole more fine-grained than the normal pyrite ore. This is also banded but on the other hand contains schlieren of pyrrhotite, a mineral which is not visible to the naked eye in the pyrite-apatite ore.

Table 17.

Chemical composition of pyrite-apatite ore.

Analysis No. 24.

Analyst: Th. Berggren.

	%		%
SiO_2	3.11	Bi	0.01
TiO_2	0.02	Pb	0.01
Al_2O_3	0.52	Cu	0.08
Fe	43.28	Ni	0.01
MnO	tr.	Co	0.11
CaO	1.27	Zn	0.10
SrO	tr.	As	0.32
MgO	0.31	Sb	0.10
Na_2O	0.01	S	48.78
K_2O	0.09	Se	0.09
$H_2O^{-105°}$	0.13	Te	tr.
$H_2O^{+105°}$	0.22	Ag	tr.
P_2O_5	0.98	Au	tr.
F	0.09		99.70
CO_2	0.04		
Sp. gr. = 4.75			

24. Pyrite-apatite ore. Stope 28, 250 m level.

Besides pyrite, which is the predominant component of the ore, small amounts of chalcopyrite, pyrrhotite, sphalerite, arsenopyrite, and gold are also present. Among the gangue minerals we note quartz, which forms the groundmass, and some apatite, chlorite, sericite, titanite, svanbergite(?), and rutile. The apatite is partly idiomorphic but the grains are generally corroded by quartz and pyrite.

The crystallization of the pyrite-apatite ore seems to have begun with arsenopyrite and cobaltite, followed by the formation of apatite. The other minerals, including pyrite, are later.

In Table 16 the composition of the apatite rock is shown. Table 17 is an analysis of a specimen of pyrite-apatite ore from Stope 28.

Pyrite is the most prominent constituent of the latter ore. The content of apatite is rather insignificant but still it is considerably higher than in the pyrite ores of the third stage (p. 116). Also the content of Co is noteworthy as it is comparable to that of the arsenopyrite ores; in the pyrite ores of the third stage, on the other hand, cobalt occurs only in traces. Besides apatite, quartz is a conspicuous gangue component.

C. Apophysis in Stope 20 (90 m Level).

When describing the contact relations of the arsenopyrite ore the appearance of apophyses at the ore contacts was mentioned. Several of these have been encountered during the survey of the mine but only one has been studied in detail, the apophysis in Stope 20 on the 90 m level. The apophysis is here unusually large and has been mined in a special stope which offered good opportunities for a study of the geological conditions.

A prominent constituent of the apophysis in Stope 20 is falkmanite ($Pb_3Sb_2S_6$), a new sulphantimonite recently described by Ramdohr and the author in a joint paper (78). A detailed account of the geological and mineralogical relations of the apophysis was given in that paper, to which the reader is referred. In the following only a summary will be given, stating merely the most important facts about the apophysis. Its occurrence is illustrated in Figs. 9 and 10.

In Stope 20 on the 90 m level the ore consisted of normal arsenopyrite ore. Around section 8, where the apophysis started, the contact of the ore to the schist is somewhat undulating and the wallrock occasionally sharply folded. The ore only partly filled the folds and broke through their anticlinal parts (as seen from the ore) in a number of places, forming two types of apophyses. In most cases they are narrow veins of a simple composition, made up of mainly quartz, chalcopyrite, and pyrrhotite. The other type, consisting of one large apophysis, is made up of a coarse-grained mass of sulphominerals, quartz, and a large number of other minerals.

At the apophysis the arsenopyrite ore contains seams and streaks of sulphominerals, increasing in quantity towards the point where the apophysis leaves the ore. Under the first part of its course the apophysis contains strongly corroded inclusions of arsenopyrite ore, partly originating from the main ore body, but partly also from a lateral lens, cut by the apophysis. The apophysis has a max. length of about 12—14 m. The width varies considerably and is in some places only a few cm, in other places as much as 4—5 m. The apophysis has a very winding course and sends out ramifications as shown in the figures (Figs. 9 and 10). In the main it follows a fissure in the folded schist, sharply cutting the foliation. The schist is then often split parallel to the foliation planes by small veinlets of sulphominerals from the apophysis (Fig. 10). Inclusions of wallrock are found in the apophysis, generally with sharp edges and sometimes dislocated with their foliation in various directions. Some of the ramifications of the apophysis have the shape of gash veins. They attain a length of 1 m and are sometimes arranged in a series of *en échelon* bodies,

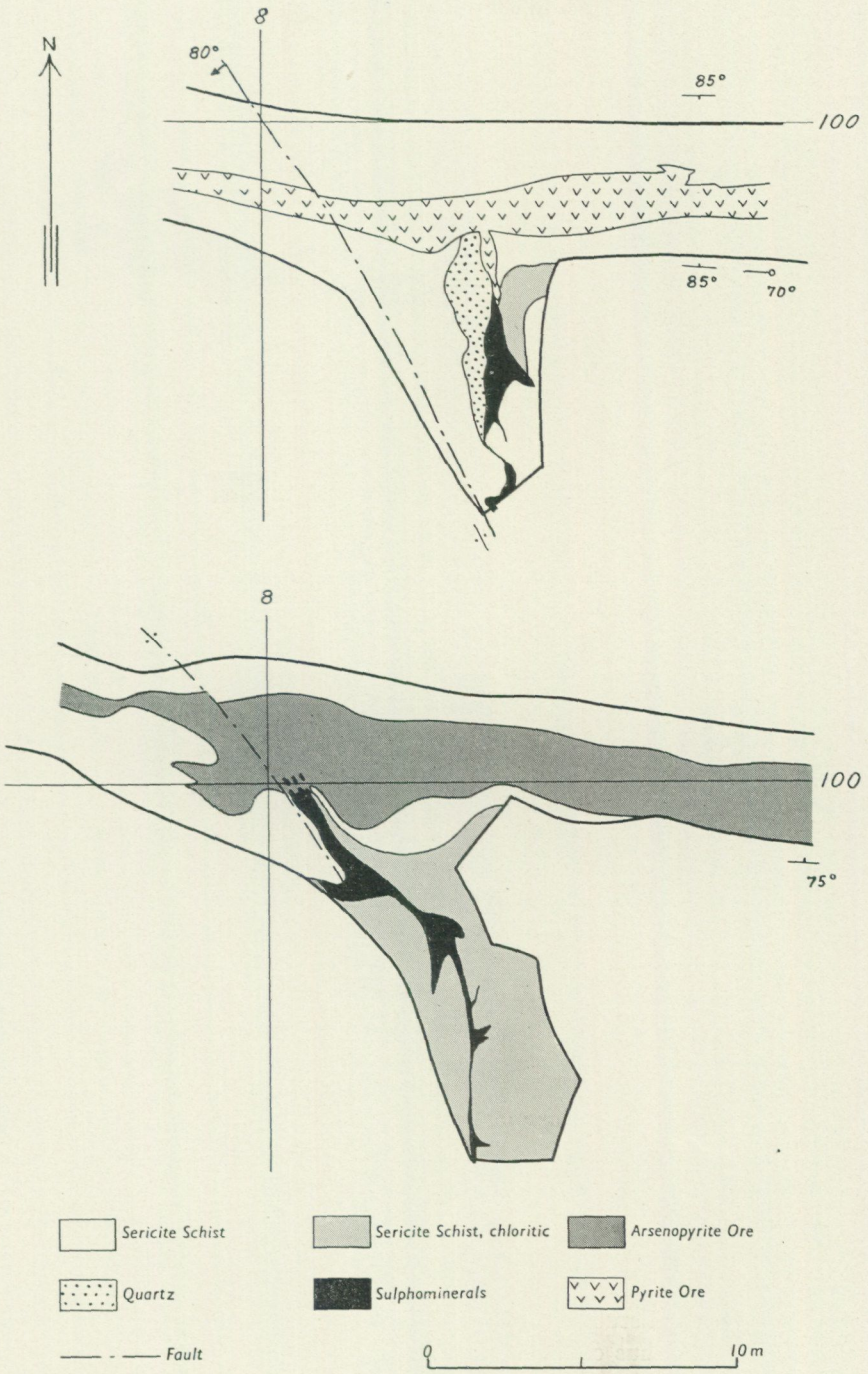

Fig. 9. Apophysis of sulphominerals and quartz emanating from arsenopyrite ore. In the upper figure pyrite ore cuts the apophysis. Stope 20, 90 m (below) and 69 m (above) level.

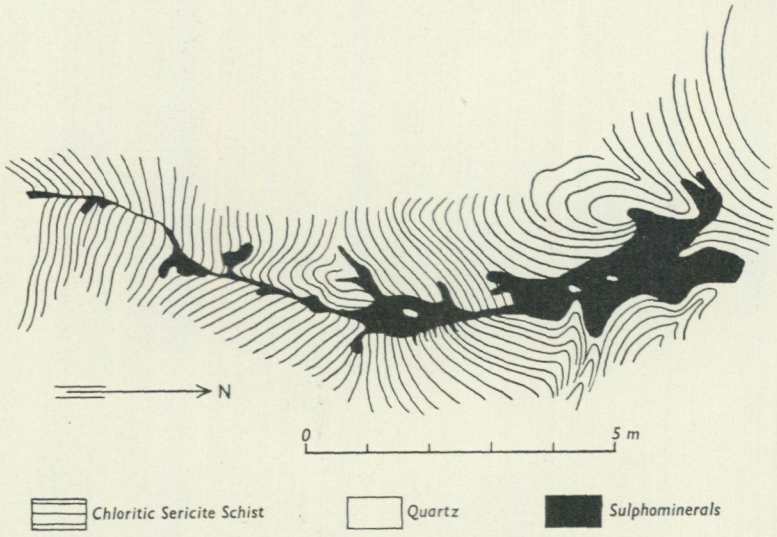

Fig. 10. Detail of apophysis. Stope 20, 78 m level.

filled with a coarse mass of sulphominerals. As in the main apophysis, they are intergrown to bundles which are sometimes arranged in rows parallel to the walls of the gash vein.

In the upper portions of the stope the apophysis and the adjoining ore change character. A pyrite ore here brecciates and replaces the arsenopyrite ore, which finally disappears. The pyrite ore was also found to brecciate the apophysis, the older age of the latter thus being proved. In the lower portions of the stope the apophysis contains small concentrations of quartz but higher up the content of this mineral increases until finally it is mainly composed of a grayish white, coarse quartz penetrated by a network of ore minerals.

The material of the apophysis is generally composed of max. 15 mm long and 10 mm broad, fibrous bundles of falkmanite, the predominant component of the lower portions of the apophysis. The ore is massive but sometimes a parallel arrangement of the falkmanite bundles is noted. In the narrow portions of the apophysis or in its terminal portions the ore is sometimes sheared, a fine-grained, almost mylonitic ore being developed. The coarse-grained ore has a steel-gray or bluish gray colour. A typical feature is the appearance of max. 15—20 mm long crystals of arsenopyrite, scattered throughout the ore. In the paper on falkmanite the arsenopyrite was erroneously called danaite. Two later analyses (Table 18) showed that the content of Co is far too small for danaite and the mineral should consequently be considered an arsenopyrite with a minor content of Co. Besides arsenopyrite, pyrite occasionally occurs in large crystals.

The microscopical study of the ore discloses that a large number of minerals are present. It is thus common to find 15—16 different minerals in one and the same polished section. The minerals identified are enumerated in Table 19[1] below (78, p. 336).

[1] The occurrence of antimony, stated in (78), is rather dubious and the mineral has here been omitted.

Table 18.

Analyses of arsenopyrite from falkmanite ore.

Analysis No.	25	26
Fe	34.41	32.5
As	42.28	40.1
S	21.43	21.6
Co	0.07	0.5
Ni	nil	—
Sb	0.18	3.8
Cu	0.04	0.2
Bi	0.03	0.1
Pb	0.22	1.7
Se	0.07	—
Ins.	1.06	0.3
	99.79	100.8
Sp. gr. = 5.903		

25. Arsenopyrite. Stope 20, 90 m level. Analyst: Th. Berggren.
26. Arsenopyrite. Stope 20, 90 m level. Analyst: A. G. Hybinette.

The oldest products of crystallization are arsenopyrite and pyrite, and they are replaced by all the other minerals, delicate replacement textures sometimes being formed. The other minerals form some very intricate intergrowths, which have been described in the paper cited above. Falkmanite is the most conspicuous component of those intergrowths and is replaced along the cleavage by galena, bournonite, bismuth, tetrahedrite, and chalcopyrite (Fig. a, Pl. 27). Delicate reaction rims with complex textures were formed during the replacement (cf. Plates 19, 21, and 22 in (78)). Pyrargyrite and arsenic, otherwise rare or absent, have been formed during reactions between the older minerals and a residual solution.

Table 19.

Paragenesis of Arsenopyrite Ore	Paragenesis of Apophysis		
	Older	Later	
		Common	Rare
Arsenopyrite	Arsenopyrite	Falkmanite	Pyrrhotite
Pyrite	Pyrite	Galena	Chalcopyrite
Sphalerite		Bournonite	Sphalerite
Pyrrhotite		Tetrahedrite	Arsenopyrite
Chalcopyrite		Bismuth	Pyrargyrite
Valleriite		Gudmundite	Gold
Cubanite		Jamesonite	Arsenic

In Table 20 below one analysis of falkmanite from the type locality Bayerland in Germany (78) and one of falkmanite ore from the apophysis described above have been placed together for the sake of comparison.

Table 20.

Analyses of falkmanite and falkmanite ore.

Analyst: Th. Berggren.

Analysis No.	27	28	Analysis No.	27	28
Pb	52.97	58.43	Fe	0.50	0.73
Sb	22.48	16.68	Ni	nil	—
Bi	1.16	3.67	Co	nil	—
Cu	1.52	0.20	Zn	nil	nil
S	19.32	17.93	Ag	0.002	0.062
Te	nil	tr.[1]	Au	< 0.001	0.004
Se	0.42	1.22	Insol.	0.56	0.68
As	1.00	0.33		99.93	99.93
Sp. gr. =	6.195	6.293			

27. Falkmanite. Bayerland Mine, Germany. (78, p. 320).
28. Falkmanite ore. Stope 20, 90 m level. (78, p. 320).

D. Felspathization and Felspar Veins.

At the contacts to the arsenopyrite ore the sericite schist has frequently been felspathized by the action of emanations from the ore solution. The phenomenon has been encountered in the walls of the a-d-lens, of the k-lens, and in other places. The pyrite ore is also followed by a similar felspathization (p. 123) and it may be difficult to distinguish the two. In the cases referred to above the felspar has been impregnated with arsenopyrite, thus indicating that it was formed during the arsenopyrite stage.

The felspar is in all cases a rather basic plagioclase and it is found either in a normal sericite schist or in a massive, non-sericitized rock, resembling the unaltered volcanics.

In the former case the plagioclase forms rounded aggregates, several mm in diameter, and is often accumulated to large masses, with their reflecting felspar faces reminding of an eruptive rock. Under the microscope the plagioclase is found to replace the surrounding mass of sericite and quartz. The mineral grows in distinct spherulitic or rosette-shaped aggregates (Fig. a, Pl. 28). The plagioclase is as a rule fresh but shows a beginning alteration, resulting in the formation of sericite, chlorite, and calcite. Twinning is rarely present and in polarized light the mineral becomes spotty and undulatory. A determination of the composition showed that the mineral varies between a labradorite with 65 % An and a basic bytownite[2]. On one occasion the content of An was only

[1] In (78, p. 320) erroneously 5.28 %!

[2] In view of the inaccuracy of the optic determination, basic plagioclases with more than 85 % An have been classified acc. to the mineralogical terminology and not acc. to the An-percentage.

30 %. Together with the plagioclase we also note some quartz, rutile, apatite, zircon, ore minerals, and svanbergite(?).

The other type of felspathized rock is not easy to classify and does not resemble any of the ordinary wallrocks of the deposit. The rock is on some occasions found in close vicinity to slightly altered volcanics and it is believed that it was formed by a felspathization of these rocks. Also in this case the plagioclase is very basic and varies in composition from 60 % An up to almost pure anorthite, according to measurements on the universal stage. The mineral forms spherulitic aggregates or completely irregular masses. The plagioclase is often clear but also shows a beginning alteration. Besides plagioclase the rock contains small quantities of quartz, apatite, a colourless hornblende, rutile, and titanite.

Vein-like formations, mainly composed of basic plagioclase, have been found in the vicinity of the ore body in Stope 28 between the 210 and 250 m levels. They occur in lenses, sometimes arranged in a vein-like manner. As a rule they are only a few dm long and 1—2 dm wide. On a few occasions they have been cut by lamprophyric dykes which indicates that they belong to the older arsenopyrite stage. Furthermore they are brecciated by the pyrite-apatite ore (Fig. 8, p. 59) which places their origin during the arsenopyrite stage practically beyond doubt.

Table 21.

Chemical composition of plagioclase vein.

Analysis No. 29.

Analyst: Th. Berggren.

	%		%
SiO_2	54.82	K_2O	0.67
TiO_2	0.82	$H_2O^{-105°}$	0.14
Al_2O_3	24.56	$H_2O^{+105°}$	0.93
Fe_2O_3	0.51	P_2O_5	1.06
FeO	0.68	F	0.06
MnO	0.03	Cl	0.02
CaO	9.78	CO_2	0.49
BaO	nil	FeS	0.08
MgO	1.33	FeS_2	0.78
Na_2O	3.42		100.18
Sp. gr. = 2.72		Or : Ab : An = 5.5 : 40.5 : 54.0	

29. Plagioclase vein. Section 12, 210 m level.

The rock in the veins is massive and gray or grayish red. It is rather coarse-grained and with its fresh and coarse plagioclase resembles certain eruptive rocks.

The plagioclase individuals attain a size of 4—5 mm and predominate the rock. They are often spherulitic or grow in feather-shaped aggregates. The

interstices between the spherulites are filled with irregular aggregates of the same plagioclase. Cleavage and twinning are rarely present. The plagioclase is generally fresh, although a weak alteration is noted. The composition of the mineral is very basic and it varies from labradorite with 50 % An to basic bytownite.

Among the other components of the rock we note a small amount of quartz, some sericite, chlorite, and a faintly coloured hornblende. In the analysed sample apatite is common. In one thin section titanite was plentiful. Occasional grains of rutile and calcite have also been noted.

The chemical composition of one of the lens-shaped veins is shown in Table 21 on p. 67.

Disseminated Ore.

Although it has been stated that the wallrock of the arsenopyrite ore is often free from disseminated sulphides, impregnations do occur in a number of places. A large area of valuable disseminated ore occurs at the eastern end of the Eastern Ore and other portions of such ore have been met with on the 210 and 250 m levels.

Also the two following stages of the ore deposition are accompanied by zones with disseminated sulphides, particularly the pyrite stage, and there is thus a certain risk that the disseminated ores of the different stages intermix and render a distinction impossible. As regards the disseminated ores of the arsenopyrite stage, the rule followed has been that as soon as an ore contains arsenopyrite it has been considered to belong to that stage.

The rock in the disseminated ore is a sericite schist, often more or less silicified and sometimes showing quartz phenocrysts. The silicification is connected with the impregnation, this being evident for instance around section 17 on the 210 m level where the schist has been transformed to an almost jaspilitic, dense rock with impregnations and veinlets of arsenopyrite (Fig. b, Pl. 27). The quartz-porphyritic disseminated ore is dark-gray and the blue quartz eyes stand out well against the impregnation of arsenopyrite. They are often quite intact and show but a faint undulatory extinction. In some places the disseminated ore also contains chlorite which gives the rock a greenish colour.

The ore minerals are as a rule irregularly disseminated throughout the rock but sometimes they accumulate to veinlets which brecciate the schist (Fig. b, Pl. 27). Some of the minerals, *e. g.* arsenopyrite and chalcopyrite, may occur in separate lenses.

The most common constituents of the disseminated ore are arsenopyrite, chalcopyrite, pyrrhotite, pyrite, sphalerite, and sulphominerals. Among the gangue minerals brought in during the formation of the disseminated ore we note quartz, felspar (cf. above), chlorite, and occasionally some calcite.

Summary; Order of Crystallization.

During the arsenopyrite stage a number of different mineral associations were formed, all more or less obviously connected with the arsenopyrite ore, which from a quantitative point of view is the most important of them all.

Several types of arsenopyrite ore have been distinguished and there is evidently some difference in age between them. The quartz-banded type thus brecciates the normal ore and the cobaltite-bearing type is accumulated toward the margins of the bodies of normal ore, indicating a somewhat later crystallization. Further, the apatite-banded ore is brecciated by the normal ore. The dense ore contains indistinct inclusions of the same type of ore. The apatite-banded and dense types are probably the oldest and are followed by the normal ore. The quartz-banded and cobaltite-bearing types were probably formed somewhat later than the others. The circumstances related indicate that the formation took place under the influence of complicated processes of crystallization and tectonic disturbances.

The genetic connection between the rutile rock, the pyrite-apatite ore, the apophyses, and the plagioclase veins, on the one hand, and the arsenopyrite ore on the other, has already been discussed and the following is only a summary of the facts. Most of the associations mentioned above are more or less intimately linked with the arsenopyrite ore in Stope 28. The pyrite-apatite ore, including also some cobaltite ore, is a direct continuation of the arsenopyrite ore. The rutile rock forms lenses at the side of the ore and the paragenesis indicates intimate relations between them. That the rutile rock belongs to this stage is best shown by the fact that it is cut by lamprophyres. Also the plagioclase veins seem to be closely related to the arsenopyrite ore. All the associations mentioned are now considered to have been formed by emanations from the crystallizing arsenopyrite ore solution.

Also the veins and apophyses with sulphominerals, *e. g.* the apophysis from Stope 20, are genetically closely related to the arsenopyrite ore and it is believed that they also represent differentiates from the arsenopyrite ore solution (78, p. 343).

Even if the above associations thus may be looked upon as belonging to the arsenopyrite stage there still remains the question as to their mutual age relations. They only seldom, in some cases never, seem to come into contact with each other and it has not been possible to ascertain the sequence of formation in detail (see below).

As regards the interpretation of the order of crystallization within the arsenopyrite ore proper and its different mineral associations great difficulties are encountered, this in view of the number of associations, the large number of minerals present, and the often very complicated relations between the minerals. It has not been possible to follow the sequence in detail but an endeavour has been made below to divide the mineral constituents of the ores into certain groups and to establish the sequence between these groups. The division does not imply that a time interval existed between the groups; on the contrary, the crystallization has been a continuous process and the groups pass gradually into each other.

It can probably not be doubted but that the main portion of the arsenopyrite crystallized at an early date, as it is everywhere brecciated by a large number of minerals. Rutile generally fills »druses» but some grains of the mineral

occur in a manner indicating that it was formed during the crystallization of the arsenopyrite. Also part of the hornblende crystallized at this stage. The first group of early crystallizing minerals would consequently comprise most of the arsenopyrite, some rutile, and hornblende.

The next group is very extensive and contains a large number of minerals, characterized by their appearance in »druses» and brecciating veins. The crystallization was extended over a comparatively long period of time and was disturbed by tectonic movements, causing a brecciation of the arsenopyrite ore. Replacement and recrystallization distinguish this group, and the relations between the minerals are often very complicated. Rutile is typical of the group. Quartz, apatite, plagioclase, Fe-Cu-sulphides, and sphalerite are also characteristic minerals. Rutile and apatite crystallized early, the latter in particular being corroded by quartz and ore minerals. Pyrite, pyrrhotite, and sphalerite are among the earlier minerals, while chalcopyrite is later and partly enters the residual solution. The same is true of the quartz which in part crystallized before the ore minerals but which to a large degree also remains in solution.

At this point it is convenient to discuss the age relationships of the other mineral associations connected with the arsenopyrite ore.

The date of formation of the rutile rock is difficult to fix. The main part of the rutile in the arsenopyrite ore crystallized early in the second group, which may indicate that the separation of the rutile rock took place at an early date during the formation of the arsenopyrite ore, perhaps already in the first group.

A dating of the formation of the plagioclase veins is also difficult. The plagioclase in the ore crystallizes in the second group. The felspar in the wallrock is sometimes impregnated with arsenopyrite and it thus seems probable that the separation of the plagioclase solution occurred already before the crystallization of the minerals of the second group. This is further indicated by the fact that the veins have been brecciated by the pyrite ore occurring in association with the pyrite-apatite ore (see below).

The pyrite-apatite ore appears as a direct continuation of the arsenopyrite ore in Stope 28. The components of the ore are typical for the second group, although the proportions are quite different, and it seems likely that the ore is the result of a local concentration of minerals of the second group and that it was formed simultaneously with that group.

The crystallization of the minerals of the second group finally grades into the formation of the last group. Prominent components are here particularly Pb-Sb-minerals and also some copper-minerals, as chalcopyrite and tetrahedrite. Some of these minerals appear even in the »druses», but at the same time they attack and replace earlier minerals. Complex processes of replacement and reaction between earlier minerals and the residual solution characterize this group. The tectonic disturbances continued with the brecciation of the arsenopyrite ore and with the formation of apophyses. Among the gangue

minerals quartz is the most prominent, but also chlorite, sericite, and calcite form. Among the ore minerals we note tetrahedrite, jamesonite, falkmanite, bournonite, galena, chalcopyrite, and others. Well developed crystals of arsenopyrite and pyrite are also typical for this stage. The formation of galena, bournonite, and bismuth closes this long and complicated process. The minerals of the third group are best represented by the apophyses which emanate from the arsenopyrite ore but most of them are also found in brecciating veinlets.

The formation of the disseminated ore cannot be ascribed to any particular phase of the crystallization. Its formation was probably a fairly continuous process which went on throughout the crystallization. Among the constituents of the disseminated ore we note minerals crystallizing even so early as arsenopyrite.

Lamprophyric Dykes with Quartz-Tourmaline and Sulphide Ores.

A. The Lamprophyres.

General.

The second stage of mineralization is characterized by the appearance of altered basic dykes, here called lamprophyres, and of quartz-tourmaline ores closely connected with them, occasionally also by the appearance of sulphide ores.

Lamprophyres are met with on all levels in the mine but in most cases they are confined to the central zone of mineralization or to the surrounding area of altered rocks. In the western part of the deposit they are scarcer and have not been found above the 170 m level. They also seem to be rare in the unaltered rocks outside the altered zone but this may be but ostensibly true as the areas of unaltered rocks are generally very little known.

The lamprophyres occur in narrow but well-defined dykes, which, although they are sometimes arranged *en échelon*, may be continuous up to 280 m (cf. Pl. 7). As a rule, however, they are not as long as that. They are best seen on the 210 and 250 m levels where they cut sericitic rocks. On the higher levels they are mostly found in the pyrite ores where they occur in the shape of inclusions. It is quite common for the dykes to appear in pairs as will be seen from the plans of the 130, 210, and 250 m levels (Pl. 4, 6, and 7).

A detailed study of the dykes shows that in places they have an irregular appearance. *En échelon* arrangement, sometimes repeated several times, is common and the dykes are occasionally twisted and folded (Fig. b, Pl. 28).

As a rule the contacts to the walls are well defined, no matter whether they are composed of sericite schist or of ore. Certain exceptions from this rule are known from the pyrite ore (cf. p. 109), which replaces and brecciates the dykes.

The dykes are generally narrow, attaining a width of 2—3 dm. In exceptional cases dykes 0.5—1.0 m wide have been encountered.

They generally strike parallel to the foliation but on certain occasions a deviation of a few degrees to the left is noted and the dykes cut the foliation at oblique angles. The foliation of the dyke is, however, parallel to the foliation of the surrounding schist, indicating an action of deformational forces after the intrusion of the dykes.

The dykes generally dip to the north at an angle of about 70°. On the deeper levels, where the dip of the wallrocks is to the north, the dykes generally dip parallel to the foliation or at a slightly smaller angle.

It is often impossible to correlate the dykes between the levels (except in the stopes, where they have been followed practically every metre), owing to the irregularities in the dykes, mentioned above.

Towards the ends of the dykes a profound change often takes place. Along their walls thin seams of mariposite (see p. 75) develop, which gradually widen out at the expense of the lamprophyre until finally the lamprophyre has disappeared and the dyke continues as a dyke of mariposite. Such mariposite dykes have been encountered on several occasions and they can be followed for several metres. In their appearance they behave in about the same manner as the lamprophyres. In one case (in section 11, 250 m level, Pl. 7) a mariposite dyke was seen cutting andalusite rock, a circumstance of interest when endeavouring to date this rock.

Relations to the Arsenopyrite Ore.

On several occasions, especially in Stopes 24, 25, and 28, the lamprophyres have been found sharply cutting the arsenopyrite ore (Fig. a, Pl. 29). Certain details in the appearance of the dykes in the ore are of interest and will be discussed below.

As soon as a dyke enters an arsenopyrite body it deviates from its former course parallel or slightly oblique to the foliation of the wallrock and turns to the left. The deviation may be as large as 30°. Upon leaving the ore body, the dyke at once resumes its earlier direction. This deviation in the direction of the lamprophyres has been seen in Stopes 24 and 25 (Fig. 11) and it has also been observed in arsenopyrite bodies enclosed in the pyrite ore (Fig. 12).

In cases where the dykes cut only marginal portions or local thickenings of an ore body, *e. g.* in some parts of Stopes 25 and 28, the deviation does not take place. The same is true of minor lateral lenses which have not exercised any influence on the direction of the dykes.

The deviation of the dykes is controlled by the difference in resistance to rupture existing between the arsenopyrite ore and the surrounding schists. Using a term introduced by Knopf when describing the deviation of the gold-quartz veins of the Mother Lode in California (48, p. 24), one might speak of the r e f r a c t i o n of the dykes. In the Mother Lode the refraction is greatest when the veins pass from black slate to massive greenstone.

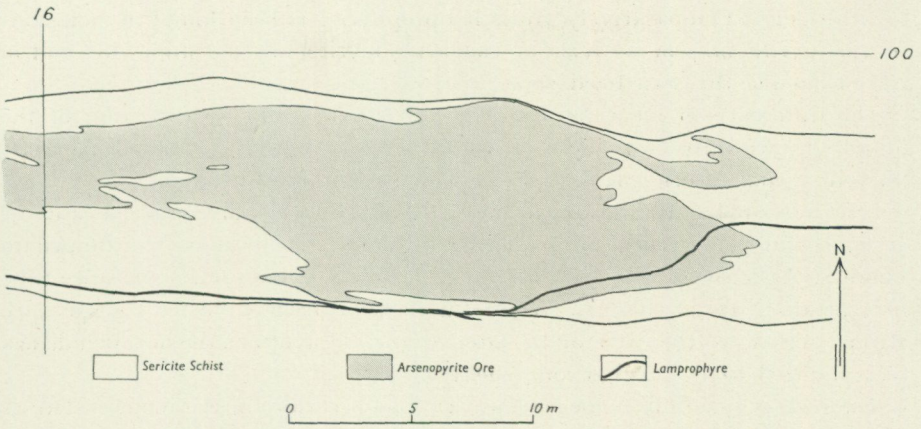

Fig. 11. Deviation of a lamprophyre when cutting arsenopyrite ore. Stope 25, 231 m level.

On some few occasions lamprophyres cutting arsenopyrite ore are broken, giving the impression that the dykes have been brecciated by the ore and that consequently they are older. Such breaks have been noted in Stope 28 and on two or three other occasions. Sometimes it is quite clear that faults have caused the breaks. In other cases the breaks are filled with sulphominerals, coarse pyrite, and sometimes even with arsenopyrite ore. The sulphominerals present are typical of the quartz-tourmaline veins and they were certainly brought in during later disturbances, accompanying the formation of the quartz-tourmaline veins. Actually, the breaks should probably be compared with the gash veins developed in the lamprophyres (cf. p. 78). During the movements that dislo-

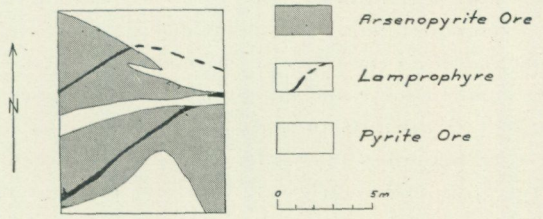

Fig. 12. Deviation of a lamprophyric dyke cutting arsenopyrite ore, enclosed in pyrite ore. Stope 3, 130 m level. (Fig. 6 in (65)).

cated the dykes and during the infilling of sulphominerals it is also quite possible that pieces of arsenopyrite ore were brought in. This may also have happened during the intrusion of the dykes and the pieces of arsenopyrite ore may have been caught in such positions as to indicate a break in the dyke. There is consequently no reason to doubt the opinion expressed above and in the earlier paper (65) that the dykes really are later than the arsenopyrite ore.

Petrographic Description.

The lamprophyres are always more or less altered and no quite fresh form has ever been encountered. They are most altered in the central part of the ore-

bearing zone. Comparatively fresh lamprophyre has been found in inclusions in the pyrite ore, in a dyke in the arsenopyrite ore in Stope 28, and in dykes outside the sericitized zone.

The difference in metamorphism serves as a basis for the division of the lamprophyres into two types: hornblende lamprophyre — the one least altered — and chloritic lamprophyre, which is the most altered type.

Hornblende lamprophyre. This rock is massive and has a dark-green colour. The rock is dominated by a fibrous hornblende arranged in bundles. As a rule the bundles are only a few mm long but sometimes they may attain a size of 2—3 cm. Where the rock has been subjected to especially strong action on the part of the later pyritic ore solutions the hornblende has recrystallized to 15—20 cm long sheaves.

The rock is generally homogeneous. On one occasion, in the main east drift on the 410 m level, it carried 3—4 cm broad marginal zones of biotite. Also the lamprophyre cutting the arsenopyrite ore in Stope 28 had thin marginal zones, in this case, however, mainly composed of fine-grained basic plagioclase.

The hornblende lamprophyre is mainly distributed in the unaltered rocks in the deposit, *e. g.* in the main east drifts on the 130, 170, and 410 m levels (Pl. 4 and 5), but it has frequently been encountered also in the pyrite ore of the Eastern Ore and in Stope 28 (250 m level).

In the latter place the lamprophyre cuts the arsenopyrite ore in a well-defined dyke. Also chloritic lamprophyre is present and it was found how the hornblende lamprophyre within a distance of about one metre passed over into the chloritic type by the gradual appearance of chlorite at the expense of hornblende in the hornblende lamprophyre.

Under the microscope the hornblende lamprophyre is found to be dominated by lobate and ragged individuals of hornblende (Fig. a, Pl. 30). Between them, or enclosed in them, we find the other constituents of the rock. The texture is evidently of a secondary nature and among the minerals present only the plagioclase may be looked upon as primary.

The hornblende is colourless or faintly greenish. A weak pleochroism in α = yellowish gray, β = yellowish green, and γ = grass green, is sometimes noticed. The extinction $c : \gamma = 15—18°$, and the optic angle $-2V$ varies between 70° and 82°. The indices of refraction are:

$$\alpha = 1.628; \quad \beta = 1.641; \quad \gamma = 1.653 \ (\pm 0.002)$$
$$\gamma - \alpha = 0.025.$$

The appearance of the mineral seems to indicate a uralitic hornblende. The mineral is replaced by chlorite, calcite, and ore minerals.

Biotite is rare and has been observed only in a few thin sections of lamprophyre, occurring in the unaltered rocks. One of the sections came from the lamprophyre with the marginal zone of biotite. Here the mineral forms a felt of subparallel flakes which replace the few grains of hornblende present. In other cases the biotite is only sparsely present and is formed in the hornblende grains.

The plagioclase is a characteristic component. Generally it occurs in irregular, microscopic grains together with quartz, interspersed between the hornblende grains, but in the marginal zones of the lamprophyre in Stope 28 it forms a fine-grained, brownish gray rock.

The zone is narrow, only 2—3 cm wide, and grades successively into the normal hornblende lamprophyre in the centre of the dyke. Besides plagioclase also scattered grains of hornblende are present. The plagioclase grains are small and the twinning is very irregular, sometimes lacking.

The composition of the mineral varies between 65 and 70 % An, values as high as 85 % having been found. The mineral has the same composition in the marginal zone as in the normal hornblende lamprophyre. The irregular shape of the grains indicates that the mineral has gone through a process of recrystallization.

Quartz is as a rule present but only in small quantities. Calcite is formed during the chloritization of the hornblende but also occurs in veinlets, replacing hornblende and cutting most of the other minerals. Zoisite and apatite are present in small quantities. Instead of rutile, which occurs in the chloritic type, titanite is here present. Ore minerals are sometimes present and we particularly note pyrite and chalcopyrite.

Chloritic lamprophyre. The rock is well foliated although as a rule not so well as the sericitic rocks. It is dark-green or grayish green. Chlorite and quartz are visible to the naked eye, and occasionally also mariposite, sericite, biotite, tourmaline, and sulphides are noticed. Grains of bluish quartz, about 4—5 mm in diameter, are spread erratically in the rock.

The microscopic study shows that the alteration is strong and that no primary features are left in the rock, except turbid remnants of plagioclase in two cases. Chlorite is the predominant mineral and occurs in parallel streaks or bands, or, as sometimes happens, in a felty mass of small flakes (Fig. b, Pl. 29). Along the margins of the dykes the chlorite may be especially plentiful. The quartz is scattered among the flakes of chlorite, either in separate grains or in fine-grained aggregates.

Under the microscope the chlorite is faintly grayish green and practically lacks pleochroism. The quartz grains are often somewhat elongate and more or less undulatory. The large, bluish quartz grains have the appearance of phenocrysts, but the assumption does not seem very likely in view of the basic composition of the less altered types of the lamprophyres. It may be more likely that they form quartz-filled amygdules.

In two cases remnants of plagioclase have been seen. The mineral is turbid and shows some alteration. The composition is approximately that of bytownite.

Among the accessory minerals the chromiferous mica mariposite is of particular interest. A small percentage of Cr is noted in one of the hornblende lamprophyres (cf. analyses on p. 77) without any mariposite ever being found, but in the chloritic lamprophyre this mineral is fairly wide-spread. It occurs in »books», sometimes attaining a diameter of 1 cm, irregularly scattered throughout the rock. Under the microscope the »books» are found to be poiki-

litically intergrown with quartz. They are evidently of the character of porphyroblasts. As shown in Fig. b (Pl. 29) the scales of mariposite are developed independent of the foliation of the rock, indicating that the mineral was formed subsequent to the foliation. The occurrence of mariposite as margins to the lamprophyre dykes or as separate dykes has already been mentioned. The mineral is in these cases very fine-grained and forms a felt of small micaceous scales.

A partial analysis of fine-grained mariposite from a dyke on the 250 m level gave the following result (Table 22). For the sake of comparison an excerpt is given from an analysis by Hillebrand, quoted by H. W. Turner (95, p. 679), of mariposite from Josephine Mine, Bear Valley in the Mother Lode.

Table 22.

Partial analyses of mariposite.

Analysis No.	30	31
Cr_2O_3	0.54	0.18
K_2O	8.17	9.29
Na_2O	1.96	[1] 0.12
Li_2O	tr.	—
V	nil	—
		Sp. gr. = 2.817

30. Mariposite. Section 11, 250 m level. Analyst: Th. Berggren.
31. Mariposite. Josephine Mine, Bear Valley, Calif. Analyst: W. F. Hillebrand (95).

The optic angle (— 2V) was measured in a number of cases and was found to vary from 38—45.5°. Larsen and Berman (51, pp. 171 and 238), however, state the optic angle to be $\pm$ 0°. The mineral, which in hand specimens is very bright green, is practically colourless and non-pleochroitic in thin sections of normal thickness. Turner (95, p. 678) also found the mariposite to be non-pleochroitic. The birefringence is high and of the same order as that of sericite.

Sericite sometimes has an appearance similar to that of mariposite but on the whole it is but seldom present. The optic angle is larger than that of mariposite and as a mean value of four determinations — 2V was found to be 46.7°. Faintly coloured biotite is rare and has been seen only on a few occasions in thin zones at the margins of the dykes.

In the lamprophyres tourmaline is occasionally met with either in the form of slender needles or as coarser aggregates resembling porphyroblasts. The mineral is only faintly coloured, its pleochroism being ε = colourless and ω = light yellowish brown.

Andalusite, apatite, calcite, rutile, zoisite, and zircon occur more seldom.

Ore minerals are occasionally present and we note *e. g.* crystals of arsenopyrite and pyrite. A strong impregnation of later sulphides is common in the places where the lamprophyre comes into contact with the pyrite ore.

[1] Includes Li_2O.

Chemical Composition of the Lamprophyres.

In order to elucidate the variations in the chemical composition of the lamprophyres four analyses have been made (Tables 23—25 below).

Table 23.

Analyses of hornblende lamprophyres.

Analyst: Th. Berggren.

Analysis No. 32				Analysis No. 33			
	%	Mol. prop. × 1000	Norm		%	Mol. prop. × 1000	Norm
SiO_2	42.67	711	Q 1.56	SiO_2	47.70	794	Or 2.78
TiO_2	0.71	9	Or 0.56	TiO_2	0.66	8	Ab 6.82
Al_2O_3	16.77	165	Ab 4.72	Al_2O_3	11.94	117	An 27.54
Cr_2O_3	0.10	1	An 43.11	Cr_2O_3	nil	—	sal = 37.14
Fe_2O_3	4.77	30	sal = 49.95	Fe_2O_3	1.37	9	
FeO	3.35	47		FeO	7.72	108	Di 24.02
MnO	0.38	5	Di 10.02	MnO	0.73	10	Hy 27.94
CaO	11.57	206	Hy 22.70	CaO	13.24	236	Ol 2.51
BaO	nil	—	Mt 6.95	BaO	—	—	Il 1.21
MgO	10.37	257	Cm 0.22	MgO	11.92	296	Ap 0.67
Na_2O	0.56	9	Il 1.37	Na_2O	0.80	13	Mt 2.08
K_2O	0.13	1	Fr 0.23	K_2O	0.48	5	Fr 0.16
$H_2O^{-105°}$	0.15	—	Sulph. 5.09	$H_2O^{-105°}$	0.05	—	Sulph. 0.93
$H_2O^{+105°}$	3.33	—	fem = 46.58	$H_2O^{+105°}$	0.87	—	fem = 59.52
F	0.10	5	$H_2O^{+105°}$ 3.33	F	0.08	4	$H_2O^{+105°}$ 0.87
CO_2	0.10	2	Cc 0.20	CO_2	0.98	22	Cc 2.20
P_2O_5	0.02	—	100.06	P_2O_5	0.22	2	99.73
$CuFeS_2$	1.06	—	III; 5; 5; 5; —	Cl	tr.	—	III; 5; 4; 4; —
FeSAs	0.41	—	— (no name)	FeS_2	0.93	—	— Auvergnose
FeS	1.64	—	Or : Ab : An =		99.69		Or : Ab : An =
FeS_2	1.98	—	= 1.1 : 9.8 : 89.1				= 7.5 : 18.4 : 74.1
	100.17						
Sp. gr.	3.04			Sp. gr.	2.94		

32. Hornblende lamprophyre. Stope 21, 130 m level.
33. Hornblende lamprophyre. Main east drift, section 21, 410 m level.

Analyses Nos. 32—33 represent the hornblende lamprophyre. No. 32, from the 130 m level, occurs as inclusions in pyrite ore. Hornblende is plentiful and also comparatively large amounts of chlorite and zoisite are present. Plagioclase, titanite, and calcite are scarcer. No. 33 is from the 410 m level and contains mainly hornblende. Plagioclase, quartz, and biotite are only rarely present. No. 34 is a sample of the plagioclase-rich margin of the dyke

in Stope 28. Finally, Analysis No. 35 represents the chloritic lamprophyre, composed of chlorite, quartz, and sericite in porphyroblastic »books». Mariposite is not visible in this case.

B. Quartz-Tourmaline and Sulphide Ores.

General.

The lamprophyres often contain lenses of quartz in the shape of ladder veins or gash veins (Fig. 13). They generally strike NE—SW or ENE—WSW and pitch about 50—60° to the east, *i. e.* in the same direction as the general pitch of the deposit. The quartz lenses occasionally carry tourmaline, and also pyrrhotite, pyrite, chalcopyrite, and sulphominerals. The lenses do not attain a length and width of more than a few dm.

Table 24.

Analysis of plagioclase-rich phase of lamprophyre.

Analysis No. 34.

Analyst: Th. Berggren.

	%	Mol. prop. × 1000	Norm	
SiO_2	42.31	705	Or	1.11
TiO_2	1.51	19	Ab	7.86
Al_2O_3	24.35	239	An	61.75
Cr_2O_3	nil	—	sal =	70.72
Fe_2O_3	nil	—	Di	8.41
FeO	2.96	41	Hy	6.24
MnO	0.15	2	Ol	3.78
CaO	15.01	268	Il	2.88
MgO	4.95	123	Ap	0.67
Na_2O	0.91	15	Sulph.	6.20
K_2O	0.16	2	fem =	28.18
$H_2O^{-105°}$	0.09	—	$H_2O^{+105°}$	1.08
$H_2O^{+105°}$	1.08	—	Cc	0.10
P_2O_5	0.24	2		100.08
CO_2	0.04	1	II; 5; 5; 5; — (no name)	
$CuFeS_2$	2.20	—	Or : Ab : An = 1.57 : 11.11 : 87.32.	
FeS_2	3.59	—		
FeS	0.41	—		
	99.96			

Sp. gr. = 2.95

34. Plagioclase-rich phase of lamprophyre. Stope 28, 250 m level.

The quartz-tourmaline formations may, however, sometimes attain a larger size and appear as continuous veins or lens-shaped bodies of considerable size.

They are particularly plentiful in the deeper parts of the mine (Pl. 7 and 8 (Stope 23), and Figs. 14 and 15). Narrow veins containing tourmaline and some ore minerals occur also between sections 1—3 and at section 16 on the 90 m level (Pl. 3) and in a few other places.

In the main east drift on the 250 m level a lamprophyre containing the usual small lenses of quartz passes over into veins of quartz-tourmaline with



Fig. 13. Schematic sketch of gash veins of quartz (black) in lamprophyre. Length of gash veins generally 0.1—0.5 m. (Fig. 7 in (65)).

Table 25.

Analysis of chloritic lamprophyre.

Analysis No. 35.

Analyst: Th. Berggren.

	%	Mol. prop. × 1000	al-fm-c-alk-values
SiO_2	56.26	937	al = 26.1
TiO_2	0.54	7	fm = 68.7
Al_2O_3	13.84	136	c = 0.8
Cr_2O_3	0.12	1	alk = 4.4
Fe_2O_3	0.38	2	100.0
FeO	6.17	86	
MnO	0.06	1	
CaO	0.20	4	
MgO	10.71	266	
Na_2O	0.43	7	
K_2O	1.47	16	
$H_2O^{-105°}$	0.09	—	
$H_2O^{+105°}$	3.23	—	
P_2O_5	0.12	1	
F	0.33	17	
CO_2	nil	—	
FeAsS	0.07	—	
FeS_2	3.09	—	
FeS	2.79	—	
	99.90		
Sp. gr. = 2.72			

35. Chloritic lamprophyre. Stope 28, 250 m level.

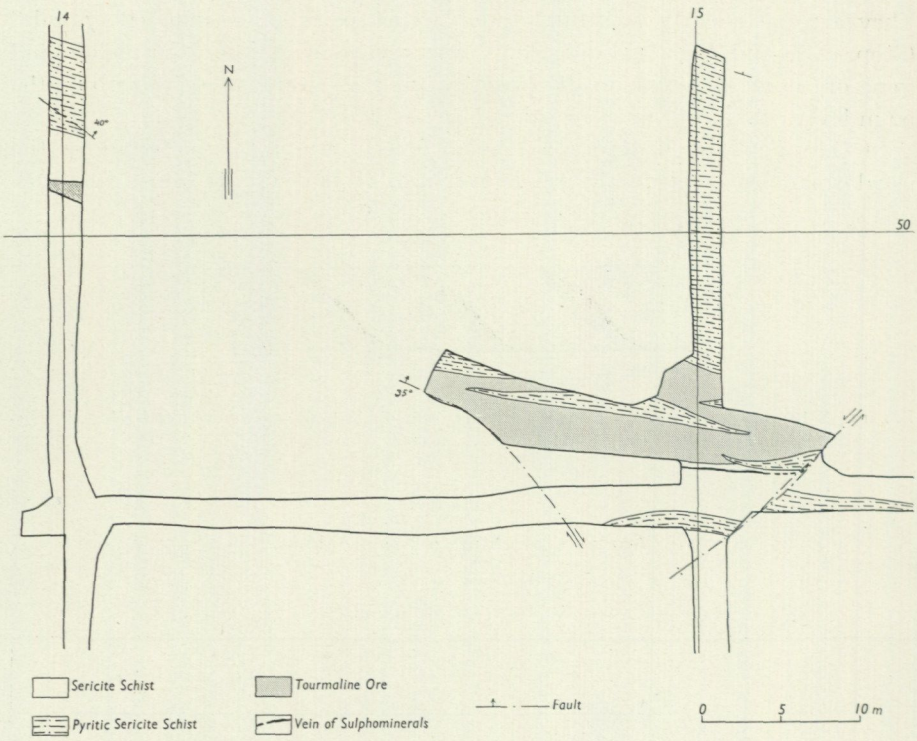

Fig. 14. Quartz-tourmaline lens. Section 14—15, 330 m level.

mariposite, chalcopyrite, sulphominerals, and gold. Similar transitions from lamprophyres to quartz-tourmaline veins have been observed on other occasions. It is on the whole fairly obvious how closely related the two formations are. The quartz-tourmaline bodies, both veins and lens-shaped bodies, appear in the vicinity of the dykes and frequently follow the same tectonic lines as the latter. The relationship is also thought to be a genetic one and the quartz-tourmaline formations are considered to be differentiates from the same magma as the lamprophyres.

The formation of the quartz-tourmaline ores occurred somewhat later than the intrusion of the dykes, as they have been cut by quartz-tourmaline veins, *e. g.* in Stope 26 on the 250 m level (Fig. 15).

As already mentioned, the quartz-tourmaline ores are accompanied by sulphide ores, mainly composed of chalcopyrite and pyrrhotite. The sulphides are closely related to the quartz-tourmaline ores but they were formed somewhat later.

Description of the Quartz-Tourmaline Ore.

Vein-shaped ores. Veins of quartz-tourmaline with varying amounts of other components are found particularly on the 250 m level, where, *e. g.* in Stope

26 (Pl. 7 and Fig. 15), several of them have been mined, and in the main east drift, where they occur in intimate relation to the lamprophyre. As a rule they have a rather insignificant extension and attain a length of maximum 40 m and a width of 0.5—0.75 m. They are thus by no means comparable to the extensive quartz veins found in certain districts in Canada, even though, as will be shown later, there exists a good resemblance as regards general appearance and paragenesis. The veins are often divided into lens-shaped parts. As a rule the lenses

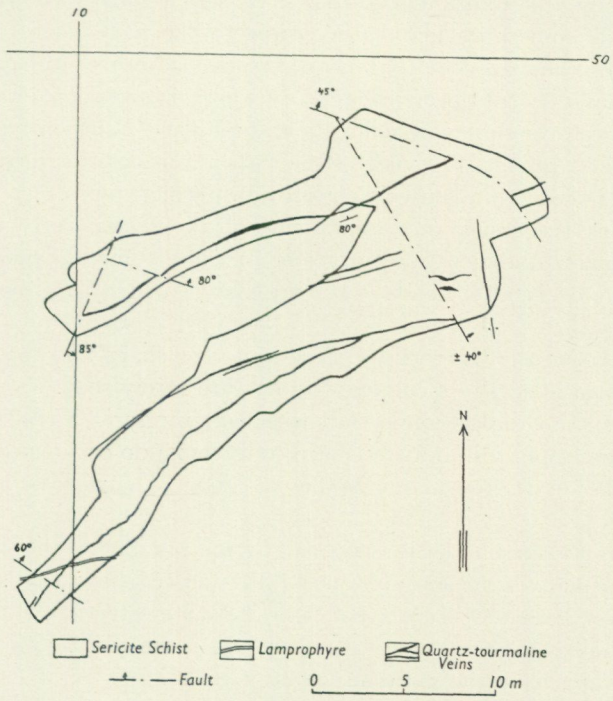

Fig. 15. Quartz-tourmaline veins. The lamprophyre in the lower left corner is cut by a vein. Stope 26, 250 m level.

follow the foliation, even in the places where the schist is corrugated, but they are also found to cut the foliation.

In some veins quartz is the predominant mineral but all gradations to veins in which tourmaline is the predominant or practically sole constituent are noticed.

The quartz is coarse and glassy and has a grayish white colour. Tourmaline in slender needles is accumulated in spots or forms continuous and parallel bands, enclosed in the vein or adhering to its walls.

The extremely tourmaline-rich veins are composed of a fine-grained to dense mass of brownish or dark greenish tourmaline, sometimes so fine-grained that the individual needles are not visible without the aid of a microscope. The fine-grained tourmaline may be banded and sometimes also contains ra-

diate suns of larger needles, attaining a size of about 1—2 cm. Besides tourmaline, this type of vein contains only small amounts of sericite and mariposite visible to the naked eye.

Lens-shaped quartz-tourmaline bodies. Large quartz-tourmaline bodies are known *e. g.* from Stope 23 between the 130 and 170 m levels (Pl. 4, 5, and 8) and from the 330 and 410 m levels (Fig. 14). The ore is mainly composed of tourmaline, but quartz, sericite, and various ore minerals are also found, sometimes in masses visible to the naked eye.

As shown on the maps, the contours of the ore bodies are often quite irregular. This is especially true of the ore in Stope 23, where, in spite of a detailed mapping of each sublevel, the sublevels being about 3 m apart, a correlation of them was sometimes very difficult. In view of the rather considerable vertical extension of the quartz-tourmaline lenses they may be termed pipes.

In Stope 23 the appearance of tail-shaped apophyses, as a rule composed of whitish quartz and rich concentrations of sulphominerals and gold, is very distinct. They occur at the ends of the ore body, but may also be found at the sides.

The contacts to the wallrock are generally very sharp and the ore smoothly follows the foliation. Cross-cutting contacts are rarely seen.

There exists no direct connection with lamprophyres, as in the case of the veins, but lamprophyres (and also mariposite veins) do occur in the immediate vicinity of the quartz-tourmaline bodies in Stope 23 as well as on the 330 and 410 m levels.

The quartz-tourmaline lenses as a rule strike parallel to the schistosity but a study of the maps of the lens in Stope 23 (Pl. 5 and 8) shows that some branches and apophyses strike NE—SW, that is in the same direction as the gash veins in the lamprophyres. Several of the gash veins in the quartz-tourmaline lenses, described below, have the same direction of strike.

The quartz-tourmaline ore is generally dark-brown or dark-green. Occasionally and especially on the deeper levels the colour is yellowish brown or yellowish green. Where the impregnation of ore minerals is strong the ore assumes the colour of the predominant ore mineral, *e. g.* yellowish for chalcopyrite, gray for sulphominerals, etc. The ore is massive and so fine-grained that the tourmaline often cannot be identified with a naked eye. In rare cases the tourmaline needles attain a size of 5—10 mm and then often form radiate groups. The ore is on the whole fairly similar to or even identical with the tourmaline veins described above. Quartz is also present in the ore, either in irregularly shaped bodies or in ladder veins or gash veins.

The latter, which may attain a length of several metres and a width of 1—2 metres, are in the shape of large discs which sharply cut the ore bodies (Pl. 8, Stope 23, and Fig. b, Pl. 30). The quartz is here milky white and practically free from ore minerals. These veins bring to mind the quartz veins or lenses found cutting the andalusite rock (p. 38).

A detailed study of the quartz-tourmaline ore reveals the appearance of

several generations of tourmaline. The ore may thus be cut by one or two systems of veins with tourmaline, having a colour different to that of the tourmaline in the ore (Fig. a, Pl. 31). The needles in the veins are arranged at right angles to the walls of the veins. Concentrations of quartz and ore minerals are sometimes met with in these veins.

The gold and silver content of the ore is erratically distributed. The highest tenor of the metals is found in the cases where the ore is impregnated with chalcopyrite or sulphominerals but appreciable quantities may occur also in unimpregnated ore. The highest concentrations are found in the quartz apophyses. On the other hand there are portions adjoining a rich zone, or entire lenses, *e. g.* on the 410 m level, which have the same appearance as the gold- and silver-rich ores, where the tenor, however, is quite negligible.

Paragenesis of the Quartz-Tourmaline Ore.

The paragenesis of this type of ore is extremely complex and a large number of minerals, especially ore minerals, are present (cf. Table 42, p. 184).

Tourmaline and quartz are the predominant constituents. The ore minerals generally occur as impregnations, although concentrations of them are found in the quartz apophyses and in spots in the tourmaline. More seldom are concentrations found in the quartz in the ore.

The microscopic study of the ores discloses that the ore minerals crystallized later than the tourmaline and that they form a groundmass in which the needles of tourmaline are enclosed. The needles are often broken and also replaced. In the denser types of the ore the ore minerals form a network which brecciates and veins the mass of tourmaline.

In the quartz-tourmaline veins in Stope 26 (250 m level) an indistinct zoning is noticed and sulphominerals and gold are concentrated in the central portions of the veins, while the terminal portions mainly contain pyrrhotite.

Ore Minerals. Bismuth is a characteristic component and occurs in places in appreciable quantities. The element may be said to be typical of this ore, whereas in the arsenopyrite and pyrite ores it is more rarely present. It mostly occurs in intimate intergrowths with a number of other minerals to be described on a later page (p. 91).

Native silver in thin sheets was observed in fissures in the ore in Stope 23. The white colour indicates that it contains but very little gold. It is believed that the mineral was formed by decomposition of a silver mineral, exercised by late hydrothermal solutions probably emanating from the ore itself at a late stage of its formation. A supergene origin is out of the question, considering the depth at which the mineral occurs and the general absence of supergene alterations in the deposit (except the formation of covellite and hydrous copper-sulphate at the surface of the ore).

Gold is often present in wires and sheets. It is generally closely associated with other ore minerals, as chalcopyrite, pyrrhotite, sulphominerals, and Bi-

tellurides. It may occur in fissures in quartz and other minerals but the fissures run in various directions and do not imply any extensive shearing of the ore. In some places the gold serves as a groundmass for the tourmaline (Fig. b, Pl. 31). The tourmaline needles are then often broken and replaced by the gold. Gold, often in association with sulphides, forms irregular veins or rounded grains in the quartz. The gold occurs in the same manner in most of the ore minerals, indicating that it is one of the last minerals formed. Some observations show, however, that gold of more than one generation occurs (cf. p. 104). On two occasions gold with moss texture was observed. The individual particles were of a size less than 0.01 mm. This moss gold occurred together with two unknown minerals in a manner suggesting that the gold was formed by their decomposition. The two minerals appear in very small grains and could not be identified but they are associated with Bi-tellurides and it is thus likely that they are gold-tellurides.

The general impression obtained from a study of the appearance of the gold is that it is genetically closely related to the other components of the ore and that it was introduced at the same time. A »later» introduction, as suggested by Mawdsley (57) with regard to some Canadian deposits, has evidently not occurred (66).

Bismuthite is fairly often present, especially in intergrowths with bismuth an other minerals (p. 91).

Bismuth-tellurides are typical of this paragenesis. Three species have been identified, tetradymite (Bi_2Te_2S), tellurobismuthite (Bi_2Te_3) (27), and an Sb-bearing variety of the latter. They are most widespread as a later mineralization in the rutile lenses in Stope 28 and a special description will be given on a later page (p. 101). In the following only their appearance in the quartz-tourmaline ores proper will be treated.

Bi-tellurides occur in quartz-tourmaline veins, *e. g.* in Stope 26 (250 m level), and in the quartz apophyses in Stope 23, where they often form scaly aggregates. As a rule it is not possible to discriminate between the three species as they are very similar in specimens as well as under the microscope. Some of the sulphominerals, *e. g.* the so-called »selenokobellite» (cf. p. 90), often contain Bi-tellurides in the shape of laths or »books», greatly resembling »books» of mica. The Bi-tellurides distinctly replace such minerals as »selenokobellite», tetrahedrite, chalcopyrite, and others. As a rule they have a rather strong tendency to form idiomorphic grains. On the whole, however, they crystallize fairly late.

Sphalerite is not very common in the paragenesis but it is found as small grains in some of the complex intergrowths (p. 91) and together with chalcopyrite and pyrrhotite.

Pyrrhotite sometimes predominates among the ore minerals, *e. g.* in the tourmaline vein in Stope 25 (cf. p. 134) and in the upper portions of the tourmaline pipe in Stope 23 (170 m level). The groundmass of the ore is here composed of pyrrhotite, which brecciates and replaces the tourmaline. In Stope 23 the pyrrhotite-bearing tourmaline ore finally grades into an ore essentially composed of pyrrhotite together with some chalcopyrite. The mineral

is later than tourmaline and quartz but it is replaced by chalcopyrite, sulphominerals, and gold.

Pyrite is rare in the ordinary quartz-tourmaline ore. As a rule it is more plentiful in the non-productive veins. It generally forms crystals, corroded by several later minerals, but it has also been seen on narrow veinlets, brecciating the fine-grained tourmaline mass.

Cobaltite is typical of the quartz-tourmaline ores, but it seldom occurs in large amounts. It is found in fine-grained, pinkish gray streaks in the tourmaline ore in Stope 23. In the tourmaline vein in Stope 25 (250 m level) it makes up the groundmass (Fig. a, Pl. 32) for the tourmaline needles or forms idiomorphic crystals in the pyrrhotite-rich parts of the vein. It is replaced by such minerals as chalcopyrite, pyrrhotite, and sulphominerals.

Arsenopyrite is extremely rare as a primary constituent. It has been observed as crystalline aggregates where tourmaline veins cut the arsenopyrite ore and it is evident that the mineral was here formed by the mobilization of the arsenopyrite ore. Primary arsenopyrite in well-shaped crystals occurs in concentrations of sulphominerals in some of the quartz-tourmaline veins. The mineral is here replaced by the sulphominerals.

Gudmundite is a comparatively rare mineral. It is mainly present in the quartz-tourmaline veins, either on veinlets with other sulphides, cutting the quartz, or as separate crystals replacing the quartz at the walls of the veinlets. It generally forms good crystals.

Galena occurs in large amounts, either as separate aggregates between the tourmaline needles or associated with other minerals in the complex intergrowths described later (p. 91). It replaces most of the other minerals and is one of the latest minerals. The mineral frequently displays a weak but distinct anisotropism in polished sections, making the boundaries of the grains appear clearly. No signs of stress action were noticed. Behrend (3, p. 172) reports anisotropism in a slightly stressed galena from the Ramsbeck District in W. Germany.

Chalcopyrite occasionally predominates among the ore minerals, *e. g.* in some parts of Stope 23 on the 170 m level. It distinctly replaces tourmaline, quartz, pyrite, pyrrhotite, and tetrahedrite (Fig. b, Pl. 32). The sulphominerals, galena, and gold are later than chalcopyrite. A second generation of chalcopyrite is found in replacing veinlets in some of the sulphominerals.

Valleriite is of rare occurrence in the present paragenesis but it has been observed in the chalcopyrite. — Cubanite has not been observed.

Sternbergite (?; $AgFe_2S_3$). In the complex intergrowths of bismuth and sulphominerals, etc., described below, and in indistinct veinlets cutting these, there occurs a mineral which is thought to be sternbergite (German »Silberkies»). As a rule it occurs in short needles (maximum 1 mm long) or in aggregates of small tabular crystals (Fig. c, Pl. 32). Its resistance to polish is less than that of galena but slightly higher than that of bismuth. The reflection power is about the same as for chalcopyrite. The reflection pleochroism is dis-

tinct: in the zone parallel to the elongation brownish yellow and greyish yellow, in cross section grayish yellow. The small grains render a distinction of the colours rather difficult. In its light position the mineral is similar to chalcopyrite or cubanite in light position; in its dark position, on the other hand, the mineral is very similar to pyrrhotite in dark position. The anisotropism is strong and between crossed nicols the colour is grayish blue in light position; when the nicols are not quite crossed the mineral displays reddish brown interference colours. The extinction is straight. The determination of the mineral is rather weakly founded and cannot be looked upon as definite. Sternbergite belongs to a group of minerals which is so far not very well known (88, pp 374—376) and a determination cannot be carried out safely without an analysis of pure material, which, however, is completely out of the question in this case in view of the fine-grained state of the mineral.

Table 26.

Chemical composition of »selenocosalite».

Analyst: Th. Berggren.

Analysis No.	36			37		
	%	% [1]	Mol. prop. × 1000	%	% [1]	Mol. prop. × 1000
Pb	43.51	44.26	214	44.20	44.43	214
Bi	31.11	31.65	151	31.40	31.57	151
Sb	2.72	2.77	23	2.88	2.90	24
S	12.26	12.47	389	12.36	12.43	388
Se	6.32	6.43	81	6.38	6.41	81
Te	0.80	0.81	6	0.80	0.80	6
Cu	0.12	0.12	2	0.14	0.14	2
Fe	0.29	0.29	5	0.29	0.29	5
Ni	nil	—	—	nil	—	—
Co	nil	—	—	nil	—	—
Zn	nil	—	—	nil	—	—
Ag	1.18	1.20	11	1.02	1.03	10
Au	nil	—	—	—	—	—
As	nil	—	—	nil	—	—
Insol.	1.62	—	—	0.66	—	—
	99.93	100.00		100.13	100.00	
Sp. gr. = 7.00 [2]						

36. »Selenocosalite». Stope 13, 210 m level.
37. »Selenocosalite». Stope 13, 210 m level.

[1] Recalcul. to 100 %.
[2] Det. by Dr. G. Assarsson.

»Selenocosalite» ($Pb_2 Bi_2 (S, Se)_5$). One of the sulphominerals occurring in large amounts was found to resemble cosalite under the microscope. Because of an appreciable content of Se it has been given the provisional name »selenocosalite». The mineral occurs as microscopic grains in the quartz apophyses to the tourmaline ore in Stope 23. It has been found in megascopically visible masses in disseminated ore from the 410 m level (cf. p. 106) and in quartz-tourmaline veins in the footwall in Stope 13 (21 0m level). The mineral is intergrown with galena in fairly large amounts, and with traces of bismuth, sternbergite, pyrrhotite, chalcopyrite, and an unknown mineral. Pure material could not be obtained for the analyses (Table 26). Consequently an accurate calculation of the composition of the mineral is hardly feasible. If chalcopyrite, pyrrhotite, and Ag_2S are deducted from Analysis No. 37[1], the remainder has the molecular proportions as shown in Table 27[2]. It seems likely that the subordinate elements Sb, Se, and Te enter into the mineral, and in the following calculation Sb has been added to Bi, and Se and Te to S. In Alternative I »selenocosalite» is deducted from the remainder. The rest should represent galena but a rather considerable surplus of Pb then appears.

Table 27.

	Pb	(Bi + Sb)	(Se + Te + S)	Alternative
Rest from Analysis No. 37	214	175	463	I
»Selenocosalite» 2 : 2 : 5	**175**	**175**	**438**	
Rest: PbS mainly	39		25	
Rest from Analysis No. 37	214	175	463	II
Galenobismuthite 1 : 2 : 4	**87**	**175**	**350**	
Rest: PbS mainly	127		113	

In some respects the mineral in question also resembles galenobismuthite ($PbBi_2S_4$) and one cannot ignore the possibility of it really being that mineral. In Alternative II, therefore, galenobismuthite has been deducted. However, the remainder, mainly representing galena, still shows a surplus of Pb. Neither of the two calculations can thus be said to be conclusive and the determination of the mineral as a subspecies of cosalite must be subject to strong reservation.

In hand specimen the »selenocosalite» is tin-white and indistinctly lamellar. Under the microscope the mineral appears as lobe- or lath-shaped grains, often intergrown with galena in a finger-like fashion (Fig. a, Pl. 33). The grains attain a maximum size of about 1—2 mm.

Optically the mineral is very similar to galena as regards colour and reflection power. It is slightly softer than the latter mineral (cf. 88, p. 405). The reflection pleochroism is weak in air but in immersion the contrasts in colour are distinct.

[1] It is of no importance which analysis is taken, as they are practically identical.
[2] The small quantity of the unknown mineral has not been taken into consideration.

In its light position (parallel to the elongation) the mineral is creamy white and in dark position gray with a greenish tint. The anisotropism is distinct and the mineral shows grayish yellow colours with a tint of red. The extinction is somewhat oblique.

The microscopic study of the mineral discloses that on some occasions it is subjected to a decomposition, the resulting textures and minerals being similar to the complex intergrowths described below (p. 91). It would appear likely that »selenocosalite», probably also other similar minerals, was at least in part the source of those intergrowths. In its simplest form the decomposition of the »selenocosalite» results in the formation of bismuth, possibly also bismuthite, and galena. They form lamellar intergrowths or devel-

Table 28.

Chemical composition of »selenokobellite».

Analyst: Th. Berggren.

Analysis No.	38		39		40		41	
	%	Mol. prop. × 1000	%	Mol. prop. × 1000	%	Mol. prop. × 1000	%	Mol. prop. × 1000
Pb	39.80	192	39.98	193	38.29	185	36.48	176
Bi	18.91	91	21.27	102	21.27	102	24.35	117
Sb	13.83	114	15.02	123	14.75	121	14.61	120
Se	5.66	72	5.00	63	5.74	73	4.78	61
Te	0.21	2	0.44	3	0.17	1	nil	—
S	15.95	498	15.93	497	15.86	495	16.89	527
As	0.68	9	0.10	1	0.79	11	0.25	3
Cu	1.57	25	1.28	20	1.37	22	1.50	24
Fe	1.84	33	0.58	10	1.02	18	0.63	11
Ni	tr.	—	nil	—	tr.[1]	—	nil	—
Co	0.04	—	nil	—	0.14	2	nil	—
Zn	0.22	3	0.09	1	0.22	3	nil	—
Hg	—	—	tr.[1]	—	tr.[1]	—	—	—
Sn	—	—	tr.[1]	—	tr.[1]	—	—	—
Ag	0.44	4	0.39	4	0.38	4	0.36	3
Au	tr.	—	tr.	—	tr.	—	nil	—
Insol.	1.00	—	nil	—	—	—	—	—
	100.15		100.08		[2] 100.00		99.85	
Sp. gr.	6.048		6.481		6.463		6.573	

38. »Selenokobellite». Stope 12, 210 m level.
39. »Selenokobellite». Main east drift, section 11, 210 m level.
40. »Selenokobellite». Stope 12, 210 m level.
41. »Selenokobellite». Main east drift, section 11, 210 m level.

[1] Spectrosc. det.
[2] Recalculated, insol. 0.64 %.

op along narrow veinlets, the interior of which is composed of the first two minerals, surrounded by ragged fringes of galena.

»Selenokobellite» ($Pb_2(Bi, Sb)_2(S, Se)_5$). In some of the quartz-tourmaline veins and occasionally in separate veins there occurs a mineral which in some respects resembles the one just described but which in its chemical composition also bears some resemblance to kobellite. Because of quite a significant content of Se it has provisionally been termed »selenokobellite». As in the above case, the composition is still open to discussion as there is some variance in the analyses (Tables 28 and 29).

The mineral is rather homogeneous and the four analysed samples contained only small amounts of arsenopyrite, cobaltite, chalcopyrite, sphalerite, bournonite, and an undetermined Bi-telluride. Galena occurs only in traces.

In the analyses the accessory minerals were deducted. The Bi-telluride had to be disregarded, as its composition is unknown, nor could the galena be considered. They both occur in but unimportant quantities and cannot influence the result to any notable degree. As in the above case Sb was added to Bi, and Se and the small amount of Te to S. The silver was added to Pb as no separate silver mineral seems to be present. After these operations the following molecular proportions are obtained (Table 29), representing the mineral in question.

Table 29.

Analysis No.	(Pb, Ag)	(Bi, Sb)	(S, Se)
38.	2	2.1	5.2
39.	2	2.3	5.4
40.	2	2.4	5.54
41.	2	2.7	6.36

There are rather considerable variations between the molecular proportions and only the proportions in Analysis No. 38 show any agreement with the theoretical composition of the mineral. The variations cannot be due to impurities as the analysed material was unusually pure and the minerals that occur admixed have been deducted. Neither did an X-ray study of the mineral (carried out by P. Lange of the University of Stockholm) give any clues to this problem. It is probable, however, that solid solutions at least to a certain degree may be made responsible. Bismuth and also the Bi-telluride, for instance, have an appearance suggesting formation by unmixing.

As is evident from the analyses, »selenocosalite» and »selenokobellite» are similar in many respects. The greatest difference lies in the contents of Bi and Sb, the former being higher in »selenocosalite» and the latter considerably higher in »selenokobellite». Also in specimens and under the microscope there exist some notable differences. It is as yet not certain, however, whether the minerals should be considered two distinct species.

»Selenokobellite» is especially accumulated in the quartz-tourmaline veins in Stope 26 (250 m level) and in some similar veins on the 170 m level. It forms separate veins in some places, *e. g.* at section 11 in the main east drift on the 210 m level. The veins are 5—10 cm thick and are built up of columnar or acicular grains of »selenokobellite», sometimes attaining a length of several centimetres. The veins often sharply cut the foliation of the surrounding schist.

The colour of »selenokobellite» is whitish gray in hand specimens, but somewhat darker than that of »selenocosalite».

Under the microscope the columnar grains are often broken and occasionally recrystallized (Fig. b, Pl. 33).

In polished sections the »selenokobellite» is somewhat softer than galena and slightly harder than the accompanying Bi-telluride. As to colour and reflection power the mineral is very similar to galena. The galena appears bluish white in comparison with »selenokobellite» in its light position (parallel to the elongation). The reflection pleochroism is stronger than in »selenocosalite» and in the dark position the »selenokobellite» has a fairly distinct gray colour. Galena is distinctly white in this case. The anisotropism is fairly strong without any marked display of colours. The optical qualities of the mineral are not distinct enough to allow a safe diagnosis; the same is true also of »selenocosalite».

The »selenokobellite» is a late crystallizing mineral and it replaces a number of minerals, among others arsenopyrite, pyrite, chalcopyrite, pyrrhotite, and quartz. Some galena often accompanies the »selenokobellite» but the age relationship is sometimes obscure. As a rule the galena seems to be about contemporaneous, but on the other hand narrow veins of galena have been seen cutting the »selenokobellite», indicating that at least part of the galena is later.

Occasionally also bismuth, chalcopyrite, bournonite, and a gangue mineral, which in view of its high birefringence and inconsiderable hardness must be calcite, occur in veinlets in the »selenokobellite». Bismuth is probably formed by decomposition of the host mineral but the other minerals have probably been introduced by late-hydrothermal solutions. The chalcopyrite is in this case evidently of a second generation as the mineral otherwise is replaced by the »selenokobellite». Some of the veins occur in zones of rupture and the solutions entered the »selenokobellite» in connection with tectonic movements in the ore.

The Bi-telluride accompanying the »selenokobellite» forms mica-shaped scales or very elongate laths, enclosed in the host mineral parallel to its longer axis. In a polished section one continuous lath had a length of 5 mm and a minimum width of about 0.01 mm. The width never exceeded 0.1 mm.

P y r a r g y r i t e is visible to the naked eye when it occurs as thin coatings in the tourmaline ore or as tiny crystals in calcite veins. An analysis of such crystals gave the following result (Table 30) (the analysed quantity was only 0.03 gr and not sufficient for a determination of Sb). The absence of arsenic and the fairly good accordance with the theoretical composition proves the mineral to be pyrargyrite. The mineral is rather often encountered in the complex intergrowths, to be described below (p. 91). It may also occur in

occasional veinlets, cutting the sulphominerals. It is clearly one of the last minerals in the paragenesis.

Lead-sulphantimonites. Antimony minerals are comparatively rare in the present paragenesis, bismuth-minerals — often with some antimony, however, — being more common. The pure antimony minerals generally seem to be concentrated to the arsenopyrite and pyrite stages. Boulangerite has been found on some occasions in association with such minerals as »selenokobellite» and Bi-tellurides and thus very likely belongs to this stage. One occurrence, already mentioned (p. 59), is on quartz lenses in the pyrite-apatite ore. The boulangerite has been determined by X-ray methods by Hiller. It appears in short-prismatic grains, fringed at the ends and replaced by galena, tetrahedrite, and bournonite.

Table 30.

Partial analysis of pyrargyrite.

Analysis No. 42.

Analyst: Th. Berggren.

	%	Mol. prop. × 1000	% [1]
Ag	58.0	538	59.76
As	0.0	—	—
S	17.8	555	17.76
	75.8		
Rest: Sb	24.2	199	22.48
	100.0		100.00

42. Pyrargyrite. Stope 23, 170 m level.

Tetrahedrite is much rarer than in the arsenopyrite ore. It occasionally occurs enclosed in other sulphominerals and often decomposes, new minerals such as bournonite, sphalerite, and arsenopyrite, being formed (Fig. a, Pl. 34). In one case tetrahedrite was replaced by chalcopyrite and a bismuth-like mineral (antimony?) along narrow veinlets with one of the walls characteristically serrate (Fig. b, Pl. 32).

Bournonite is also comparatively rare. It has been encountered in veinlets in »selenokobellite» and is seen to replace boulangerite and tetrahedrite. It is also a component of the complex intergrowths.

Magnetite is on the whole very rare in the ores at Boliden and in the quartz-tourmaline ore it has only been observed in one case, in a pyrrhotite- and sulphomineral-bearing portion of an ore on the 330 m level. It occurs in rounded grains veined by pyrrhotite.

Complex intergrowths. The already mentioned intergrowths between several of the minerals of the paragenesis are typical of the sulphomineral-rich portions of the quartz-tourmaline ore, especially the quartz apo-

[1] Theoretical composition of pyrargyrite.

physes in Stope 23 (170 m level). In hand specimens nothing is seen of the intergrowths and the ore looks like an unusually dark galena ore. At a slight magnification the intergrowths are seen to be composed of a confusion of somewhat subparallel bundles of a fine-grained mineral mass, surrounded by a more or less plentiful groundmass of galena (Fig. b, Pl. 34). Lath-shaped grains of Bi-tellurides also occur. The bundles are often of about the same size and shape as the grains of »selenocosalite». When highly magnified the bundles are dissolved and it is noted that their components form lamellar grains with irregular contours (Figs. a, b, Pl. 35). Some of the intergrowths are irregularly shaped and they seem to represent sections obliquely across the elongation of the lamellar bundles. Each bundle may be built up of several minerals, among which we particularly note pyrrhotite and galena, and also chalcopyrite, sphalerite, tetrahedrite, bournonite, sternbergite, pyrargyrite, and smaller amounts of one or two not identified minerals (sulphominerals?). All these minerals are intergrown with bismuth in the shape of rounded or intricately ramified grains. The impression obtained is that bismuth replaces the other minerals. Bismuth is occasionally accumulated to large spots containing grains of a grayish mineral, probably bismuthite. In the intergrowths also a gangue mineral is found. The strong birefringence and the slight hardness indicates calcite. It shows the same texture as the ore minerals.

It seems unlikely that these intergrowths were formed by a simple crystallization and it is believed that they were largely caused by a decomposition of other minerals. »Selenocosalite» shows a similar but simpler decomposition and this mineral at least in part formed the source of the intergrowths. It is, however, out of the question that »selenocosalite» alone with its comparatively simple composition, can have furnished material for this complex paragenesis, and it is very likely that also other, now completely destroyed minerals took part. Another thing is that new mineral matter obviously was added during the decomposition. Calcite is thus an otherwise foreign component and it has certainly been introduced at a late stage. A further proof of the late introduction of the minerals is the occurrence of later veinlets cutting the intergrowths. These veinlets contain calcite, some quartz, sternbergite, chalcopyrite, bismuth, gold, and other minerals, and several of them are also typical in the intergrowths. Some of these minerals here form a second generation as they are found also in the normal tourmaline ore. It is possible that the source of the later veinlets and of some of the minerals in the intergrowths may be sought in the quartz-tourmaline ore itself and that they constituted a late-hydrothermal fraction of the solutions that formed that ore.

A decomposition of the Bi-tellurides is connected with the processes which resulted in the formation of the intergrowths. As is shown by Fig. b (Pl. 36) these minerals decompose to at least two very intimately intergrown minerals. The decomposition occurs in zones. The new minerals are extremely fine-grained and it has not been possible to identify them.

Unidentified minerals. Besides the minerals described on the foregoing pages some others occur which could not be identified. Two were

mentioned above. Two others were mentioned in connection with the moss gold (p. 84). Finally the galena has been found to contain small, even at high magnification barely visible grains of one or two minerals in the shape of laths, which have not been identified. They may be so-called »Silberträger» (88, p. 258), possibly partly formed by the unmixing of a solid solution of Ag- and Bi-sulphides in the galena (77).

Gangue minerals. Tourmaline is the predominant gangue mineral in many of these ores. The general appearance of the mineral has already been touched upon. It is often very fine-grained and cases are known where the needles are but 0.05 mm. As a rule they are longer however, and measure some tenths of a millimetre. As the needles increase in size they are also better crystallized. They often form radiate aggregates but generally the tourmaline ore is massive. In a tourmaline vein at section 15 on the 250 m level the mineral had a most peculiar spherulitic texture. The vein is composed of fine-grained, partly banded tourmaline containing fine-grained schlieren of mariposite. In the mariposite there are enclosed perfectly spherical bodies about 1—3 cm in diameter and composed of radiate needles (Fig. a, Pl. 36; Fig. a, Pl. 37) of tourmaline.

In thin sections the mineral is as a rule but slightly coloured. Colourless tourmaline is met with occasionally, especially on the deeper levels. The coloured tourmaline has the pleochroism: ε = colourless and ω = yellowish to greenish brown. The colouring is sometimes zonal. The refractive indices were determined in a slightly brown tourmaline:

$$\omega = 1.641;\ \varepsilon = 1.617\ (\pm 0.002)$$
$$\omega - \varepsilon = 0.024.$$

Almost without exception the tourmaline is an early crystallizing mineral, and it is brecciated and replaced by *e. g.* quartz, sericite, and ore minerals. Apatite is at least in part older, for in an apatite-rich vein it was replaced by fine-grained tourmaline. As mentioned on a previous page, several generations of tourmaline occur. In some of the quartz-rich veins containing only streaks of tourmaline, the mineral is intimately intergrown with ore minerals, *e. g.* gold, the surrounding quartz being completely free from any such components. It seems as if the tourmaline had promoted the precipitation of the ore minerals.

Quartz occurs in spots or in streaky bands in the tourmaline, and contains remnants of tourmaline and some ore minerals. The mineral is here of a grayish colour. It is replaced by the ore minerals. The quartz in the apophyses in Stope 23 is whiter and is rather undulatory. The quartz in the ladder veins in some of the tourmaline bodies is on the other hand distinctly white. The veins are definitely younger than the ore and cut sharply across the tourmaline as well as the gray quartz in the ore. They are strictly confined to the ore bodies and are probably genetically related to the ore. The quartz in the ladder veins is exceptionally pure and contains only traces of other minerals.

It has to some extent dissolved the tourmaline at the contacts, where it contains small needles of that mineral in a zone a couple of cm wide. In those veins where quartz is the predominant mineral it has a light gray colour. It is generally coarse-grained and somewhat fissured. The grains are more or less undulatory and have complicated boundaries. In some rare cases it is fine-grained and evidently recrystallized. The quartz occasionally contains cloudy formations of opaque minerals, occurring in the vicinity of brecciating veinlets (Fig. b, Pl. 37). The particles of these clouds are extremely small (about 0.01—0.001 mm in diameter) and have a rounded shape. They are accumulated along continuous planes forming a criss-cross pattern in the quartz which does not follow fissures or grain boundaries. Several ore minerals may occur in this fashion; gold was observed in one case. The close relation to later veinlets of ore minerals suggest that the clouds were formed by replacement.

R u t i l e is a typical mineral also in this paragenesis. It is especially frequent in the tourmaline- and ore-bearing parts of the veins where it forms separate grains or streaky accumulations. Such accumulations are known from Stope 23 where the tourmaline ore brecciates the arsenopyrite ore (p. 99). Rutile is one of the earliest minerals in the paragenesis and it may be suspected that in some cases it crystallized even earlier than the tourmaline.

S e r i c i t e occurs in schlieren or separate large »books» in the tourmaline ore but is also found in coarse accumulations particularly in the quartz apophyses or in the quartz veins. The scales may here attain a size of 1 sq.cm. The sericite is later than the quartz and tourmaline and is often associated with the ore minerals. The latter invade and crumble the mica »books» and are consequently somewhat later, although the difference of age is only slight (Fig. a, Pl. 38). Under the microscope sericite has been observed as a fine-grained groundmass surrounding the tourmaline needles. Some tourmaline veins are cut by ladder veins composed of coarse yellowish white sericite and forming rosette-shaped tufts growing out from the walls of the veins. The occurrence of fine- to coarse-grained vein-shaped schlieren of sericite cutting the andalusite rock has already been mentioned on a previous page (p. 36). They are clearly connected with tourmaline veins and some of them contain fine-grained masses of tourmaline attached to the walls of the veins. The prevailing conditions obviously show that the sericitization of the andalusite was caused by emanations from the quartz-tourmaline veins.

M a r i p o s i t e is occasionally present in fine-grained schlieren in the quartz-tourmaline veins (cf. above). It may sometimes occur in masses where the individual scales are clearly visible. In Stope 26 (250 m level), where quartz-tourmaline veins cut lamprophyric dykes, a thin seam of mariposite is developed in the lamprophyre at the contact with the vein.

C h l o r i t e is uncommon but it has been seen on a few occasions.

A p a t i t e is seldom present in large quantities. It occurs in the tourmaline ore as small rounded grains. In one case at section 15 on the 250 m level a narrow quartz vein contained abundant amounts of apatite in grains measuring 1 cm in length. The apatite was replaced by tourmaline (cf. above). Coarse gold accom-

panied the apatite. The occurrence brings to mind gold-apatite veins described by Hulin (42) from the Mother Lode of California.

Plagioclase was observed on a few occasions only, in inclusions of tourmaline ore in sulphides belonging to the same stage (p. 99) and in veins of tourmaline ore cutting arsenopyrite ore (p. 100). Only in one case was plagioclase found in a quartz-tourmaline vein. The mineral was rather turbid and decomposed and seemed to have the composition of albite. Plagioclase has further been observed together with sulphominerals. Here it is fresh and sometimes forms idiomorphic crystals. The composition varies between 37 and 45 % An. In one case the plagioclase, together with some tourmaline, formed a disc-shaped body, about 5 cm in diameter, wholly enclosed in »selenokobellite».

Analcite. Close to a quartz-tourmaline vein in Stope 11 (210 m level) the wallrock contained small porphyroblasts of andalusite almost completely decomposed to a white, powdery mineral. It was first thought to be kaolin but an X-ray test, carried out by O. Alvfeldt of the Boliden Research Laboratory at Stockholm, showed that the mineral is analcite. It was most likely formed by late-hydrothermal emanations from the solutions during the formation of the veins. The appearance of the mineral is of interest, for nowhere else in the deposit do any Na-minerals seem to have been formed. It should be pointed out, however, that the analysis of the tourmaline ore (p. 96) shows a distinct preponderance of Na over K. Nevertheless sericite is a very common mineral in the tourmaline ore and the formation of the latter is also accompanied by an extensive sericitization of the andalusite rock.

The following minerals have a sporadic occurrence. Calcite has been found as an interstitial mass in tourmaline ore but as a rule the mineral occurs on late veins in association with a number of other minerals (p. 92). Andalusite has been observed in quartz-rich tourmaline ore from Stope 23 (170 m level) where it forms a rock composed of up to 4 cm long crystals. A formation of pink andalusite in large crystals and tourmaline suns is found in the wallrock of the tourmaline vein in Stope 25 (250 m level). It should be pointed out that in this place there are present two generations of andalusite, for some lenses of older andalusite rock also appear in the vicinity and the sericite schist contains porphyroblasts of the older generation of andalusite. Finally, andalusite has been observed in some quartz-veins, carrying tourmaline and evidently belonging to this stage. Kaolin is here and there developed by the decomposition of the andalusite. Diasporite has also been found. Kaolin of a »primary» nature has been found in the interstices between tourmaline needles in a few cases. Flourite of a violet colour occurs as thin coatings on fissures in the quartz-tourmaline ore. In one place greenish flourite forms vein-like streaks in sericite schist (Stope 18 on the 210 m level). As the mineral here lacks all connection with other mineral associations, its age cannot be definitely stated. At last the occurrence of small grains of zircon may be mentioned.

Concluding remarks. The gangue minerals on the whole crystallized early, except *e. g.* sericite and calcite. Then followed the crystallization of the ore minerals. They are closely related to the gangue minerals and appear as a

groundmass in the ore. The general impression is obtained that both gangue and ore minerals successively crystallized from a common ore solution. By the action of the stress that prevailed during the formation of the ore, the minerals formed earlier were brecciated and the remaining solution was given the opportunity to migrate on veins and to replace the older minerals. No successive addition of material during the formation of the ore seems to have taken place.

Chemical Composition of the Quartz-Tourmaline Ore.

In order to illustrate the composition of the ore an analysis has been made of a specimen of tourmaline ore from Stope 23 (Table 31).

Table 31.
Chemical analysis of tourmaline ore.

Analysis No. 43.
Analyst: Th. Berggren.

	%		%
SiO_2	30.24	Pb	11.73
TiO_2	0.71	Cu	0.41
Al_2O_3	27.51	Bi	2.24
Cr_2O_3	nil	As	nil
FeO	3.50	Sb	0.24
MnO	0.01	Fe	1.09
CaO	0.55	Ni, Co, Zn	nil
MgO	4.18	Ag	0.398
Na_2O	1.29	Au	0.049
K_2O	0.73	S	2.91
$H_2O^{-105°}$	nil	Se	0.55
$H_2O^{+105°}$	1.80	Te	0.25
B_2O_3	9.01		99.637
P_2O_5	0.17	Sp. gr. = 3.340	
CO_2	0.07		

43. Tourmaline ore. Stope 23, 170 m level.

The high content of boron combined in the tourmaline is at once obvious. The preponderance of Na over K has already been pointed out. Among the metallic elements Pb is most prominent and galena is the essential ore mineral present. The absence of arsenic is conspicuous. As already stated on a previous page, arsenic minerals, especially arsenopyrite, are very seldom present. The content of Se and Te is not particularly high but the two elements are typical of the ores of this stage. As is evident from the analyses of the arsenopyrite ore (p. 54), Se and Te are present also here, but only in insignificant quantities. Although only one analysis of tourmaline ore can be presented, it can with

a high degree of certainty be stated that the concentration of the two elements is considerably higher in this stage. Furthermore, separate minerals with Se and Te were formed during this stage. This does not occur in the arsenopyrite stage.

Copper-Pyrrhotite Ore in Connection with the Quartz-Tourmaline Ore.

The survey of Stope 23 on the 179 m level showed that the tourmaline ore in the upper portions of the stope grades into pyrrhotite ore with more or less chalcopyrite. The sulphides brecciate the tourmaline ore and obviously crystallized somewhat later. In one exceptional case tourmaline replaced pyrrhotite (Fig. b, Pl. 38). This is, however, only a local phenomenon and may be explained by a mobilization of tourmaline by the ore solution.

Similar sulphide ores are known also from other places in the mine. In the eastern part of Stope 23, for instance, there occur bodies of chalcopyrite and pyrrhotite brecciating the neighbouring arsenopyrite ore (Pl. 8). In Stope 22 (130 m level), above Stope 23, there also occurs a body of similar ore. In the latter two cases the ores do not stand in direct connection with any tourmaline ore but their paragenetic conditions strongly support the assumption that they belong to the second stage.

The sulphide ores in question are quite massive and are mainly composed of pyrrhotite and chalcopyrite. The amounts of these minerals vary from place to place and either of them may be preponderant. In the pyrrhotite ore chalcopyrite is often enriched in narrow parallel bands. The same is true of pyrrhotite in the chalcopyrite ore.

The contacts to the surrounding schists are as a rule sharp and the foliation is often cut by the ore. Apophyses are sometimes formed and here an enrichment of quartz or chalcopyrite takes place. In one case the apophysis was composed of pyrite and quartz. Inclusions of schist are occasionally found in the sulphide mass.

The paragenetic conditions of the ores are on the whole fairly simple. As stated above, pyrrhotite and chalcopyrite are the most prominent minerals, generally forming rather fine-grained aggregates. Sometimes the chalcopyrite ore may, however, be rather coarse-grained. As regards the age relations of the two minerals it seems as if chalcopyrite crystallized somewhat later.

Cubanite is in places quite common in these ores. — Valleriite is present in the usual small grains in chalcopyrite. — Sphalerite occurs in small corroded grains. — Arsenopyrite is rare but it has been found in some places in the form of small isometric crystals. The mineral probably derived from adjacent arsenopyrite bodies. — Cobaltite is comparatively common in some parts of the ore in Stope 23. It occurs in separate crystals, sometimes accumulated to large aggregates. — Bismuth, a Bi-telluride, and one or two unidentified sulphominerals occur erratically in small grains.

The gangue minerals are erratically distributed in the sulphides and as a rule occur only in small grains, replaced by the sulphides. Quartz is the most common gangue mineral and may sometimes accumulate to coarsely crystalline

masses. The ore minerals associated with this quartz are also exceptionally coarse-grained and one can indeed speak of a »pegmatitic» development of the ore. — Tourmaline, an important mineral in classifying the ores of this stage, occurs in needles which have been ruptured and often replaced by the ore minerals. — Rutile is common and forms grains which attain a diameter of 0.5 mm. — Apatite is also present. — Sericite and chlorite are found in occasional flakes. — Calcite in small grains is sometimes present among the sulphides. Two carbonate minerals form peculiar amygdules in a pyrrhotite ore from Stope 23. They have an irregular shape and attain a maximum length of 0.5 cm. The microscope discloses that nearest to the wall there is a layer of a carbonate with very strong refringence and birefringence, forming well developed crystals pointed towards the interior of the amygdule (Fig. c, Pl. 38). The crystals are sometimes coloured by a limonitic substance, indicating the carbonate to be ankerite. The interior is then filled with another carbonate, with a lower refringence and birefringence than the former. It is most likely calcite. — Felspar is seldom present and only a few grains of a rather fresh albite have been observed. — Zircon is occasionally present.

Table 32.

Chemical composition of pyrrhotite ore.

Analysis No. 44.

Analyst: A. G. Hybinette.

	%		%
SiO_2	3.50	S	34.88
TiO_2	0.31	Cu	0.18
Al_2O_3	0.88	Pb	tr.
Fe	53.35	Bi	0.22
MnO	tr.	Ag	tr.
CaO	1.92	Au	tr.
SrO	tr.	Hg	nil
MgO	0.16	Sn	tr.
Na_2O	0.03	As	0.87
K_2O	0.74	Sb	tr.
BaO	tr.	Se	0.18
$H_2O^{-105°}$	0.03	Te	0.02
$H_2O^{+105°}$	0.30	Co	0.63
Cl	0.04	Ni	0.06
F	0.26	Zn	tr.
P_2O_5	1.21		100.03
CO_2	0.26	$-O=F$	0.11
ZrO_2	nil		99.92
Sp. gr. = 4.42			

44. Pyrrhotite ore of the second stage. Stope 23, 170 m level.

The sequence of crystallization was mainly as follows. The gangue minerals, excepting the carbonates in the amygdules, are early products of crystallization. Tourmaline locally shows an overlapping and may brecciate pyrrhotite. The formation of the ore minerals then follows and among them arsenopyrite and cobaltite are the first to crystallize. Pyrrhotite, sphalerite, and chalcopyrite are later. As usual the sulphominerals are the last minerals.

Table 32 is an analysis of a pyrrhotite ore from Stope 23. The ore is exceptionally pure and contains very few other constituents but pyrrhotite. Quartz and apatite are the only minerals present in any quantity.

Inclusions of Tourmaline Ore in the Sulphide Ore.

In the aforementioned sulphide ores in Stopes 22 and 23 inclusions of tourmaline ore have been observed on some occasions. They are composed of fine-grained tourmaline in a groundmass of chalcopyrite or pyrrhotite and are identical with some types of tourmaline ore. The inclusions appear very distinctly in the sulphide ores, particularly when, as often happens, chalcopyrite-bearing tourmaline ore is enclosed in pyrrhotite ore and *vice versa*.

The inclusions may have quite sharp outlines but they may also be replaced and resorbed by the surrounding sulphides (Fig. a, Pl. 39). They attain a length of about 1 dm and a width of a few cm. As regards the paragenesis the inclusions are very similar to the tourmaline ore but as a rule they have a less complicated composition than the tourmaline ore generally.

The tourmaline has the same optical qualities as that in the quartz-tourmaline veins. Besides chalcopyrite and pyrrhotite, which constitute the groundmass, also small grains of sphalerite and rutile are observed. In an inclusion from the sulphide ore in the eastern part of Stope 23 the groundmass was composed of a plagioclase with about 55 % An. A similar type of tourmaline ore occurs in veins cutting the arsenopyrite ore in the eastern part of Stope 23 (p. 100).

The appearance and mineral composition of the inclusions clearly show that they originated from tourmaline ores in the vicinity and that they were carried in by the sulphide ore solution.

Relation of the Quartz-Tourmaline Ore to the Arsenopyrite Ore.

An important testimony to the later age of the ores of the second stage in relation to the arsenopyrite ore is supplied by the fact that in the upper portions of Stope 23 an arsenopyrite ore body is distinctly brecciated by tourmaline ore. The ore, which is partly rich in pyrrhotite, is black and fine-grained. The inclusions of arsenopyrite ore are sometimes still rather sharp (Fig. b, Pl. 39) but they are often strongly replaced by the tourmaline, which cuts into the fine-grained arsenopyrite in the shape of needles (Fig. a, Pl. 40). In the tourmaline mass in the breccia the needles show a parallel arrangement, resembling a flow structure. Rod-shaped grains of rutile are plentiful among the tourmaline needles.

The pyrrhotite which in places is accumulated in the tourmaline ore also brecciates the arsenopyrite ore. It has had a strong influence on the texture of that ore and has resorbed and mobilized a large part of the arsenopyrite. The mineral is recrystallized and in some of the inclusions it has a skeleton texture with the interstices filled with pyrrhotite. The brecciating veins of pyrrhotite contain comparatively little arsenopyrite, however, indicating that the mineral never migrated very far abroad during the mobilization.

In the eastern part of Stope 23 small irregular veinlets of tourmaline brecciate the arsenopyrite ore. No connection with any larger body of tourmaline ore can be traced.

The veins are of two types. In one case they are composed of a fine-grained felt of tourmaline with a base of plagioclase. In the other case the plagioclase predominates and contains erratic needles of tourmaline and grains of rutile, titanite, chlorite, sericite, apatite, and calcite. The latter type is similar to one of the inclusions, described above.

The tourmaline has the same appearance as in the tourmaline ore. — The plagioclase is generally fresh although it may locally contain sericite, chlorite, and calcite. It is very basic and repeated measurements on the universal stage showed that the composition varies between bytownite and almost pure anorthite.

Besides the gangue minerals some ore minerals are also present, *viz.* pyrrhotite, chalcopyrite, sphalerite, gold, and galena. They brecciate and replace the tourmaline and plagioclase.

It may finally be added that small lens-shaped quartz-tourmaline veins, occurring as gash veins in lamprophyre dykes, have been seen brecciating arsenopyrite ore where the latter is cut by the lamprophyres. Such cases have been noted *e. g.* in Stope 24 on the 210 m level. The quartz-tourmaline here contains crystals of arsenopyrite which evidently derives from the adjoining arsenopyrite ore.

Relation of the Quartz-Tourmaline Ore to the Andalusite Rock.

In a previous chapter the sericitization of the andalusite rock was described (p. 34) and the resulting formation of vein-like schlieren of coarse- or fine-grained sericite. In some of these veins there also occurs tourmaline, deposited along the margins of the veins (p. 94). It was concluded that the sericitization of the andalusite rock was genetically connected with the quartz-tourmaline ores.

The conditions are best illustrated at section 15 on the 250 m level, where a vein of massive tourmaline cuts the andalusite rock (Pl. 7 and Fig. 16). Veins of sericite and tourmaline are here seen to branch off from the main tourmaline vein and the andalusite rock around them is especially strongly sericitized and also tourmalinized.

In other places the close connection between the sericitization and the quartz-tourmaline veins may not be so obvious but it should be pointed out

that tourmaline veins are often found in the vicinity of andalusite lenses and that needles of tourmaline are not rarely distributed in the andalusite rock, thus indicating the migratory quality of the solutions emanating from the tourmaline veins.

Concentrations of Bi-tellurides.

The occurrence of Bi-tellurides in the quartz-tourmaline veins has been described on a previous page. In large, compact masses the minerals occur mainly in the rutile lenses in Stope 28 and in a few other places. The concentrations of the Bi-tellurides are of great interest from a paragenetic point of view and they will be treated in some detail.

The minerals are interesting also in view of the fact that one of them, the rare tellurobismuthite (Bi_2Te_3), occurs in unusually pure masses, allowing a closer study.

In co-operation with Paul W. Lange of the University of Stockholm, the author has undertaken a study of the Bi-tellurides occurring at Boliden. Part of the available material emanated from an occurrence of andalusite rock at Mångfallsberget (cf. p. 151), about 2 km N of Boliden, where one Bi-telluride is found in rather large amounts.

The preliminary results of this study[1] show that the Bi-telluride at Mångfallsberget is related to tellurobismuthite but that to some extent Bi is substituted by Sb (Analysis No. 47, p. 103). It is not yet clear whether this mineral structurally differs so greatly from tellurobismuthite that a new name is advisable. At Boliden tellurobismuthite and tetradymite have been identified, the latter by X-ray methods (by Lange). Also

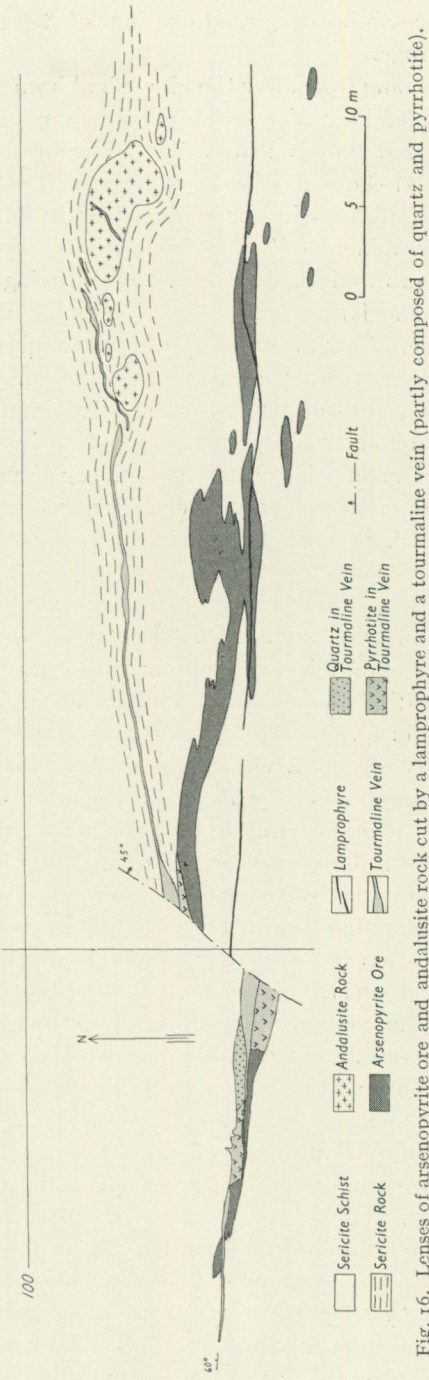

Fig. 16. Lenses of arsenopyrite ore and andalusite rock cut by a lamprophyre and a tourmaline vein (partly composed of quartz and pyrrhotite). Stope 25, 225 m level.

[1] A preliminary paper has recently been published by Lange (50).

the Sb-bearing modification of tellurobismuthite has been identified by Lange.

Some time after the above had been written a paper by C. Frondel (27) on the mineralogy of tellurobismuthite came into the hands of the writer. Frondel here definitely shows that tellurobismuthite is a distinct mineral species.

Bi-tellurides in Stope 28 (250 m level). The richest concentrations of tellurides in the mine occur in this stope. As regards the age relations of the minerals it was found that they appear in veins cutting lamprophyre dykes and rutile lenses, thus proving them to belong to the second stage.

The largest quantities of the minerals occur in the veins in the rutile lenses, where they form massive lumps weighing several kilograms. The veins are as a rule narrow or are mere cracks on which the minerals appear as thin coatings. They also occur in the shape of impregnations in the rutile rock and in the adjoining sericite rock.

The telluride masses are built up of micaceous »books» of brittle foils, attaining a diameter of max. 1 cm. The »books» are intergrown to massive aggregates which because of the silvery lustre of the minerals present really beautiful specimens.

In polished sections two telluride minerals are distinguishable even to the naked eye (Fig. b, Pl. 40). One is pure white and is identical in appearance to the tellurobismuthite from the 210 m level (see below). The analysis of the ore discloses a considerable amount of Sb and as will be shown below, the mineral in question is identical with the Sb-bearing tellurobismuthite from Mångfallsberget. Whether this modification is present throughout these telluride concentrations, or if pure Bi_2Te_3 also occurs, cannot be determined at present.

The other telluride is on the other hand faintly grayish green and is made up of tetradymite, according to an X-ray analysis by Lange.

On a few occasions there were observed thin coatings of another telluride on narrow fissures in the rutile rock, this telluride differing somewhat from those mentioned above. The mineral is silvery white but has a faint pinkish tint. It has been strongly sheared and the coatings are so thin that a microscopic study of the mineral did not reveal anything as to its nature. An analysis was made, the results of which are discussed below (Analysis No. 48).

The mixture of tellurobismuthite and tetradymite has also been analysed, the analysis being reproduced as No. 45 in Table 33, together with analyses of tellurobismuthite from the 210 m level (No. 46) and Sb-bearing tellurobismuthite from Mångfallsberget (No. 47).

In Analysis No. 45 the high content of Sb is conspicuous. No separate antimony mineral could be detected in the ore and it therefore seemed likely that Sb entered into one of the tellurides, as it does at Mångfallsberget. This could be confirmed by Lange who found that the Sb-bearing modification of tellurobismuthite was present. This is also in agreement with the analysis. If Fe is deducted as pyrrhotite and the remainder of the sulphur is combined with Bi and Te to form tetradymite, (Bi + Sb) and (Te + Se) remain in the proportions 119 : 201, which fairly well corresponds to the formula $(Bi, Sb)_2(Te, Se)_3$.

Table 33.

Analyses of Bi-tellurides.

Analyst: Th. Berggren.

Analysis No.	45		46		47		48
	%	Mol. prop. × 1000	%	Mol. prop. × 1000	%	Mol. prop. × 1000	%
Bi	52.09	249	52.48	251	46.40	222	42.93
Te	39.14	307	46.10	362	48.92	384	48.35
Se	3.63	46	0.94	12	0.58	7	2.24
S	2.50	78	0.18	6	0.13	4	0.25
As	0.05	—	0.06	—	0.10	—	nil
Sb	2.63	22	nil	—	3.92	32	nil
Cu	nil	—	nil	—	nil	—	nil
Fe	0.12	2	0.04	—	0.03	—	0.14
Ni, Co, Zn	nil	—	nil	—	nil	—	nil
Pb	nil	—	nil	—	nil	—	5.17
Ag	0.02	—	0.01	—	0.02	—	0.85
Au	0.02	—	0.04	—	nil	—	0.10
	100.20		99.85		100.10		100.03
Sp. gr.	7.580		7.209		7.061		7.71

45. Telluride ore. Stope 28, 250 m level.
46. Tellurobismuthite. Main east drift, section 14, 210 m level.
47. Sb-bearing tellurobismuthite. Mångfallsberget.
48. Telluride ore. Stope 28, 250 m level.

In Analysis No. 48, of the pinkish telluride, the high content of Pb and the low value for S are at once conspicuous. Au and Ag occur in the native state and Fe combines with part of the S. The remaining elements do not occur in proportions that fit with any known mineral. It would seem likely that either altaite (PbTe) or clausthalite (PbSe) were present but they would certainly appear under the microscope. In view of the imperfect nature of the material so far obtained, a further discussion of the identity of this mineral is fruitless, and the question will be left open.

It should finally be added that chemical tests for gold- and silver-tellurides in the telluride ore failed to indicate their presence, at least in any appreciable quantity. As will be mentioned on the following page small grains of a mineral occur which could not be identified but which may be a gold-telluride.

Gold is one of the more conspicuous megascopical components of the telluride ore. It occurs on fissures in the rutile rock, forming sheets of a maximum thickness of 2 mm. It may occasionally cover areas the size of a hand. The gold is here finely crystalline but regular crystals are never developed. Tellurides are often intergrown with the gold. The colour of the metal is deep yellow and the content of silver is probably comparatively low.

Among other minerals visible to the naked eye we note pyrite, chalcopyrite, pyrrhotite, sphalerite, arsenopyrite, and »selenokobellite». The quantities are, however, rather insignificant.

Under the microscope the tellurobismuthite sometimes seems to possess a slightly higher degree of idiomorphism than the tetradymite. The latter tends to fill the interstices between the »books» of tellurobismuthite.

A diagnosis under the microscope is hardly possible as the minerals are very similar in polished sections. Their power of reflection is very strong and of the same strength as that of some native metals. Compared with the tellurides galena is bluish gray and slightly harder. The tellurobismuthite is pure white with a creamy tint. Its reflection pleochroism is very weak and no distinct changes in colour are noticeable. The tetradymite is slightly darker than the tellurobismuthite and shows a weak pleochroism in greenish gray tones. It is also softer than the tellurobismuthite and more difficult to polish (Fig. b, Pl. 40). Both minerals are distinctly anisotropic but do not show any marked change of colour on rotating the microscopic stage. The colour is gray with yellowish and bluish tints.

Minerals such as pyrite, arsenopyrite, cobaltite, and pyrrhotite occur in rounded grains corroded by the tellurides. Chalcopyrite, galena, »selenokobellite», and two unknown minerals are also replaced by the tellurides but they are accumulated to the grain boundaries. Galena may also rarely form myrmekitic skeletons in the tellurides. Of the unknown minerals one is grayish blue in comparison with the tellurides; it is indistinctly pleochroitic but strongly anisotropic. It is softer than the tellurides. Gold is prone to associate with this mineral and forms short veinlets in it. It may be conceived that gold was formed by the decomposition of the unknown mineral, in which case it is likely to be a gold-telluride. The other unknown mineral is only present in erratic and small grains. It has a brownish red colour and weak anisotropism.

Gold is often present in microscopic grains. It may occur as presumable replacement remnants on the grain boundaries of the tellurides or in veinlets in the unknown mineral. It has also been observed in narrow veinlets cutting tellurides, indicating that at least part of the gold crystallized later than these minerals.

In fringes around pyrrhotite, or as separate grains, there occurs a mineral which in comparison with the tellurides has a gray colour. It is isotropic and slightly harder than pyrrhotite, and shows a distinct cleavage. The mineral could not be identified but it resembles gersdorffite (NiAsS) or ullmannite (NiSbS). The absence of Ni in the analysis is, however, at variance with the assumption that either of those minerals should be present.

Finally it may be observed that marcasite occurs in the pyrrhotite.

Bi-tellurides on the 210 m level. At section 14 on the 210 m level in the main east drift, there occurs, between the a-d-lens and the Eastern Ore, a rutile- and andalusite-bearing schist which is strongly sheared and cut by horizontal and vertical fissures. They are generally filled with quartz but on some occasions they also contain tellurides, gold, and kaolinite. The fissures are about 0.5 m long and only a few cm wide. The walls of the fissures are covered with »books» of tellurides, cemented together by a soft mass of kaolinite. Coarse-grained gold accompanies the tellurides.

Also in this case two tellurides are present. One of them, seemingly identical with tellurobismuthite, occurred in large foils. These were isolated and analysed, the result of the analysis (No. 46 in Table 33) proving the identity with tellurobismuthite. The other telluride is present only in small grains between the larger foils of the former. It has the same microscopic qualities as tetradymite and it is quite likely that mineral. The cleavage parallel to the basis is very distinct in both minerals. Along this cleavage there occur inlayers of a gangue mineral which may be kaolinite.

In order to ascertain the true character of the soft, white powder between the tellurides, supposed to consist of kaolinite, an analysis was carried out (Table 34). Although the content of water is rather low, it cannot be doubted that the mineral belongs to the kaolin group.

Table 34.
Analysis of kaolinite.

Analysis No. 49.

Analyst: Th. Berggren.

	%	Mol. prop. × 1000		%	Mol. prop. × 1000
SiO_2	48.1	801	K_2O	[1] nil	—
Al_2O_3	39.9	391	Na_2O	[1] 0.16	3
CaO	nil	—	H_2O	12.1	672
MgO	nil	—		100.26	

49. Kaolinite. Main east drift, section 14, 210 m level.

The mineral was also subjected to an X-ray study by O. Alvfeldt of the Boliden Research Laboratory at Stockholm. The diffraction pattern thus obtained shows a good agreement with that of kaolinite. In a recent study on the kaolin minerals by Ross and Kerr (81) it is concluded that among the kaolin minerals kaolinite is stable at the lowest temperature and generally formed by the weathering of felspathic rocks. It is added, however, that »some kaolinite is also formed by the action of sulphate-bearing or thermal carbonate-bearing waters» and that »it seems evident that kaolinite is never normally formed by waters with a very high temperature» (81, p. 151). In the present case a formation by weathering or really low-temperature solutions is out of the question. Although the temperature of formation cannot be stated, it seems likely, because of the association with tellurides, gold, quartz, etc., that in this case it was higher than indicated by the above quotation.

Among the tellurides we note small grains of gold and of a mineral bearing some resemblance to bournonite. Erratic crystals of cobaltite are also noted.

[1] Determ. spectrosc.

Impregnations of Gangue and Ore Minerals (Disseminated Ores).

Disseminated ores rarely accompany the quartz-tourmaline ores but certain mineral associations occur in connection with them which demand a further description.

Accumulations of tourmaline are often met with in the schists without any tourmaline veins occurring in the vicinity. The mineral is prone to accumulate in schlieren or veinlets. They may often be corrugated in a way resembling ptygmatic folds. The tourmaline is greenish gray in hand specimens and almost colourless under the microscope. It is believed that the tourmaline was formed by solutions emanating from the tourmaline ores.

Impregnations of ore minerals are observed in a few places but of these only those occurring in Stope 26 (250 m level) and between sections 16 and 17 on the 410 m level are of any interest.

The quartz-tourmaline veins in Stope 26 are cut by a cross vein which to a large extent is composed of »selenokobellite» together with much gold. The minerals have invaded the adjacent schist, forming a disseminated ore extraordinarily rich in gold.

The main components of the ore are »selenokobellite», galena, chalcopyrite, and gold. They form veins which invade the foliation of the schist even into the most minute folds and fissures (Fig. a, Pl. 41). A typical replacement is also noticed. In the gold-rich portions of the ore gold has a similar appearance (Fig. b, Pl. 41).

The ore minerals in general appear in the same manner as in the normal quartz-tourmaline ore and no further description is necessary. It should only be added that a mineral, probably miargyrite ($AgSbS_2$), has been observed in small grains in this ore. It has deep red inner reflection colours, is strongly anisotropic, but is distinctly lighter than pyrargyrite.

The disseminated ore on the 410 m level has a different appearance. It may be connected with a body of tourmaline occurring in the immediate vicinity. The ore minerals impregnate an andalusite-bearing sericite schist which is so strongly replaced that only minor parts of the andalusite and the quartz remain. The ore forms a fine-grained mass of essentially galena with grains of andalusite, quartz, and bundles of the tin-white »selenocosalite».

In thin sections the replacement of the gangue minerals by the ore minerals is clearly noticeable. The andalusite and the quartz have also been kaolinized and kaolin appears on veins cutting these minerals or as a narrow border between the latter and the surrounding ore minerals. Also these are cut by kaolin veinlets, built up of small scales standing vertically on the walls of the veinlets. The kaolinization is consequently a fairly late phase in the mineralization. It is not known for certain but it seems likely that this process of kaolinization was contemporaneous with the kaolinization in the andalusite rock which appears in close connection with the sericitization of this rock.

Galena is the predominant ore mineral. Two sulphominerals have been observed and one of them is obviously »selenocosalite». The other could not be

identified. The former occurs in lobe-shaped or columnar grains, sometimes accumulated to complex aggregates, and is often replaced by galena along the axis of elongation. When the grains are cut at right angles to this axis the intergrowth with galena has a myrmekitic texture. The unknown sulphomineral is darker than galena. It may be an Ag-Bi(Sb)-mineral, as a grain showed a decomposition to bismuth and pyrargyrite. Besides the minerals mentioned we also note small grains of pyrite, pyrrhotite, sphalerite, and chalcopyrite.

Summary; Order of Crystallization.

The ores of the second stage are rich in mineral species and as in the arsenopyrite ore the paragenetic conditions are also here rather complicated. The arsenopyrite ore was characterized by a number of separate mineral associations which rendered the interpretation of the sequence of crystallization and differentiation very difficult. In the present case the conditions are simpler and there are in fact only two main types of mineral associations to consider, the quartz-tourmaline phase and the sulphide phase. The two phases are closely related to one another and there is a gradation from the former to the latter.

In the original solution apatite, tourmaline, and rutile together form a group of early crystallizing minerals. The remaining solution is especially enriched in SiO_2 but it also contains all the metals, sulphur etc. The separation of the pyrrhotite-chalcopyrite phase may take place at this stage of the crystallization, the remaining solution containing mainly SiO_2, S, Pb, Bi, Te, Ag, and Au.

The crystallization of this solution begins with the formation of quartz, particulary on tail-shaped apophyses and veins. The main crystallization of the ore minerals now follows. Sericite also forms during this stage, the crystallization of this mineral being antecedent to that of the ore minerals. It is not possible to follow the crystallization of the ore minerals in detail but the sequence is essentially the same as in the arsenopyrite ore and as in sulphide ores in general. Pyrite, arsenopyrite, and cobaltite are the oldest minerals and are followed by Cu-, Fe-, and Zn-sulphides. The crystallization ends with the formation of an extensive group of minerals, as galena, sulphominerals, native metals, and tellurides. There still remains a residual solution, however, which circulates in the ores and causes processes resulting in the complex intergrowths and the veinlets with calcite, sternbergite, gold, bismuth, pyrrhotite, and other minerals. These minerals were partly formed by the decomposition of »selenocosalite» and probably also of other minerals.

The ladder veins with quartz, cutting the tourmaline bodies, are also a late formation. The source of the quartz is not certain but the appearance of the veins in the ores suggests a close genetic relationship to the latter. The quartz-filled fissures in the andalusite rock (p. 38) may be a related formation.

Returning now to the pyrrhotite-chalcopyrite phase, we find that in some places it has migrated some distance from its source in the tourmaline ore. With local exceptions tourmaline, remaining in the solution, together with quartz and most of the other gangue minerals are the first minerals to form.

They are followed by arsenopyrite and cobaltite and they in their turn by pyrrhotite, sphalerite, and chalcopyrite. Sulphominerals, bismuth, tellurides, all in insignificant quantities, and the calcite in the amygdules, are the latest minerals formed in this phase.

Pyrite Ore.

Distribution.

The main part of the Eastern and Western Ores is composed of ores formed during the third stage of mineralization. Pyrite ore is here the essential ingredient but pyrrhotite ore, quartz-felspar veins, and disseminated ores are also present.

The maps (Pl. 1—7) show the distribution of the ores and a description of the ore bodies is given in a following chapter (p. 135). It should here only be pointed out that besides in the large bodies mentioned above, pyrite and pyrrhotite ore also occurs in a number of smaller bodies on several other levels of the mine.

Relation to the Wallrock.

The ore bodies are surrounded by sericite schists, the normal and pyritic types being most common. The chloritic schist is locally developed, *e. g.* around the western faulted portion of the Eastern Ore. A chloritization is also noted within restricted portions of the wallrock in other places, either in the shape of chloritic sericite schist or as thin coatings of chlorite on the foliation planes.

The contacts between ore and wallrock are as a rule very sharp. A thin transitional zone, about 2—3 cm wide, may occasionally be developed. Only at the ends of the ore-bodies are the contacts more diffuse, the ore petering out in fringes which finally grade into impregnated wallrock. The ores are generally frozen to the walls but occasionally a clayey gouge is developed. It has in all cases been caused by later movements along the contacts.

An impregnation is often noticed in the wallrock but on the other hand it is also very common for even the nearest portions of the schist to be quite free from sulphides. When the impregnation is composed of chalcopyrite, sulphominerals, etc., disseminated ore is formed. As in the case of the arsenopyrite ore an intense felspathization has sometimes taken place at the contacts.

Felspar also appears together with quartz and various ore minerals on vein-like formations at the contacts.

The foliation of the schist generally follows the outlines of the ore bodies. Exceptions from this rule are rather common in some places, and veins or apophyses from the ore cut the foliation. These occurrences are especially plentiful in the central portion of the hanging-wall of the Eastern Ore but are occasionally met with also in other places. A further description of these interesting phenomena will be given on a later page (p. 117).

The pyrite ore often contains remnants of wallrock, in which respect it differs

from the arsenopyrite ore where such remnants were fairly uncommon. The remnants are generally composed of sericite schists but other types of rocks are also present. The occurrence of inclusions of lamprophyres is of particular importance.

Relation to the Arsenopyrite Ore.

The pyrite ore intensely brecciates the arsenopyrite ore bodies which are enclosed in the former. The arsenopyrite bodies are surrounded by brecciated zones containing inclusions of arsenopyrite ore in a more or less advanced stage of replacement. In some cases the arsenopyrite ore is traversed by clean-cut fissures filled with pyrite and sometimes also with chalcopyrite, and with hardly any traces of replacement. The inclusions may occasionally be made to match each other in the breccia. In other cases, on the other hand, the inclusions are rounded and have clearly been absorbed by the pyrite.

The base in the breccia is generally fine-grained pyrite ore but in the interior parts of the breccia zones and close to the homogeneous arsenopyrite ore the brecciating veinlets are often composed of chalcopyrite. Sulphominerals are also present though they are not so common.

The massive arsenopyrite ore is sometimes cut by veins of pyrite ore. The contacts may be sharp but generally there is a narrow zone of brecciated arsenopyrite ore developed along the walls of the veins.

The pyrite ore in the breccias and in the veins in many places displays a distinct banding, parallel to the contacts. The banding cannot have been inherited from any replaced, foliated schist as the veins often occur within the arsenopyrite bodies and strike in other directions than the wallrock. No effects of pressure are noted in the ore in the veins.

The nature of the breccia indicates that it was formed by a rupture of the arsenopyrite ore and an invasion of pyrite solution under stress. The replacing action of the solution was in some cases strong, in other cases rather insignificant.

Relation to the Lamprophyre Dykes.

In the arsenopyrite ore the lamprophyres appeared as distinctly younger, continuous dykes. Lamprophyres occur also in the pyrite ore but their appearance is different. During the detailed mapping of the stopes they could here be followed throughout the ore, although they are broken and appear in the shape of inclusions (Pl. 2—6 and Figs. 8 and 17). They are, however, confined to the Eastern Ore.

The dimensions of the inclusions vary from slabs several metres long down to barely visible pieces. As a rule the wider dykes furnish the largest inclusions.

As soon as one of the dismembered dykes leaves the pyrite ore and enters the wallrock or an arsenopyrite body, it resumes its common and continuous appearance. If the arsenopyrite ore itself is brecciated and replaced by the pyrite ore, also the dyke is brecciated.

Even though it is possible to follow the broken dykes for long distances, it also happens that gaps appear in which only the merest trace or nothing at all of the dyke is left. Displacements, measuring several metres, are also observed.

The inclusions are many a time quite regular and the immediate impression produced is that they were formed merely by the dyke being pulled apart. A detailed study shows that in reality the dykes have been extensively brecciated and replaced by the ore (Fig. b, Pl. 43). Some inclusions have the character of ghostlike remnants. The ore also enters the inclusions on fissures from which a replacement may take place. In the fissures the ore sometimes undergoes a differentiation, the inner parts being filled with chalcopyrite and quartz and the outer portions with pyrite (Fig. b, Pl. 42). The rock in the inclusions is sometimes also recrystallized and very coarse-grained.

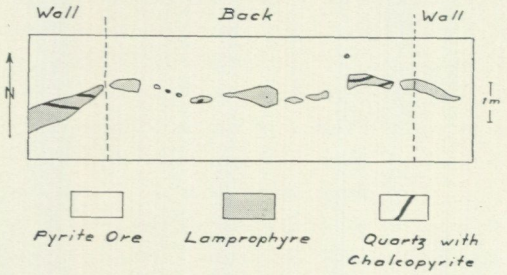

Fig. 17. Inclusions of lamprophyre in pyrite ore. Stope 3, 130 m level. (Fig. 5 in (65)).

The above observations inevitably lead to the conclusion that the lamprophyres are older than the pyrite ore. They have not only been subjected to brecciation and replacement but the positions of the inclusions suggest that the dykes were dislocated by movements that took place during the formation of the pyrite ore.

As a rule the composition of the ore suffers no changes at the contacts of the inclusions but in the gaps between them there may be coarse-grained concentrations of chalcopyrite, pyrrhotite, sulphominerals, calcite, and quartz.

The banding of the pyrite ore (see below) follows the contours of the inclusions and curves into the gaps, the ensuing structure resembling boudinage. Boudinage structure is sometimes developed also around inclusions of wall-rock.

Description of the Pyrite Ore.

It has been found that different types of pyrite ore occur, presenting variations in structure and paragenesis, but on the whole the ore is much less complicated than the two older ores (Table 42, p. 184).

The normal pyrite ore, which forms the main part of the ore bodies, is fine-grained and light yellowish and in many cases displays a parallel structure or banding. It sometimes has a very fine grain and is then of a whitish yellow colour. The colour may also change according to the preponderant mineral

in the groundmass, *e. g.* brown for pyrrhotite and sphalerite and yellow for chalcopyrite.

The banding is best developed in the massive ore but it is also seen in ore containing remnants of wallrock and arsenopyrite ore. As mentioned above the banding often smoothly follows the contours of the inclusions. Banding is also developed in veins of pyrite ore cutting the arsenopyrite ore.

A banding of the ore may also sometimes be due to band-shaped inlayers of sphalerite or to an elongate network of pyrrhotite veinlets. Streaks of galena, chalcopyrite, and sulphominerals may also produce a banded structure.

In the normal ore the pyrite grains are densely packed and the amount of groundmass is insignificant (Fig. a, Pl. 44). In a porphyritic type, found here and there in the normal type, large grains of pyrite are scattered in a groundmass of pyrrhotite (Fig. b, Pl. 44). The pyrite is here developed in octahedrons, sometimes attaining a diameter of one centimetre, whereas in the fine-grained ore the pyrite is developed in cubes.

On some occasions a very fine-grained and yellowish gray quartz-banded ore has been observed in the normal ore.

Massive pyrrhotite ore sometimes occurs at the margins of the normal pyrite ore (Pl. 2—6). It has a decided resemblance to the pyrrhotite ore of the second stage but the fact that it brecciates the pyrite ore proves it to belong to the third stage. Bands of chalcopyrite may occur and among other components visible to the naked eye we note crystals of pyrite and, on one occasion, crystals of cobaltite.

Paragenesis of the Pyrite Ore.

Ore minerals. Pyrite predominates among the ore minerals. In the normal ore the grains attain a size of 0.8—1.0 mm but the average size is about 0.3 mm. The grains are sometimes euhedral and developed in cubes. It is, however, a common feature for the grains to lack crystal form. Pyrite is one of the first minerals to crystallize and it is replaced by most other minerals. Also the octahedral crystals in the porphyritic ore are strongly corroded and replaced. As to the optical qualities of the mineral it may be mentioned that it sometimes shows a weak anisotropism.

Bismuth is present only in traces in the normal ore (cf. analyses on p. 116) but it occurs in concentrations of sulphominerals as small grains in bournonite and galena, formed by the decomposition of the sulphominerals. The bismuth is probably chemically combined in the latter or forms a solid solution.

Gold has but rarely been observed in the pyrite ore. It is associated with *e. g.* pyrite, chalcopyrite, pyrrhotite, tetrahedrite, gudmundite, and calcite.

Sphalerite is a component of the groundmass in which it on certain occasions may be the predominant mineral. It is replaced by chalcopyrite, stannite, galena, and sulphominerals.

Pyrrhotite is one of the most common components of the ore. It is later than pyrite and quartz. The relationship to sphalerite is not clear, but it seems likely that the two minerals are more or less contemporaneous. Pyrrhotite, together with chalcopyrite, is the most important component of the residual solution after the crystallization of pyrite and is often met with on veins and apophyses. It also accumulates as a later differentiate at the margins of the pyrite bodies (cf. above).

Niccolite (NiAs) is rare, but occurs in small grains in a lateral pyrrhotite body on the 210 m level.

Cobaltite has also been observed in the pyrrhotite ore where it may form small cubic crystals.

Marcasite is found as spear-shaped grains in pyrrhotite, or, rarely, as separate grains between the pyrite grains. It was most likely formed by late-hydrothermal solutions.

Arsenopyrite is frequently met with in connection with brecciated arsenopyrite ore. It sometimes forms cloudy aggregates which replace the pyrite, but it may also occur in the groundmass as euhedral grains. Most of this arsenopyrite probably originated by the mobilization of arsenopyrite ore. The pyrite may contain small euhedral crystals of arsenopyrite and in this case it should probably be considered a primary constituent of the ore. The content of As in the pure pyrite ore is on the whole rather insignificant, as shown by the analyses (p. 116).

Gudmundite is present also in the pyrite ore but on the whole more seldom than in the older ores. It replaces most of the other minerals.

Galena occurs only in concentrations of sulphominerals, where it forms the base and cuts the sulphominerals in thin veinlets. It also forms graphic intergrowths with bournonite around decomposed sulphominerals.

Chalcopyrite is one of the commonest ingredients of the ore. It may in some cases constitute the base and sometimes occurs with pyrrhotite in the marginal bodies. The chalcopyrite replaces *e. g.* pyrite, quartz, pyrrhotite, and sphalerite. — Cubanite is rare but is occasionally present. — Valleriite is plentiful in the usual small inclusions in chalcopyrite or as fringes on pyrrhotite.

Pyrargyrite is exceedingly rare and was observed in one case only. Its presence was established by M. Scherbina of the University of Berlin.

Sulphominerals (boulangerite, jamesonite, falkmanite, bournonite, tetrahedrite, etc.). As mentioned above the ore occasionally contains schlieren of sulphominerals. They are often accumulated to the margins of the ore bodies. Their appearance shows that they are the latest minerals. In their mutual relations they do not differ from the related sulphominerals in the arsenopyrite ore. The sulphantimonites occur in elongate prismatic grains, intergrown to bundles and replaced along their axis of elongation by galena, bournonite, and tetrahedrite. The latter form a graphic intergrowth surrounding the sulphantimonites and were formed by their decomposition

under addition of copper. An older generation of tetrahedrite is also present and decomposes to bournonite, sphalerite, and gudmundite.

Stannite (Cu_2FeSnS_4) is not plentiful but it is one of the typical minerals of the pyrite ore. It is on the whole a frequently occurring mineral in some of the ores of the Skellefte District (29, 67). At Boliden it is strictly confined to three minerals, *viz.* sphalerite, pyrrhotite, and chalcopyrite. The one first mentioned is distinctly replaced by stannite. Chalcopyrite on the other hand replaces the stannite as is evident from its appearance in this mineral in the shape of small irregular grains. In pyrrhotite the mineral is found in small rounded grains which do not give any clear idea as to the age relationship. The optical properties of the mineral are typical of stannite. The presence of tin in some samples of stannite-bearing ore has also been chemically proved.

Finally the presence of magnetite should be mentioned, a mineral on the whole exceedingly rare in the Boliden ores. In the pyrite ore it has been encountered on a few occasions, when it occurs as small rounded grains, often containing inclusions of pyrite, arsenopyrite, and even gold in one case.

Gangue minerals. Quartz is the most important of the gangue minerals, and it often constitutes the main part of the groundmass. It is as a rule fine-grained and replaces the pyrite except in a few rare cases, where the quartz evidently is older. It is quite likely that it here represents unreplaced remnants of wallrock. Feather quartz of the same appearance as in the arsenopyrite ore (p. 52) is sometimes developed in the pyrite ore. Lamellar quartz grains form fairly regular coronas around idiomorphic pyrite crystals. As in the case of the feather quartz in the arsenopyrite ore, it is also here believed that the texture primarily is a phenomenon of growth and that stress only played a minor part in its formation.

Calcite occurs in small grains in almost every sample and in exceptional cases it even forms the groundmass of the ore. Then it is a late crystallizing mineral. It sometimes occurs in coarsely crystalline spots together with some hornblende, galena, and sulphominerals. The spots are arranged in zones which can be followed for considerable distances in the pyrite ore. This calcite is older than the ore minerals and it is quite probable that it originally constituted a calcareous zone in the volcanic rocks. Also in the pyrrhotite ore some very coarse-grained pieces of a carbonate mineral have been seen. An analysis of carbonate from a pyrrhotite ore on the 210 m level gave the following values (Table 35). The contents of MgO and FeO are rather high and the mineral should be considered a fairly iron-rich dolomite[1].

Hornblende is generally present but only in small quantities. Exceptions are known and in some cases a pyrite ore has been observed containing abundant, about 1 cm long, grayish green or colourless bundles of hornblende.

[1] According to analyses, quoted by Doelter (20, pp. 371—376), the content of FeO is too low for ankerite.

Under the microscope the mineral is colourless and has an extinction of 15—18° (c: γ). —2V varies from 81—87°. The indices of refraction are:

$\alpha = 1.610$ ($\pm$ 0.002); $\beta = 1.616$ ($\pm$ 0.004); $\gamma = 1.630$ ($\pm$ 0.003); $\gamma - \alpha = 0.020$

The hornblende grains are impregnated with pyrite and probably crystallized earlier than that mineral. The hornblende is replaced by calcite and quartz.

Table 35.

Chemical composition of carbonate.

Analysis No. 50.

Analyst: Th. Berggren.

	%	% [1]	Mol. prop. × 1000	
SiO_2	0.13	—	—	
TiO_2	0.02	—	—	
Al_2O_3	0.77	—	—	
Fe_2O_3	0.14	—	—	
$H_2O^{+105°}$	0.54	—	—	
FeO	2.54	3.3	46	
MnO	0.65	0.8	11	1,049
CaO	26.82	34.6	617	
MgO	11.70	15.1	375	
CO_2	35.88	46.2	1,050	
Sulphides	21.08	—	—	
	100.27	100.0		

50. Carbonate. Stope 14, 210 m level.

Plagioclase. An interesting feature of the pyrite ore is the occasional occurrence of plagioclase crystals. They attain a length of maximum 1 cm and are often quite fresh and idiomorphic (Fig. a, Pl. 45). Occasionally the borders or even the interior parts of the crystals are decomposed and minerals such as zoisite and chlorite have been formed. The plagioclase is an early mineral and has been replaced even by the pyrite. It is generally very basic, the composition varying between a labradorite with 60 % An and an almost pure anorthite. In one case the composition was Ab_{70} An_{30}.

Sericite and chlorite are spread throughout the pyrite ore but are generally only present in insignificant quantities. The chlorite is as a rule gray and non-pleochroitic under the microscope; occasionally grayish green chlorite, showing a weak pleochroism, is also present.

Rutile, apatite, and tourmaline, partly very common minerals in the earlier stages, are seldom present. Rutile has thus never been seen in the normal ore but is met with in pyrrhotite ore and in the quartz-

[1] Recalculated to 100 %.

felspar veins accompanying the ores. Titanite has, however, been observed in a few cases. — Apatite occurs in small grains in the quartz groundmass and the mineral undoubtedly belongs to the paragenesis. — Tourmaline is very rare but has been observed under circumstances indicating that it quite likely is a primary constituent of the ore.

Hisingerite (hydrous Fe-silicate). Concretionary formations of hisingerite, attaining the size of a walnut, have on a few occasions been found in the pyrite ore. Hisingerite may also occur on veinlets cutting the ore and indicating the late formation of the mineral. The interior of the concretions is composed of a partly slightly brownish carbonate. The mineral is somewhat turbid under the microscope, probably due to a beginning decomposition. As the carbonate effervesces for cold dilute hydrochloric acid, it is most likely calcite, though possibly containing some iron. The calcite is replaced by two different kinds of hisingerite, one appearing on veins mainly in the interior of the concretions and the other appearing essentially in their marginal portions. The calcite is cut by veinlets of sulphides which have been retained in the hisingerite and thus are apt to produce the erroneous impression that the sulphides are later than the hisingerite. The hisingerite in the interior portions of the concretions is brown and partly isotropic. It is very fine-grained and in some parts amorphous. In the outer portions, on the other hand, the brown hisingerite grades into a blackish substance with conchoidal fracture. Under the microscope this substance is dark brown and partly amorphous, partly anisotropic. It is also faintly pleochroitic. The extinction is straight and the optic character negative. The optic angle is small. The refringence is less than that of Canada balsam. Both these substances are considered to be composed of hisingerite but with varying chemical compositions.

The mineral has been compared with hisingerite from Riddarhyttan and Dannemora. The material from Dannemora, collected by Prof. Quensel, was very similar to that from Boliden and the hisingerite had evidently been formed by the replacement of a carbonate.

The hisingerite at Boliden cannot have been formed by the influence of percolating surface waters. No supergene alteration takes place in the deposit and cannot be expected at the depth where hisingerite has been found, 112 m. It is believed, instead, that the mineral was formed by silica-bearing late-hydrothermal solutions which circulated in the ore body.

A very similar occurrence of hisingerite has been described by Hewett and Schaller (37) from the Mineral Hill District, Blaine County, Idaho. As at Boliden, the hisingerite replaces a carbonate (siderite) and according to the authors mentioned it was formed by the alteration of siderite by hot-spring waters probably of hypogene origin.

Garnet, biotite, and zircon, finally, are extremely rare minerals in the pyrite ore.

Chemical Composition of the Pyrite Ore.

Table 36 shows the chemical composition of a number of hand specimens of pyrite ore. The first four analyses (Nos. 51—54) represent normal pyrite ore, the fifth analysis (No. 55) being of a pyrrhotite ore belonging to the third stage.

Table 36.

Chemical composition of pyrite ores.

Analyst: A. G. Hybinette.

Analysis No.	51	52	53	54	55	Analysis No.	51	52	53	54	55
SiO_2 . . .	14.70	11.30	8.48	10.40	12.80	Cu . . .	0.92	0.86	0.09	0.63	1.15
TiO_2 . . .	0.01	0.01	0.01	0.01	0.06	Pb . . .	tr.	tr.	0.28	tr.	0.02
Al_2O_3 . .	0.07	0.12	0.07	0.09	0.22	Bi	tr.	tr.	tr.	tr.	0.02
Fe	38.15	37.44	41.39	39.30	50.90	Ag . . .	tr.	tr.	tr.	tr.	tr.
MnO . .	0.01	0.04	tr.	0.02	tr.	Au . . .	tr.	tr.	tr.	tr.	tr.
CaO . . .	0.10	2.32	0.34	0.05	0.03	Hg . . .	tr.	tr.	tr.	tr.	tr.
SrO . . .	nil	tr.	nil	nil	nil	Sn	0.04	0.05	tr.	tr.	tr.
BaO . . .	tr.	tr.	tr.	tr.	tr.	As	0.18	0.83	0.29	0.08	0.07
MgO . .	0.13	0.76	0.08	0.12	0.05	Sb	nil	0.07	0.18	tr.	tr.
Na_2O . .	tr.	0.01	tr.	tr.	0.01	Co . . .	tr.	tr.	tr.	tr.	tr.
K_2O . . .	0.64	0.62	0.56	0.60	0.69	Ni	nil	nil	tr.	nil	tr.
$H_2O^{-105°}$.	0.07	0.08	0.10	0.06	0.08	Zn	1.09	1.08	0.26	2.35	0.02
$H_2O^{+105°}$.	0.23	0.43	0.20	0.51	0.13	Se	0.02	0.02	0.08	tr.	0.11
Cl	nil	nil	nil	nil	nil	Te	tr.	tr.	nil	nil	tr.
F	0.01	nil	nil	nil	0.02	S	44.05	42.75	47.44	46.00	33.60
P_2O_5 . . .	0.05	tr.	tr.	tr.	tr.		100.55	100.07	100.07	100.31	100.04
CO_2 . . .	0.08	1.28	0.22	0.09	0.06						
ZrO_2 . . .	nil	nil	nil	nil	nil						
Sp. gr. . .	4.41	4.33	4.63	4.51	4.07						

51. Pyrite ore. Stope 9, 130 m level.
52. Pyrite ore. Stope 5, 130 m level.
53. Pyrite ore. Stope 21, 130 m level.
54. Pyrite ore. N of the e-lens, 50 m level.
55. Pyrrhotite ore. Stope 11, 210 m level.

A mere glance at the analyses discloses the preponderance of the Fe-sulphides. Among the other ore minerals present only sphalerite and in some cases also chalcopyrite occur in any quantity. The gangue-forming oxides are present in small quantities only, except SiO_2 which in the form of quartz is the only gangue mineral present in any appreciable amount.

Apophyses.

General. Apophyses and veins of massive sulphides are typical features along the ore contacts at Boliden. They reach their most characteristic development, however, in the third stage.

The apophyses at the contacts of the pyrite ore appear in particular abundance along the central portions of the Eastern Ore between sections 9 and 13. They do occur at other places along the Eastern Ore as well and also at the Western Ore, but as a rule they are scarcer in these places. At the ends of the ore bodies the apophyses are lacking, the ore contacts here being diffuse and evidently formed by replacement.

The apophyses have been studied in great detail in the stopes, especially in those on the 210, 130, and 90 m levels. They are wedge- or lens-shaped bodies, composed of mainly massive Cu-Fe-sulphides, which emanate from the main ore body, cutting sharply across the foliation of the wallrock. In sections cut at right angles to the direction of strike of the ore and the wallrock the wedge-shape of the apophyses is generally quite distinct (Figs. 18, 19, and 20). In sections parallel to the strike, on the other hand, the apophyses form elongate lenses, often arranged *en échelon*. The direction of the apophyses varies, but as a rule they have a horizontal or a vertical position.

There are also variations in the size of the apophyses. Some are only a few cm in length and width at the base close to the ore and peter out rapidly. Others are larger and at their base attain a length of several metres and a width of about 1—2 m. They may be followed several metres at right angles from the ore before they peter out.

The apophyses sharply cut the foliation of the wallrock, that rock in most cases being composed of a normal sericite schist. Impregnations are practically absent at the contacts and only thin coatings of chalcopyrite, pyrrhotite, or gold are found on the planes of foliation. Inclusions are often encountered in the apophyses. The most common ones are of arsenopyrite ore. Some of them may still be very sharp but others are strongly absorbed and replaced by the surrounding sulphides. It is interesting to note that arsenopyrite ore is generally lacking in the wallrock around the apophyses and may also be absent in the neighbouring pyrite ore, so the inclusions must have been transported from unknown sources into the apophyses during their formation. Inclusions of sericite schist are also found. A typical case is illustrated in Fig. a, Pl. 42—43. The inclusions are here, as in most other cases, quite sharp-edged and free from disseminated sulphides. As is shown in the figure, the foliation of the inclusions does not coincide with that of the wallrock and they have obviously been turned and also transported some distance.

The apophyses are composed of fine- to medium-grained massive sulphides, either chalcopyrite or pyrrhotite as a rule being the predominant mineral, generally the former. Pyrrhotite may occur in the chalcopyrite in the shape

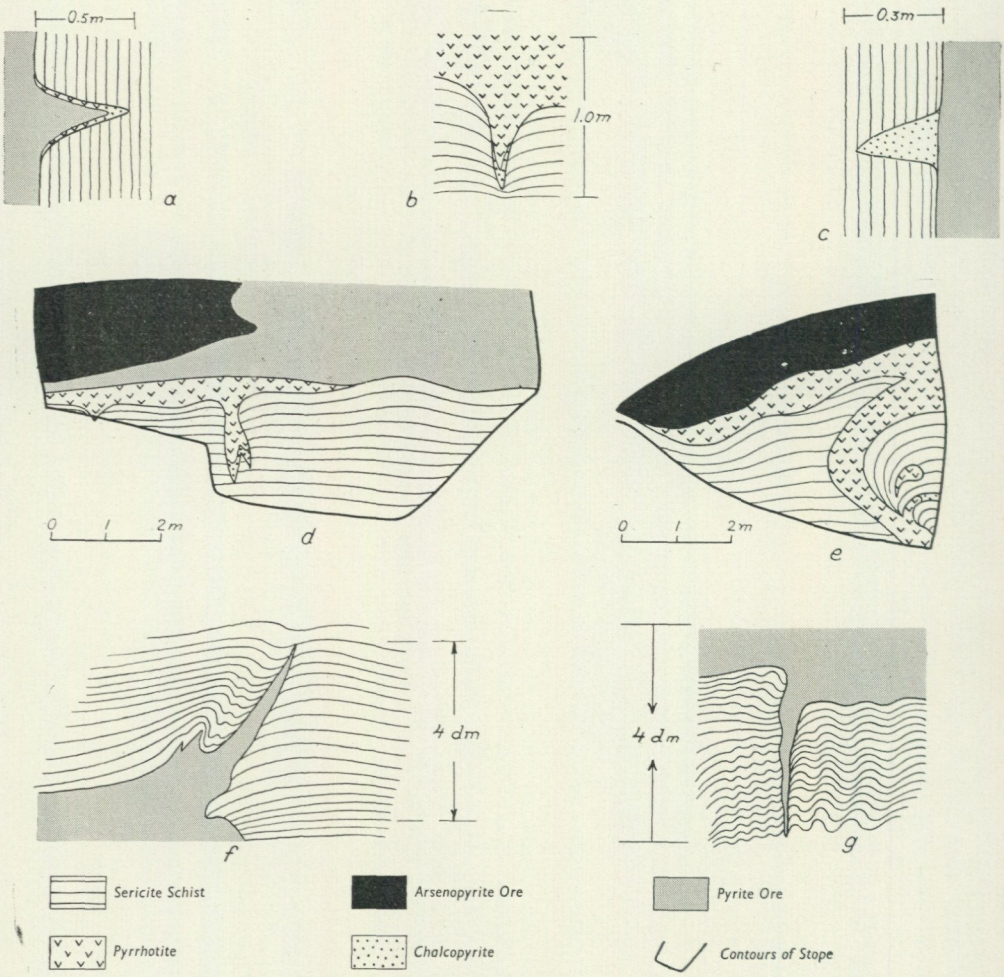

Fig. 18. Apophyses along the contacts of the pyrite ore.

of narrow bands which in a cross section have the appearance of a cone-in-cone structure (Fig. 19), or it may accumulate in a narrow zone along the margins of the apophysis (Fig. 18 a). In rare cases pyrite may be the predominant component (Fig. 18 f and g), other minerals such as chalcopyrite, quartz, and gold sometimes being concentrated at the end of the apophysis. In some cases pyrite occupies only the basal part of the apophysis, forming a wedge-shaped body which soon peters out (Fig. 18 a). The contact to the interior part, filled with chalcopyrite, is indistinct, and the pyrite grains gradually disappear.

An interesting fact is that the minerals in the apophyses as a rule display no rupturing or shearing. Locally, where movements have taken place along faults, the minerals have been crushed and the ore is fissured. The crystalli-

zation of the apophyses seems to have proceeded without any noticeable disturbances.

Somewhat different in their development are two apophyses which appeared in the open pit at section 3 in the Western Ore and an apophysis in Stope 3 on the 130 m level. They all appeared in the footwall. The apophyses in the open pit could not be studied in the precipitous walls, but a picture of them

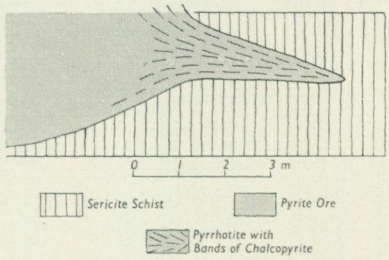

Fig. 19. Apophysis with cone-in-cone structure. Stope 3, 130 m level.

taken from across the pit is reproduced in Fig. b (Pl. 46). The apophysis in Stope 3 is described in detail below.

It is mainly composed of pyrite and as shown in Fig. 20 it occurs in a fold-shaped curvature in the footwall. The wedge-shaped body of pyrite smoothly punches the folded schist, cutting the foliation. At the outmost portion of the fold the sericite schist is strongly corrugated and broken along a fault zone along which small veinlets of chalcopyrite and pyrrhotite appear. In the fault zone there also appears a narrow vein with quartz and various sulphides which could be followed for a distance of several metres.

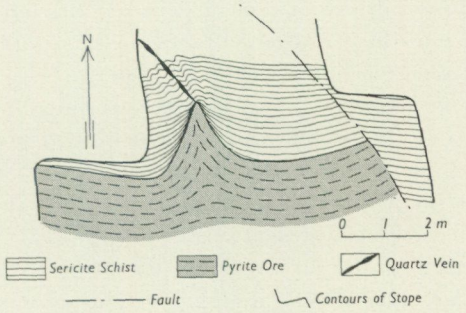

Fig. 20. Apophysis in Stope 3, 130 m level.

The ore in the apophysis was of the same character as the normal pyrite ore. It also displayed a banding which smoothly followed the contours of the fold.

It may finally be added that from the pyrite ore in the fold small horizontal fissures ran into the sericite schist which were filled with chalcopyrite and which had the same wedge-shape as the normal apophyses in the hanging-wall (Fig. b, Pl. 45). The chalcopyrite was unusually coarse-grained and

contained exceptionally much gold. Sharp-edged inclusions of sericite schist occurred in the chalcopyrite.

The apophyses are closely related to the pyrite ore bodies, both as regards appearance and mineralogical composition. The latter is characterized by chalcopyrite and pyrrhotite, minerals which crystallized comparatively late and generally form the groundmass of the pyrite ore. The apophyses are interpreted to have been formed by residual solutions from the ore bodies, those solutions being squeezed out into fissures in the walls by deformational forces active during the crystallization of the ore solution.

Paragenesis. The mineralogical composition of the apophyses is comparatively simple and the following description can be made brief.

Chalcopyrite crystallized somewhat later than pyrrhotite and replaces it. In the coarsely crystalline chalcopyrite the pyrrhotite may occur as elongate, winding grains on the grain boundaries. In this form the mineral seems to be later and has probably been formed by unmixing. The pyrrhotite may also form lamellate grains in the chalcopyrite, possibly representing decomposed lamellae of cubanite.

Cubanite, valleriite, and sphalerite are present in about the same proportions as in the pyrite ore.

Pyrite forms rounded, distinctly replaced grains. — Marcasite has rarely been found in the pyrrhotite. — Arsenopyrite is most plentiful in the aforementioned inclusions of arsenopyrite ore but may also occur in small grains in chalcopyrite or pyrrhotite. In the inclusions the mineral is generally strongly recrystallized and forms a framework of small, idiomorphic crystals. — Gudmundite has the same appearance as in the normal pyrite ore.

In comparison with what is the case in the pyrite ore, gold is strongly enriched in the apophyses. It is particularly evident in chalcopyrite or as thin coatings in the sericite schist at the contacts to the apophyses.

Stannite is rarely seen in chalcopyrite or sphalerite. — Sulphominerals are present but there is no marked concentration of these minerals. Boulangerite has been identified and the presence of falkmanite and jamesonite is suspected. The minerals form intergrowths of the same type as described before. In the intergrowths small quantities of bournonite, tetrahedrite, galena, bismuth, and bismuthite are also present.

Small grains of magnetite occur in a few cases.

Gangue minerals are rare in the apophyses, but erratic grains of quartz, sericite, chlorite, calcite, plagioclase, hornblende, titanite, tourmaline, and apatite have been encountered. The microscopic study shows that all of them, except calcite, are older than chalcopyrite and pyrrhotite. Calcite is distinctly later, and it is well demonstrated in polished sections that it replaces ore minerals (Fig. a, Pl. 46). — Plagioclase is rare and has been observed only in a chalcopyrite apophysis in Stope 9 (130 m level). The mineral formed clear and fresh grains about 1 cm large, showing good crystal outlines and a grayish colour. The composition is $Ab_{74}An_{26}$. — Apatite is as a rule very

rare but in one case it was found in large grains in connection with inclusions of apatite-banded arsenopyrite ore. It most likely derives from that ore.

Sulphide-bearing Quartz-Plagioclase Veins.

In connection with the pyrite ore there occur vein-like formations of quartz with varying amounts of plagioclase and sulphides. They appear at the ore contacts and continue for some distance into the walls. They are mainly distributed along the central portions of the ore bodies and are absent at their ends. As a rule the veins are small, the largest attaining a length of about 10—12 m and a width of 3—4 dm.

The plagioclase in the veins forms grayish green tabular crystals, 3—4 cm large, generally of a fresh appearance. Occasionally the mineral is of a gray colour, in which case it is still less altered than the grayish green type. In connection with veinlets of sulphides cutting the plagioclase, minerals such as sericite, chlorite, a fibrous hornblende, and calcite are developed in turbid spots. A number of measurements were carried out in order to determine the composition of the plagioclase and values varying between 27 and 37 % An were obtained. The refractive indices were determined on two plagioclases:

$\alpha = 1.543$	$\alpha = 1.546$
$\beta = 1.547$ ($\pm$ 0.002)	$\beta = 1.550$ ($\pm$ 0.002)
$\gamma = 1.550$	$\gamma = 1.554$
An = 28 % (calc.)	An = 33 % (calc.)
An = 32—33 % (meas.)	An = 32—35 % (meas.)

An analysis was made of a particularly pure plagioclase from a vein in Stope 9 on the 130 m level, the result of which is given in Table 37 below.

A calculation of the composition of the mineral founded on the analytical data gives: Or = 1.0 %, Ab = 65.2 %, and An = 33.8 %. On the universal stage the composition was found to be: Ab = 72 % and An = 28 %.[1] There is a notable excess of SiO_2 in the analysis which is due to a certain amount of quartz which could not be separated from the analysed material. It is of interest to note that in the ore, a short distance from this quartz-plagioclase vein, there occurred grains of plagioclase showing a considerably higher content of An, *viz.* 60—65 %.

In one case the plagioclase in a vein had a more basic composition than usual, the An-content varying between 68 and 75 %. The mineral formed rather well-shaped crystals which were surrounded by sharply delimited zones composed of plagioclase with 31—34 % An.

It may finally be added that in some of the veins felspar is completely lacking, quartz being the only gangue mineral present. These veins often attain

[1] Measured in section $\perp$ P and M.

a larger size than the plagioclase-bearing ones and have been indicated on the maps (Pl. 3 and 4)[1].

The quartz in the veins is coarsely crystalline and fills the interstices between the plagioclase grains. The latter are replaced by the quartz. Quartz on the other hand, is replaced by the sulphides. — Calcite is occasionally present between the plagioclase grains or cuts this mineral in narrow veinlets. At least part of the calcite is very late, as it is seen to cut also the sulphides. — Tourmaline is sometimes present in erratic needles. In a few cases the mineral is accumulated in schlieren which penetrate the quartz-plagioclase mass irrespective of the grain boundaries. — Apatite, titanite, and rutile are rarely present in the veins.

Table 37.

Chemical composition of plagioclase.

Analysis No. 56.

Analyst: Th. Berggren.

	%	Mol. prop. × 1000		%	Mol. prop. × 1000
SiO_2	59.68	994	MgO	nil	—
TiO_2	nil	—	Na_2O	7.15	115
Al_2O_3	25.12	246	K_2O	0.15	2
Fe_2O_3	0.23	1	$H_2O^{-105°}$	0.17	—
FeO	0.10	1	$H_2O^{+105°}$	1.00	56
MnO	0.02	—	S	0.04	1
CaO	6.31	113	P_2O_5	nil	—
BaO	nil	—		99.97	
			Sp. gr. = 2.65		

56. Plagioclase. Stope 9, 130 m level.

The sulphides are distinctly later than quartz and plagioclase and occur on fissures or along cleavage planes. In certain cases the ore minerals serve as a groundmass for the idiomorphic plagioclase (Fig. a, Pl. 47). The formation of sericite and chlorite, etc., along the sulphide veinlets has already been mentioned. Chalcopyrite and pyrrhotite are the most common minerals but small amounts of galena, sphalerite, stannite, sulphominerals, and others are also present.

Stannite occurs in unusually large grains. It replaces sphalerite and probably also pyrrhotite. In chalcopyrite it is found either as replacement remnants or as beautifully star-shaped grains, very similar to the star-shaped grains of sphalerite often met with in chalcopyrite (Fig. c, Pl. 48).

Among the sulphominerals we note falkmanite, jamesonite, and probably

[1] Indicated with a »P».

also boulangerite (?). They form the usual intergrowths with bournonite, tetrahedrite, galena, bismuth, and bismuthite.

Gold appears together with the other ore minerals in veinlets cutting the quartz-plagioclase mass. It sometimes forms unusually coarse wires in the plagioclase.

The coarse development of the quartz and the plagioclase in the veins gives them an almost »pegmatitic» aspect. Their occurrence at the ore contacts and their mineralogical composition in general indicate that they constitute a differentiate of the pyrite ore.

Felspathization and Disseminated Ores.

In some places the wallrocks are impregnated with ore minerals and contain later gangue minerals. This particularly takes place at the ends of the ore bodies.

Among the gangue minerals formed at the ore contacts we note chlorite, plagioclase, and quartz.

Chlorite may occasionally form as thin coatings on planes of foliation in the sericite schist, but it can also locally transform the rock to a chloritic schist.

The formation of the plagioclase is rather typical. It should be pointed out that it took place also during the first stage (p. 66). The plagioclase is generally localized to the immediate neighbourhood of the ores but it may also appear several metres from the ore contact. As a rule the mineral forms rounded aggregates which sometimes display a radiate texture and obviously grow at the expense of the surrounding sericite schist. The texture is of the same type as characterized the plagioclase at the arsenopyrite ore. The felspathization of the wallrock is sometimes so far advanced that a medium-grained crystalline rock results, to a certain degree resembling an igneous rock.

The texture of the rock can be said to be hypidiomorphic granular, the plagioclase grains showing a varying degree of idiomorphism (Fig. b, Pl. 47). The interstices are filled with quartz, calcite, or chlorite. The ore minerals present replace the other components.

Under the microscope the grayish plagioclase is often found to be fresh. The mineral is frequently zonal, the interior, more basic parts showing a slight decomposition. The composition of the plagioclase consequently varies, values between 20 and 45 % An being the most common. Occasionally the An-content is much higher, the mineral having the composition of bytownite; in one exceptional case the plagioclase contained only 3 % An.

As a similar felspathization also accompanies the arsenopyrite ore, it may often be difficult to determine whether a felspathized rock belongs to the third or to the first stage of mineralization. As a rule the plagioclase at the contacts of the arsenopyrite ore seems to be richer in An than at the pyrite ore, and on this basis a classification is generally possible. The cases mentioned

above, where the plagioclase had a bytownitic composition, are therefore rather doubtful and the mineral may belong to the arsenopyrite stage.

Quartz has also been introduced in some places at the ore contacts, especially at the ends of the ore bodies. The sericite and chlorite of the schist are then replaced by quartz and the resulting rock obtains a cherty appearance.

Among the ore minerals that form in the disseminated ore pyrite is the most important. When it occurs in parallel streaks in the sericite schist the ensuing rock resembles the pyritic sericite schist and has been mapped as such.

We also note the presence of chalcopyrite, pyrrhotite, and in rare cases also of tetrahedrite, gold, and sulphominerals.

Inclusions of Wallrock.

It has been mentioned previously that inclusions are comparatively abundant in the pyrite ore. The detailed mapping of the stopes showed that inclusions may occur almost anywhere in the ore, but it has been found that they follow certain zones in which they are particularly abundant and which can be followed for some distance. This is true practically only of the Eastern Ore, for in the Western Ore inclusions on the whole are rarer. The inclusions vary in size from »horses» several metres in length down to mere fragments. The replacement is sometimes very pronounced.

One distinct zone with inclusions is found between the 90 and 130 m levels at sections 10—13 in the centre of the ore body. Towards the 90 m level it gradually approaches the footwall. Another zone appears between the 170 m and 210 m levels in the centre of the ore at sections 10—12. The inclusions are here on the whole rather small and are accumulated to a distinctly delimited zone. During a great part of its course it accompanies inclusions of lamprophyre. The surrounding pyrite ore is distinctly banded.

Where the banded ore appears around the inclusions a boudinage structure is developed as around the inclusions of lamprophyre. It was formed by the ore being pressed into the gaps between the inclusions. As there are no traces of shearing or rupture, the process took place during quiet conditions while the ore was in a plastic state. The inclusions may also contain narrow ladder veins standing at right angles to the direction of strike of the inclusions and filled with quartz, chalcopyrite, and sulphominerals.

As a rule the inclusions are composed of normal sericite schist, sometimes pyritic where the impregnation is strong. The content of chlorite is in some cases appreciable, and occasionally the rock has a quartz-porphyritic texture. In one case an inclusion was composed of black phyllite.

Among the inclusions there has been observed a type of altered rock never previously met with in the deposit. In one case, in Stope 21 on the 90 m level, the same kind of rock constituted the wallrock of the ore.

The rock in question is fine-grained and has a dark gray or greenish gray colour. It is slightly foliated. The main components are quartz and chlorite

and the rock may consequently be classified as a chloritic schist. The chlorite appears in fine-grained bands or in scattered foils. It is faintly pleochroitic in grayish green colours. The quartz often has a rather uneven grain. Here and there remnants of turbid, chloritized felspar are seen. As to composition, it is a basic plagioclase with about 70—75 % An.

A most characteristic component is a faintly green, isotropic mineral with high refringence, occurring in grains showing a (111) cleavage. It is sometimes present in grains visible to the naked eye. The mineral is most likely gahnite, or zincspinel. It is altered to a greenish, weakly anisotropic and uniaxial negative mineral very similar to serpentine.

In close association with the spinel there occurs a dark-brown, faintly pleochroitic mineral which could not be identified. It is but seldom present and occurs in insignificant grains. The mineral is uniaxial (or has a very small optic angle) and negative. Some grains are columnar and somewhat fibrous with a cleavage parallel to the elongation. The refringence is of the same magnitude as that of spinel; the birefringence is weak. The mineral often forms plates, covering the octahedron faces of the spinel. It may also form incomplete pseudomorphs after this mineral.

Among other constituents we note a phlogopitic mica, epidote, clinozoisite, greenish hornblende, calcite, zircon, apatite, and ore minerals. The latter are mainly sulphides but ilmenite and magnetite are also present. Lamellar grains of ilmenite are intergrown with calcite to an octahedral pattern, probably formed by the alteration of titanite. This is the only occasion on which ilmenite has been found in the deposit. Magnetite forms unusually large grains, which, however, lack crystal outlines and are filled with small grains of gangue minerals and sulphides. Among the sulphides pyrite is the most conspicuous.

This rock is entirely restricted to the inclusions and to a local occurrence as wallrock in Stope 21. Its close association with the pyrite ore indicates that it originated from portions of the sericitic rocks which were enclosed in the pyrite ore and were altered by emanations given off during its formation.

The rock here described is suggestive of some rocks from the Bjurträsk and Bjurliden deposits recently described by S. Gavelin (29).

Apophyllite-bearing Fissures.

In about half a dozen cases apophyllite-bearing fissures have been observed in the deposit. The pyrite ore as well as the arsenopyrite ore and the wallrock are cut by the fissures and it thus seems obvious that they form the last manifestation of mineralization in the deposit. Their time of formation cannot be definitely stated but it seems likely that it was at the close of the third stage.

The fissures are generally only a few mm wide and are filled with clear and rather coarsely crystalline aggregates of apophyllite.

In the hanging-wall of Stope 5 on the 118 m level the fissures were vein-

shaped and somewhat more complicated. The largest fissure was about 3 cm wide and cut the sericite schist at the ore contact. It had a symmetrical structure and was built up of a gray and finely fibrous mass which grew out from the walls in two layers of uniform thickness. They met at the middle of the fissure where aggregates of well crystallized and glassy apophyllite sometimes appeared (Fig. a, Pl. 48). The aggregates often presented a rhombic cross section and were built up of radiate, thin, lamellar crystals.

Table 38.

Chemical composition of apophyllite-bearing fissure.

Analyst: Th. Berggren.

Analysis No.	57		58		59	
	%	Mol. prop. × 1000	%	Mol. prop. × 1000	%	Mol. prop. × 1000
SiO_2	51.16	852	51.90	864	52.21	870
TiO_2	0.19	—	nil	—	—	—
Al_2O_3	4.04	40	nil	—	0.46	5
Fe_2O_3	0.17	—	nil	—	—	—
MnO	nil	—	nil	—	—	—
CaO	23.04	411	25.24	450	25.16	445
MgO	0.04	—	nil	—	—	—
Na_2O	0.63	10	0.53	9	0.63	10
K_2O	4.98	53	4.69	50	4.82	51
$H_2O^{-105°}$	0.06	—	0.14	—	—	—
$H_2O^{+105°}$	15.19	843	16.53	918	16.49	915
P_2O_5	nil	—	nil	—	—	—
Cl	nil	—	nil	—	—	—
SO_3	nil	—	nil	—	—	—
CO_2	nil	—	nil	—	—	—
F	1.23	65	1.70	90	1.40	74
	100.73		100.74		101.17	
− O = F	0.52		0.71		0.59	
	100.21		100.03		100.58	
Sp. gr.	2.365		2.361		2.371	

57. Fibrous intergrowth between sericite and apophyllite. Stope 5, 118 m level.
58. Apophyllite. Stope 5, 118 m level.
59. Apophyllite. St. Andreasberg, Germany. No. 3 in (32, p. 597).

The microscopic study of the fine-grained mineral mass showed that it was composed of elongate blades of apophyllite intergrown with small scales of sericite arranged in streaks. The fibrous mass grows at right angles to the walls. An interesting fact is that small grains of apatite and needles of a colourless tourmaline were contained in the mass of sericite and apophyllite.

The occurrence of these minerals, supposed to be formed at comparatively high temperatures, in association with such a decidedly low-temperature mineral as apophyllite is rather astonishing. The presence of small grains of rutile and calcite is also noted.

Chemical analyses were made of both the pure apophyllite and of the intergrowth of apophyllite and sericite (Table 38).

The content of Al_2O_3 in Analysis No. 57 is explained by the presence of sericite. In spite of the occurrence of apatite no phosphorus is shown in the analysis. It may depend on the grains of apatite being so rarely present in the analysed material that the mineral was insufficient to be detected by ordinary analytical methods. Analysis No. 58 which was carried out on pure material shows good agreement with four recent analyses of apophyllite published by Gossner and Kraus (32)[1] and with the formula $KF \cdot Ca_4(Si_2O_5)_4 \cdot 8H_2O$ given by these authors.

Summary; Order of Crystallization.

Compared with the earlier mineralizations in the deposit the pyrite ore is a fairly homogeneous and simple formation (Table 42, p. 184). The only individual differentiates are the apophyses and the quartz-plagioclase veins which undoubtedly were formed by solutions given off by the crystallizing ore.

When discussing the crystallization in the other stages, an endeavour was made to divide the paragenesis into groups of minerals related to each other as regards their order of crystallization. In the less complicated pyrite ore this division is considerably easier to accomplish.

A group of early crystallizing minerals is made up of hornblende and plagioclase, which are distinctly replaced by the other minerals, including also the pyrite.

The main crystallization of the pyrite then follows. The idiomorphic arsenopyrite crystals, enclosed in the pyrite, were probably formed at about the same time. These minerals are veined and replaced by a large number of minerals, *viz.* quartz, calcite, pyrrhotite, chalcopyrite, and others.

After the crystallization of the pyrite there remains a residual solution containing Cu, Fe, Zn, Pb, Bi, Sb, etc., and also large quantities of SiO_2, CaO, MgO, alkalis, and volatiles. These components enter into the minerals in the apophyses and the groundmass of the pyrite ore. At this point of the crystallization a separation of part of the residual solution takes place, resulting in the formation of apophyses and lateral lenses of pyrrhotite. The microscopic study of these formations shows that their crystallization followed the same course as the crystallization of the groundmass of the pyrite ore.

The first step in the crystallization of the residual solution is the formation of quartz and probably also of sericite and chlorite.

The next step is the formation of an important group of minerals, namely pyrrhotite, sphalerite, stannite, and chalcopyrite. Within the group a certain

[1] One of these analyses is reproduced as No. 59 in Table 38.

sequence is noted, and, as was stated on a previous page, sphalerite and pyrrhotite were the first minerals to form. Stannite replaces these minerals but is older than chalcopyrite, which is the latest mineral in this group. Some sericite, chlorite, and calcite were probably formed during this stage.

The last group is composed of sulphominerals, galena, gudmundite, gold, bismuth, and bismuthite. Quantitatively they play but an insignificant rôle. A large part of the calcite is very late and was probably formed during the crystallization of this group of minerals.

The crystallization of the quartz-felspar veins began with the formation of plagioclase and quartz. The ore minerals are later and replaced the former. The ore minerals in the main followed the same order of crystallization as those of the pyrite ore.

The mineralization is brought to an end by the formation of the apophyllite-bearing fissures. They cut the pyrite ore and are believed to represent the last, low-hydrothermal phase of this stage.

Description of the Ore Bodies.

Arsenopyrite Ore Bodies.

General.

The largest arsenopyrite ore in the mine is the a-d-lens which has a maximum length of about 120 m. All variations in size have been found from this large body down to very small inclusions of brecciated arsenopyrite ore in the pyrite ore.

In Fig. 21 an attempt has been made to reconstruct the appearance of the deposit at the time when the arsenopyrite ore was formed but before the formation of the other ores. The figure shows that the ore bodies are irregularly distributed but that they are localized to the central part of the altered zone. There is no connection between the various bodies, and each lens forms a separate locus of mineralization. The ore solutions evidently followed several ducts and deposited their contents within a restricted sphere around each duct.

The a-d-lens.

The ore body was inaccessible down to the 170 m level when the author began the survey of the mine and the upper portions of the lens have therefore not been studied. The deeper portions, on the other hand, have been studied in detail in Stopes 24 and 25 (210 and 250 m levels).

On the surface the a-d-lens was in reality composed of five smaller bodies, partly lying in the pyrite ore and partly in the sericite schist (Pl. 1). On the 50 m level the lenses joined to two large bodies, the a- and d-lenses proper. In the eastern part of this level the arsenopyrite ore tends to separate from

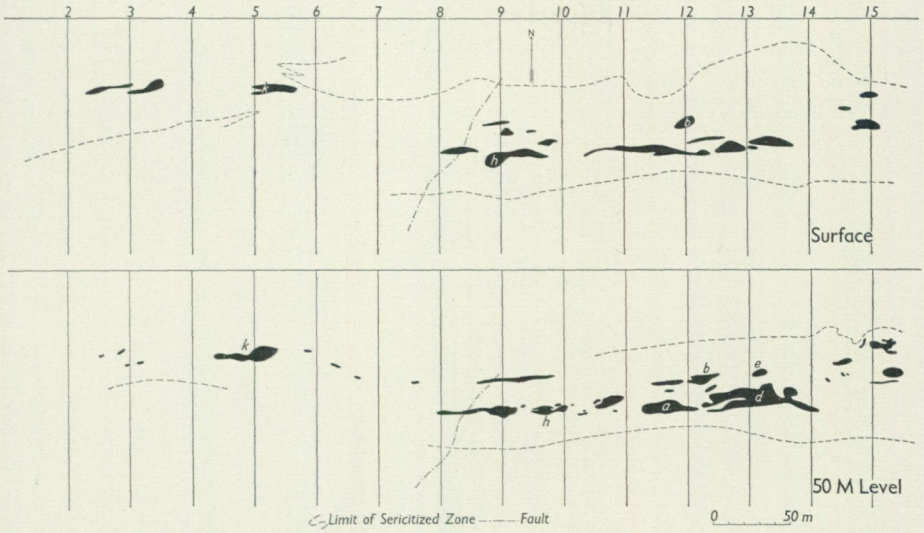

Fig. 21. Distribution of arsenopyrite ore lenses (black) at the surface and on the 50 m level. The picture is a reconstruction and shows the position of the ore bodies before the formation of later ores and faults.

the pyrite ore, a circumstance which becomes more prominent as the depth increases. Between the 50 and 90 m levels the two lenses join to one large body (Pl. 3).

On the 170 m level the ore body has lost all connection with the pyrite ore and appears exclusively within the sericite schist (Pl. 5). At section 15 the

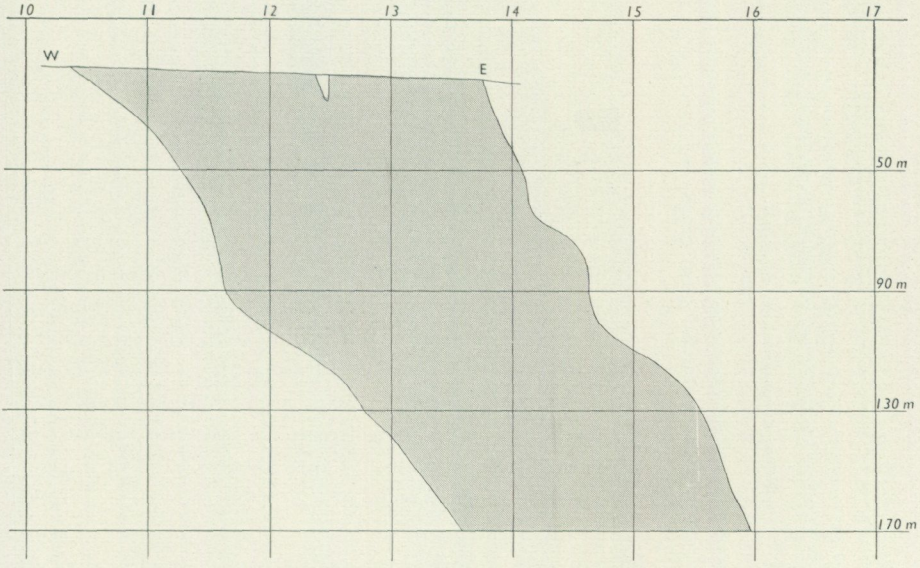

Fig. 22. Longitudinal section of the a-d-lens.

ore body is contracted and the western part grows thinner. This is the first sign of the splitting of the ore into two different bodies which occurs on the following level.

The longitudinal section of the ore body, reproduced in Fig. 22, shows its well-marked linear structure and the pitch of about 55° to the east. The dip is on the whole regular, as shown in Fig. 23, and amounts to about 75° S; on the deeper levels, however, the ore body stands almost vertical.

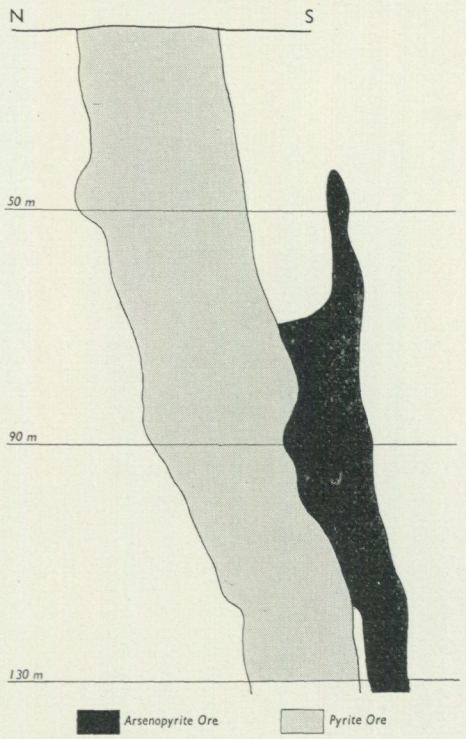

Fig. 23. Cross-section through the Eastern Ore and the a-d-lens at section 14.

The ore of the a-d-lens is generally a normal arsenopyrite ore, practically free from any inclusions of wallrock. In comparison with many other arsenopyrite ore bodies the a-d-lens is less brecciated, a circumstance very likely associated with the fact that from the 170 m level downwards this ore is entirely enclosed in sericite schist and has not been influenced by later mineralizations to the same degree as the arsenopyrite bodies in direct contact with *e. g.* pyrite ore or quartz-tourmaline veins. The present composition of a large part of the a-d-lens may thus be considered primary and the brecciating minerals which appear derive from the residual solution after the crystallization of the arsenopyrite. In the western part of the a-d-lens in Stope 25 (250 m level) the ore is cut by a tourmaline vein and here tourmaline and pyrrhotite have been added, changing the composition of the ore quite considerably (Fig. 16 and p. 135).

The k-lens.

The k-lens begins at the surface and is situated between sections 5 and 6 (Pl. 1). The contours in the longitudinal section are rather irregular and the pitch is not distinctly marked. The lens has been studied especially in Stope 22 (130 m level) and in Stope 23 (170 m level).

The ore is intensely brecciated by pyrite ore in the upper portions and by quartz-tourmaline ore on the deeper levels. In Stope 23 it was thus brecciated by the large quartz-tourmaline ore body in that stope (p. 99). In a number of places in the same stope the ore is also brecciated by pyrrhotite belonging

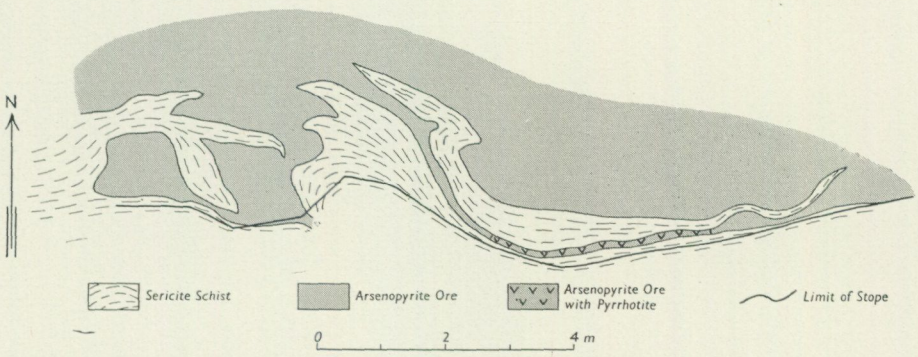

Fig. 24. Detail of contact between the k-lens and the hanging-wall on the 130 m level.

to the second stage. The breccias here formed belong to the best developed in the mine.

In the places where the arsenopyrite ore borders on sericite schist the contacts are as usual exceedingly sharp. The sketch in Fig. 24 gives some details from a contact on the 130 m level. The foliated sericite schist forms smooth folds which are closely followed by the ore. The latter is a compact arsenopyrite ore of normal type. The sericite schist is practically free from impregnations. At a point of the contact a vein-shaped branch of arsenopyrite ore leaves the main ore body and, following a smooth fold in the schist, again joins the main ore after a distance of about 9—10 m. At the narrowest part of the branch pyrrhotite with some chalcopyrite and quartz appears and is then the predominant component until the branch again widens out. The pyrrhotite brecciates the arsenopyrite ore and in places contains only small inclusions of the latter. The conditions related are not consistent with the supposition that the ore was formed entirely by metasomatic replacement of the schist. The pyrrhotite is considered to derive from a residual solution which was squeezed out into the foliated schist after the crystallization of the first group of minerals (cf. p. 69).

In Stope 23 apophyses of arsenopyrite ore are comparatively common. They cut sharply across the foliation of the schist and form wedge-shaped bodies, attaining a length of about 0.5 m. In the same stope the ore also forms

bulges which follow folds in the schist. Lateral lenses of arsenopyrite ore, appearing in the schist a short distance from the bulging ore, are bent without showing any signs of rupture. These facts indicate movements contemporaneous with the formation of the ore. That movements did occur is also indicated by the cross-cutting apophyses which evidently followed tension cracks in the schist.

The b- and h-lenses.

These lenses, situated on the surface at sections 12 and 9, respectively (Pl. 1), are almost entirely enclosed in pyrite ore and are consequently strongly

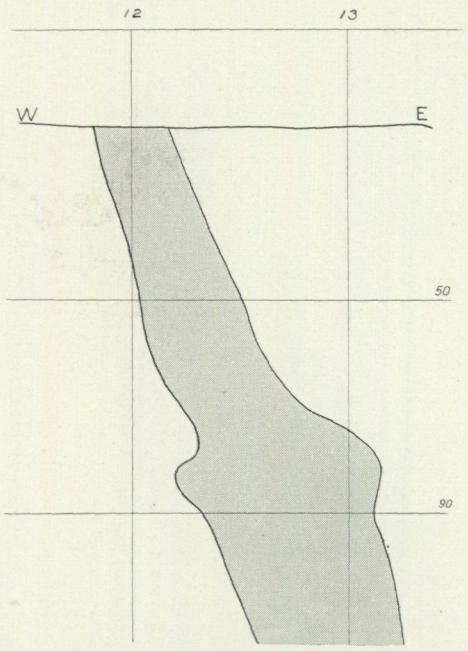

Fig. 25. Longitudinal section of the b-lens.

brecciated and have irregular outlines. They show a good lens-shape, however, and pitch regularly 60—65° to the east (Fig. 25).

The e-lens.

The e-lens is one of the smaller arsenopyrite bodies in the mine. It is situated east of section 13 on the 50 m level (Pl. 2), where it is surrounded on all sides by pyrite ore. The lens was 9—10 m long and had a maximum width of 4 m. The lens was almost mined out when the author began the survey of the mine.

The e-lens is of particular interest as it is mainly composed of apatite-banded arsenopyrite ore. Besides in the e-lens, this type of ore has only been found on two occasions as inclusions in pyrite ore.

Quartz-Tourmaline Ore Bodies.

General.

The quartz-tourmaline ores have been described in a previous chapter and it was there pointed out that they appear especially on the deeper levels of the deposit and that they are closely related to the lamprophyres. The relationship is believed to be genetic.

The ores have either the shape of lenses (or pipes), or they appear in veins.

Quartz-Tourmaline Ore in Stope 23 (170 m Level).

This ore body which so far has been studied only between the 170 and 130 m levels is in some places rather irregular but on the whole it may be said to have the shape of a pipe, pitching steeply to the east.

The ore which on the 170 m level was composed mainly of tourmaline with varying amounts of ore minerals, began towards the 130 m level to grade into a sulphide ore essentially composed of pyrrhotite and chalcopyrite (Pl. 8). The intimate relationship between the two types of ore was definitely proved during the detailed mapping of the stope.

Quartz-Tourmaline Ore on the 330 m Level (Section 15).

A fairly large ore body, also mainly composed of tourmaline, appears on the 330 and 410 m levels. It has been studied in some detail only on the 330 m level (Fig. 14). The ore body is here 26 m long and has a width of 6 m. At both ends of the stope the ore is cut by faults. The fault in the western end is the main NW—SE break (p. 142), which can be followed on all the levels of the mine.

The ore is lens-shaped in plan and pitches in the shape of a pipe steeply (52°) to the ENE. No transition to pyrrhotite ore was observed in this case but the mineral is fairly plentiful as a groundmass between the tourmaline needles. The younger ladder veins with quartz, mentioned on a previous page, are here typically developed (Fig. b, Pl. 30).

Quartz-Tourmaline Veins in Stope 26 (250 m Level).

Quartz-tourmaline veins are plentiful on the 250 m level and they have been studied in some detail in several places.

In Stope 26 no fewer than six parallel veins have been mined. In the eastern part of the stope a cross-vein appears; it contains »selenokobellite» in exceptional quantities (Fig. 15). Otherwise the veins are essentially composed of quartz which here and there contains concentrations of tourmaline or ore minerals.

The rock in the stope is sericite schist with small inlayers of sericite rock. The rocks are often strongly folded and corrugated to sharp Z-folds. The

quartz veins partly run parallel to the foliation but they frequently cut across the folds. Some of the thinner veins may be ptygmatically folded, indicating that movements took place also after the formation of the veins.

The veins cut two lamprophyric dykes (Fig. 15)[1] in the stope. It has already been pointed out on several occasions that there exists an intimate relationship between the dykes and the veins. That the latter were introduced somewhat later is obvious in view of the circumstances in Stope 26. It has also been observed in other localities.

In one respect the veins differ from veins in other places in the mine. They strike N60°E whereas in most other cases the veins strike due E—W. The dip is steeply to the SE. This divergent direction of strike is only locally developed and already on the 210 m level it has essentially resumed an E—W direction. The divergence was probably caused by the direction of the contact between schist and arsenopyrite ore between the 250 and 210 m levels, which here strikes about N60°E. The schist at the contact assumes the same strike, and consequently the veins, which find an easy way along the foliation of the schist, also take this direction.

It should be noted, however, that the two lamprophyres in the stope do not follow the strike of the foliation but as usual strike E—W. This circumstance may be due to the fact that the continuous and well marked tectonic lines along which the lamprophyres were intruded, were not affected by the comparatively unimportant and local obstacle formed by the divergent strike at this point.

Tourmaline Vein between Sections 14 and 15 (250 m Level).

This vein is one of the few almost entirely composed of tourmaline. Quartz has a sporadic occurrence in some places only. Ore minerals are generally lacking, except in local concentrations, *e. g.* in Stope 25 (250 m level) where pyrrhotite and cobaltite occur.

The tourmaline is generally fine-grained and of a dark-green or brown colour. In certain spots the mineral is coarser and often developed in radiate needles. The occurrence of fine-grained mariposite with spherulites of tourmaline has been described on a previous page. In some parts the vein is cut by ladder veins with coarse sericite.

The vein has been exposed only in two crosscuts and in Stope 25. It is exposed in section 15 where it cuts the eastern end of an andalusite body (Pl. 7). The vein here strikes N 50° E and dips about 50° to the SE. After leaving the andalusite body and entering the sericite rock, the vein resumes the usual direction of strike (E—W). The vein's diversion to the left as it cuts the andalusite rock is of the same character as the diversion of the lamprophyres when they cut arsenopyrite bodies (p. 72) and is caused by the difference in resistance to rupture existing between the foliated sericite rock and the hard and massive andalusite rock.

[1] Only one is visible on the level represented by the figure.

In the western part of Stope 25 the tourmaline vein, which here carries much pyrrhotite, cobaltite, and quartz, comes in contact with the western end of the a-d-lens. The conditions are very complicated at the contact but a detailed study showed that the vein undoubtedly is later than the arsenopyrite ore (Fig. 16). Around the contact the ore is strongly impregnated with needles of tourmaline and pyrrhotite. The amount of pyrrhotite is sometimes so large that the arsenopyrite ore almost loses its original charac-

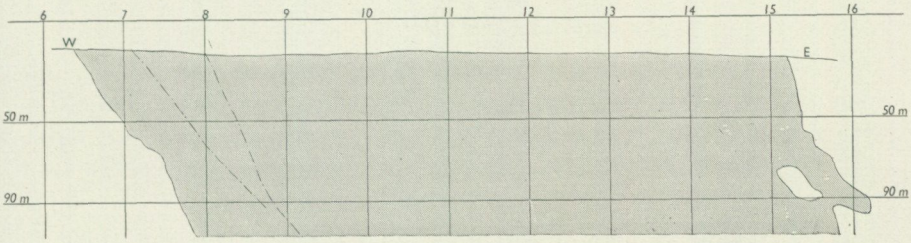

Fig. 26. Longitudinal section of the Eastern Ore.

ter and is composed of pyrrhotite with strongly absorbed and partly recrystallized portions of arsenopyrite ore. A large amount of cobaltite has also been introduced into the ore from the tourmaline vein.

Pyrite Ore Bodies.

General.

The pyrite ore mainly forms two large ore bodies, here termed the Eastern and Western Ores. They are arranged *en échelon*, the two bodies overlapping toward the right. The NE—SW fault has brought the two bodies into contact with each other, thus apparently producing one large, continuous body. In Fig. 5 the faulted blocks have been moved back towards their original positions, showing the appearance of the two ore bodies before the faulting.

Besides these two bodies a number of smaller ones appear on various levels in the deposit. As a rule they have not been subjected to a detailed study and will be only briefly mentioned.

At the eastern end of the Eastern Ore there were three lenses which are now partly mined out (Pl. 1). Only one of them was composed of pyrite, the other two being composed of pyrrhotite with more or less pyrite.

In the easternmost part of the Eastern Ore on the 90 m level there appears an irregular pyrite body which seemingly has no connection with the main body (Pl. 3). In the longitudinal section (Fig. 26) it is seen, however, that the intervening portion of wallrock only forms a »window» in the ore. Immediately below the 90 m level the ore body joins the main ore body.

In the eastern portion of the 170 m level there appear, in the crosscuts at sections 13, 14, and 15, small bodies of pyrite ore which so far cannot be link-

ed up with any known ore body (Pl. 5). It seems probable that they are protruding parts of the Eastern Ore.

Finally, between the 210 and 250 m levels, there appears an isolated body (between sections 13 and 14, Pl. 6) which probably has no connection with any ore body on the higher levels. The ore has already been described in conjunction with the description of the pyrite-apatite body in Stope 28 (Fig. 8).

Western Ore.

The Western Ore has its largest dimensions on the surface, where, including the faulted portion, it has a length of 365 m. The width is maximum 16 m (Pl. 1). The elongate ore generally strikes E—W but its western end turns about 20° to the south as does the whole complex of altered rocks in this part of the deposit. As mentioned on a previous page this is probably due to the diverting effect of the large mass of quartz-porphyritic schist which occurs N of the Western Ore.

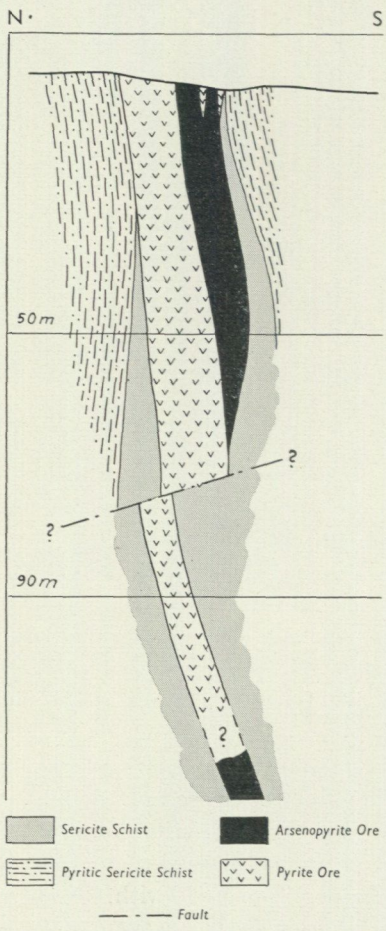

Fig. 27. Cross-section through the Western Ore midway between sections 4 and 5.

The western part of the ore dips about 70—80° S (Fig. 27) but the central part stands almost vertical, except on the deeper levels, where the dip has turned and is directed 80° to the N.

The configuration of the ore body in longitudinal section cannot be depicted as the exposures are as yet incomplete. On the whole the contours of the ore body seem to be irregular and it lacks a marked pitch. Only in some places can a steep pitch be noticed, directed to the east.

The gently dipping fault which cuts the ore body down to the 90 m level has caused a distinct displacement. The eastern block seems to have been moved obliquely upwards to the west, the displacement measuring about 30 m along the fault plane (p. 142).

The ore of the Western Ore is of the normal type. Inclusions of wallrock are on the whole rare. Exceptional amounts of sphalerite, accumulated in schlieren, is a characteristic feature of the eastern, upper portions of the ore body.

The contacts to the wallrock are as a rule very sharp. Apophyses of the type common along the walls of the Eastern Ore are generally lacking but clean-cut fissures of a smaller size and filled with coarse chalcopyrite, are often encountered. Two unusually large apophyses, similar to the apophysis in Stope 3 (130 m level) in the Eastern Ore, are found in the hanging-wall at section 3 on the surface (Fig. b, Pl. 46). Sulphide-bearing quartz-plagioclase veins are met with at the contacts.

The wallrock is generally sericite schist, sometimes the pyritic type. The latter makes up the wallrock particularly of the upper portions of the ore.

Eastern Ore.

The Eastern Ore is the largest accumulation of sulphides in the deposit. The greater part is a pyrite ore. On the surface the ore body has a length of 357 m (including the faulted portion) and a maximum width of 37 m (Pl. 1). The strike of the axis of the ore body is about E 10° N on the upper

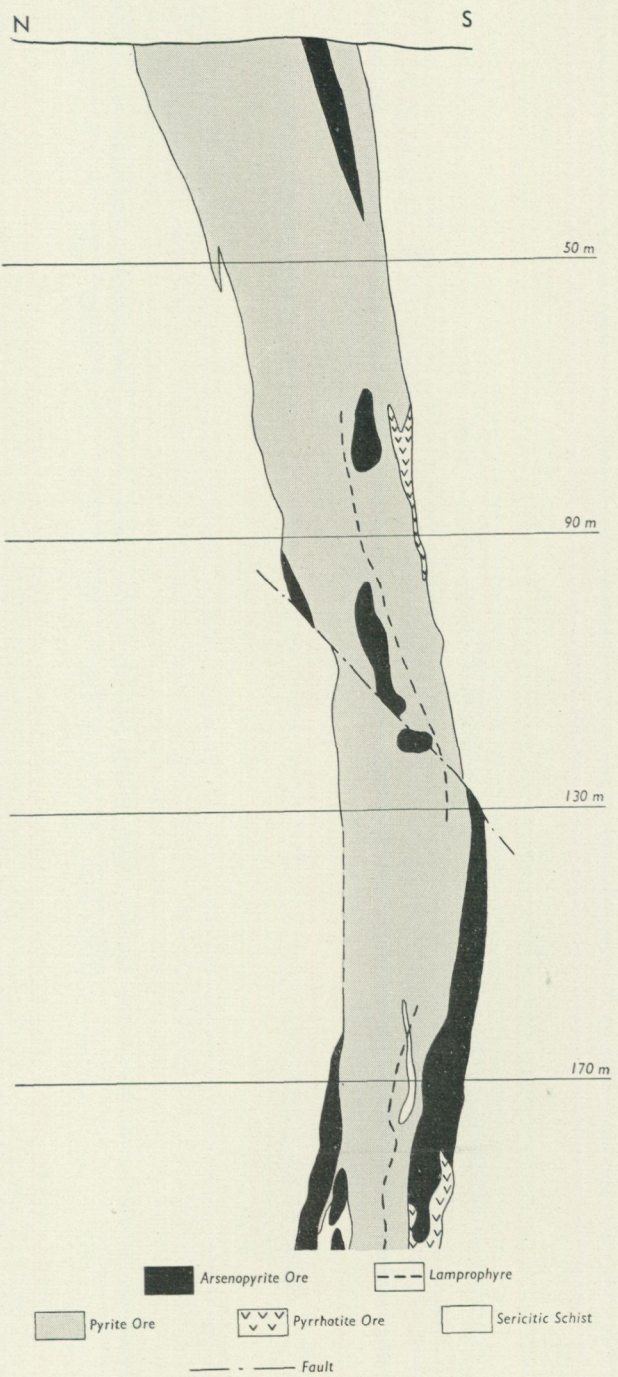

Fig. 28. Cross-section through the Eastern Ore at section 11.

levels, but due E—W on the deeper levels. The dip is very regular. Down to about the 130 m level it is 70—85° S. Between the 130 and 170 m levels the ore generally stands vertical but changes on the deeper levels, as do the surrounding schists, and there dips about 70—85° to the north (Fig. 28).

The longitudinal section in Fig. 26 shows that as far as is known the ore has a regular configuration. The keel, which pitches about 55° to the east, displays but minor irregularities. The upper limit of the lens is not quite so even and irregularities exist, *e. g.* at the »window» on the 90 m level. The pitch is also steeper and is as much as 70°.

The ore body has not the well-marked elongate lens-shape characterizing some of the arsenopyrite bodies but on the whole it seems to follow the same structure as the latter and it is believed that the ore solution entered along the same structural lines as the earlier solutions.

The boundaries of the ore are as a rule smooth and follow the foliation of the wallrock. Tongue-shaped protuberances sometimes appear (Pl. 1, 2, and 4) and run parallel to the foliation of the surrounding schist. As mentioned before, the boundaries change character toward the ends of the ore bodies. They are no longer sharp and the ore peters out in irregular and indistinct protuberances, the wallrock at the same time becoming strongly impregnated with sulphides.

The occurrence of apophyses and quartz-plagioclase veins at the contacts, particularly in the central parts of the ore, has already been described in some detail and need not be discussed here.

The wallrock is essentially a normal sericite schist but pyritic and chloritic types may also occur.

All the types of ores included in the pyrite stage are found in this ore body and a further description is hardly necessary. The fine-grained, normal type is most common, but pyrrhotite ore, accumulated especially along the margins of the pyrite ore, is not at all rare.

A most typical feature of the Eastern Ore is the appearance of inclusions of lamprophyre. The inclusions are strongly replaced by the pyrite but nevertheless it has been possible to follow them throughout the ore as is indicated on the maps (Pl. 2—6)[1]. In certain zones inclusions of wallrock are also common.

Structure.

Folding.

For the interpretation of the structural features of the deposit, the electrical indications of the graphite- and pyrrhotite-bearing sediments (phyllites and graywackes; p. 12) have been of great value, this due to the scarcity of exposures in the surrounding area and because of the information obtainable

[1] They have not been plotted on the surface plan and only in some places on the 50 m level owing to the mining method here applied (glory-holing) not being suitable for a detailed mapping.

underground in the mine being rather incomplete. The compilation of the indications, supplemented by drill-hole sections, which work was done by Grip (Fig. 3), shows how the contact between the volcanics and the sediments, which for a distance of several km has a smooth course to NE or ENE (38, Pl. 1), at Boliden forms a sharp S-shaped fold and then continues in its original direction.

The S-shaped fold has the character of a dragfold, the axis of which, as well as the linear structure of the wallrocks and the longer axis of many of the ore bodies, pitches about 50—60° in an easterly direction. The dragfold has a complicated structure and is composed of three different lobes (Figs. 3 and 4). The irregular course of the indications shows that shearing and overthrusting took place within the fold. The dragfold was produced by shearing or rotational forces acting upon the folded rock complex under a small angle to the direction of strike and moving the southern part of the complex to the east and the northern to the west (Figs. 3 and 4).

In the mine itself there are very few signs of the dragfold. In the easternmost portion of the 50 m level (Pl. 2), for instance, the foliation shows a distinct change from an E—W strike to a strike NE—SW, probably marking the southern, anticlinal part of the dragfold. Another example is known from the eastern part of the 90 m level. The banded, tuffaceous rocks in the northeastern crosscut (sections 16—17) here strike N 30—40° E and dip 40° SE. The rocks are probably situated close to the sediments and presumably represent the north-western limb of the largest, central lobe of the dragfold.

The dragfold developed at the contact of the volcanics and sediments dipping steeply to the south. The general fold axis of this complex has a gentle pitch but the dragfold has a steep easterly pitch. As emphasized by Derry in a recent paper (18), two types of dragfolds may be distinguished, d e p e n d e n t d r a g f o l d s, formed by differential movements between the strata during the main folding, and i n d e p e n d e n t d r a g f o l d s, formed after the main folding by a shearing stress acting upon the folded strata. The pitch of the first type as a rule coincides with the pitch of the main fold. The pitch of the independent dragfolds, however, is generally steep and differs considerably from the pitch of the fold in which they occur. The dragfold at Boliden is of the latter, i n d e p e n d e n t t y p e.

Many examples of dragfold structure are known from Canada in particular, where they have attracted much attention because of the structural control they exercise on ore deposition. In many cases there is a resemblance to the structural conditions at Boliden, and the following may be mentioned: The Canadian Malarctic Gold Mine in N. Quebec, described by Derry (19), the Tashota Goldfields Mine in Ontario, described by Flaherty (26), and the Britannia Mines in Br. Columbia, described by Ebbutt (21).

It is evident that the dragfold at Boliden played an important part in the deposition of the ores and that it exercised a structural control on the channels followed by the ore solutions. There is a pronounced difference in resistance to rupture between the volcanics and the sediments in the dragfold.

The incompetent sediments are not liable to the formation of permanent fissures and the deformation of these beds was of a plastic nature. Thrusting and flowage very likely took place within them and fissures formed in zones of pressure minima were rapidly closed.

The competent, brittle volcanics acted in a different way. Before the thorough alteration fissures readily opened in these rocks during the shearing, forming ducts for rising magmatic solutions. The pyroclastic rocks often occurring in the altered zone were probably particularly suitable in that respect. As will be shown in the following chapter these solutions in the first place brought about an alteration of the volcanics, in that respect being supported by the shearing, the two processes resulting in the development of a marked schistosity in the rocks. Even after the sericitization, when the rocks had more or less the same consistency as the sediments, they were, as indicated by several circumstances, still rather adapted to the formation of ducts for the ore solutions later introduced. An important rôle was here played by the massif of quartz-porphyritic schist in the western part of the deposit. It acted as a buttress against which the sericitized complex was pressed, the ensuing differential movements in the schists resulting in the formation of pressure minima. Pressure minima were also formed within the schists as a result of differential movements between the incompetent sericitic rocks and the competent lenses of andalusite rock.

The channels formed in this manner in the schists had the same pitch as the dragfold, as is evident from the parallelism between the linear structure of the fold and the pitch of the arsenopyrite ore bodies occupying these channels. The formation of the arsenopyrite ore was consequently structurally controlled by the dragfold.

The shearing process continued during the formation of the arsenopyrite ore as is evidenced by the breccias in the ores and the apophyses in the wall-rocks.

The second stage of ore deposition is inaugurated by the intrusion of lamprophyric dykes which call for the formation of long, continuous fissures, cutting schists as well as arsenopyrite ores. The deflexion of the lamprophyres to the left when entering arsenopyrite bodies is here of great importance as it gives a clue to the direction of the forces that formed the fissures. It seems obvious that the deflexion of the fissures must have been caused by a shearing couple, acting at a low angle on the foliation of the complex and trying to rotate the ore-schist complex counter-clockwise. The stress consequently had more or less the same direction as during the development of the dragfold.

The lamprophyres were closely followed by quartz-tourmaline ore in veins and lenses. Some of the veins have followed the same lines of weakness as the lamprophyres and have the same direction of strike. The lens-shaped bodies of quartz-tourmaline ore, on the other hand, often have another position as they appear as gash veins, striking NE or ENE. In Stope 25 (250 m level) a tourmaline vein was deflected to the left when cutting an andalusite

body. There is thus also from a tectonic point of view a strong relationship between the lamprophyres and the quartz-tourmaline ores, and it would seem very likely indeed that the channels for the latter were opened by the same stress that formed the fissures for the lamprophyres. The stress also produced a foliation in the lamprophyres.

If we now turn to the pyrite ore, we find that the ore bodies are accumulated in the same space as the older ores and that at least the Eastern Ore has a pitch parallel to that of the dragfold and the older ores. The reconstructed picture (Fig. 5) of the deposit at the surface shows, however, two *en échelon* bodies overlapping to the right, and at first sight it seems rather unlikely that they could occupy fissures formed by a shearing stress of the same direction as before. A stress of this direction (»south-side-east» and »north-side-west») would rather tend to close these fissures and try to develop fissures with the same orientation as the quartz-tourmaline lenses.

It should be pointed out that the *en échelon* position of the Eastern and Western Ores is very likely only fortuitous. As will be discussed in the following chapter (p. 169), the pyrite ore solution probably entered along several separate channelways and with these as centres the solution replaced a large part of the intervening schists and older ores, the final result being two seemingly homogeneous ore bodies. The separate channelways were probably scattered in the complex of schist and older ores in much the same manner as the arsenopyrite ores and their channelways (Fig. 21). It is now believed that also the channelways of the pyrite ore were formed by the shearing stress that controlled the earlier mineralizations in the deposit and that they were the result of differential movements in the complex of different ore bodies and lenses of andalusite rock in the ductile schists. The unyielding mass of quartz-porphyritic schists in the west has also played a part in deflecting the schist, a circumstance which very likely would result in channelways in the area, now occupied by the Western Ore.

The dragfold, and the couple of shearing forces which caused its formation, have thus had very great influence on the ore deposition at Boliden and one may even say that the dragfold is a *conditio sine qua non* for an ore deposition at this place. The dragfold did not only localize the initial alteration and mineralization but it also exercised a structural control on the continued appearance of ore solutions during the whole mineralization.

Within the sericitic rocks, particularly in close relation to the ore bodies, sharply folded portions are often encountered, as has already previously been stated. The schistose rocks are intensely corrugated, knife-edged Z-folds often being formed (Fig. b, Pl. II). The folds are cut by fissures along their axial planes or along directions at various angles to the axial plane. These folds, which may be called folds of the second order, have generally a vertical pitch, although variations from this rule are known. It is believed that their formation was caused by local movements in the schists during the *mise en place* of the ores.

Faults.

Post-ore movements have taken place along two systems of faults, as a rule striking NE—SW and NW—SE. The former system is the most important. The faults are decidedly later than the mineralization as they cut all the ores, even the pyrite ore. The faults are never mineralized but they may contain a clayey gouge.

The most important fault in the mine is the one which has dislocated the two ore bodies at their point of overlapping and brought them into contact with each other, as is shown on the surface plan (Pl. 1). On the upper levels the strike is almost due NE—SW but on the deeper levels it has changed to a more northerly direction. The dip is fairly uniformly 70° to the SE. In many places it is composed of two or more branches (cf. Pl. 1—7). When the fault intersects the sericitic rocks it may attain a width of one or two metres and contains a clayey gouge with broken pieces of rock. In the ores, on the other hand, the fault is clean-cut and well defined. The horizontal displacement amounts to about 30 m in the upper portions of the mine but on the deeper levels it is only about 15—20 m. The striae on the fault plane, which at least represent the later movements on the fault, indicate a relative displacement of the eastern block upwards to the north at an angle of about 20—25°. The magnitude of this displacement is not known but it probably amounts to a few metres only.

Another rather important fault, having the same main direction as the former, appears farther to the east. It may be a branch of the fault just mentioned (cf. *e. g.* 50 m level, Pl. 2) but because of its more gentle dip it recedes in an easterly direction. The direction of the movement is the same as in the former case but the displacement is only a few metres.

As shown on the maps (Pl. 1—7) there are several other faults with the same direction but their displacements are very insignificant.

Among the faults striking NW—SE there is only one which is of any importance, and that is the reverse fault cutting the Western Ore on the upper levels. Between the 170 and 210 m levels it is then faulted by the main NE—SW fault. The fault generally has a gentle dip (25—45°) to the east and its course is in many places irregular. The fault could be well studied in a stope between the 90 and 130 m levels and here it was evident that the eastern block had been pushed up about 30 m westwards along the fault plane in relation to the Western block[1]. The horizontal displacement amounted only to a few metres. On the deeper levels the horizontal displacement is, however, somewhat greater.

Longitudinal faults, striking parallel to the foliation, are often encountered in the schists. They contain a clayey gouge but the displacements never seem to be of any importance.

[1] The fault was not accessible in the open pit and its position on the surface plan has been constructed from the 50 m level.

Origin of the Altered Rocks.

Origin of the Sericitic and Chloritic Rocks.

Age of Sericitization.

The formation of the zone of sericitized rocks surrounding the ore bodies bespeaks an extensive soaking of the bedrock by altering solutions. This could be accomplished only after the bedrock had been tectonically prepared by the development of the dragfold and after the shearing in the volcanics had produced suitable channelways for the free circulation of ascending magmatic solutions.

Apophyses of arsenopyrite ore and of sulphominerals emanating from the arsenopyrite ore cut the sericitic wallrocks, indicating that at least part of the sericitization was accomplished at the time of the introduction of the arsenopyrite solution. The appearance of lateral lenses of arsenopyrite ore in the wallrocks also indicates that they were formed in an already sericitized schist. A further support for this assumption lies in the fact that many of the mineral associations connected with the arsenopyrite ore have an appearance in the wallrocks suggesting that these rocks were sericitized to the present degree when these associations were formed.

Between the 210 and 250 m levels there is a marked accumulation of arsenopyrite ore and the sericitization is here unusually strong. As the maps show (Pl. 6 and 7), the sericite rock, the most thoroughly sericitized rock of the deposit, is widely distributed in this place, and also the quartz-free andalusite rock, representing a further step in the alteration, has its main area of distribution between these levels. The sericite rock constitutes the final phase of the sericitization and the andalusite rock was formed at the cost of the sericite rock. The underground survey has now shown that the andalusite rock is clearly older than the quartz-tourmaline stage, and that sericite rock, containing porphyroblasts of andalusite and appearing in close relation to lenses of andalusite, is replaced by arsenopyrite ore (p. 46). It may thus be considered proved that even the most intensely altered rocks of the deposit were formed before the arsenopyrite stage[1] (cf. p. 149).

This, however, does not imply that the circulation of altering solutions in the bedrock came to an end before the beginning of the arsenopyrite stage. The climax of the alteration process may have been reached but it is very likely that altering solutions were still given off throughout the arsenopyrite stage and that the altered zone was continuously widened.

Turning then to the second stage, we find that during that stage an extensive sericitization of the quartz-free andalusite rock took place and that sericite was also formed in the quartz-tourmaline ores. It is thus likely that also the sericitization of the volcanic rocks continued during this stage.

[1] When preparing the preliminary paper (65), the observations were rather incomplete on this point and it was concluded that the sericite and andalusite rocks were formed during the arsenopyrite stage. This opinion can no longer be upheld.

The lamprophyric dykes of the second stage were probably subjected to a process of alteration contemporaneous with the alteration of the andalusite rock, that process in many respects being similar to the sericitization. This question is discussed later and it will only be pointed out here that the basic dyke rocks were largely altered to a chloritic schist (»chloritic lamprophyre»).

It then remains to discuss whether also the third stage was accompanied by sericitization. As a rule the pyrite ore is surrounded by sericitic rocks which are often cut by apophyses from the ore, sometimes containing inclusions of sericite schist. The pyritic solution consequently entered a complex of thoroughly sericitized rocks. The small pyrite ore body situated N of the Eastern Ore at section 14 (Pl. 1) is, however, partly bordered by a rock which, although it is sericitized, is not at all a typical sericite schist and besides also still contains remnants of plagioclase. It may further be added that in many cases the inclusions of lamprophyre in the pyrite ore have not been subjected to any hydrothermal alteration (chloritization). The general impression obtained is consequently that the pyrite stage was not accompanied by any sericitization to speak of.

Original Composition of the Sericitic Rocks.

Primary minerals and textures are with a few exceptions completely obliterated in the sericitic rocks. The quartz-porphyritic sericite schist does, however, contain phenocrysts of quartz which still possess primary features. In this case there is no doubt but that the primary rock had the composition of a quartz-porphyry. The same is true of the chlorite-bearing quartz-porphyritic type.

Occasionally a distinct fragmental structure is noticed in the sericite schist. The fragments, which are strongly sericitized themselves, consist of differently coloured rocks among which quartz porphyries can be recognized. In spite of the strong alteration it can be concluded that the rock primarily constituted an agglomerate, probably of an acid composition. Agglomerates have been observed in the keratophyres and it is likely that the sericitized agglomerates originally also had a keratophyric composition.

The normal sericite schist, most wide-spread of the sericitic rocks in the mine, is completely altered and no immediate conclusions can be drawn as to its original composition. The underground survey has shown, however, that keratophyre and quartz-keratophyre are the most common unaltered rocks and that there exists a transition from these rocks to sericitized rocks. The inference may therefore be drawn that originally the sericite schist had a keratophyric composition. As a further support for this assumption it may be pointed out that the sericite schist sometimes contains phenocrysts of quartz and that similar quartz-porphyritic textures are met with in the fresh keratophyres.

The pyritic schist may be considered to be a special facies of the normal

schist and it very likely also derived from the keratophyre. The question as to the origin of the chloritic sericite schist is not quite so simple, however, and this rock will be treated separately below.

Chemistry of the Sericitization.

Sericitization is one of the most common hydrothermal alteration processes in ore deposits. It has been subjected to much study and has been described from all parts of the world.

In our search for sericitic rocks that can be compared with those at Boliden, we may first view the Skellefte District. Sericitization of the volcanic rocks occurred there on a large scale, not only around several of the ore deposits, *e. g.* Rakkejaur, Åkulla, Holmtjärn (67), and Kristineberg, but also in large areas without any appreciable mineralization (38).

Saksela has described sericitization in some Finnish ore deposits, namely Otravaara (83), Karhunsaari (84), and Jalonvaara (84). Some of the rocks formed are very similar to those at Boliden. The cited occurrences are of particular interest because of the appearance of chromiferous mica of hydrothermal origin.

The American literature on ore deposits abounds in descriptions of sericitization but it will suffice here to mention a few examples. The quartz-porphyry which intrudes the Keewatin rocks in the Porcupine District in Ontario is often strongly sericitized and schisted and may well be compared to the quartz-porphyritic schist at Boliden, although the alteration at Porcupine does not seem to be as complete as at Boliden. A notable difference is that a large amount of calcite is formed at Porcupine, whereas at Boliden this mineral is absent in the sericitic rocks. The rhyolite in the Noranda District, Quebec, is also sericitized in places (73) and bears some resemblance to certain types of sericite schist at Boliden. The same may be said of some sericitized rocks, in part acid volcanics, from Flin Flon in Manitoba (10), United Verde Mine at Jerome, Arizona (54), and the San Francisco District in Utah (12). Particularly in the last-mentioned case there exists a good resemblance to the sericitic rocks at Boliden. An interesting example of an alteration of granite to sericite schist has been described by Schwartz (89). The resulting rock somewhat resembles the pyritic sericite schist at Boliden.

In a recent compilatory paper Schwartz (90) gives a detailed account of the transport of material involved in the process of sericitization.

Graton has recently discussed the nature of the ore-forming fluid (35) and arrives at the general conclusion that the formation of hypogene ores and the transport of material in the wallrocks in connection therewith were brought about by alkaline aqueous solutions. He thus rejects the opinion expressed by Bowen (7) and Fenner (25) that these processes were caused by primarily acid and gaseous solutions.

Schmedeman discusses the chemistry of sericitization and points out (86, p. 803) that sericite is not indicative of either alkaline or acid attack but

that it is probably formed in zones of hydrothermal alteration from alkaline or weakly acid solutions only under addition of potash. In the case of the Boliden schists one may therefore adopt Schmedeman's interpretation, as a marked addition of potash takes place, and assume that the sericitizing agent was alkaline or weakly acid solutions.

Experimental investigations of the formation of sericite were carried out by Noll (64), who found that the mineral was formed in potash-bearing alkaline solutions.

The sericitization implies an extensive shifting of material. A comparison between analyses of the fresh and altered rocks as a rule gives a concept of the gains and losses. A q u a n t i t a t i v e calculation of the amounts involved in the metasomatic process is possible on the presumption that no volumetric changes take place during the alteration, or, if a change does occur, that its magnitude is known. These questions have been dealt with by Lindgren on several occasions (*e. g.* 55, p. 92, and 53) who points out that replacement in rigid rocks is generally not accompanied by any volumetric changes (The Law of Equal Volume).

Descriptions of sericitized rocks show that the intensity of alteration varies quite considerably. The felspars are as a rule the first minerals to fall victims to the sericitization and among them the plagioclases are most easily attacked (90, p. 192). Also femic minerals are to a varying extent replaced by sericite. Quartz is as a rule left intact but the mineral is also known to be replaced (52, p. 642, and 89, p. 541). The sericitization is often incomplete and the sericitized rocks may contain remnants of primary minerals and textures.

The sericitization of the volcanic rocks at Boliden is of particular interest as the alteration is unusually complete and the gains and losses consequently are easy to follow.

A comparison in the first place between the analyses of the normal sericite schist and the keratophyres shows a considerable decrease in, or a complete loss of FeO, MgO, and CaO in the latter rocks. The alkalis have gone through great changes. The fresh keratophyres are predominantly sodic rocks and the content of potash is fairly insignificant. The sericitized rocks, on the other hand, are distinctly potassic and it is obvious that considerable amounts of potash were introduced during the alteration whereas some sodium was subtracted. An appreciable amount of H_2O has been added. As regards the content of SiO_2 it is about 12—13 % higher in the schist and it is possible that at least some silica has been added. The content of free quartz in the schist (about 62 %) is considerably higher than in the fresh keratophyre. The largest part of this surplus of quartz was very likely formed by the breaking down of the silicates. The amount of Al_2O_3, finally, has slightly decreased in the sericite schist.

Turning now to the sericite rock, we find that also here the contents of FeO, MgO, and CaO are very insignificant. The amount of K_2O has considerably increased and it seems probable that the addition of potash continued

during the formation of this rock. Silica shows a considerable decrease and very much has been carried away in solution. As regards the content of Al_2O_3 a great change is noted and it has increased from about 13 % in the sericite schist to almost 38 % in the sericite rock which implies that an introduction of alumina must probably be counted with at this stage of the sericitization. There is finally also an increase in H_2O and F.

The underground data show that there is a gradual transition from normal sericite schist to sericite rock and it is concluded that the latter is the result of the most intense phase of the sericitization in the deposit. During the formation of the normal sericite schist the solutions mainly brought about the breaking down of the silicates, resulting in the removal of FeO, MgO, and CaO, and in the formation of sericite under addition of potash and water. During the next phase, with no primary silicates left for an assault, the quartz is attacked by the solutions. Potash was continuously introduced but at this stage an appreciable addition of alumina is also noted, resulting in an increased formation of sericite.

TiO_2 occurs in both the unaltered and the sericitized rocks in about the same amounts and there has hardly been any transport of this oxide. The sericite rock contains unusually much TiO_2. In this case the oxide was introduced later and it emanated from the lenses of rutile rock often occurring in the sericite rock.

Several of the sericitized rocks contain small amounts of F. In the sericite rock the amount has increased considerably and it is evident that the fluorine was brought in during the formation of the sericite. It may have taken an active part in the transportation of material during the alteration; the total amount of fluorine present in the altered rocks is very considerable. The importance of fluorine in sericitization has been emphasized by S. Paige (71, p. 27, and 70).

As regards the formation of the remaining types of sericitic rocks, the quartz-porphyritic and pyritic schists, essentially the same conditions have been ruling as in the case of the normal schist.

The mother rock of the quartz-porphyritic schist was a quartz porphyry of unknown composition. The composition of the felspar in the porphyry also being unknown, it cannot be settled to what extent the amounts of K_2O in the schist — 2.58 % — are primary or to what extent they were introduced during the sericitization. Most of the femic oxides have been removed as in the preceding case. The amount of SiO_2 in the analysed specimen is very high and is partly due to the acid nature of the original rock. Some types of the quartz-porphyritic schist, occurring on the deeper levels of the mine, are still richer in silica and it is possible that part of it was introduced during the sericitization. The explanation may also be that the deeper portions of the altered zone were leached and that potash and alumina were carried away by the solutions, thereby increasing the amount of silica. On the whole there do not seem to be any reasons for assuming that the solutions which brought about the formation of the quartz-porphyritic schist

had a composition different to that of the solutions forming the normal schist.

This is very likely true also of the pyritic schist. This rock is different to the normal schist mainly in view of the sometimes high amounts of Fe-sulphides present. A formation of *e. g.* pyrite often accompanies the sericitization and occasionally the mineral is formed by the addition of sulphur which unites with the iron from the decomposing femic minerals (90, p. 200). One such case is described by Kirk (45, p. 46) from Butte in Montana. At Boliden, where the original rocks are very poor in femic minerals, it seems most likely that both sulphur and iron were introduced. The pyrite has, however, been brought in rather late and after the sericitization, probably in connection with the formation of the pyrite ore (p. 171).

Origin of the Chlorite-bearing Schists.

A wide-spread chloritization is encountered in the chloritic sericite schist which occurs in zones on several of the levels (Pl. 2—6). A local chloritization is also met with in the quartz-porphyritic schist and occasionally also in the normal schist. The latter cases will be treated first.

The chlorite in the quartz-porphyritic sericite schist is accumulated to schlieren and bands which sometimes cut the schistosity. The occurrence of the chlorite does not seem to depend on any primary features in the rock and it may be concluded that the mineral was brought in independent of and later than the main sericitization. It is at present not possible to state either the source of the chlorite-bearing solutions or their time of appearance.

Chloritization is occasionally met with in the normal sericite schist in the vicinity of the ores. It is always of a local nature and it is evident that it occurred in close relation to the mineralization. Small amounts of chlorite are present in most of the ores and it seems likely that the mineral was formed by emanations from the latter.

Turning now to the chloritic sericite schist, we note that it occurs in homogeneous and fairly continuous zones which can be followed long distances and which often are well delimited from the surrounding sericite schists. This regular appearance of the rock at once gives rise to the suspicion that the chlorite in this case has another origin than in the rocks mentioned above and that the composition of the original rock was different to what it was in the case of the sericitic rocks. It seems likely that the original rock had a more basic composition and it is then close at hand to suspect that dacite constituted the mother rock in this case, as dacite is the only rock of a tolerably basic composition among the volcanics in the deposit. The chloritic schist does not contain primary features of any kind and the assumption that dacite formed the mother rock is based mainly on the fact that the dacite contains those oxides — FeO and MgO — which enter into the chlorite. Consequently the chloritization should not require any addition of these oxides. If dacite be the mother rock, the alteration would primarily comprise a con-

version of the hornblende in the dacite to chlorite and a breaking down of the plagioclase under formation of sericite. The process involves a gain in potash and a removal of considerable amounts of Na_2O and CaO. Water has also been added. It is also likely that some magnesia has been carried away. The combined process of chloritization and sericitization of the dacite does not principally differ from the sericitization of the keratophyres. The main difference lies in the fact that considerable quantities of MgO and FeO have been left. It seems probable that the same solutions as caused the sericitization also brought about the alteration of the dacite but that the different concentrations of MgO and FeO in the latter are responsible for the retaining of these oxides.

As was stated in a previous chapter (p. 28) the pyritic schist sometimes contains appreciable quantities of chlorite. In many cases it is believed that the chlorite was brought in together with the pyrite but in other cases, where a transition to the chloritic schist is noted, it seems likely that the original rock was a dacite and not a keratophyre as is normally true of the pyritic schist.

Origin of the Andalusite Rocks.

Age of the Andalusite Rocks.

It has been pointed out previously that the quartz-free andalusite rock[1] was formed by replacement of the sericite rock and that it is considered to have been formed during a late but very intense phase of the main alteration. The relation of the andalusite rock to the ores has been touched upon before on a few occasions and summing up the data it may be stated:

1) The andalusite rock is cut by tourmaline and mariposite veins and is strongly sericitized by emanations from the tourmaline solution.

2) In Stope 25 (250 m level) a sericite rock with erratic porphyroblasts of andalusite, close by containing lenses of andalusite rock (Fig. 16), is replaced by arsenopyrite ore. The porphyroblasts are partly resorbed by the ore.

3) Rutile, very likely emanating from rutile lenses of the arsenopyrite stage, impregnates the andalusite rock.

From these facts the conclusion may be drawn that the andalusite rock is older than the two first stages of mineralization and that its formation occurred between the formation of the sericite rock and the appearance of the arsenopyrite ore.

Chemical Relations of the Formation of the Andalusite Rocks.

A direct comparison between the analyses of the andalusite rock and the sericite rock would give a false conception of the gains and losses occurring during the alteration as the present composition of the andalusite rock does

[1] The quartzose type will be discussed separately (p. 150).

not represent its original composition, this owing to the subsequent, intense sericitization that the rock has been subjected to. The analysed specimen of andalusite rock, for instance, contains 16.5 % sericite and about 43 % corundum and diasporite, minerals which were all formed during the later alteration. The original composition of the andalusite rock is not known, as it is more or less altered everywhere in the mine, but it may be surmised that it fairly well tallied with the theoretical composition of andalusite (62.93 % Al_2O_3 and 37.07 % SiO_2), making an allowance, however, for the presence of alkalis, water, fluorine, and accessory oxides derived from unreplaced remnants of sericite rock.

The andalusite is seen to replace the sericite rock volume for volume and it is considered possible to apply the law of equal volume in this case and to calculate the gains and losses taking place during the replacement (Table 39). The values obtained are only approximate and reservation must be made for the amounts of alkalis, water, and fluorine lost, as, on the grounds stated above, the andalusite rock is likely to have contained a certain amount of sericite.

Table 39.

Gains and losses during the formation of the andalusite rock.

	1	2	3
SiO_2	123.4	114.9	− 8.5
Al_2O_3	105.2	195.1	+89.9
Na_2O	5.7	?	(− 5.7)
K_2O	24.32	?	(−24.32)
H_2O	11.17	?	(−11.17)

1. Gr. per 100 cm^3 in sericite rock.
2. Gr. per 100 cm^3 in theoretical andalusite rock ($Al_2O_3 . SiO_2$).
3. Absolute gains and losses.

A large quantity of alumina has been added and a small amount of silica has been removed. Alkalis and water show the most considerable changes and large quantities have been carried away during the breaking down of the sericite.

As regards the quartz-bearing andalusite rock we note that it sometimes carries phenocrysts of quartz and occurs in such a relation to the quartz-porphyritic sericite schist that its formation from the latter rock is beyond doubt. In part it has also been formed from the normal sericite schist. The quartzose andalusite rock has not been subsequently altered and a comparison between the analyses of this rock and the quartz-porphyritic schist at once reveals the gains and losses involved. It is thus found that the alkalis and water have disappeared to a large extent and that also a considerable quantity of SiO_2 has been carried away. Al_2O_3, on the other hand, has largely increased. This type of andalusite rock is thus principally formed by the same process as the quartz-free andalusite rock.

The unusual accumulation of alumina may give birth to the conception that it be a »primary» concentration and that originally an argillaceous sediment (or a lateritic or bauxitic sediment) was present. This is, however, inconsistent with the geological appearance of the andalusite rocks, which shows that there is a transition from the volcanics via the sericitized rocks to the andalusite rocks and that they appear exclusively in the most intensely sericitized parts of the altered zone. As regards the quartzose andalusite rock, the quartz phenocrysts definitely prove that the mother rock partly was a quartz-porphyritic schist.

It may further be added that occurrences of hydrothermal andalusite, more or less similar to that found at Boliden, are known from a number of localities. A review of these is given below.

Comparison with Other Occurrences of Andalusite-bearing Rocks.

At the prospect at Mångfallsberget, situated 2 km N of Boliden, we find an exact counterpart of the andalusite rock at Boliden. A sericitic rock with more or less quartz here contains lenses of andalusite rock, besides andalusite composed of corundum, sericite, diasporite, tourmaline, and a number of sulphides such as Sb-bearing tellurobismuthite, tetrahedrite, and pyrite. The complex is cut by lamprophyric dykes. The rocks are identical with those at Boliden and are believed to have had the same mode of origin.

From the Riddarhyttan ore field in Central Sweden, Geijer (30, pp. 20—21) describes the formation of porphyroblasts and veins of andalusite in a cordierite-bearing mica schist. The schist as well as the andalusite is considered by Geijer to have been formed by hydrothermal alteration of leptites. A certain resemblance exists to the rocks at Boliden but there is a notable dissimilarity in that an addition of MgO and FeO occurred at Riddarhyttan.

In a monograph on the San Francisco District in Utah, B. S. Butler describes (12, pp. 78—81) the hydrothermal alteration of a Tertiary quartz latite into a quartz-sericite rock. By an intensified alteration this rock is subsequently transformed into an andalusite-bearing quartz-sericite rock. It also contains some diasporite. There exists a good resemblance to the Boliden rocks both from a mineralogical and a chemical point of view. In Table 40 below a comparison is made between similar rock types from the two occurrences.

The sequence of the alteration is the same as at Boliden, and Butler remarks (p. 80) that »as long as there was sufficient potash or soda in the rock to unite with the alumina that was liberated by the breaking down of the felspars» sericite was formed rather than andalusite. When still more alkalis are carried away from the sericitized rock, an excess of alumina is left, resulting in the origin of andalusite or diasporite.

Concentrations of aluminium silicate in the form of cyanite are widely distributed in North Carolina. They were recently described by J. L. Stuckey

who considers them to be formed by »metasomatic replacement of acid crystalline rocks, pegmatite dykes, and quartz veins» (93, p. 670). The cyanite occurs in disseminated deposits, forming irregular lenses in schistose rocks, and in pocket or bunchy deposits occurring as lenses in pegmatite dykes or quartz veins (93, p. 663). The solutions which caused the formation of the cyanite are considered to be residual solutions from the pegmatites and their parent magma. The process seems to imply a considerable addition of alumina.

Table 40.

Comparison between altered rocks from Boliden and the San Francisco District.

	1.	2.		3.	4.
Quartz	61.3	58.0	Quartz	51.1	56.34
Sericite	36.6	40.9	Andalusite	38.4	26.35
Rutile, apatite	1.7	—	Sericite	7.8	15.60
Calcite	—	0.6	Rutile, apatite	2.7	[1] 1.60
	99.6 %	99.5 %	CaO	—	0.15
				100.0 %	100.04 %

1. Sericite schist, Boliden. Analysis No. 5 (p. 30).
2. Quartz-sericite rock, San Francisco District, Utah (12, p. 80).
3. Quartzose andalusite rock, Boliden. Analysis No. 15 (p. 39).
4. Quartz-andalusite-sericite rock, San Francisco District, Utah (12, p. 80).

Illustrative examples of andalusitic and sericitic rocks, very similar to those at Boliden, have been described from several districts in Russia, *e. g.* from NE Kazakstan. According to Nakovnik (61, 62) acid Devonian volcanics are here hydrothermally altered to »sericite quartzite» and »andalusite quartzite» (cf. p. 24). The presence of quartz, diasporite, corundum, rutile, kaolin, alunite, barite, and jarosite is also stated. Nakovnik considers CaO, MgO, MnO, and Na_2O to have been removed and TiO_2 and Al_2O_3 to be constant, while K_2O, F, B, H_2O, S, and metals have been introduced. The course of the alteration is more or less parallel to that at Boliden, although the addition of alumina was more marked at the latter place.

Another Russian occurrence of similar rocks is described by Movsesian (59) from the Paraga-Tchai deposit in the Konguru-Alanguez Range (Azerbaijan). The bedrock is composed of Eocene volcanics and the alteration is caused by a granodiorite. Quartz-sericite rocks are formed, sometimes carrying andalusite, sillimanite, diasporite, corundum, rutile, and pyrite, etc. The content of andalusite varies from a few per cent up to 80—70 per cent. According to Movsesian the andalusite is replaced by corundum and sericite.

Andalusitic rocks, somewhat similar to the types above, but looked upon as formed by metamorphism of primary aluminous rocks, have been described by P. F. Kerr and P. Jenney (44) from Oreana, Nevada. The bedrock consists

[1] Including 1.05 % ilmenite.

of Triassic rhyolites with tuffaceous beds, to a great extent altered to quartz-sericite schists. After an albitization of the rocks there followed a formation of andalusite, quartz, tourmaline, rutile, etc. Kerr and Jenney are of opinion that no introduction of alumina took place but that the andalusite was formed by recrystallization of alumina-rich material in the tuffs. The metamorphism is ascribed to »aqueous-igneous and pneumatolytic influence, due to the proximity of an igneous body» (44, p. 297). This metamorphism was subsequently followed by a hydrothermal alteration of the andalusite rock, resulting in the origin of dumortierite and sericite.

Origin of the Hornblende-Plagioclase Rocks.

It has been pointed out that the volcanic rocks have been subjected to a metamorphism which resulted in the formation of rocks with abnormally basic plagioclase, hornblende, epidote, chlorite, and biotite. These rocks seem in particular to be developed next to the sericitic rocks, although they have been encountered also within the fresh volcanics. Their geological appearance indicates that they stand in genetic connection with the sericitization.

The rocks in question show an increase mainly of CaO, MgO, and FeO. The rocks are further completely recrystallized, occasional phenocrysts of quartz being the only primary feature left intact.

Only one analysis has been made of these rocks (p. 22). The analysed sample represents a metamorphic facies of the keratophyre described on a previous page (p. 16). An analysis of the keratophyre was presented in Table 1 (Analysis No. 2). Although the metamorphic keratophyre does not contain any hornblende in this case, it may be considered typical and a comparison between the two analyses will give an idea of the changes that have taken place.

The amount of CaO increases in the metamorphosed rock as is evident also from a comparison between the normative compositions of the plagioclases (Table 41). The contrasts are even greater if we make the comparison with the still fresher keratophyre from the 130 m level (p. 17, Analysis No. 1).

Table 41.

	Or	Ab	An
Keratophyre (Analysis No. 1)	2.60	94.81	2.59
Keratophyre (Analysis No. 2)	21.30	59.20	19.50
Metamorphic keratophyre (Analysis No. 4) . . .	39.50	11.16	49.34

We further note an increase of MgO and FeO which mainly combine in chlorite and biotite. The content of Na_2O decreases continuously, while K_2O and also H_2O increase with the alteration.

The increase of the femic oxides in this metamorphic process is rather sig-

nificant in view of the fact that these very oxides are removed during the formation of the sericitic rocks. It is consequently close at hand to presume that the ascending sericitizing solutions took up these oxides during the alteration and then continued their course upwards and to the sides into the still unaltered volcanics. Here an addition of substances took place and the solutions, loaded with CaO, MgO, FeO, H_2O, etc., reacted with the fresh rocks under the formation of basic plagioclase, hornblende, biotite, and others. Some CaO combined with CO_2 and formed calcite, now occurring in veins.

Summary.

The hydrothermal alteration of the volcanic rocks in the deposit is a continuous process in which, however, three phases can be distinguished, the formation of 1) quartz-sericite rocks (or chlorite-bearing types, where the mother rock was a dacite), 2) quartz-free sericite rock, and 3) andalusite rocks, in part quartz-bearing. The formation of these rock types was accomplished before the beginning of the ore deposition, but it is evident that sericitizing solutions were given off at least during the first two stages of ore deposition. Especially during the second stage the sericitization is well marked.

The phases of alteration are each characterized by a transfer of different substances, indicating that the altering solutions continuously changed not only as regards concentration but also as to temperature and pressure. The changes in concentration can to a certain extent be followed by studying the gains and losses of the various substances. Although such changes are of great importance, it is certain that also variations in temperature and pressure play an important part. It is hardly possible to follow the changes in the solutions in this complicated alteration in detail but the following points may be emphasized.

During the first phase we find that mainly K_2O and in part also SiO_2 were introduced. The femic oxides were removed and the solution loaded with these oxides brought about the formation of basic plagioclase, hornblende, biotite, etc., in the surrounding volcanics. During the second phase the sericitization is accentuated and still more K_2O, and in this case also Al_2O_3, are added. Quartz was replaced and a large amount of silica was brought into solution. The solutions also introduced F and H_2O during these two phases.

In the third phase a radical change in the alteration has taken place and no more alkali is introduced. We instead find a fairly complete removal of the alkalis, H_2O and F, combined with a considerable addition of Al_2O_3. Also some silica was removed.

The transfer of all these substances, some of which have a low vapour pressure, is believed to have been accomplished by the action of heated aqueous solutions. Although it seems likely that the solutions when they left their magmatic source were of an acid nature (56, pp. 6—7), the experience from many deposits indicates that the sericitization was accomplished by the ac-

tion of alkaline or still weakly acid solutions (86, p. 803). This is probably also true of the sericitization at Boliden, the original acid solutions having been more or less neutralized on their ascent through the surrounding rocks (56, p. 7). The neutralizing effect gradually diminishes (35, p. 236), however, and a state is finally reached, where the solutions still possess their acid nature even at a considerable distance from their source. An acid leaching of the alkalis from the walls of the channelways now sets in, resulting in an aluminous residuum which together with the amount of alumina added and the silica in the rocks forms andalusite. The source of the added alumina may be purely magmatic, or it may have been leached from deeper horizons, where the solutions very likely possessed a still higher acidity.

Origin of the Ores.

Origin of the Arsenopyrite Ore and its Differentiates.

Evidence of the Contacts.

Two distinctly different types of contacts between the arsenopyrite ore and the wallrocks were distinguished. Along the central portions of the ore bodies the contacts are generally sharp and the ore abuts against the walls, as a rule without any gradational zone being developed. Although disseminations of sulphides are sometimes developed at the contacts, there is in many cases hardly a trace of sulphides in the sericitic wallrocks. The contacts are also cut by apophyses of arsenopyrite ore, or sulphominerals, forming offsets from the main ore body. Inclusions of wallrocks are generally very rare in the solid ore.

The other type of contact is mainly developed around the ends of the ore bodies which here finger out or split up into smaller bodies. The contacts to the wallrocks are indistinct and they are strongly impregnated by a number of ore minerals.

The two types of contacts are so fundamentally different that they must have been formed under different conditions.

The last-mentioned kind is a typical replacement contact and was formed by metasomatic replacement of the schist along capillary openings and fissures.

The appearance of the first type of contact, on the other hand, suggests an intrusive formation, the intrusive body — in this case the ore solution — having been introduced into the schisted rock complex under heavy pressure, pushing the walls of the channelways apart.

As will be explained in greater detail in a following chapter (p. 178), the author adopts the term displacement to designate the mode of origin of ore deposits formed in this intrusive manner. As far as the author is aware, the term was first used in this meaning by S. Gavelin (29).

The cross-cutting apophyses and the folding of the contacts, in which also the lateral lenses in the wallrocks are sometimes involved, and the brecciated character of the ore, indicate the action of stress during ore deposition. This stress plays an important part in the *mise en place* of the ore bodies and in the differentiation of the ore solution.

Evidence of Structures and Textures.

The most typical feature of the normal arsenopyrite ore is the occurrence of pores or »druses» with borders of idiomorphic arsenopyrite crystals. As far as the author is aware this structure has not been described before from any other ore deposit.

The pores can be considered to have originated in two ways, 1) by replacement and partial recrystallization of the fine-grained ore, and 2) by direct crystallization.

The first alternative postulates that the homogeneous and fine-grained arsenopyrite ore had been punctured in countless places by replacing solutions of varying composition. The replacement was confined to the more or less rounded areas of the pores and then the replacing solution brought about a recrystallization of the surrounding arsenopyrite. The »druses», however, generally appear without relation to any fissures, and, what is more, the microscopic study indicates that they probably form closed spaces in the ore. On the whole the above explanation seems to lack a sound foundation and cannot be applied.

The other alternative, suggested already in the preliminary paper (65, p. 143), seems to furnish a more adequate explanation. The fine-grained texture of the ore is indicative of a rapid crystallization of the arsenopyrite, which together with a few other minerals forms an early group. Before the arsenopyrite has completely crystallized, a residual solution, enriched in S, Cu, Zn, Fe, Pb, Sb, CaO, SiO_2, etc., is concentrated in numerous places. Part of this solution accumulates to globules, forming the embryos of the »druses». In the globules the crystallization of the arsenopyrite continues, the strong ability of this mineral to form crystals resulting in the increasing size and idiomorphism of the arsenopyrite grains towards the pores. The gradual transition from the fine-grained ore to the fringes of idiomorphic arsenopyrite around the »druses» indicates an unbroken crystallization.

In the description of the ore it was mentioned that sometimes the »druses» are so closely spaced that a skeleton texture is developed. A similar texture may also develop in the places where the ore has been intensely brecciated and absorbed by later mineralizations. The arsenopyrite has here been mobilized and has crystallized out again in more or less closely spaced crystals.

The origin of the brecciation of the ore now remains to be discussed. The stress acting on the partly crystallized ore promotes movements which produce a filter-press action on the residual solution remaining in the ore. The movements also cause a rupturing of the ore and the solution is pressed in

on fissures. In some places the crystallization of the brecciating solution is rapid and the replacement of the fragments is slight or quite insignificant. In other places the crystallization is slow and the brecciated ore becomes strongly replaced and absorbed. The minerals which form in these breccias, as well as those in the »druses», belong to the second and third groups.

It should be pointed out that the arsenopyrite ore is brecciated not only by its own residual solution, but also by solutions of the two later stages. The ensuing breccias have often the same appearance as the former and, as emphasized already on an earlier page, it is many a time impossible to distinguish between them.

The interpretation of the structures and textures now presented implies that the ore was formed by a continuous and fairly rapid crystallization of a composite ore solution, containing all the elements present in the ore. A fractional addition of solutions of varying composition is not considered to have taken place. Within the solution a differentiation occurred, resulting in the formation of the various mineral associations which accompany the arsenopyrite ore.

Mise en Place of the Ore Bodies by Displacement.

The plans in Fig. 21, showing the distribution of the arsenopyrite ore bodies on two levels before the formation of the later ores, indicate that the ore solution followed several separate ducts in the schisted bedrock. The ducts represent pressure minima, formed by the action of the shearing stress which caused differential movements between the schists and the lenses of andalusite rock enclosed in them.

As explained above, the ore solution was intruded in the zones of pressure minima and made the space which the ores now occupy by displacement in the schists. The stress is still active and locally a corrugating of the sericitic wallrocks takes place. Some of the folds are broken through by arsenopyrite ore or sulphominerals which are squeezed out, forming the apophyses.

The development of a gas phase and its propelling force exercised on a liquid phase has generally been considered as the motive power of a rising ore solution (55, p. 117, and 82, p. 143). Graton who asserts the liquid character of the ore-forming fluid, considers the weight of the overlying rock column to be the main cause of the ascent (35, p. 342).

A co-operation of these causes may have contributed to the ascent of ore solutions in general, but as regards the arsenopyrite ore at Boliden it is doubted whether these causes alone could have generated a force strong enough to transport the heavy ore solution a long distance and to overcome the resistance of the wallrocks at the time of displacement.

An important source of motive power is, however, to be found in the orogenic pressure, and it is believed that in many cases the transport and the *mise en place* of ore solutions may be attributed to this force. Ore deposits of magmatic affiliations are as a rule closely related to orogenic zones in the

crust of the earth, and the deposition of the ores as well as the intrusion of igneous rocks is to a large extent dependent on the orogenic pressure. The ore deposits of the Skellefte District are situated in an orogenic belt (38, p. 43) with intense folding and intrusion of deep-seated igneous rocks. As regards Boliden, the position of the deposit in the dragfold and the structural control exercised by the dragfold on the ore bodies indicate a close relationship between ore deposition and orogenesis.

An ore solution that has been mobilized and is being propelled upwards through a suitable duct by the orogenic pressure may have its communications with the source magma cut off, the duct being closed by the same pressure as is moving the solution upwards. In other words, the ore solution is transported through the bedrock as a closed fraction in an intrusion-like manner. It is suggested that well delimited and solid ore bodies such as the arsenopyrite ores of Boliden may be formed in this manner. A necessary condition for such an intrusion to take place is a tectonically well prepared bedrock, *e. g.* the dragfold with its thoroughly foliated rocks at Boliden. In the case of the arsenopyrite ore at Boliden, the solution was introduced along several separate ducts, the directions of which were controlled by the linear structure of the dragfold.

It must be pointed out that traces of these closed ducts have never been found in the bedrock below the ore bodies in the deposit. Their lower portions peter out in the same manner as do the upper portions. The sericite schists are, however, very well foliated and it seems possible that the solution, which was moved upwards under a heavy pressure, may have been smoothly injected in them without any marked rupturing or brecciation. It also seems very likely that just in these rocks fissures may be healed out of recognition by stress action in combination with the action of later hydrothermal solutions which circulated in the bedrock.

The absence of visible channelways below many ore bodies is a difficult problem which in most cases has not been adequately solved. The difficulties are even still greater in the cases where solid ores were formed by a metasomatic replacement by dilute solutions which penetrated the bedrock along countless fissures and capillary openings. As regards ores of the present type the explanation now given, although admittedly open to criticism, seems to afford a plausible solution of the problem.

A decrease in the orogenic pressure or an increase in the resistance offered by the intruded rocks finally puts a stop to the ascent of the arsenopyrite solution. The main period of ore deposition and crystallization now sets in. The crystallization begins with the formation of arsenopyrite and a few other minerals. At the same time, but mainly during a more advanced stage of the crystallization, the ore solution becomes enriched in volatiles and it gradually acquires the character of a hydrothermal solution. Under favourable circumstances even a boiling may occur. The replacing capacity of the primary solution was probably insignificant but as soon as crystallization begins, and particularly during its hydrothermal stage, a strong replacement

occurs, chiefly around the edges of the ore bodies, where an infiltration of the solutions into the schist was most easily accomplished. Part of the remaining hydrothermal solution migrates some distance into the wallrocks and forms the disseminated ore. Even if the arsenopyrite ore in its initial stage is considered to have been formed by displacement in the schists, it must be emphasized that during the later stages of its deposition replacement played an important part.

Nature of the Ore Solution.

The discussion above is an attempt to show that the arsenopyrite ore was formed by a complex ore solution by displacement in the schisted wallrocks. The textures and structures indicated that the crystallization of the ore was a process that took place in the solution without any subsequent addition of substances from the magmatic source.

Even in the preliminary paper (65, p. 144) it was pointed out that the solution which gave birth to an ore of this character could not be considered hydrothermal. The appearance and character of the ore rather indicated that the solution was closely related to the magmatic stage and in the paper quoted it was characterized as p n e u m o t e c t i c.

This term was created about twenty years ago by Graton and McLaughlin (34, p. 85) who defined as pneumotectic those »processes and products of magma consolidation in which fundamental influences of a sort that was magmatic in the strictest sence were recognizably modified and to some extent controlled by gaseous constituents or so-called mineralizers . . .» The pneumotectic solution is thus still closely related to the magmatic — orthotectic — stage but constitutes an early residual solution which was separated from the magma immediately after its main crystallization (»Hauptkristallisation»). Berg (2, p. 137) characterizes the pneumotectic solution as a »magma» enriched in dissolved gases and volatiles, which because of a low viscosity can intrude the surrounding bedrock.

Compared with hydrothermal solutions, which as a rule have a low concentration, the pneumotectic solutions must be considered fairly concentrated. The orthotectic crystallization in the primary magma brings on a concentration under heavy pressure of several metals, volatiles, and rock-forming oxides, in the pneumotectic solution.

The pneumotectic state of the arsenopyrite solution and the presence in the ore of several minerals which are generally considered to be indicative of a high temperature of formation would imply that at the time of displacement the solution had a rather high temperature. The absence of an infallible »geologic thermometer», however, renders a determination of the temperature impossible. Recent investigations indicate that deep-seated igneous rocks may solidify at such low temperatures as between 500 and 700° C and it seems likely that a pneumotectic solution of the character indicated in its initial state had a slightly lower temperature, say about 400—500° C.

As mentioned above the original pneumotectic solution at the beginning of the crystallization changes character and gradually becomes hydrothermal. A lowering of the temperature gradually takes place and the later phases of crystallization are characterized by low-temperature minerals.

Differentiation of the Ore Solution:
A. Origin of the Various Types of Arsenopyrite Ore.

Some of the arsenopyrite ore types occur together in one and the same lens and it seems probable that their differentiation was caused by some process of fractional crystallization, some parts of the solution being enriched in *e.g.* quartz or cobalt. The quartz-banded and the cobaltite-bearing types which occur in the marginal or terminal parts of the ore bodies are thus later crystallized phases of the normal arsenopyrite ore. The dense type is considered to be a rapidly crystallized variety of the normal ore.

The apatite-banded ore is rather puzzling because of its appearance and composition and as, at least so far, it has been found *in situ* (cf. p. 44) only in one place in the deposit, in the e-lens. The banding is probably due to a differentiation in a liquid state and the folding of the bands took place before the ore had solidified. The exceptional concentration of apatite is a difficult question to which no adequate answer can be given. It may depend on an unusual abundance of apatite in the primary solution.

B. Origin of the Various Mineral Associations Related to the Arsenopyrite Ore.

In the description of the arsenopyrite ore it was shown that the ore was associated with certain formations of varying mineral composition, such as rutile rock, pyrite-apatite ore, and quartz-plagioclase veins, which could be regarded as differentiates of the primary arsenopyrite solution. The mode of separation of these mineral associations is one of the most difficult problems offered by the deposit and no satisfactory explanation can be given, although the following points of view may throw some light on the question.

Besides sulphide-forming components the arsenopyrite solution contained a number of rock-forming oxides, such as CaO, Al_2O_3, MgO, alkalis, and SiO_2. According to the general conception these groups of components are immiscible in a dry melt at ordinary magmatic temperatures[1]. The pneumotectic nature of the ore-forming fluid implies a high concentration of volatiles, as H_2O, CO_2, P, and others, and it is very likely that they involve an increased solubility of the sulphides in the silicate phase. This circumstance has been pointed out by Lindgren (55, p. 799), J. H. L. Vogt, and Th. Vogt (97). Also Collins assumes a certain solubility of sulphides in a silicatic residual magma when

[1] At higher temperatures (1,700° C), there is, however, an appreciable mutual solubility (6, Vol. I, p. 300).

discussing the origin of the Sudbury nickel deposits (14). Berg (5, p. 83) deals with the same problem, but is inclined, as regards the Sudbury deposits, to consider the magma to be an emulsion rather than a solution. With our present knowledge on this subject no definite conclusion can be drawn and we must be content merely to establish the fact that in the case of the arsenopyrite ore at Boliden the pneumotectic solution did contain a considerable percentage of rock-forming oxides. The mineral associations under consideration are essentially composed of gangue minerals of the second group of crystallization, *e. g.*, rutile, apatite, plagioclase, and quartz, and it seems very likely that their separation was caused by liquid immiscibility, either at the moment the solution was expelled from the magmatic source, or, if the pneumotectic solution is able to keep gangue minerals and sulphides mutually dissolved as discussed above, at a later moment after the displacement when cooling sets in[1].

Even if the separation from the sulphidic solution of a fraction enriched in gangue minerals can be explained in the manner outlined, we are still faced with the difficult problem as to how the further separation in the individual parageneses occurred. With the exception of the rutile, the mineral associations are all exclusively tied to the arsenopyrite ore in Stope 28 and it thus seems evident that specific conditions prevailed during the crystallization of that ore body, or that in this case the ore solution for reasons unknown had a composition different from that in the other cases.

Immiscibility can hardly be conceived as a cause of separation in this fraction with mainly gangue minerals — in the pyrite-apatite ore there is, however, also a large percentage of pyrite, pyrrhotite, and cobaltite — and it seems more likely that a fractional crystallization has been the main operative cause. Squeezing and filter-press action have then co-operated in the transfer of the separate fractions from the main ore body out into the wallrocks. A gaseous transfer may perhaps, *e. g.* in the case of the rutile, also be considered. No definite solution of this problem can be suggested and as mere guesses are of no avail, the question will be left open.

As regards the felspathized wallrocks and the disseminated ores, they are considered to have been formed by a kind of »contact metamorphism» through the action of emanations from the crystallizing ore solution. The felspar in the wallrocks is sometimes impregnated with arsenopyrite and it is believed that its formation took place at the close of the crystallization of the first group of minerals. Among the ore minerals in the disseminated ores, finally, we note practically all the minerals occurring in the solid ore and it is probable that their formation continued practically throughout the crystallization. It was accentuated when the solution had assumed a more hydrothermal character. As stated on a previous page this type of ore is mainly present at the terminal portions of the ore bodies, where the emanations had easy access to the surrounding rocks along the schistosity.

[1] Also the formation of the apatite-banded ore may have been caused by liquid immiscibility of apatite and sulphides.

The Lamprophyres and the Origin of the Quartz-Tourmaline Ores.

Original Composition of the Lamprophyres.

The petrographic description of the lamprophyre showed that both types of this rock are metamorphosed, although the hornblende-rich type still possesses some primary features.

The plagioclase is thus very likely primary as regards composition. In Stope 28, where a lamprophyre dyke is enclosed in the arsenopyrite ore, the dyke has thin marginal zones of fine-grained plagioclase whereas the central part is composed of normal hornblende lamprophyre. These features are certainly primary and they have been kept intact because of the sheltered position of the dyke in the ore.

The hornblende makes the impression of being secondary and it was probably formed by uralitization of a pyroxene, now completely destroyed. The amount of hornblende is sometimes so large that the rock deserves the name »hornblendite».

The analyses clearly show the basic character of the hornblende lamprophyre. The percentages of alkalis are remarkably low and it is quite possible that some alkali was carried away at an early stage of the metamorphism. The marginal zones of plagioclase are also basic but here the amount of hornblende is quite inconsiderable.

Before the chloritization of the lamprophyre the rock was subjected to a recrystallization, accompanied by a chemical alteration mainly resulting in the above-mentioned uralitization of the pyroxene. Some plagioclase was probably also destroyed and part of the sodium was removed. A certain amount of biotite was formed in some places. Contrary to the later chloritization, this alteration does not imply any considerable transfer of substance. The metamorphism now described occurred soon after the intrusion of the dykes and was probably caused by after-effects from the lamprophyric magma. It was closely followed by an intense chloritization.

It is difficult to form an opinion of the original composition of the lamprophyre. We can safely state only, that it is a basic dyke rock and that the normative composition of the rock indicates a certain kinship to rocks of diabase- or gabbro-character. A differentiation has sometimes taken place in the dykes, resulting in an enrichment of the plagioclase towards the margins and of femic minerals in the centre of the dykes.

Seeing that the question as to the primary nature of the rock cannot be considered definitely solved, it has been found advisable to use the term »lamprophyre» throughout the paper.

Chloritization of the Lamprophyre.

The hornblende lamprophyre is as a rule strongly chloritized. The chloritization was caused by hydrothermal solutions and their source may in the

first place be sought in the quartz-tourmaline ores which closely followed upon the intrusion of the lamprophyres. The andalusite rock has been extensively altered by hydrothermal solutions, given off by the quartz-tourmaline ores (p. 100), and it seems very likely that these solutions also caused the chloritization of the lamprophyres. The alteration may have continued to a lesser extent also during the pyrite stage, although this stage does not seem to have been accompanied by any hydrothermal alteration to speak of (p. 144). During the chloritization a foliation was developed in the lamprophyres, caused by the stress.

There is a certain resemblance between the chloritization of the lamprophyre and the formation of the chloritic sericite schist. The CaO of the silicates is thus in both cases completely removed, which in the case of the hornblende lamprophyre implies a large transfer of substance in view of the high percentage of CaO in this rock. The amounts of FeO and MgO, and of Al_2O_3, seem to be fairly constant. The percentage of Fe_2O_3 varies in the two analyses of hornblende lamprophyre but has decreased considerably in the chloritic type. An increase in the percentages of SiO_2, K_2O, and H_2O is noted as in the case of the sericitized and chloritized volcanics. The amounts of alkalis are rather low in the hornblende lamprophyre and Na_2O predominates over K_2O. In the chloritized rock the relation is reversed and some K_2O has very likely been added.

The mariposite is another interesting product of the hydrothermal alteration of the lamprophyre. A discussion of its occurrence and formation will be found on a later page (p. 166).

Mise en Place of the Lamprophyres and the Quartz-Tourmaline Ores.

As outlined in the chapter on structure (p. 140), the fissures and channelways now occupied by the lamprophyres and their accompanying ores were formed by the same shearing stress as caused the formation of the dragfold. Also in this case the ore deposition is thus controlled by the same structure as in the arsenopyrite stage.

A study of the contact relations of the ore bodies belonging to this stage shows that in many respects they are similar to those of the arsenopyrite stage and it is concluded that also in this case the ores were brought into place by displacement. The ore solutions were pressed into the schisted rock complex by the force of the orogenic movements.

The displacement is accompanied by a metasomatic replacement of wallrocks and lamprophyric dykes but it does not attain the same extension as in the arsenopyrite stage. Especially the tourmaline shows a strong ability to migrate and the mineral is found long distances from any tourmaline veins. Disseminations of ore minerals are only rarely present (p. 106).

Nature of the Ore Solution.

When discussing the genesis of the quartz-tourmaline ore in the preliminary paper (65, p. 145), the author characterized the ore solution as »pneumatolytic». It was pointed out that the solution must have been heavily loaded with B and that it contained also other mineralizers, *e. g.* F and P. What was the physical state of this solution? This is a difficult question and no definite answer can be given, but the sharp delimitations of the ore bodies, the sharply defined and cross-cutting apophyses at the sulphidic portions of the ores, and the comparatively rare occurrence of impregnations rather favour the belief that the solution was brought in in a liquid state. A further support for this assumption is afforded by similar tourmaline veins at the Buffalo Ankerite Mine in the Porcupine District (p. 174). Some of these veins are identical with some tourmaline veins at Boliden but contain sharp-edged inclusions of various rocks (Fig. b, Pl. 48), indicating that the vein solution was brought in as a liquid. These breccia veins remind of the tourmaline-brecciated arsenopyrite ore from Stope 23 at Boliden which was also most likely formed by a brecciating solution in a liquid state.

All these circumstances indicate that in its initial state the solution was pneumotectic as defined in a previous chapter. The solution was, however, richer in mineralizers, particularly in B, F, and H_2O, than the arsenopyrite solution. On the other hand, the pneumotectic solution in this case contained a comparatively small amount of metals, sulphur, and arsenic. The last-mentioned substance is on the whole very rare. The solution also contained appreciable amounts of Si, Al, and Mg, which still more stresses the dissimilarity to the arsenopyrite solution. Particularly silica is in many cases extremely abundant and in some veins forms the predominant constituent.

As in the case above, nothing definite can be stated regarding the temperature of the solution. The high percentage of volatiles implies a considerable lowering of the freezing points of the minerals present. In the initial stage the temperature may have been comparable with that of the arsenopyrite solution.

The paragenesis of the ore embraces a rather wide range of temperature as the crystallization begins with such relatively high-temperature minerals as apatite, rutile, and tourmaline, and ends with the formation of fissures with calcite and pyrargyrite, and the formation of kaolin and analcite. The same is to a certain extent true of the arsenopyrite ore but there the range of temperature is not quite so wide as in the case of the tourmaline ore.

Even if the ore solution at the time of the displacement was of a pneumotectic character, it soon changed to a hydrothermal state. This is indicated by the occurrence of sericite, appearing together with some of the sulphides, and the appearance of sericite and mariposite in schlieren and veins. Hydrothermal emanations are also given off during the crystallization and attack the andalusite rock and the lamprophyres.

Differentiation of the Ore Solution.

Also in this case the ore solution went through a differentiation, resulting mainly in the separation of a sulphide fraction and a fraction chiefly composed of quartz and tourmaline with some sulphides.

These two fractions are best studied in Stope 23 (170 m level). The tourmaline ore there often contains appreciable amounts of pyrrhotite and chalcopyrite in the groundmass. In the upper portions of the ore body there is a gradation from a tourmaline ore to an ore chiefly composed of pyrrhotite and chalcopyrite. The latter contains scattered needles of tourmaline and inclusions of tourmaline ore. The separation in this case may be adequately explained by filter-press action (15, pp. 325—326), which pressed the still liquid sulphide fraction into the schisted rock complex above.

The separation is not complete, however, and the tourmaline ore still contains an appreciable amount of metallic minerals. Some of them are fairly late-crystallizing minerals, *e. g.* galena, sulphominerals, and gold, and they seem to accumulate especially in quartz-rich tails at the tourmaline ores or in separate quartz veins. The reason for this incomplete separation is not known and the problem must be left open.

An unsolved differentiation problem is also the appearance of the Bi-tellurides as comparatively pure masses on fissures in the rutile rock in Stope 28 (250 m level) and in schist on the 210 m level. The minerals were undoubtedly formed during this stage as they appear also in the quartz-tourmaline ore and are found on fissures cutting lamprophyric dykes. The occurrence of kaolinite with the Bi-tellurides on the 210 m level indicates that the paragenesis was formed under hydrothermal conditions.

An interesting point in this connection is the abundant appearance of free gold together with the Bi-tellurides. Gold-tellurides are probably completely absent or they occur in quite insignificant quantities only.

Sericitization of the Andalusite Rock.

The geological evidence proves beyond doubt that the sericitization of the andalusite rock was caused by emanations from the quartz-tourmaline ore. Sericite is the main product of alteration, but corundum, diasporite, kaolin, and andalusite of at least two later generations were also formed.

The andalusite is consumed by sericite along cracks and cleavage planes and its formation was brought about by a solution, adding alkalis (mainly K_2O), H_2O, and F. The process may have followed the schematic formula:

$$6(Al_2O_3 \cdot SiO_2) + 2H_2O + K_2O = 2H_2O \cdot K_2O \cdot 3Al_2O_3 \cdot 6SiO_2 + 3Al_2O_3.$$

In strongly sericitized portions of the andalusite rock corundum forms in the andalusite. Its formation is probably due to the surplus of Al_2O_3, which, according to the above formula, is liberated upon the formation of sericite. The diasporite, formed contemporaneously with the sericite and the corundum, has a similar origin.

The occurrence of kaolin in close relation to sericite shows that also this mineral is a product of the same alteration.

The main result of the alteration process is thus a decomposition of the andalusite by the action of aqueous alkali- and fluorine-bearing solutions and the formation of a number of new minerals. In some cases the process also leads to the formation of andalusite in crystals in sericite veinlets, or in separate veins of at least two generations. This later andalusite is in places again slightly altered. These circumstances imply that the altering solutions circulating through the andalusite rock continuously changed their nature from place to place during the alteration.

The appearance of analcite on one occasion (p. 95) as a decomposition product of andalusite shows that locally also sodium-bearing solutions may have been given off by the ore solution.

Origin of Mariposite and the Source of Chrome.

An interesting feature in the paragenesis of the chloritic lamprophyre and the quartz-tourmaline ores is the occurrence of the chromiferous mariposite. It is chiefly found in the quartz-tourmaline ores and many reasons indicate that it is genetically related to them and that it is of a hydrothermal origin. The appearance of the mineral in separate veins shows that in places it was formed by a separate, chrome-bearing hydrothermal solution which followed the fissures occupied by the lamprophyres[1].

Chrome occurs in nature chiefly in the form of chromite, a mineral which generally has been regarded as an early product of crystallization from basic magmas, although it has been shown by recent studies by Sampson (85) and Cl. S. Ross (80) that chromite, as well as some chromiferous silicates, may crystallize late and even may have a hydrothermal origin. Eskola arrives at the same conclusion as regards chromite, fuchsite, chrome-diopside, and chrome-tremolite from Outokumpu in Finland, and emphasizes that »the occurrence of chromium at Outokumpu illustrates the ability of this element to migrate and to take part in metasomatic replacements» (22, p. 43). Also Saksela (83, 84) describes hydrothermal chromiferous mica from some Finnish ore deposits.

Mariposite is known particularly from the Mother Lode gold-quartz veins in California, and in a paper on those veins, Knopf (48) gives a description of the occurrence of the mineral. Knopf considers that the mariposite was formed by hydrothermal alteration of chromite, occurring in serpentine rocks.

At Boliden the wallrocks were primarily acid or intermediate and in the first place only the primarily basic lamprophyres can be considered to have

[1] A few words may be said here about the peculiar spherulites of tourmaline occurring in schlieren of mariposite in the solid tourmaline vein at section 15 on the 250 m level. The mariposite evidently crystallized later than the tourmaline in the vein and it is possible that some of it was brought into solution by the remaining mariposite solution. The crystallization of the dissolved tourmaline then began at certain centres in the mariposite, from which the mineral grew in radiate needles.

been the source of the chrome. It should be noted, however, that the analysed hornblende lamprophyre from the 410 m level, situated outside the main ore-bearing area, and the fresh plagioclase-bearing marginal zone of the lamprophyre in Stope 28 are devoid of any chrome. Mariposite seems to occur only in the more or less altered lamprophyres in the main ore-bearing zone, where they have been influenced by emanations from the quartz-tourmaline veins. It may also be added that most of the mineral is found within these veins. The evidence thus seems to indicate that the chrome was brought in by the quartz-tourmaline solutions and that during the differentiation of the source magma it followed the pneumotectic-hydrothermal ore solution rather than the lamprophyric magma. The chrome remained in solution until the hydrothermal phase of the ore deposition and was deposited as hydrothermal mariposite.

Relation between the Lamprophyres and the Accompanying Ores.

There are many cases known where gold-quartz veins are closely associated with basic dykes. Junner, for instance, reports from the gold occurrences of Victoria, Australia, that »narrow dykes of hornblende and biotite lamprophyres are frequently accompanied by auriferous quartz reefs . . .» (43, p. 85), and points out in the same paper that the richest ores are associated with dioritic and gabbroid rocks. Examples of similar conditions are known from California, Idaho, and British Guiana.

Hulin (41) discusses the relations between acid and basic differentiates, on the one hand, and ores, on the other, and expresses the opinion that the siliceous gangue of ore deposits derives from the acid members whereas the largest part of the ore minerals derives from the basic differentiates. Also Spurr has recently renewed the discussion on the relation between basic and acid dykes and ores. He considers, as against Hulin, that these formations »have been derived from a relatively small sub-magma that remained fluid after the consolidation of the major (generally intermediate in composition) magma, and thereafter split into the various injections in the grouping» (*viz.* basic dykes, acid dykes, and ores) (92, p. 45). Berg (5) criticizes Spurr's opinions as expressed in the paper quoted, raising the objection that this threefold division of the magma is incompatible with the current ideas of magmatic differentiation. He considers that the relationship between the three formations is only of a formal nature. Berg does not deny the possibility, however, of the formation of residual solutions rich in mineralizers and metals from a basic differentiate.

No general solution of this problem can be suggested, but as far as Boliden is concerned the author desires to point out that the close geological relations between the basic lamprophyres and the accompanying ores are not only of a formal nature but indicate a genetic kinship and that the two formations very likely originated from a common source magma. As a further support for this assumption, it may be alleged that the lamprophyres and their ores

form a distinct stage in the ore deposition at Boliden, clearly separated from the older arsenopyrite ore and the younger pyrite ore.

We do not know anything of the character of the magma that delivered the dykes and the ores, or of the cause of the differentiation. There are, however, no indications of a »double mineralization», as suggested by Hulin, during which the gangue minerals — chiefly quartz and tourmaline — should have been introduced as differentiates from an acid sub-magma, the ore minerals, derived from a basic sub-magma, being introduced later. The hypothetic (sub)magma in the present case separated in a basic (lamprophyric) silicate fraction and in a fraction chiefly containing SiO_2, B, F, H_2O, K_2O, S, Te, Se, and metals.

Origin of the Pyrite Ore.

Mise en place of the Ore.

The description of the contacts between the pyrite ore and the wallrocks showed that particularly along the central parts of the ore bodies they were quite sharp. The contacts often cut the schistosity of the wallrocks, however, and apophyses of varying shape appeared. The contacts were on the whole of the same character as along the arsenopyrite ore and it is concluded that also the pyrite ore was initially formed by displacement in very much the same manner as the ores of the two older stages.

The apophyses throw a great deal of light on the mode of ore deposition. The extremely sharp contacts to the sericitic wallrocks, the sharp-edged fragments of sericite schist, and the banding in some of the apophyses, which does not coincide with the foliation of the surrounding schists, prove, according to the author's opinion, that to a large extent the ore was formed by a displacing intrusion of the ore solution. The dislocated schist fragments and the appearance of fragments of arsenopyrite ore in places where no arsenopyrite ore occurs in the vicinity of the apophyses show that the ores in them were forced in on fissures in a liquid state. The fragments have been transported a certain distance by the solution. The fissures in which the apophyses appear as a rule have the character of tension cracks, formed by the stress acting also during the pyrite stage. The apophyses in Stope 3 (130 m level) and at section 3 in the open pit in the Western Ore were on the other hand formed by a compressive stress which caused a local bulging of the wallrocks. The bulges, or folds, were then broken through by the ore solution.

In this connection attention may be drawn to certain phenomena at the ore contacts in the Rammelsberg deposit, Germany, which remind of the apophyses at Boliden (4, p. 460; 87, p. 266). The fabric of the ores and also the disturbed appearance of the wallrocks at Rammelsberg indicate that heavy pressure played a great part in the formation of the ore. This pressure caused a flowage in the sulphidic mass which was pressed in along fissures and foliation planes in the surrounding slates, thus forming apophyses. The undis-

turbed tectonic conditions around and in the apophyses at Boliden, however, preclude the possibility of their having been formed by »cold-pressing».

Also the breccias in the arsenopyrite ore throw some light on the ore deposition. The inclusions of arsenopyrite ore in the pyrite ore are very often sharp-edged and can be brought to match. The breccias were evidently formed by a rupturing of the arsenopyrite ore and on the fissures thus formed the pyrite ore solution was forced in under heavy pressure.

The circumstances now discussed favour a formation of the ore by displacement in the schist complex, but there are certain features in the ore which indicate that metasomatic replacement played an important part in the ore deposition. Those features are the contact relations at the ends of the ore bodies and the occurrence of inclusions of various rocks in the ore.

At the ends of the ore bodies the contacts are very indistinct and the ore peters out irregularly. The wallrocks are also strongly impregnated with and replaced by various ore minerals.

The pyrite ore fairly often carries inclusions of wallrocks and lamprophyres. Both types are extensively veined and replaced by the pyrite ore, and some of them form only »ghost-like remains»[1]. The inclusions are often accumulated in zones which can be followed considerable distances through the ore. Most striking in this respect are the inclusions of lamprophyres, which, although they are strongly replaced and also dislocated, can be followed throughout the ore bodies. The inclusions are replacement remnants and demonstrate in an illustrative manner the great part played by replacement in the formation of the pyrite ore. During this stage replacement took place on a considerably larger scale than during the arsenopyrite stage.

The initial phase in the formation of the pyrite ore was characterized by displacement and the ore solution forced its way along zones of weakness and fissures in the complex of schists and older ore bodies. The pyrite ore appears in two large bodies and in some smaller ones and it seems evident that the solution was introduced through several channelways. In view of the complex geological conditions in the deposit, with sericite schists and scattered lenses of various ores and andalusite rock of highly varying competence, the stress at this stage of the ore deposition very likely produced a large number of fissures in the wallrocks as well as in the older ores.

After the displacement of the ore solution crystallization sets in and the metasomatic phase of the ore deposition begins. The replacement started from the channelways filled with ore solution and attacked the wallrocks and the older ores. The replacement was exceptionally strong in the portions of the wallrocks that were situated between the channelways and the older ore bodies and which probably were particularly ruptured and fissured by the stress, whereas the probably smooth, outer walls of the channelways, now forming the central portions of the pyrite bodies, did not offer any suitable points of aggression for the replacing solution. Here the stress opened

[1] There is a striking difference between these inclusions and the sharp-edged inclusions in the apophyses.

fissures in which the apophyses were formed. A strong replacement took place also towards the ends of the ore bodies, where the solutions could penetrate along the foliation of the schists.

The replacement generally proceeded so far that only remnants of wall-rocks and lamprophyres remained and large coherent ore bodies were formed. They also enclose remnants of arsenopyrite ore. In some places the latter was strongly replaced, as evidenced by the appearance of indistinct fragments of arsenopyrite ore.

The sericitic rocks seem to have been readily replaced by the ore solution, whereas the lamprophyres offered greater resistance to the replacement. This may be due to the basic composition of these rocks, but it is also due — at least in the case of the hornblende lamprophyre — to their lack of schistosity.

It is believed that also the pyrite solution was brought into place by the same orogenic pressure as forced up the solutions of the first and second stages. All along the pyrite ore bodies there are distinct traces of the action of a stress. The stress propelled the ore solution upwards through the schisted rock complex in the dragfold and closed the channelways behind the solution in the same manner as in the case of the arsenopyrite ore.

In the chapter on structure it was pointed out (p. 141) that the positions of the two main pyrite bodies suggested a stress acting rather in a direction opposite of that of the stress that formed the dragfold and controlled the location of the older ores. As already emphasized this position of the ore bodies is very likely only fortuitous and may depend on the ore solutions having entered along several separate channelways from which they replaced the intervening schists until two homogeneous bodies were formed. These bodies were consequently not formed along two fissures with the position and extension indicated by the outlines of the present ore bodies. It was concluded in the chapter quoted that the channelways along which the pyrite solution ascended were caused by the same stress as acted during the earlier mineralizations and during the formation of the dragfold. At least the Eastern Ore has a pitch parallel to that of the dragfold and the older ores. It may finally be added that no evidence of a stress acting in a different direction to that which formed the dragfold has been observed in connection with the pyrite ore.

Nature of the Ore Solution.

The similarity in appearance and *mise en place* between the arsenopyrite and the pyrite ores indicates that they were formed by solutions of more or less the same nature. Broadly speaking, also the pyrite solution may thus be considered to have been pneumotectic in its initial stage during the displacement.

Chemically the solution is characterized by the high percentages of S, Fe, Cu, Zn, SiO_2, CaO, and CO_2. Minor constituents are Pb, Sb, Bi, Al_2O_3, and MgO. Contrary to the solutions of the older stages, the pyrite solution contained very little As, Se, Te, Au, Ag, B, F, P, and TiO_2.

The mode of appearance of the ore and also some features of the paragenesis indicate a comparatively concentrated and viscous solution. The presence of idiomorphic crystals of plagioclase and grains of hornblende suggest that the solution was still fairly close to the magmatic stage at the time of displacement. The banding of the pyrite veins cutting the arsenopyrite ore cannot be explained as inherited from replaced wallrocks or by »cold-pressing» but is most likely due to flowage in a fairly viscous solution. The same explanation is valid also in the case of the banding of the apophyses. Also the transportation of fragments in the apophyses implies a rather concentrated and viscous medium.

As regards the temperature of the ore solution, the same difficulties are encountered as in the case of the older ores. No definite »geologic thermometer» exists among the minerals present. The basic plagioclase in the ore and the plagioclase of intermediate composition in the quartz-plagioclase veins at the ore contacts are, however, suggestive of a fairly high temperature[1] and it may be concluded that the temperature of the solution at the time of the displacement was about the same as that of the arsenopyrite and quartz-tourmaline solutions, *viz.* 400—500° C.

The temperature gradually decreases, and the solution tends to the hydrothermal state. Considering the extensive replacement, which is characteristic of the pyrite ore and in which respect it differs from the arsenopyrite ore, the nature of the pneumotectic pyrite solution must in some respects have been different to that of the arsenopyrite solution. It is difficult to conceive the nature of this difference, but the solution may have been richer in water and may comparatively soon have changed to a hydrothermal state. The hydrothermal solution was well adapted to accomplish the extensive replacement within the ore as well as in the areas of disseminated ores outside the solid ore bodies. It also seems probable that this solution caused the impregnation in the pyritic sericite schist.

The temperature successively decreases during the hydrothermal stage and we finally arrive at the last, low-temperature manifestations of the ore deposition, the formation of hisingerite and of the fissures of apophyllite. Also during this stage the range of temperature was thus exceptionally wide.

Differentiation of the Ore Solution.

The crystallization of the original pneumotectic solution begins with the formation of chiefly hornblende and plagioclase, followed by the formation of pyrite. The remaining solution is mainly enriched in Fe-Cu-sulphides, Pb, Zn, Bi, Sb, etc., and gangue components. By stress action this fraction is in part squeezed out from the crystallizing ore and is accumulated along the margins of the ore bodies. Another part of this fraction, mainly contain-

[1] In a recent paper on a zonal gold mineralization in Nova Scotia, Newhouse (63) emphasizes the importance of plagioclase with a higher content of calcium, when occurring in ore deposits, as an indicator of a high temperature of formation.

ing chalcopyrite and pyrrhotite, is pressed out into fissures in the walls to form apophyses.[1]

The accumulation of late crystallizing Fe-Cu-sulphides as chalcopyrite and pyrrhotite at the ends and margins of sulphide deposits is known from various localities and has been mentioned *e. g.* by Carstens (13, p. 28) and Beyschlag-Krusch-Vogt (6, Vol. I, p. 340) from Norwegian deposits, and by G. Williams (99, p. 32) from the Perrunal-La Zarza deposit in Spain.

The quartz-plagioclase veins at the ore contacts are also a differentiate of the pyrite solution. The plagioclase formed by replacement in the wallrocks is probably related to these veins. As stated above the composition of the plagioclase in the veins implies a formation at a relatively high temperature and it may be concluded that the veins were formed soon after the displacement, when the solution still possessed a pneumotectic character. The mode of separation of the vein solution from the ore solution is not known, but in view of the preponderance of gangue minerals in the veins it seems possible that it was caused by immiscibility.

Origin of the Spinel-bearing Inclusions.

As mentioned on a previous page (p. 124) there occur among the inclusions in the pyrite ore (and in one case in the wallrock) certain rocks which are composed chiefly of chlorite, basic plagioclase, and spinel. As to composition they differ quite considerably from the other altered rocks of the deposit. Their occurrence is, however, strictly localized to the pyrite ore, mostly as inclusions, and it is very likely that they were formed contemporaneously with that ore. The pyrite ore was formed in an already sericitized rock complex and the spinel-bearing rocks were formed by metasomatic alteration of sericite schists.

Origin of the Apophyllite Fissures.

The apophyllite fissures constitute the last manifestation of mineralization in the deposit and they were probably formed by a low-temperature residual solution from the pyrite ore. It will be recalled that apophyllite, as well as some zeolites, has been observed in other sulphide deposits as a late product of mineralization, *e. g.* at Sulitelma, Norway (97, p. 605).

Apophyllite is considered to be formed at low temperatures. W. H. Bradley (8, p. 4) mentions the formation of apophyllite and analcite at a temperature probably below 30° C. Daubrée (16, p. 158) described some zeolites which were formed in thermal waters at about 50° C.[2] On the other hand the maximum temperature for the formation of zeolites is probably as high as about 250° C. The appearance of apatite, tourmaline, and rutile, minerals

[1] The appearance also of pyrite ore in some apophyses probably implies that the pyrite, although in a crystalline state, behaved as a plastic mass before the groundmass had crystallized.

[2] In bricks from the Roman baths at Plombières Daubrée also found apophyllite as the result of thermal activity (55, p. 70).

generally ascribed to a high to medium temperature of formation, together with the apophyllite is thus rather striking.

The appearance of apophyllite and a number of zeolites associated with high-temperature minerals is known from certain volcanic rocks (55, p. 517) and from veins of the Alpine type (49, 72). The formation of the latter is considered to have taken place at 300—130° C and to have been caused by leaching in the surrounding rocks due to the action of CO_2-bearing aqueous solutions.

As regards the apophyllite at Boliden, the following views may be expressed. Apatite, tourmaline, and rutile are rarely present in the pyrite ore and are early crystallized minerals. They can thus hardly have remained in solution until the late phase when apophyllite was formed. The apophyllite solution carried abundant fluorine and had a strong chemical activity and a dissolving power on minerals. It would therefore seem likely that the solution on its way through *e. g.* arsenopyrite and tourmaline ores could dissolve the minerals in question. The sericite may have been formed in a similar way.

Comparison between the Boliden Ores and Similar Ores.

The Arsenopyrite Ore.

The character of this ore is rather unusual and excluding some occurrences in other parts of the Skellefte District, no similar type of ore is known to the author. In the following passages some examples of arsenopyrite ore from this district will be discussed.

One arsenic deposit which in some aspects is comparable with the arsenopyrite ore at Boliden is found at Holmtjärn, about 55 km NW of Boliden (Fig. 1). For a detailed description of that deposit the reader is referred to a recent publication by the present author (67), and on this occasion only a few points of interest will be ventilated. The ore is mainly composed of coarse-grained arsenopyrite but also contains a number of later crystallized minerals, such as chalcopyrite, pyrite, galena, boulangerite (?), bournonite, and gold. The paragenesis is on the whole simpler than at Boliden. The arsenopyrite ore is brecciated by a pyrite ore which reminds of the pyrite ore at Boliden. The ore is considered to have been formed by a hypothermal solution which replaced the sericitized wallrocks along steeply dipping channelways. The ore solution was more dilute and had a lower temperature than at Boliden.

At the Rakkejaur deposit, about 64 km WNW of Boliden (Fig. 1), there is also an arsenopyrite ore which may be compared with the ore at Boliden. The deposit is so far insufficiently known but as is shown in a short description by A. Högbom (38, pp. 89 and 117), and by a sketch map of the surface geology (38, Fig. 39), the arsenopyrite ore occurs as at Boliden in a number of separate lenses. The ore is also in this case mainly composed of arsenopyrite together with chalcopyrite, pyrrhotite, and an appreciable amount

of magnetite. The latter mineral was not observed in the arsenopyrite ores from Boliden and Holmtjärn.

From the Ö Högkulla mine S. Gavelin (29, p. 141) has described the occurrence of small fragments of solid, fine-grained arsenopyrite ore in a sphalerite-rich ore. Gavelin says: »These fragments display sharp contacts to the surrounding ore, and are often angular, the structure resembling the brecciation of dense arsenopyrite ores that occurs at Boliden». Similar fragments also occur in the Bjurliden deposit (29, p. 101).

In all the deposits now mentioned the arsenopyrite ore forms, as at Boliden, a distinct type, constituting the oldest manifestation of mineralization. In view of this circumstance and the similarities as to paragenesis one may conclude that the arsenopyrite ores were formed more or less contemporaneously during one and the same epoch and that the ore solutions emanated from a similar magmatic source.

The Quartz-Tourmaline Ore.

Quartz-tourmaline ores of the Boliden type have so far been found nowhere else in the district and on the whole no similar type of ore is known in Sweden.

If we turn to the Canadian Shield, however, we often find ores bearing some striking points of resemblance to the quartz-tourmaline ores at Boliden. This is particularly the case with the gold-quartz veins in some of the mines in the Porcupine District. These veins are as a rule developed on a much larger scale than at Boliden but some of the tourmaline-bearing gold-quartz veins of the Hollinger and Buffalo Ankerite Mines are almost identical with the veins at Boliden, as the author could confirm on a visit to the Porcupine District in 1937. The points of resemblance are confined not only to the general appearance of the veins but in some respects apply also to mineralogy and paragenetic conditions. Certain dissimilitudes are also noted, however. The Porcupine veins thus often contain *e. g.* ankerite and scheelite, minerals which so far have not been found in the veins at Boliden. On the other hand the latter often contain concentrations of a large number of sulphominerals and Bi-tellurides, which do not occur at Porcupine. The Porcupine veins are classed as hypothermal. The pneumotectic vein solutions at Boliden were probably more highly concentrated than in the case of most of the gold-quartz veins at Porcupine, but the parageneses indicate that the formation took place at about the same temperature.

Exact counterparts to some of the compact tourmaline veins at Boliden were seen in the Buffalo Ankerite Mine[1]. The veins are here sometimes composed of compact and fine-grained tourmaline of a dark brownish colour, containing some pyrite and quartz. The quartz occurred in schlieren or in regular gash veins. The wallrocks were in places strongly tourmalinized and silicified. Under the microscope the tourmaline is faintly brownish. It re-

[1] The author here wants to express his gratitude to Mr. A. R. Kinkel, geologist at the Buffalo Ankerite Mine, for calling his attention to these veins.

places small patches of a carbonate (ankerite?). The tourmaline mass is cut by narrow veinlets of carbonate, quartz, and albite.

In some places the fine-grained tourmaline vein was developed as a breccia and contained numerous fragments of various kinds of wallrocks (often strongly altered) and quartz (Fig. b, Pl. 48). These veins remind of some fragment-bearing gold-quartz veins described by Farmin from Grass Valley, California (24). The Buffalo Ankerite veins may be explained in the manner advocated by Farmin for the Grass Valley veins, *viz.* by injection of a relatively concentrated magmatic solution. The explanation is principally the same as advocated by the present author for the Boliden veins.

It may finally be added that the breccia veins at the Buffalo Ankerite Mine, as well as the veins at Grass Valley (24, p. 598), may be compared with the so-called »pebble dykes» (23), known from Tintic, Utah, and from other mining districts in the United States.

A feature of particular interest at Boliden is the transition of the quartz-tourmaline ores to a solid sulphide ore, chiefly composed of pyrrhotite and chalcopyrite. Quartz-tourmaline veins and the related gold-quartz veins from other parts of the world as a rule do not show any close relationship to sulphide ores and their sulphide content is generally low. The Morro Velho deposit, in Brazil, constitutes a notable exception, however, with an ore containing 30—40 % metallic minerals (6, Vol. II, p. 122). Also the Passagem Lode, Brazil, contains some sulphides and is indeed considered by Lindgren to be a transition between the gold-bearing quartz veins and the tourmaline-bearing sulphide deposits (55, p. 684).

On the other hand it may be pointed out that the tourmaline ore at Boliden with its content of various sulphides may be compared with some other types of deposits, for instance with Lindgren's copper-tourmaline type (55, p. 684), as found at the Braden Mine, Chile, and the Cactus Mine, San Francisco District, Utah (12), with Knopf's silver-lead and silver-copper tourmaline ore types (46, 47), mainly represented by some deposits in the Helena Mining Region, Montana, and with Stutzer's cobalt-tourmaline veins (94), represented by some veins at San Juan, Departement Freirina, Chile.

The Pyrite Ore.

Pyrite ores of the same general type as the Boliden pyrite ore are well known from a number of mining districts all over the world. An exhaustive comparative study is not possible and in the following only those deposits will be considered that bear a more or less pronounced resemblance to the pyrite ore at Boliden as regards appearance, mineralogy, and origin.

In Sweden. — Within the Skellefte District there occur several pyritic ores that are comparable with the Boliden pyrite ore, but only two of them, recently described by S. Gavelin, will be considered here.

The Eastern Bjurfors deposit (29, pp. 110—130) offers a good example of comparison. The deposit mainly carries a cupriferous pyrite ore which

has sharply defined contacts to the wallrocks. As at Boliden the ore peters out irregularly towards the ends and replaces the wallrocks at these points. Chalcopyrite is often enriched along the margins of the ore, where cross-cutting veins and apophyses, mainly composed of chalcopyrite and pyrrhotite, are formed. More or less strongly resorbed fragments of wallrock are enclosed in the ore.

At the Östra Högkulla deposit (29, pp. 137—146) the ore is mainly composed of pyrite and sphalerite with an appreciable content of pyrrhotite. The latter seems to be enriched towards the margins of the ore body. The contacts to the wallrocks are very sharp and there is only little evidence of replacement. The ore is banded, but the banding is not inherited from a replaced wallrock, which is distinctly massive in this case. Veins of solid ore are found to branch off from the main ore.

Both these deposits are considered by Gavelin to have been formed by displacement, although the displacement was followed by a varying degree of metasomatic replacement.

In Norway. — In many respects there is a good resemblance between the pyrite ore at Boliden and the ores of the Sulitelma District in N Norway, particularly as regards contact relations. The contacts are often sharp but veins and apophyses of solid sulphides branch off from the ore, cutting the foliation of the schisted country rock. Rock fragments are enclosed in the solid ore. The Sulitelma ores are considered by some students to be typical representatives of the injected pyrite deposits. Th. Vogt in a recent paper (97) explains the ores to have been formed by a liquid-magmatic solution that »procures the room . . . by pushing aside the adjacent rock masses» (p. 604), or, in other words, by displacement. As at Boliden and Bjurfors the solid ores at Sulitelma grade towards the ends into disseminated ores, formed by replacement of the wallrocks. Vogt emphasizes that the association of displacement (Vogt's »liquid-magmatic») ores with replacement ores is natural and that, as the crystallization proceeds, the ore solution becomes continuously enriched in volatiles and finally grades into a hydrothermal solution of lower temperature. At Sulitelma there are observed low-temperature veins, closely related to the sulphide ores and containing galena, tetrahedrite, arsenopyrite, and a number of sulphominerals. This paragenesis, described in detail by Ramdohr (75), is similar to the sulphomineral associations at Boliden. Finally there also occurs at Sulitelma a low-temperature paragenesis with apophyllite, heulandite, stilbite, etc.

On the other hand some students, *e. g.* Carstens, have laid particular stress on the metasomatic replacements accompanying the ores and are inclined to regard them as metasomatic low-temperature formations (13, p. 25).

In Finland. — In describing the Outokumpu mine in E Finland, Väyrynen (96) emphasizes the sharp contacts of the ore body and the massive structure of the ore and concludes that the ore was formed by intrusion. Sulphide-impregnated remnants of wallrock are present but they are »rather

few and lie in haphazard directions, not indicating replacement *in situ* but considerable movements» (p. 85).

In Spain. — The large copper-pyrite deposits of Rio Tinto have for a long time been the subject of discussion and there have been, and still are, divergent opinions as to their origin. Some of the deposits are comparable with the pyrite bodies at Boliden, as regards shape and general appearance, and also in view of the chemical and mineralogical composition there exist certain similarities. Many authors interpret the Rio Tinto deposits as formed by hydrothermal replacement, but other students, *e. g.* J. H. L. Vogt (6, Vol. I, p. 354), Broughton Edge (9), and Gordon Williams (99), class them among the intrusive pyrite deposits. Their opinion principally coincides with the author's conception of the displacement origin of the Boliden ores. The ore solution that formed the pyrite ores is characterized by the authors mentioned as an aqueo-igneous melt (or »hydro-pyritic-matte» according to Broughton Edge). The solution was thus more closely related to the magmatic state than to a normal hydrothermal solution and may be comparable with the pneumotectic solution in the sense of the term as used in the present paper. As emphasized particularly by Broughton Edge and G. Williams, the injected bodies are as at Boliden associated with disseminations of ore minerals formed by replacement by residual solutions.

In Canada. — Of the sulphide deposits that occur in the Pre-Cambrian of the Canadian Shield there are some that may be compared with the pyrite ore at Boliden. The Mandy Mine, Manitoba, described by Spurr (91, Vol. I, pp. 110—120), is of particular interest. The ore is often banded and is composed of chalcopyrite, sphalerite, and pyrite. The ore shows sharp contacts to the green schistose wallrocks, but apophyses cutting them are described by Spurr. The banding in the solid ore, in the apophyses, and around inclusions in the ore is explained as flowage in a viscous ore solution that was brought in as an intrusion.

Source of the Ore Solutions.

The pneumotectic nature of the ore-forming fluids indicates a rather near-magmatic source of the solutions. The survey of the mine does not give any direct clues as to the nature of this source as no igneous rocks that could have yielded such solutions are exposed underground. The nearest exposures of any such rock are found 3 km SSW of the deposit, where a massif of Revsund granite appears (Fig. 2).

Our knowledge of the source of the ores in the Skellefte District is on the whole still rather incomplete and as regards the Boliden ores only vague suggestions can be made at present.

Most of the geologists working in the district earlier considered that the oldest granite, the Jörn granite, constituted the source of the ores, as set forth by A. Högbom in his comprehensive study of the district (38, pp. 43 and 106). In a later publication the same author again stresses the importance

of the oldest granite as a likely source of many of the ores in the district, but at the same time points out the likelihood of the Revsund granite being the source in some cases (39, p. 229).

As regards the cause of the mineralization in the Malånäs ore field S. Gavelin says that »all results from the field here contradict a relationship to the Jörn granite» (29, p. 168), and he instead turns to the Revsund granite as the possible source of the ores. The present author followed the same line of thought when discussing the origin of the Holmtjärn deposit (67) and pointed out that the distribution of several of the deposits in the eastern part of the district suggested a connection with the Revsund granite rather than with the Jörn granite.

As a summary of our present knowledge on this subject it may thus be said that although the Jörn granite undoubtedly can be made responsible for certain of the deposits, it is highly probable that also the Revsund granite played a part in the mineralization.

The author is not in a position to give any positive contributions as regards the source of the Boliden ores, but he nevertheless advocates the opinion, as being the most likely one at present, that the mineralization was caused by action on the part of the Revsund granite. As mentioned above this granite is the only deep-seated rock in the vicinity, the distances to the nearest massifs of Jörn granite being 8 and 12 km, respectively (38, cf. plate)[1].

In view of the presence of fairly large amounts of basic plagioclase, hornblende, and calcite in the ores and the appearance of the basic dykes, it does not seem very likely that the magma which delivered the pneumotectic solutions had the composition of a normal granite. The facts quoted rather seem to indicate a sub-magma of a more basic composition, highly loaded with volatiles and metallic elements.

Formation of Ore Deposits by Displacement — A General Discussion.

S. Gavelin (29, pp. 146, 165, and 182) proposed the term »displacement» when discussing the formation by intrusion of some deposits in the Malånäs ore field. The present author adopted this term when trying to explain the *mise en place* of the ores of the Boliden deposit. The term »displacement» as used by Gavelin and the author implies that the ores were brought into place by the intrusion of the ore solution into a more or less schisted rock complex in which the solution pressed the walls of suitable channelways apart thanks to its intrusive force. The displacement is often followed by a more or less intense replacement of the wallrocks.

[1] It may here be added that in a recent paper Ramdohr (79, p. 28) mentions the occurrence of ortho-magmatic arsenopyrite in Revsund granite. In view of the preponderance of this mineral in the arsenopyrite ore this m a y be a support for the above assumption but before a thorough study of the granite has been carried out too much weight must not be attributed to this observation.

It is believed that the term displacement may be used to advantage to denote the mode of formation of certain types of deposits in which the evidences of intrusions are more conspicuous than those of replacement. In a classification of ore deposits according to the mode of *mise en place*, the displacement type of deposit denotes ore bodies mainly formed by intrusion of the ore solution in contradistinction to the replacement deposits which are formed by metasomatic replacement of the country rock by the action of dilute hydrothermal solutions ascending along fissures and capillary openings.

The conception of an ore body being formed as an intrusion is by no means new and it has been advocated by several students on ore deposits. A complete review of the deposits that may be considered to have been formed by displacement is beyond the scope of this paper and only a few will be mentioned. J. H. L. Vogt was a strong advocate of the formation of certain pyritic ores by intrusion, *e. g.* the Norwegian deposits at Röros and Sulitelma, which Vogt classed in the group of »injected pyrite deposits». In later years, also Th. Vogt has discussed these deposits and emphasizes their intrusive formation. At the same time he points out that after the displacement of the ores a strong replacement of the country rock took place (97, p. 604).

The Sudbury nickel deposits may also be referred to the displacement type, according to the recent investigations by Collins (14). A gravitative settling of the sulphides in the norite magma was previously looked upon by many as the cause of formation of these deposits. Collins also assumes a concentration of the sulphides in the molten state but tries to show that the ultimate formation of the deposits was due to the injection on fractures of the still molten sulphides together with a fraction of the rock magma (the offset magma of Collins) by the weight of the overlying rocks and deformational movements.

Also Spurr has advocated the explanation that certain ore deposits are formed by intrusion, or displacement, to use the term adopted here. The Mandy ore body mentioned above (p. 177) is one case, but Spurr adopts the same explanation also for lenses and lenticular veins of auriferous quartz at Silver Peak in Nevada, of which he says that they »made their own room» and »shoved and shouldered their own way in, pushing aside the shaly (country) rock» (91, Vol. 1, pp. 90—100). The intrusion is considered to have been caused by the telluric pressure of the intruding magma. Similar gold-quartz deposits were described by Graton from the Southern Appalachians and were explained by him as due to displacement in the surrounding rocks by concentrated and high-temperature solutions (33, pp. 60 and 69). A similar view has recently been expressed by Farmin (24) as regards gold-quartz veins at Grass Valley, California.

In an interesting paper (98) Wandke discusses the formation of epithermal veins in the Guanajuato District, Mexico. In the light of the observations

on the structure of the veins Wandke arrives at the conclusion that they have been formed by intrusion and that the walls of the veins were forced apart by the pressure of the ore solution.

To the displacement type may also be counted the iron ores of Geijer's Kiruna type (31). They are considered to have been formed by intrusion of a magma enriched in volatiles, which Geijer characterizes as a pneumotectic solution. The ores of the Kiruna type were formed at comparatively high temperatures but as emphasized by Geijer the type shows transitions to deposits formed by hydrothermal replacement.

Several other deposits could be mentioned which probably may be classed as formed by displacement but those enumerated above will suffice. They may be considered fairly typical, although in some cases controversies still exist as to their mode of origin.

The above deposits vary quite considerably as to shape, appearance, and mineralogical composition, and they were formed by solutions which varied considerably as regards composition and temperature. The conception of the formation of ore deposits by displacement only refers to the mode in which the deposits in question were brought into place and it is only to be expected that they were formed during physico-chemical conditions that varied from case to case.

Summary.

1. The Boliden deposit is situated in the Skellefte Mining District of Västerbotten in northern Sweden. The deposit was found by electrical prospecting in 1924. Mining operations started in 1925.

2. The bedrock around the deposit is of pre-Cambrian age and is composed of acid to intermediate volcanic rocks overlain by phyllites and graywackes. A massif of Revsund granite intrudes the supercrustal rocks south of the mine. The supercrustal rocks are folded and strike approximately E—W; they dip steeply to the south.

3. The deposit is chiefly made up of two large ore bodies, the Western and the Eastern Ore, which have been brought into contact with each other by a fault. They have a total length of about 600 m and a maximum width of about 40 m. Originally the two bodies had an *en échelon* position and overlapped to the right. The deposit is composed of three main types of ore, 1) arsenopyrite ore, 2) lamprophyres with quartz-tourmaline and sulphide ores, and 3) pyrite ore. These ores represent three stages in the mineralization and were formed in the above sequence. Each main type is composed of various kinds of ores of varying mineralogical composition. The ores are built up of a large number of minerals and the paragenetic conditions are exceedingly complex (Table 42, p. 184).

4. The development of an independent dragfold in the contact between the volcanic and the sedimentary rocks is of fundamental importance for the ore deposition. It was caused by a shearing stress, acting in the direction north-side-west and south-side-east. The axis of the dragfold pitches 50—60° E and this direction has exercised a structural control on the deposition of the ores.

5. In the dragfold the stress formed suitable channelways for ascending hydrothermal solutions which brought about an alteration of the volcanic rocks. The process was complicated and began with a thorough sericitization, resulting in the formation of various quartz-sericite schists. Some types also contain pyrite and chlorite. The alteration continued and the next phase was marked by the development of a pure sericite rock. During the third phase the sericite was broken down and andalusite rocks were formed. During the sericitization large amounts of CaO, MgO, and FeO were liberated and they partly migrated into the surrounding fresh volcanics where they brought about a recrystallization and a formation of basic plagioclase, hornblende, biotite, etc. The altering solutions are considered to have been hydrothermal and from the beginning weakly acid or alkaline; in the final phase of the alteration the solutions were probably of a decidedly acid nature. The shearing in combination with the alteration produced a schisted bedrock, well suited for the formation of channelways by the shearing stress still acting on the dragfold. The formation of the altered rocks was largely accomplished even before the appearance of the ore solutions but it is believed that hydrothermal solutions were given off also during the different stages of ore deposition, thus widening the zone of alteration. A strong sericitization was particularly evident during the second stage. During the third stage, on the other hand, the alteration seems to have been very unimportant.

6. Along channelways in the schisted rocks the solution of the first, or arsenopyrite stage of mineralization now ascended. The solution is considered to have been pressed into the schisted rocks by the orogenic pressure in the manner of an intrusion, forcing the walls of the channelways apart. The term »displacement» has been adopted to denote the *mise en place* of an ore body in this intrusion-like manner. The ore bodies formed have the shape of elongate lenses with their long axes pitching steeply to the east, parallel to the axis of the dragfold. The solution of the arsenopyrite ore was presumably fairly concentrated and of a comparatively high temperature and was characterized as pneumotectic. The solution was very complex and contained a large number of metals, gangue-forming oxides, and volatiles. The crystallization began with the formation of various types of arsenopyrite ore in which the main component is arsenopyrite. The remaining solution was partly retained in pores in the arsenopyrite ore but the main part was squeezed out by the stress into fissures in the solidified arsenopyrite ore, forming a breccia. In some places the residual solution was pressed out on apophyses in the wallrock.

The arsenopyrite ore is in some places accompanied by separate mineral associations, *viz.* rutile rock, pyrite-apatite ore, and quartz-plagioclase veins, which are considered to be differentiates of the original ore solution. They sometimes form separate bodies. After the displacement of the ore solution replacement set in and the pneumotectic solution tended to pass over into a hydrothermal solution which replaced the wallrocks. The replacement is particularly conspicuous at the terminal portions of the ore bodies, where areas of disseminated ores were formed.

7. The second stage was initiated by the intrusion of lamprophyres on fissures formed by a stress with the same direction as that which formed the dragfold and the channelways for the arsenopyrite solution. The lamprophyres are largely altered, mainly by chloritization, and the primary nature of the rocks cannot be ascertained. It can only be said that they were basic dyke rocks. The continued stress formed fissures, partly in the lamprophyres and partly in the surrounding altered rocks and arsenopyrite ore bodies, on which the quartz-tourmaline ore solution was brought in by displacement. Emanations from this solution brought about the chloritization of the lamprophyres and a sericitization of the andalusite rock. During the latter process also corundum, diasporite, and kaolin were formed. The ore solution contained SiO_2, MgO, Al_2O_3, alkalis, B, F, and other components but only relatively small amounts of metals. Arsenic is comparatively rare in this solution. Characteristic components are Bi, Te, and Se, elements which are comparatively rare in the solutions of the first and third stages. Also Cr is a characteristic component of the ore solution; it enters into the hydrothermal mineral mariposite. The ore solution is considered to have been fairly concentrated and of a high temperature and has been classed as pneumotectic. Compared with the arsenopyrite solution, the quartz-tourmaline solution contained more gangue-forming components and was heavily loaded with B and H_2O. The ores formed by the solution are chiefly quartz-tourmaline veins and lenses. In some cases quartz is the predominant component, in others tourmaline forms almost the sole constituent. In local concentrations a number of metallic minerals are found, including some rare minerals characteristic of this locality, as »selenocosalite», »selenokobellite», tellurobismuthite, and tetradymite. One of the tourmaline lenses in its upper portion passes over into a sulphide ore composed of pyrrhotite and chalcopyrite. It forms a sulphidic fraction which was squeezed out from the quartz-tourmaline solution. The range of temperature of the solution was exceptionally wide, as high temperature minerals occur side by side with such low-temperature minerals as pyrargyrite. The intimate relationship between the lamprophyres and the ores suggests that they are differentiates from a common magma.

8. The last stage is characterized by the formation of chiefly pyrite ores, forming two large ore bodies and a number of smaller ones. The pitch of the Eastern Ore is on the whole parallel to the axis of the dragfold and the pitch

of the older ores. The ore bodies contain brecciated lenses of arsenopyrite ore and in some places replaced remnants of wallrocks and lamprophyres. The pyrite solution entered the ore zone along several channelways formed by a stress with the same direction as before. The solution was brought in by displacement but replacement is very pronounced in this stage and from the channelways the solution largely replaced the intervening portions of wallrocks, lamprophyres, and bodies of older ores. The replacement resulted in the formation of the two large ore bodies. The ore solution is considered to have been of a pneumotectic character at the time of the displacement but its strong replacing ability indicates that in some respects it was different to the earlier solutions. It probably rapidly changed to hydrothermal conditions. The crystallization began with the formation of pyrite and some other minerals, the remaining solution being enriched in chalcopyrite, pyrrhotite, and quartz. Part of this solution crystallized as groundmass in the ore but a large part was squeezed out towards the margins of the ore bodies or into the wallrocks, where apophyses were formed. Another fraction of the ore solution formed veins of quartz, plagioclase, and sulphides at the contacts of the ore bodies. Also in the pyrite stage the range of temperature was exceptionally wide as is evident from the appearance of apophyllite, which constitutes the last manifestation of mineralization in the deposit.

9. No igneous rock occurs in the mine that can be made responsible for the ore solutions. Some data seem to indicate, however, that the mineralization was caused by action on the part of the Revsund granite, which outcrops in a small massif south of the mine. The magma that delivered the pneumotectic solutions can hardly have had the composition of a normal granite, the mineralogical composition of the ores rather indicating a more basic submagma as their ultimate source.

Table 42.

List of minerals in the Boliden ores.

Minerals	Arsenopyrite Stage	Quartz-Tourmaline Stage	Pyrite Stage
Arsenic[1] As	+	–	–
Bismuth Bi	+	+ +	+
Gold[2] Au	+	+	+
Silver Ag	–	+	–
Bismuthite Bi_2S_3	–	+	+
Tetradymite Bi_2Te_2S	–	+ +	–
Tellurobismuthite Bi_2Te_3	–	+ +	–
Sphalerite ZnS	+ +	+	+ +
Pyrrhotite FeS	+ + +	+ + +	+ + +
Niccolite NiAs	+	–	+
Pyrite FeS_2	+	+	+ + +
Cobaltite CoAsS	+ +	+ +	+
Gersdorffite NiAsS	+ ?	+ ?	–
Marcasite FeS_2	+	+	+
Arsenopyrite FeAsS	+ + +	+	+
Gudmundite FeSbS	+ +	+	+
Safflorite $CoAs_2$	+	–	–
Dyscrasite Ag_3Sb	+	–	–
Galena PbS	+	+ +	+
Covellite CuS[3]	+	–	–
Au-(Ag-)tellurides	–	+ ?	–
Chalcopyrite $CuFeS_2$	+ + +	+ + +	+ +
Cubanite $CuFe_2S_3$	+	+	+
Valleriite $Cu_3Fe_4S_7$	+	+	+
Sternbergite $AgFe_2S_3$	–	+ ?	–
Miargyrite $AgSbS_2$	–	+	–
Pyrargyrite Ag_3SbS_3	+	+	+
Tetrahedrite $Cu_3(Sb, As)S_3$	+ +	+	+
Jamesonite $Pb_2Sb_2S_5$	+	–	+
Falkmanite $Pb_3Sb_2S_6$	+ +	–	+
Boulangerite $Pb_5Sb_4S_{11}$	+	+	+
Bournonite $PbCuSbS_3$	+	+	+
»Selenocosalite» $Pb_2Bi_2(S, Se)_5$	–	+ +	–
»Selenokobellite» $Pb_2(Sb, Bi)_2(S, Se)_5$	–	+ +	–
Stannite Cu_2FeSnS_4	–	–	+
Magnetite Fe_3O_4	–	+	+

[1] Decomposition product in falkmanite (78, p. 340).
[2] Always contains more or less silver.
[3] Formed by surface waters in the open pit.

Minerals	Arsenopyrite Stage	Quartz-Tourmaline Stage	Pyrite Stage
Quartz SiO_2	+ + +	+ + +	+ + +
Rutile TiO_2	+ + +	+ + +	+
Zircon $ZrSiO_4$	+	+	+
Diasporite $Al_2O_3 \cdot H_2O$	—	+	—
Fluorite CaF_2	—	+	—
Calcite $CaCO_3$	+ + +	+ +	+ +
Dolomite $CaCO_3 \cdot MgCO_3$	—	—	+
Copper-sulphate $CuSO_4$ + aq.[1]	+	—	—
Fluor-apatite $FCa_5(PO_4)_3$	+ + +	+ +	+
Erythrite $Co_3As_2O_8 \cdot 8H_2O$	+	+	—
Svanbergite $AlPO_4 \cdot SrSO_4 \cdot Al_2(OH)_6$	+ ?	—	—
Garnet	—	—	+
Andalusite Al_2SiO_5	—	+	—
Amphibole	+	—	+
Sericite $2H_2O \cdot K_2O \cdot 3Al_2O_3 \cdot 6SiO_2$	+	+ +	+
Mariposite (chromiferous mica)	—	+ +	—
Phlogopite	+	—	+
Chlorite	+	+	+
Kaolinite $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	—	+	—
Hisingerite (hydrous Fe-silicate)	—	—	+
Apophyllite $KF \cdot Ca_4(Si_2O_5)_4 \cdot 8H_2O$	—	—	+
Plagioclase	+	+	+
Tourmaline	+	+ + +	+
Analcite $NaAlSi_2O_6 \cdot H_2O$	—	+	—
Titanite $CaTiSiO_5$	+	—	+

[1] Formed by surface waters in the open pit.

+ = rare
+ + = common
+ + + = abundant
— = not present
? = identity of mineral not quite certain

The list of minerals published in the preliminary paper (65, p. 130), included emplectite, guanajuatite, and klockmannite. Further studies have shown, however, that these minerals do not occur.

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Explanatory Notes to the Maps (Pl. 1—8).

The maps in Pl. 1—7 were originally made in scale 1 : 200 and were then reduced to the present scale, 1 : 800, which is the scale used on the official mine plans in Swedish mines.

The heavy black figures in the stopes refer to the numbers of the stopes as used in the text. Some stopes, situated above the main levels, are not marked on the maps.

The contours of some stopes in Pl. 4, 6, and 7 are denoted by broken lines, this indicating that they were situated about 5 m above the level. Contour lines and geological boundaries have then been projected on the level.

In order to facilitate the reading of the maps, chutes, raises, blind shafts, etc., have not been indicated.

The outlines of the ore bodies on the surface plan were largely mapped by the mine surveyors, before the author began his survey in 1935.

~~Plates 5, 6, and 7 of the 170, 210, and 250 m levels are not included. They will be distributed to the recipients of the paper at a later date.~~

PLATES

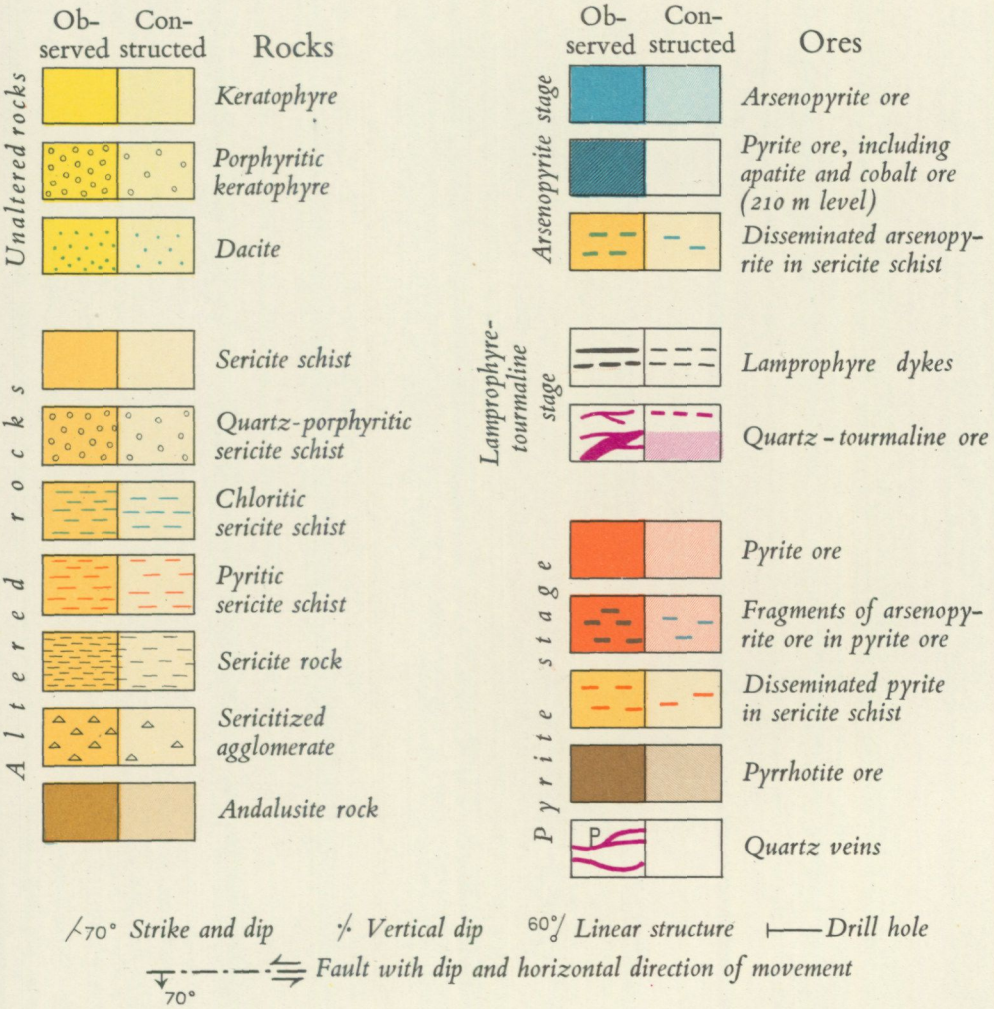
Geological Maps (Plates 1-7)
of
THE BOLIDEN MINE

by

OLOF H. ÖDMAN

1935-1940

Scale 1:800



A. B. KARTOGRAFISKA INSTITUTET
ESSELTE AB. STOCKHOLM 1941

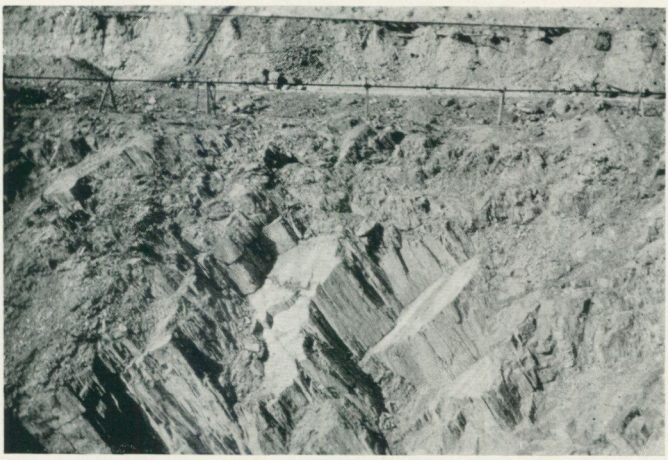


Photo Grip.

Fig. a. Linear structure in sericite schist. Eastern part of open pit.



Photo Larsson.

Fig. b. Keratophyre with phenocrysts of albite in a microgranitic groundmass. Analysis No. 1, p. 17. Section 17, 130 m level. Thin sec., Nic. +, 8 ×.



Photo Larsson.

Fig. a. Dacite with pilotaxitic laths of plagioclase and grains of hornblende. Analysis No. 3, p. 19. Section 11, 170 m level. Thin sec., Nic. +, 77 ×.



Photo Larsson.

Fig. b. Metamorphosed volcanic rock (keratophyre) with basic plagioclase (with relief), quartz, and biotite. Analysis No. 4, p. 22. Section 11, 250 m level. Thin sec., ord. light, 77 ×.

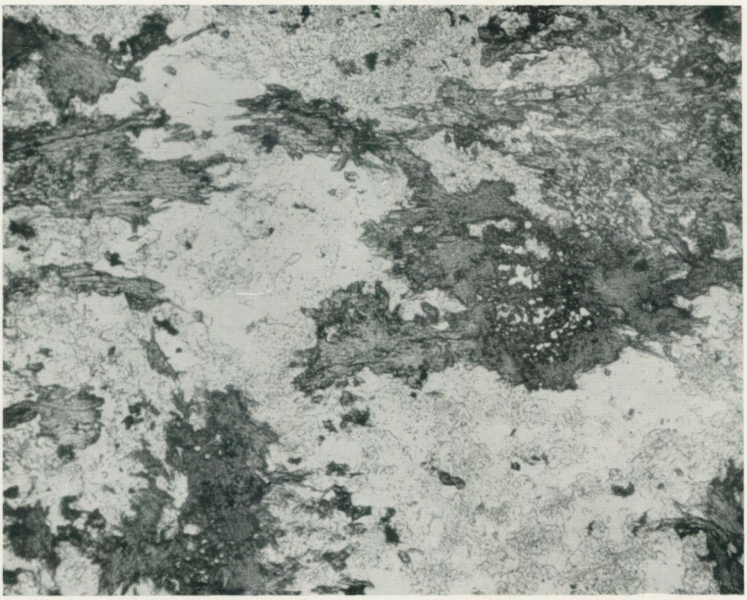


Photo Larsson.

Fig. a. Metamorphosed volcanic rock (dacite?) with hornblende, basic plagioclase (light gray with relief), and quartz. 410 m level. Thin sec., ord. light, 39 ×.

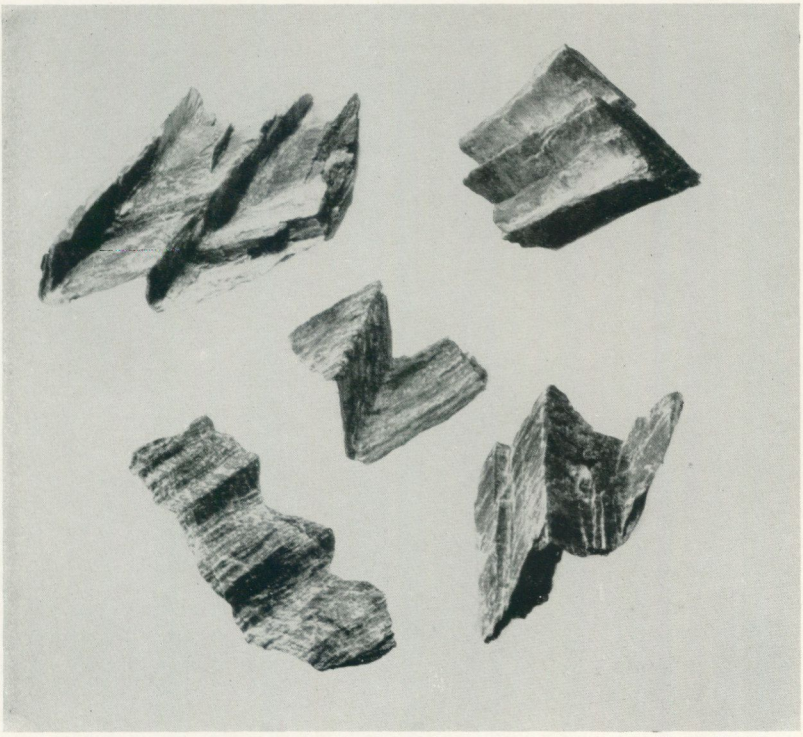


Photo Björkman.

Fig. b. Folded sericite schist. 1/3 nat. size.

Pl. 12.

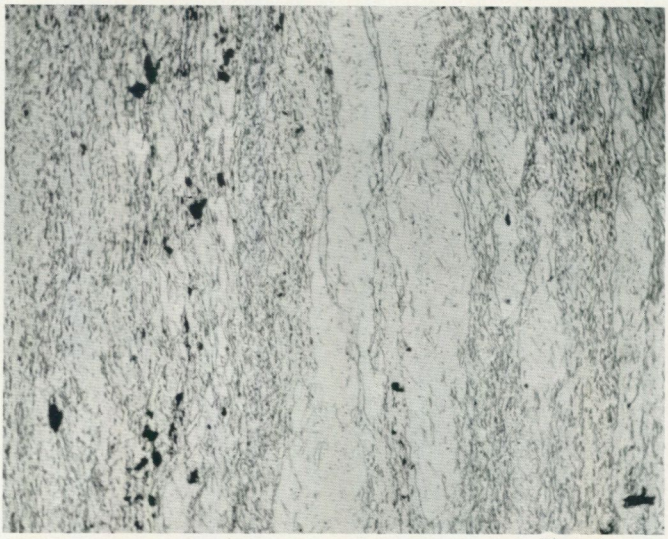


Photo Larsson.

Fig. a. Sericite schist (quartz white, sericite gray, rutile black). Analysis No. 5, p. 30. Main east drift, 210 m level. Thin sec., ord. light, 30 ×.



Photo Larsson.

Fig. b. Same as Fig. a. Nic. +, 19 ×.

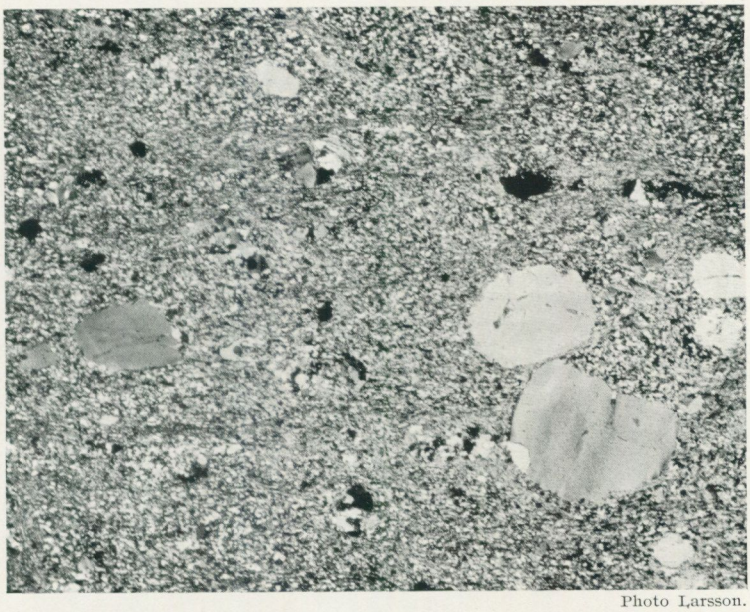


Photo Larsson.

Fig. a. Quartz-porphyritic sericite schist showing intact quartz phenocrysts; groundmass composed of quartz and sericite. Analysis No. 6, p. 30. Crosscut to stope, section 2—3, 90 m level. Thin sec., Nic. +, 8 ×.

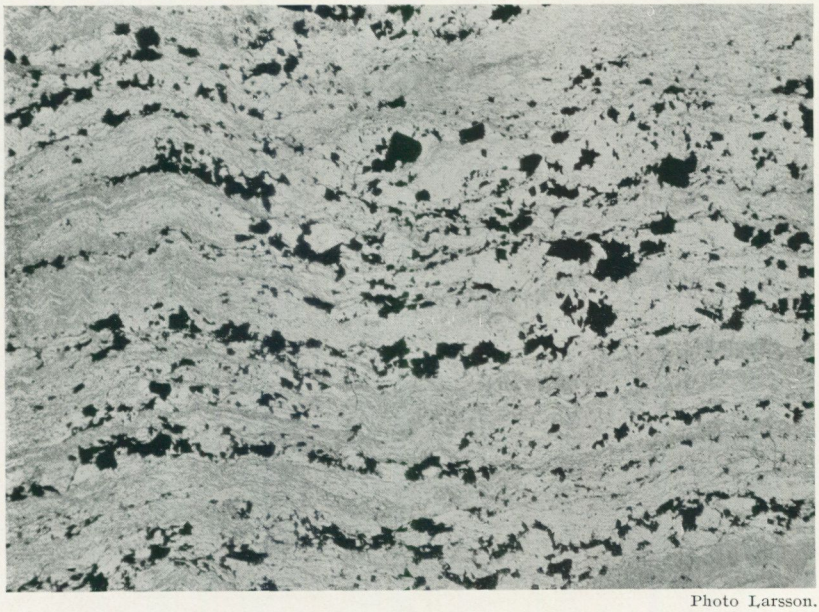


Photo Larsson.

Fig. b. Pyritic sericite schist. Corrugated bands of sericite dark gray, quartz medium gray, pyrite black. Main west drift, section 7, 210 m level. Thin sec., ord. light. 8 ×.

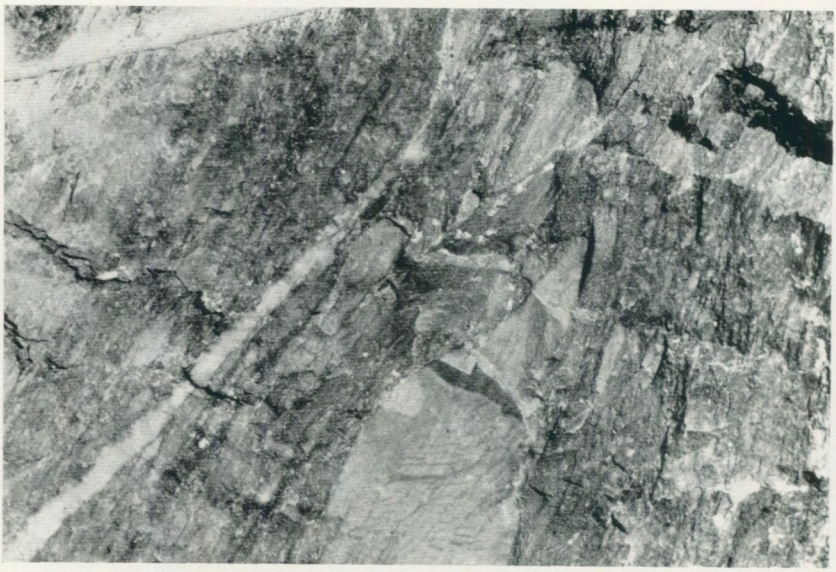


Photo Fellström.

Fig. a. Sericitized agglomerate. Main west drift, section 5—6, 210 m level. Scale 1: 8.

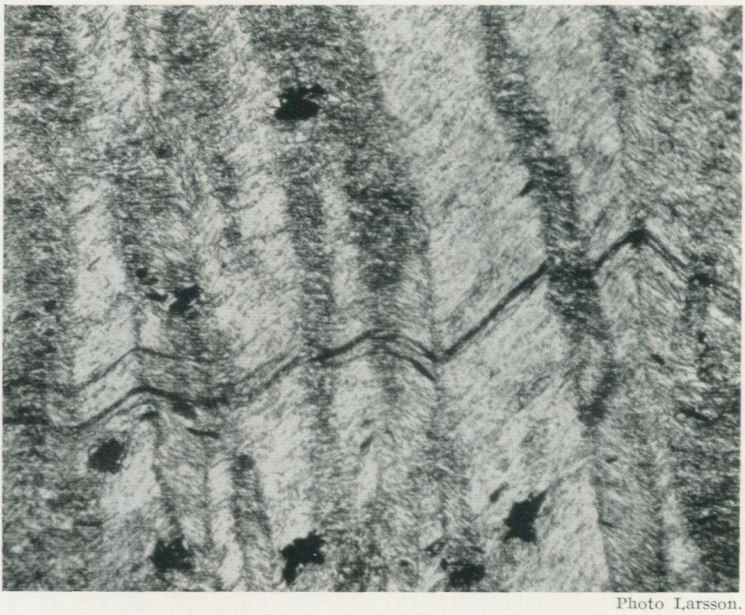


Photo Larsson.

Fig. b. Sericite rock, corrugated. Rutile in black spots. Main east drift, abt. section 14, 250 m level. Thin sec., Nic. +, 47 ×.



Photo I,arsson.

Fig. a. Quartz-free andalusite rock. Besides andalusite only sericite and rutile in small amounts. 410 m level. Thin sec., Nic. +, 8 ×.

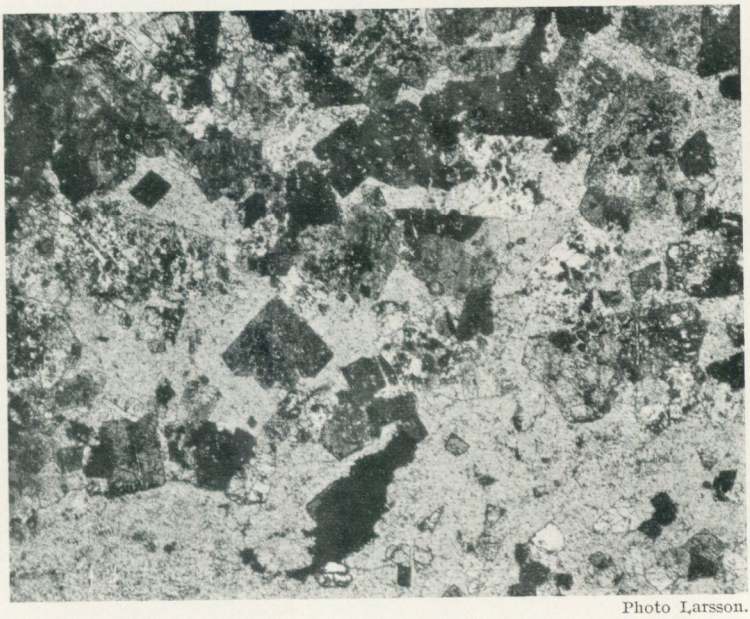


Photo I,arsson.

Fig. b. Quartz-free andalusite rock with unreplaced sericite rock. 330 m level. Thin sec., Nic. +, 8 ×.

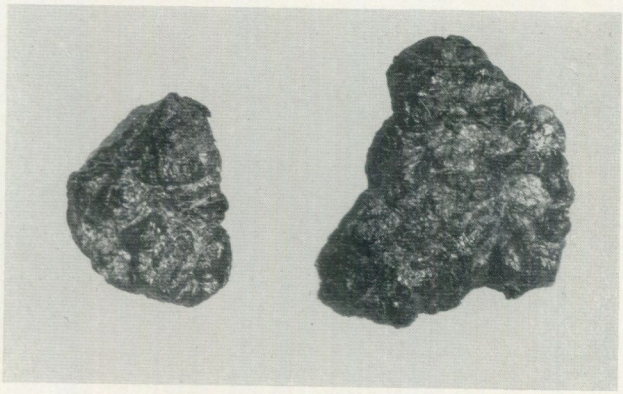


Photo Björkman.

Fig. a. Reniform pieces of graphitic matter in andalusite rock. Nat. size. 250 m level.

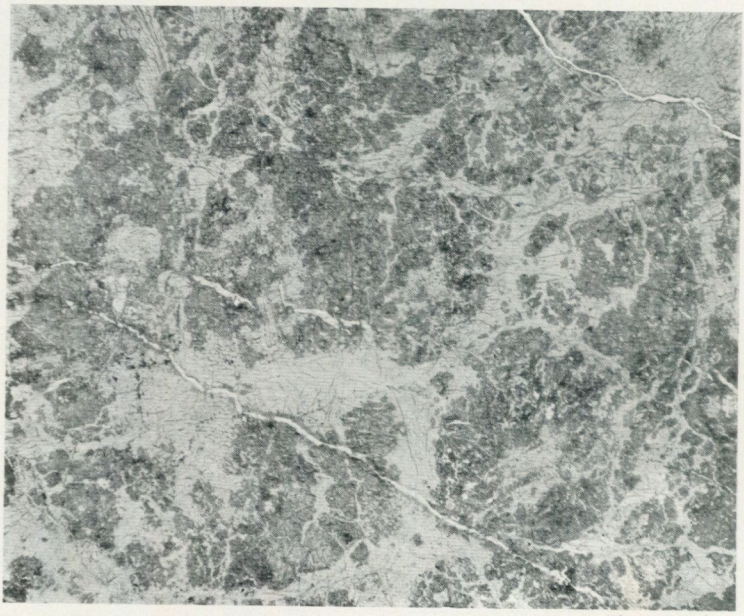


Photo Larsson.

Fig. b. Corundum (medium gray) replacing andalusite. Analysis No. 14, p. 39. Crosscut between sections 17 and 18, 410 m level. Thin sec., ord. light, 12 ×.



Photo Björkman.

Fig. a. Andalusite veins of two generations cutting andalusite rock. $^2/_3$ nat. size. 250 m level.

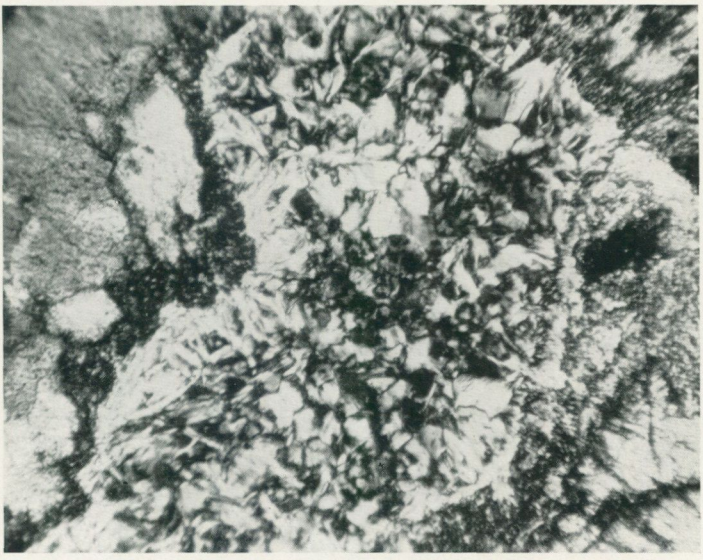


Fig. b. Kaolin (scaly felt in centre) replacing andalusite. Section 14, 250 m level. Thin sec., Nic. +, 84 ×.



Photo Fellström.

Fig. a. Arsenopyrite ore brecciated by quartz and sulphominerals. Polished surface, nat. size. Pl. I: 1 in (65).

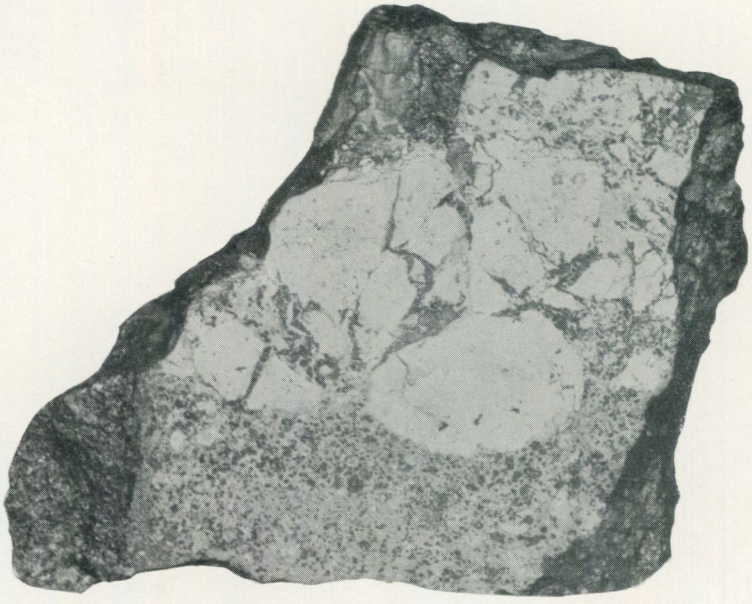


Photo Fellström.

Fig. b. Arsenopyrite ore brecciated and partly replaced by pyrrhotite with some chalcopyrite and quartz. Polished specimen from contact between arsenopyrite ore and pyrrhotite ore. 3/4 nat. size. Stope 23, 170 m level. Fig. 9 in (65).

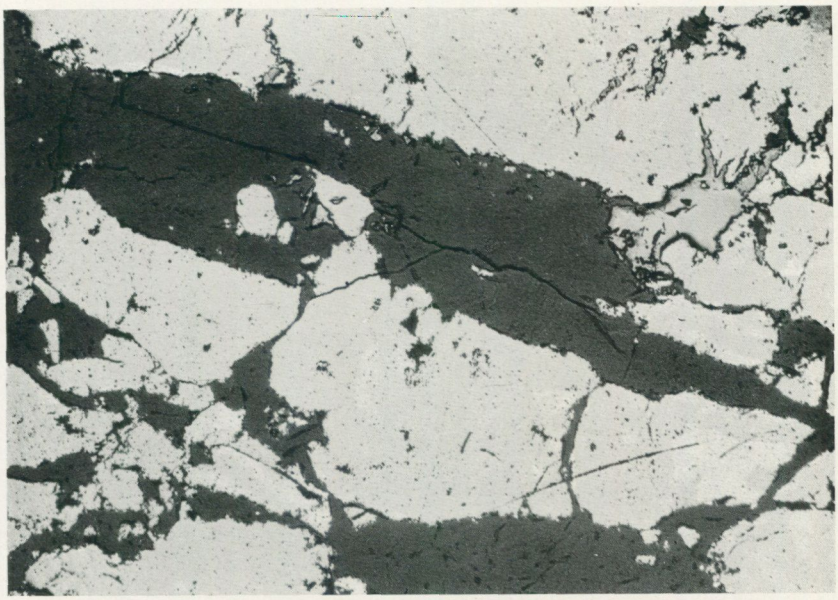


Fig. a. Arsenopyrite ore (white) brecciated by quartz (dark gray). Open pit. Pol. sec., ord. light, 11 ×.

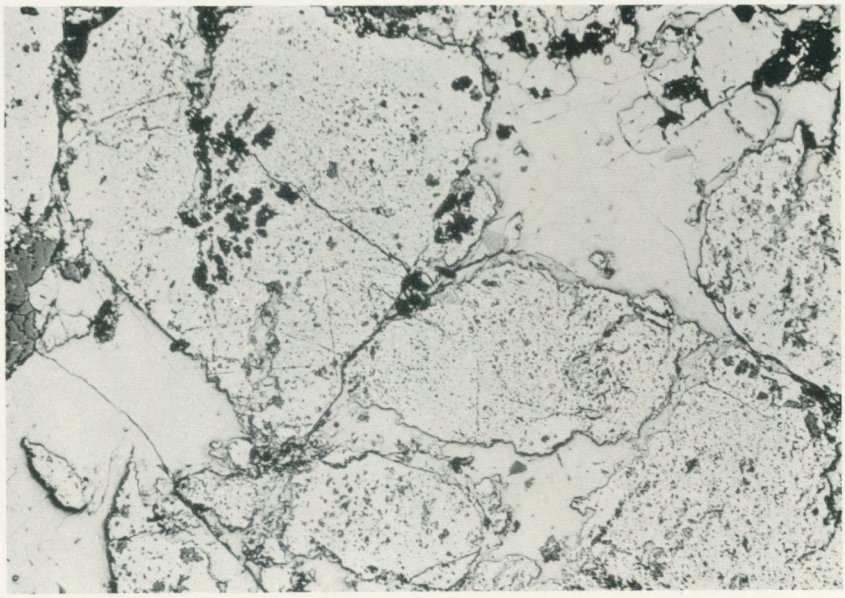


Fig. b. Arsenopyrite ore (mottled gray) brecciated and partly replaced by chalcopyrite. Stope 23, 170 m level. Pol. sec., ord. light, 12 ×.

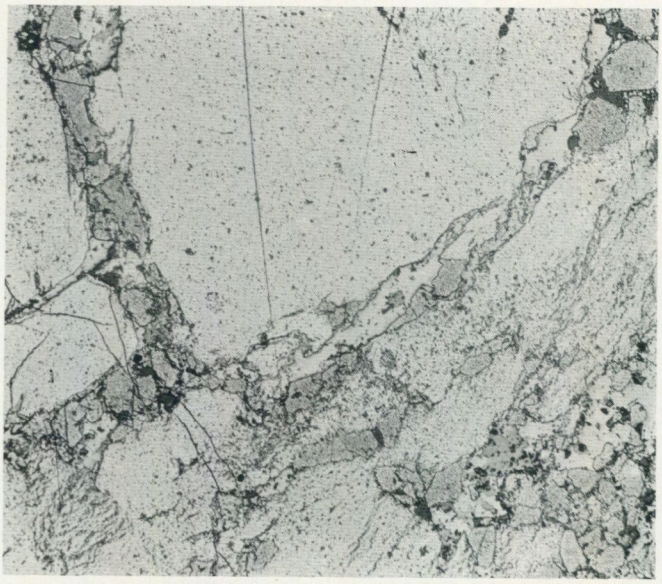


Fig. a. Arsenopyrite ore (mottled gray) brecciated by veins of pyrite (dark gray crystals) and chalcopyrite. 60 m level. Pol. sec., ord. light, 12 ×.



Fig. b. Micro-structure of normal arsenopyrite ore. The k-lens, open pit. Pol. sec., Nic. +, 62 ×.



Fig. a. Micro-structure of normal arsenopyrite ore. Stope 16, 210 m level. Pol. sec., Nic. +, 62 ×.

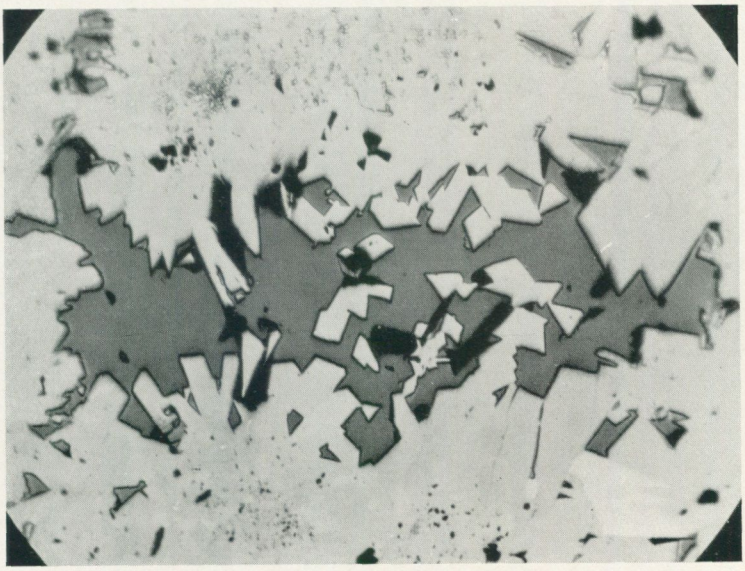


Fig. b. Pore or »druse» in normal arsenopyrite ore filled with pyrrhotite (dark gray). Pleochroism in arsenopyrite faintly noticeable. 170 m level. Pol. sec., ord. light, immersion, 190 ×. Pl. II: 1 in (65).

Pl. 22.

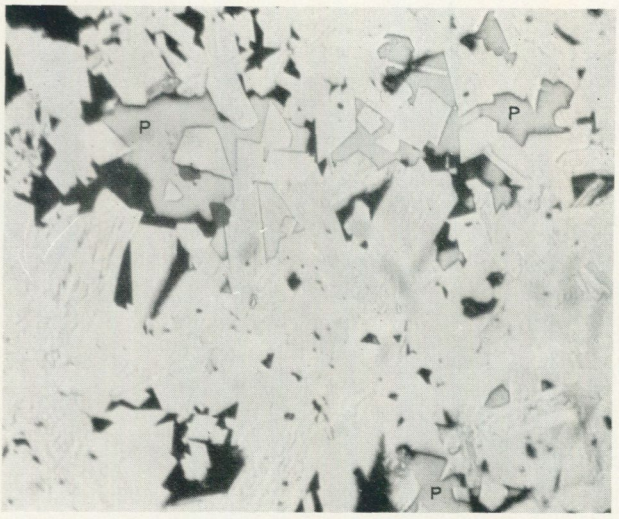


Fig. a. Irregular »druse» in normal arsenopyrite ore filled with pyrite (P) and quartz (black). 170 m level. Pol. sec., ord. light, immersion, 260 ×. Pl. II: 2 in (65).

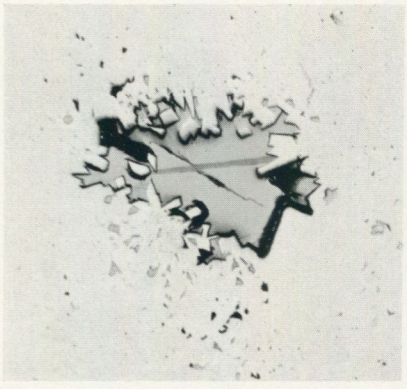


Fig. b. Pore or »druse» in normal arsenopyrite ore filled with chalcopyrite (medium gray) and cubanite (dark gray). 60 m level. Pol. sec., ord. light, immersion, 120 ×. Pl. III: 3 in (65).



Fig. c. Framework of arsenopyrite crystals with interstitial chalcopyrite (medium gray), quartz (black), and gold (white speck above centre). Pol. sec., ord. light, 260 ×. Pl. III: 2 in (65).



Fig. a. Micro-structure of apatite-banded arsenopyrite ore. Apatite dark gray to black, arsenopyrite in white bands, and chalcopyrite in later veinlets. The e-lens, open pit. Pol. sec., ord. light, 11 ×.

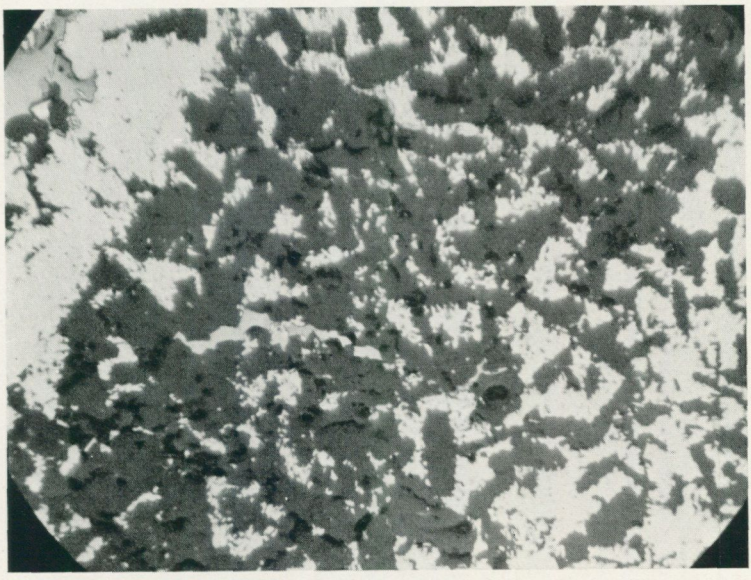


Fig. b. Crystals of apatite (dark gray) in apatite-banded arsenopyrite ore. Later chalcopyrite (medium gray) in upper left corner and to the left of centre. The e-lens, open pit. Pol. sec., ord. light, immersion, 120 ×. Pl. IV: 2 in (65).

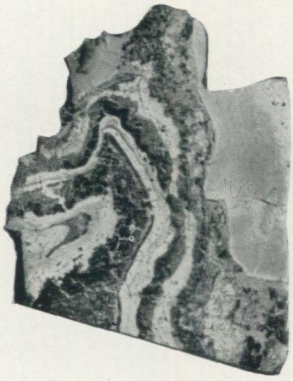


Photo Fellström.

Fig. a. Apatite-banded arsenopyrite ore. Apatite dark gray to black, later chalcopyrite in thin, transverse veinlets. The e-lens, open pit. Pol. surface, $^2/_3$ nat. size. Pl. II: 3 in (65).



Photo Fellström.

Fig. b. Quartz-banded arsenopyrite ore brecciating normal ore. Open pit. $^1/_2$ nat. size.

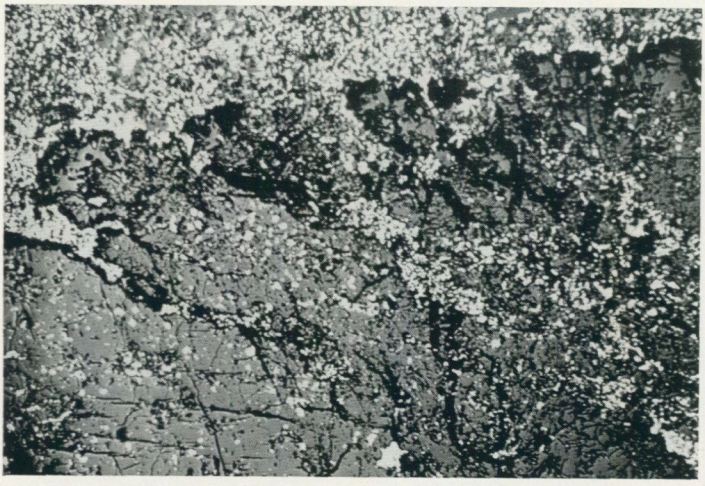


Fig. c. Crystal of andalusite replaced by arsenopyrite. Stope 25, 250 m level. Pol. sec., ord. light, 12 ×.

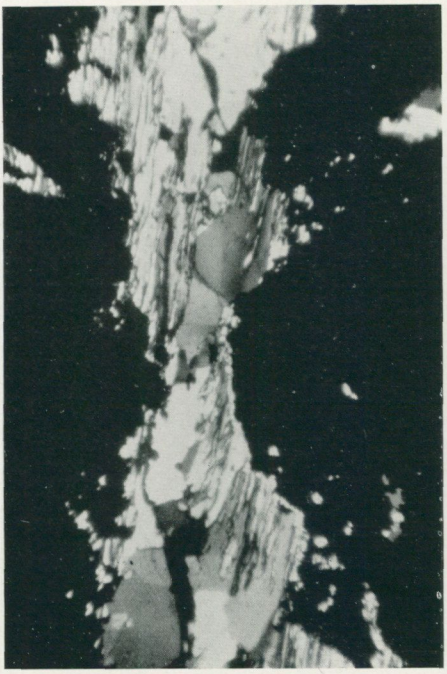


Fig. a. Lamellar quartz in arsenopyrite ore. Section 12, 170 m level. Thin sec., Nic. +, 42 ×.



Fig. b. »Feather quartz» around crystal of pyrite in quartz vein brecciating arsenopyrite ore. Section 12, 170 m level. Thin sec., Nic. +, 70 ×.



Fig. c. Crystals of plagioclase growing out from the wall of a quartz vein cutting arsenopyrite ore. Scales of sericite at the top. Eastern end of the a-d-lens at section 17, 250 m level. Thin sec., Nic. +, 120 ×.

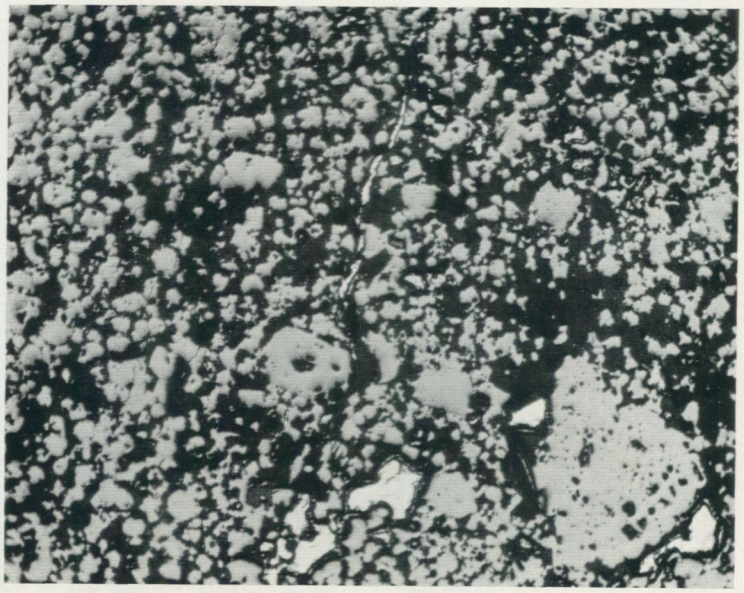


Fig. a. Rutile rock (medium gray; the dark groundmass is mainly quartz). Irregular veinlet of gold in centre; Bi-telluride at the bottom. Stope 28, 250 m level. Pol. sec., ord. light, 166 ×.

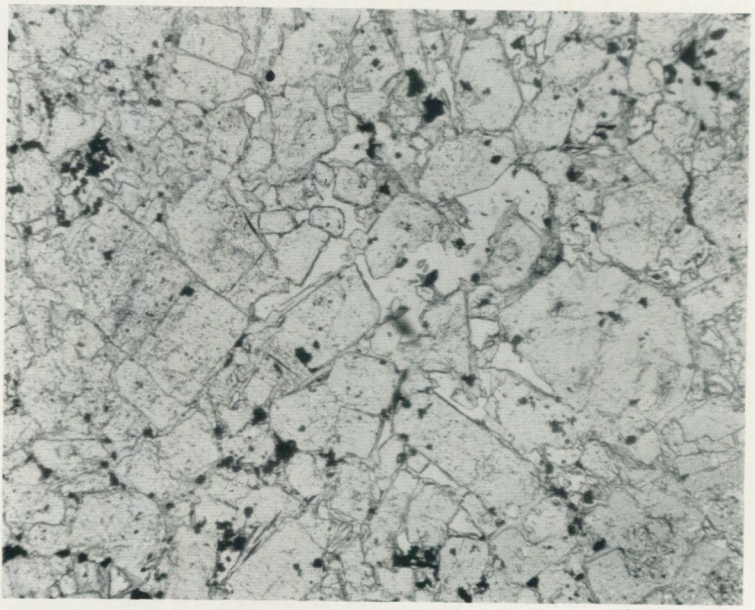


Photo Larsson.

Fig. b. Apatite rock. Crystals of apatite in groundmass of quartz (white) and some chlorite (gray). Rutile and sulphides in black spots. Stope 28, 250 m level. Thin sec., ord. light, 45 ×.

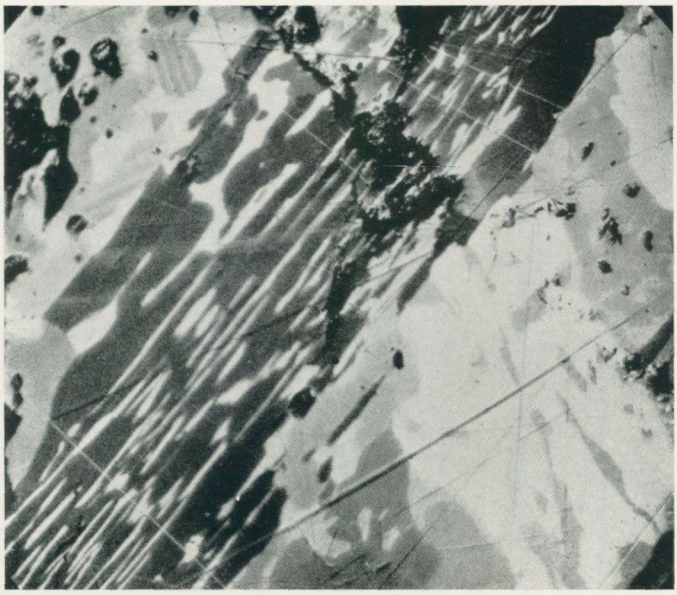


Fig. a. Fine-grained falkmanite (dark gray — cut // b, white — cut ⊥ b) replaced by galena and bournonite (twin lamellae). Stope 20, 90 m level. Pol. sec., Nic. +, immersion, 240 ×. Pl. XXII: 7 in (78).

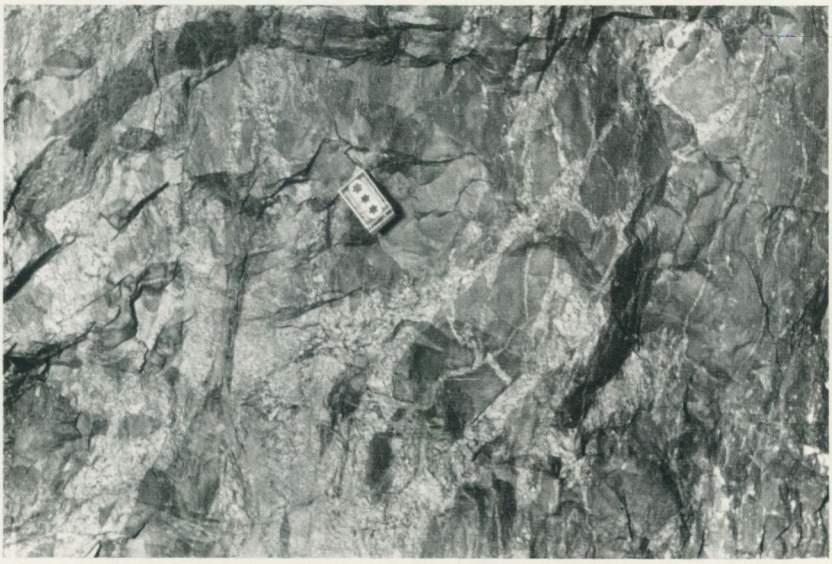


Photo Fellström.

Fig. b. Disseminated ore. Arsenopyrite in veinlets brecciating silicified sericite schist. Cross-cut in section 17, 210 m level.



Photo Larsson.

Fig. a. Plagioclase spherulite in sericite schist. Stope 28, 250 m level. Thin sec., Nic. +, 20 ×.



Photo Björkman.

Fig. b. Folded lamprophyre (chloritic) in sericite schist. Stope 14, 210 m level. Scale 1: 5.

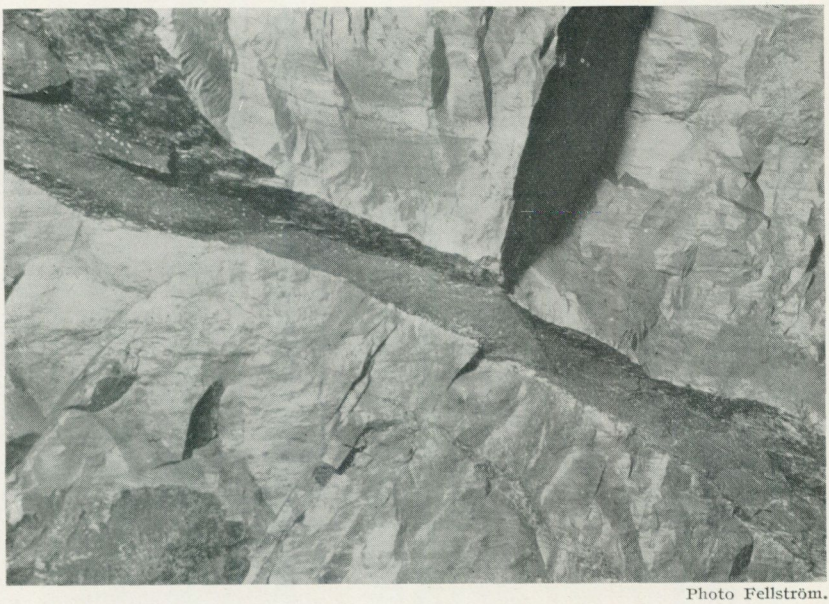


Photo Fellström.

Fig. a. Chloritic lamprophyre cutting quartz-banded arsenopyrite ore. Photo of back of stope. Width of dyke 15 cm. Stope 28, 250 m level. Fig. 4 in (65).

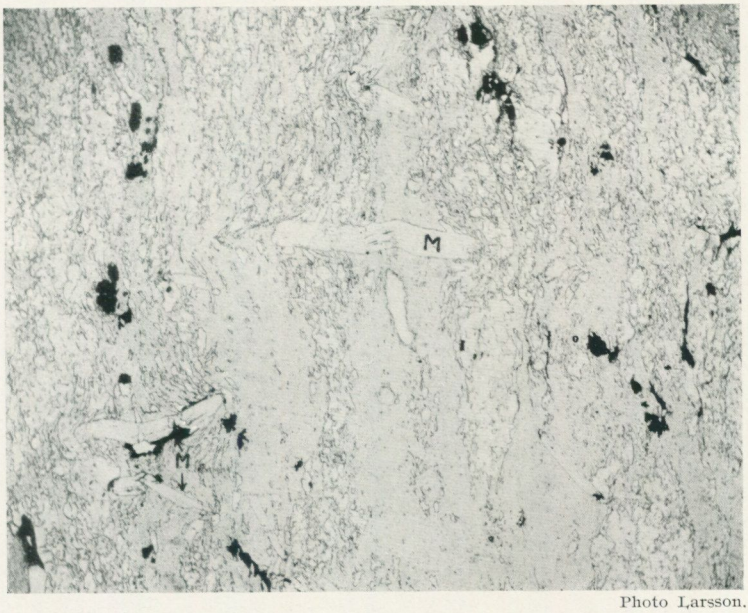


Photo Larsson.

Fig. b. Chloritic lamprophyre with porphyroblasts of mariposite (M). Quartz white, chlorite gray. 250 m level. Thin sec., ord. light, 21 ×.



Photo Larsson.

Fig. a. Hornblende lamprophyre. Hornblende gray, quartz and plagioclase white, pyrite black. Analysis No. 33, p. 77. Main east drift, 410 m level. Thin sec., ord. light, 19 ×.

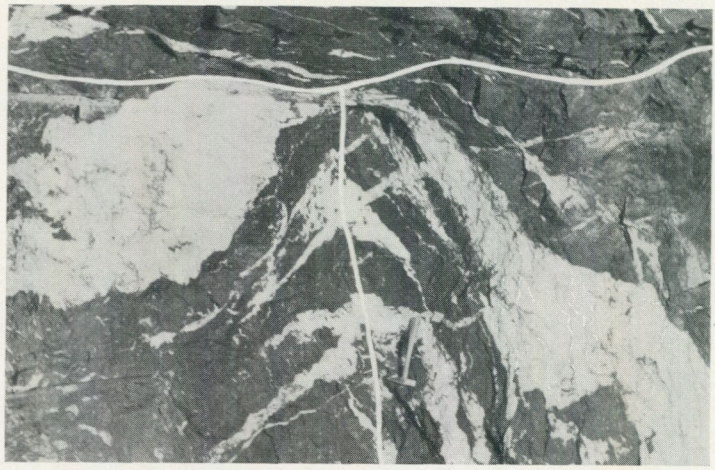


Photo Fellström.

Fig. b. Tourmaline ore cut by ladder veins of quartz. Photo from a corner of a stope on the 330 m level; the white lines mark the corner and the contours of the back. Fig. 8 in (65).

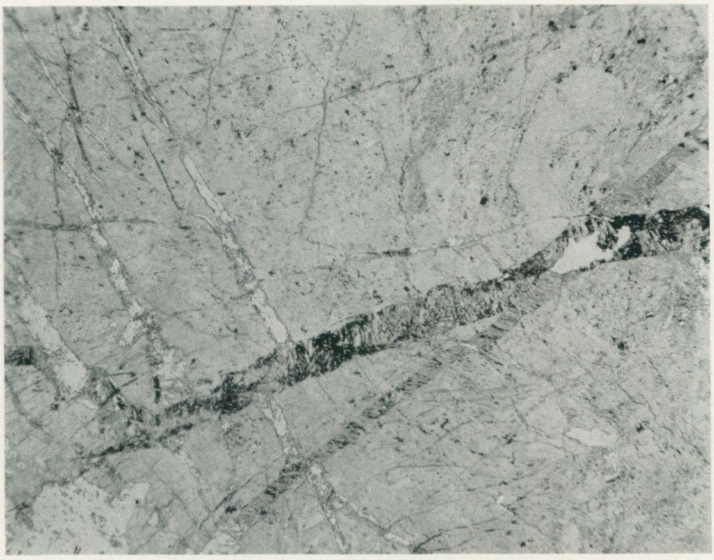


Fig. a. Fine-grained tourmaline ore cut by two systems of tourmaline veins with quartz (white) and ore minerals (black). Stope 23, 170 m level. Thin sec., ord. light, 7 ×.



Fig. b. Gold (white) as groundmass in tourmaline ore (black). Grain of galena (G) at the bottom. Stope 23, 170 m level. Pol. sec., ord. light, 60 ×.

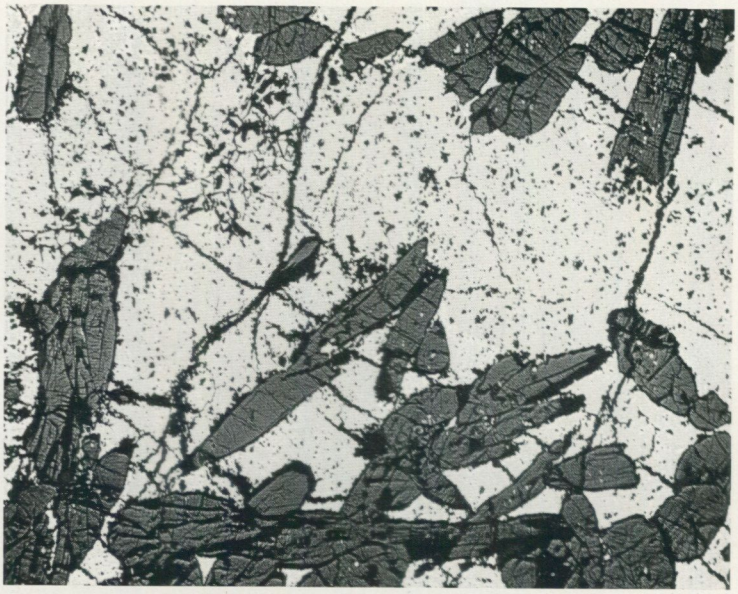


Fig. a. Tourmaline needles in cobaltite. Stope 25, 250 m level. Pol. sec., ord. light, 11 ×.

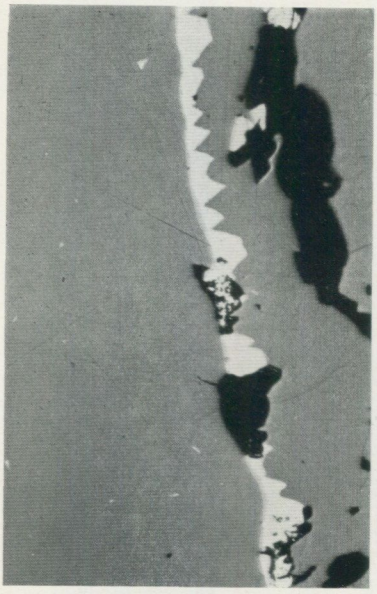


Fig. b. Chalcopyrite (white) replacing tetrahedrite (gray) along serrate vein. From quartz-tourmaline vein in drift at the W end of the a—d-lens, 170 m level. Pol. sec., ord. light, immersion, 320 ×.



Fig. c. Needles of sternbergite in vein of calcite (black) and pyrrhotite (gray with relief) cutting galena-pyrrhotite ore. White grains of bismuth at centre and at the top. Stope 23, 170 m level. Pol. sec., ord. light, 166 ×.

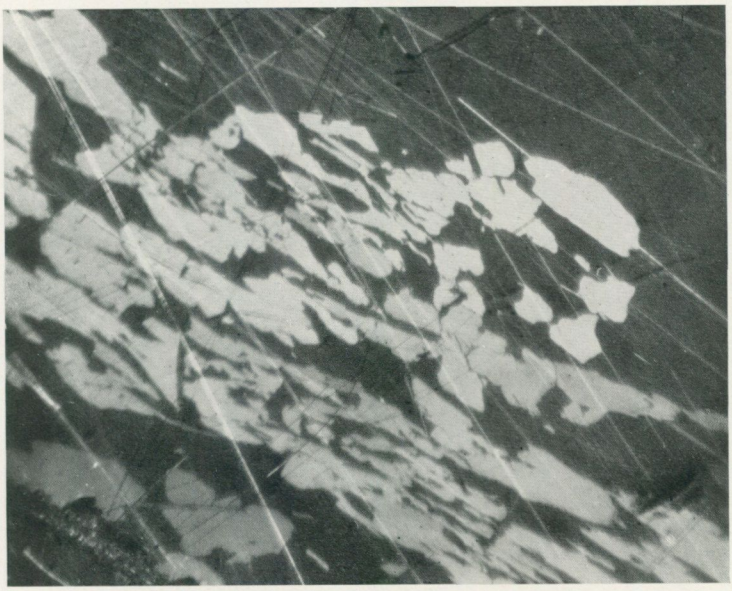


Fig. a. »Selenocosalite» (white and medium gray) intergrown with galena (black). Stope 23, 170 m level. Pol. sec., Nic. +, 51 ×.



Fig. b. »Selenokobellite», partly recrystallized. Grain of arsenopyrite to the left. Main east drift, section 11, 210 m level. Pol. sec., Nic. +, 56 ×.

Pl. 34.

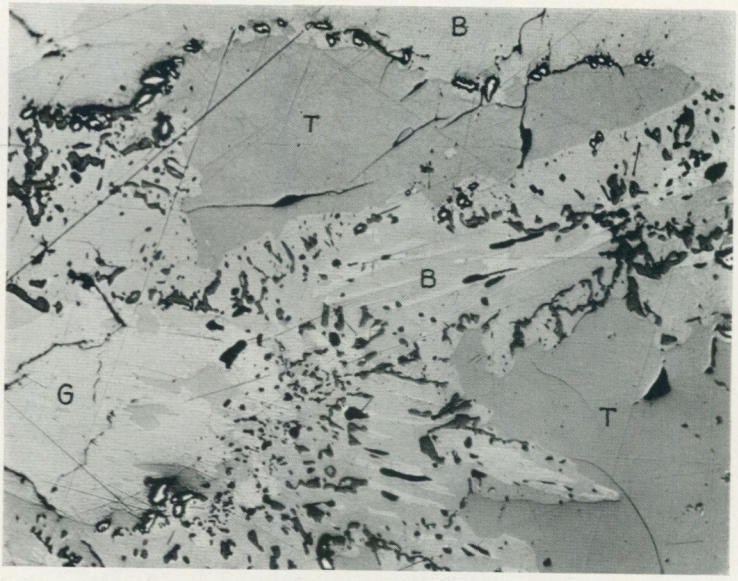


Fig. a. Tetrahedrite (T) decomposes to bournonite (B), galena (G), sphalerite (dark gray), and arsenopyrite (white grains). Stope 22, 130 m level. Pol. sec., ord. light, 200 ×.



Fig. b. Bundles of various minerals in complex intergrowths. Stope 23, 170 m level. Pol. sec., ord. light, 12 ×.

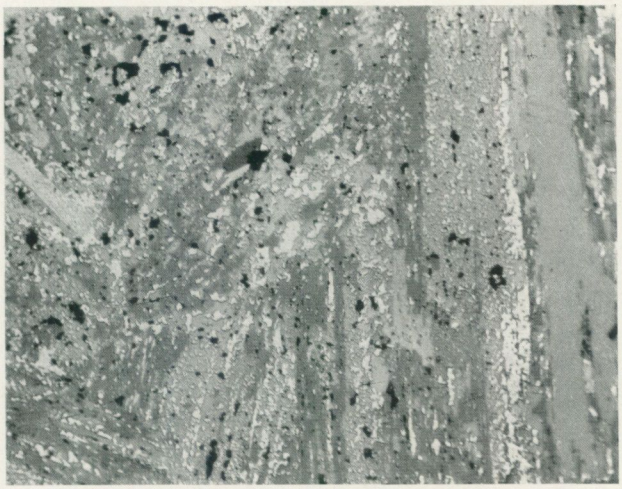


Fig. a. Lamellar intergrowth of unknown sulphomineral and galena (medium gray), sphalerite and tetrahedrite (dark gray), and bismuth (white). Small grains of pyrrhotite, chalcopyrite, and bournonite are not discernible. Stope 23, 170 m level. Pol. sec., ord. light, immersion, 225 ×

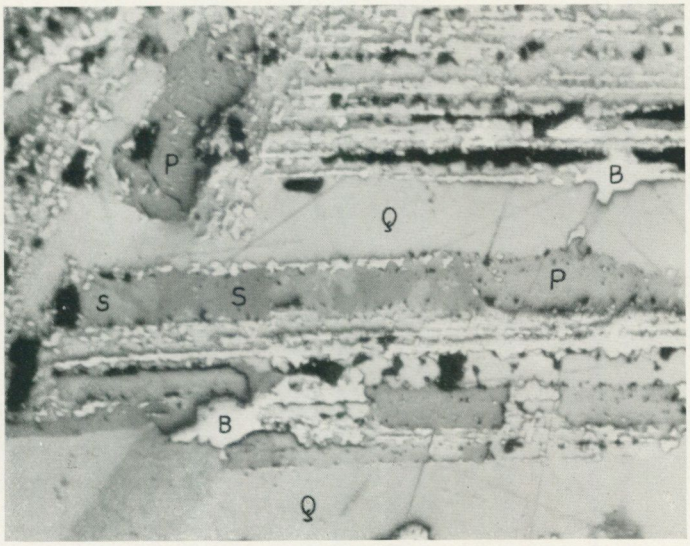


Fig. b. Lamellar intergrowth of galena (Q), pyrrhotite (P), sternbergite (S; shows pleochroism), and bismuth (B). Stope 23, 170 m level. Pol. sec., ord. light, immersion, 260 ×.



Photo Larsson.

Fig. a. Spherulites of tourmaline in mariposite. Section 15, 250 m level. $^2/_3$ nat. size.

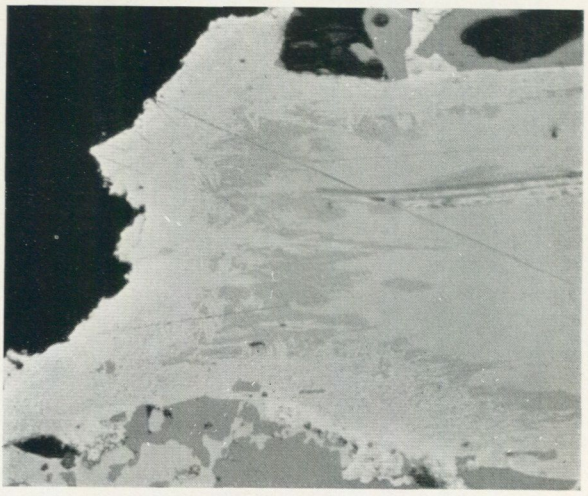


Fig. b. Bi-telluride (to the right) decomposed to at least two unknown minerals. Stope 23, 170 m level. Pol. sec., ord. light, immersion, 210 ×.

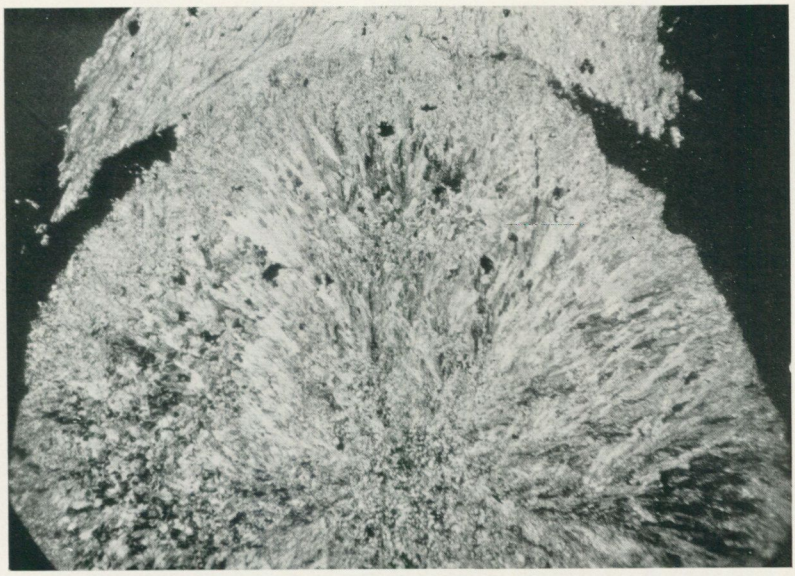


Fig. a. Spherulite of tourmaline in mariposite (at the top). Section 15, 250 m level. Thin sec., Nic. +, 5 ×.

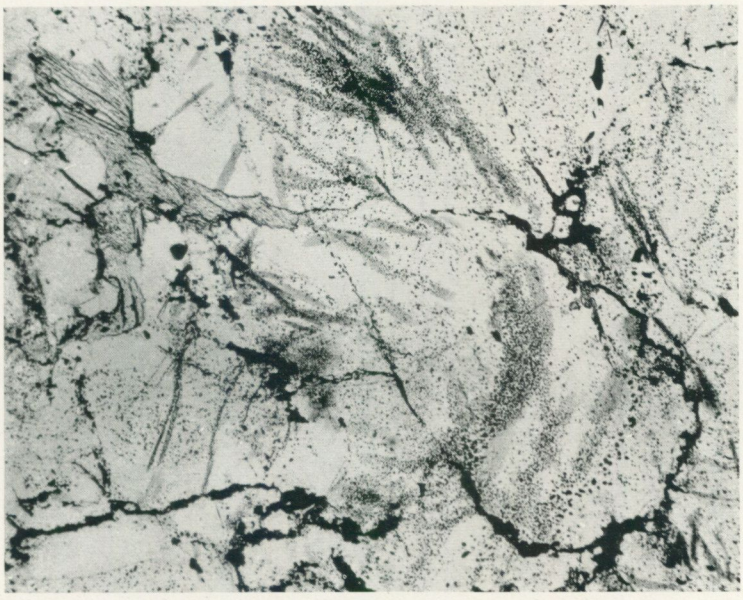


Fig. b. Clouds of opaque minerals in quartz. Stope 23, 170 m level. Thin sec., ord. light, 46 ×.



Fig. a. Sericite in chalcopyrite. Tourmaline in the top right-hand corner. Stope 23, 170 m level. Pol. sec., ord. light, 11 ×.

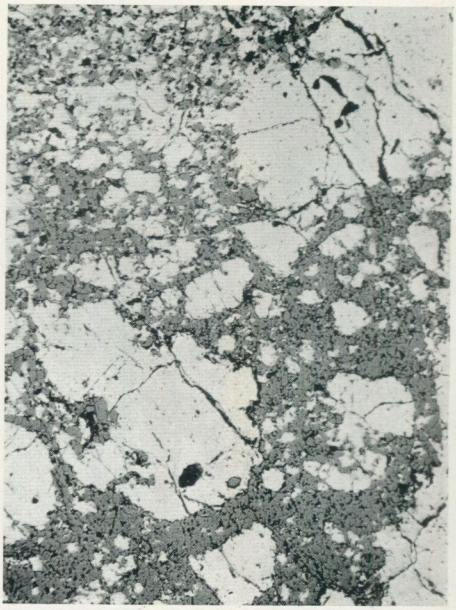


Fig. b. Pyrrhotite (white) brecciated by tourmaline (dark gray). Stope 23, 170 m level. Pol. sec., ord. light, 10 ×.



Fig. c. Amygdule with two carbonates in pyrrhotite ore. Stope 23, 170 m level. Thin sec., ord. light, 28 ×.

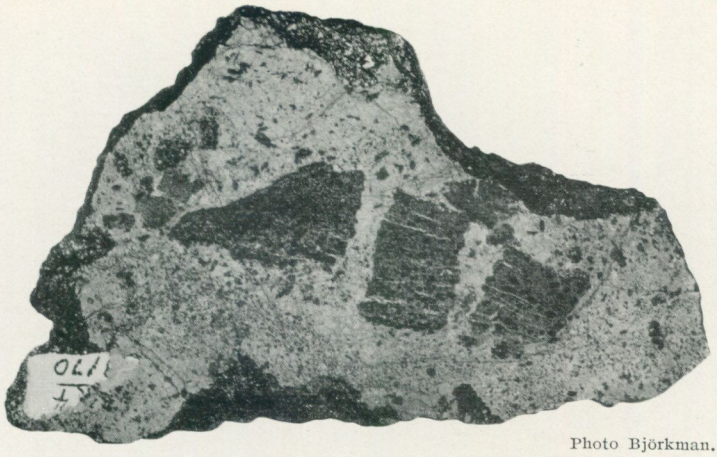


Photo Björkman.

Fig. a. Inclusions of tourmaline ore in pyrrhotite-chalcopyrite ore. Stope 22, 130 m level. Nat. size.

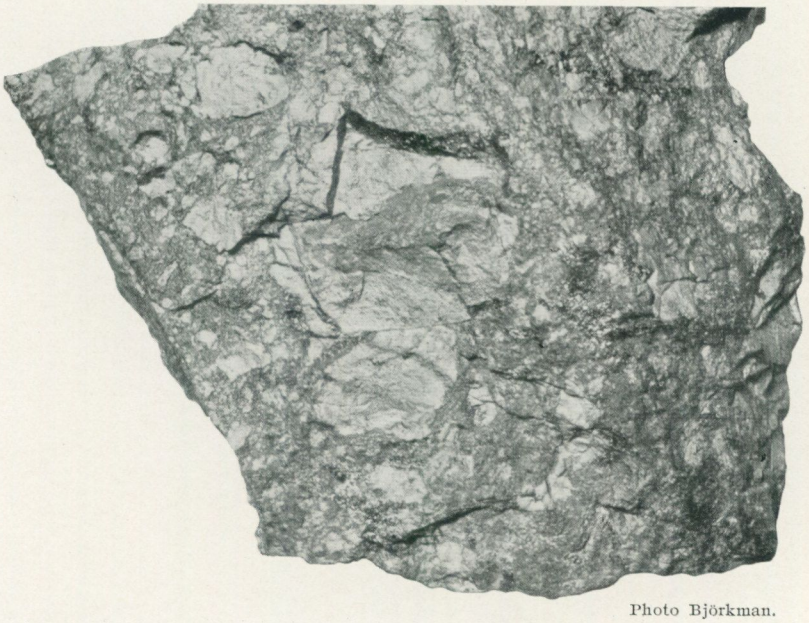


Photo Björkman.

Fig. b. Arsenopyrite ore (gray inclusions) brecciated by tourmaline ore (black) with pyrrhotite. Stope 23, 170 m level. $^2/_3$ nat. size.

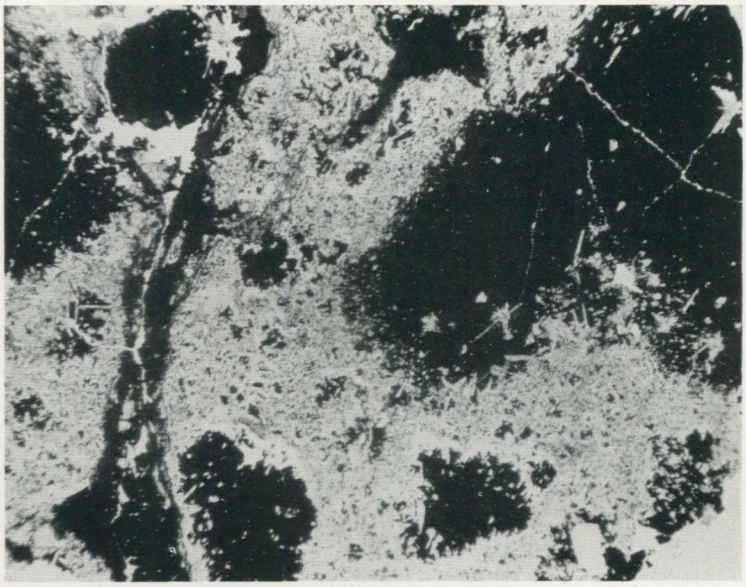


Fig. a. Arsenopyrite ore (black) brecciated and replaced by tourmaline. Note tourmaline needles growing into the arsenopyrite ore. Black streak to the left and black grains in the tourmaline mass are composed of rutile. Stope 23, 170 m level. Thin sec., ord. light, 7 ×.



Fig. b. Tellurobismuthite (T) and tetradymite (B) (the difference between the minerals has been exaggerated in the photographic copy). Stope 28, 250 m level. Pol. sec., ord. light, 11 ×.

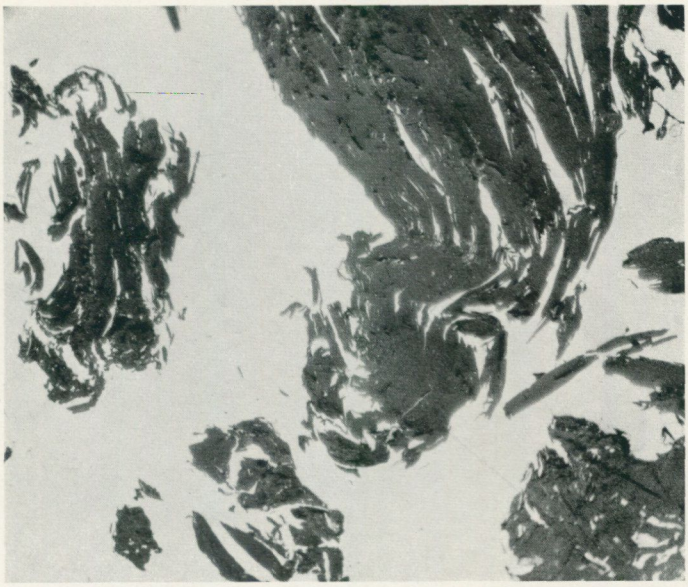


Fig. a. Chalcopyrite invading sericite schist. Stope 26, 250 m level. Pol. sec., ord. light, 135 ×.



Fig. b. Gold (white) with small grains of galena (light gray) invading sericite schist. Stope 26, 250 m level. Pol. sec., ord. light, 10 ×.

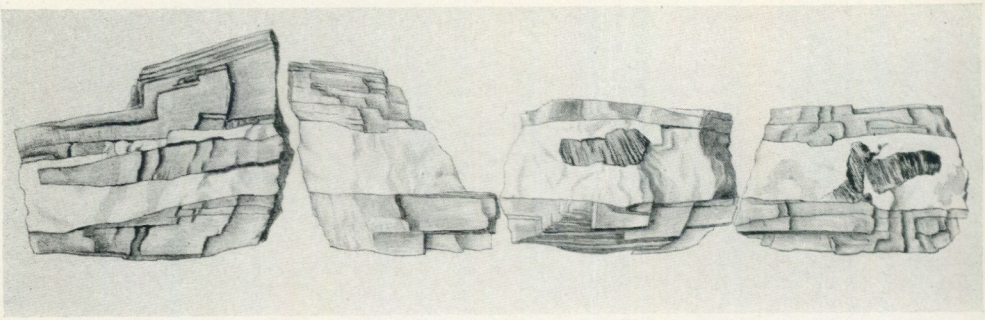
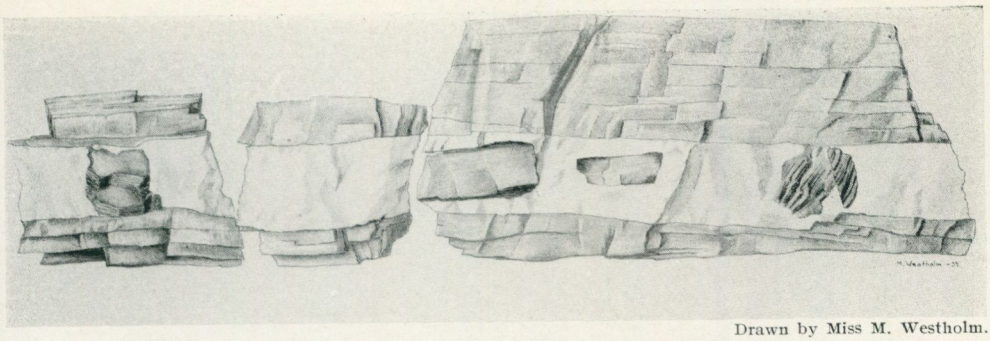


Fig. a. Horizontal apophysis from the pyrite ore, cut about 4 m from its base at the pyrite ore and close to runs parallel to the plane of the figure. The apophysis is composed of chalcopyrite. Note the sharp apophysis. 1/3



Photo Fellström.

Fig. b. Inclusion of hornblende lamprophyre in pyrite ore (P) cut by vein of quartz with chalcopyrite (Q), and chalcopyrite (C), emanating from the pyrite ore. Stope 3, 130 m level.



Drawn by Miss M. Westholm.

the point where the wedge-shaped apophysis petered out. The schistosity of the surrounding sericite schist contacts to the schist and the dislocated inclusions of schist, indicating a transport during the formation of the nat. size.



Photo Björkman.

Fig. b. Hornblende lamprophyre brecciated and partly replaced by pyrite ore. Stope 15, 170 m level. Scale 1: 22.

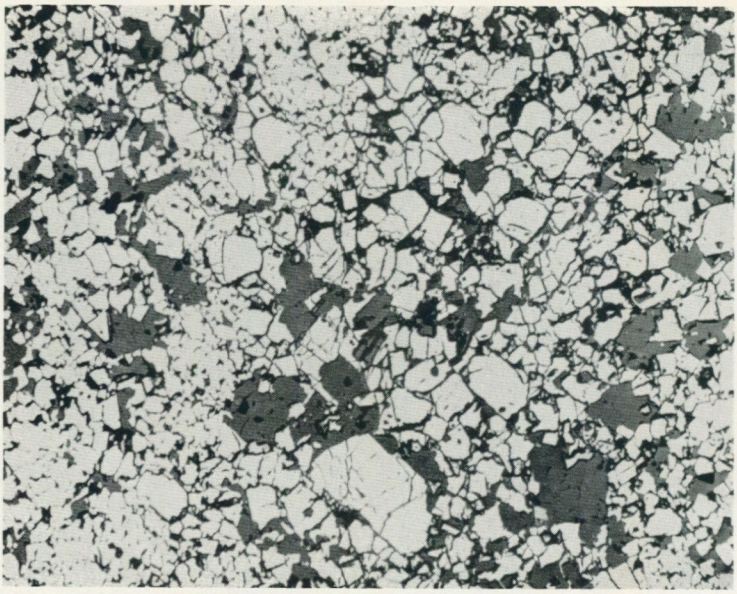


Fig. a. Pyrite ore (pyrite white, quartz gray). Stope 1, 130 m level. Pol. sec., ord. light, 12 ×.

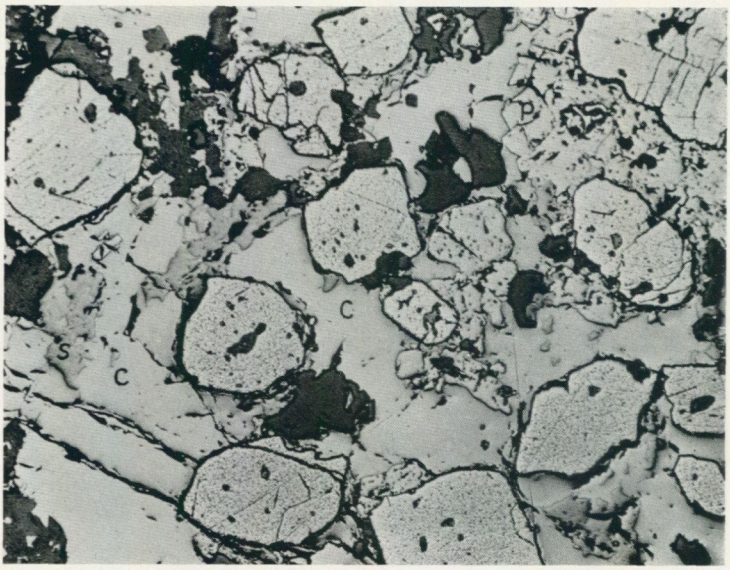


Fig. b. Porphyritic pyrite ore. Pyrite grains in groundmass of mainly chalcopyrite (C) with sphalerite (S), pyrrhotite (P), and quartz (black). Eastern ore, 50 m level. Pol. sec., ord. light, 12 ×.



Fig. a. Idiomorphic grains of plagioclase in pyrite ore. Stope 4, 130 m level. Thin sec., ord. light, 8 ×.



Photo Fellström.

Fig. b. Apophysis of chalcopyrite from large apophysis of pyrite ore. The wedge of chalcopyrite (0.5 m long) cuts sericite schist, the foliation of which runs parallel to the plane of the figure. Stope 3, 130 m level.

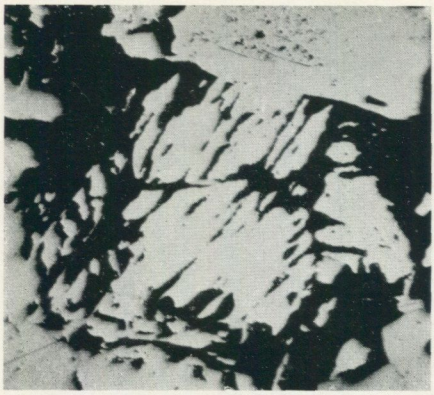


Fig. a. Chalcopyrite replaced by calcite. From hanging wall of the Eastern Ore, section 12—13, 170 m level. Pol. sec., ord. light, 186 ×.



Photo Björkman.

Fig. b. Apophysis of pyrite ore in the footwall of the Western Ore. Section 3, open pit. Hammer in the top left-hand corner shows the scale.



Fig. a. Idiomorphic grains of plagioclase in galena. Stope 6, 130 m level. Pol. sec., ord. light, 10 ×.

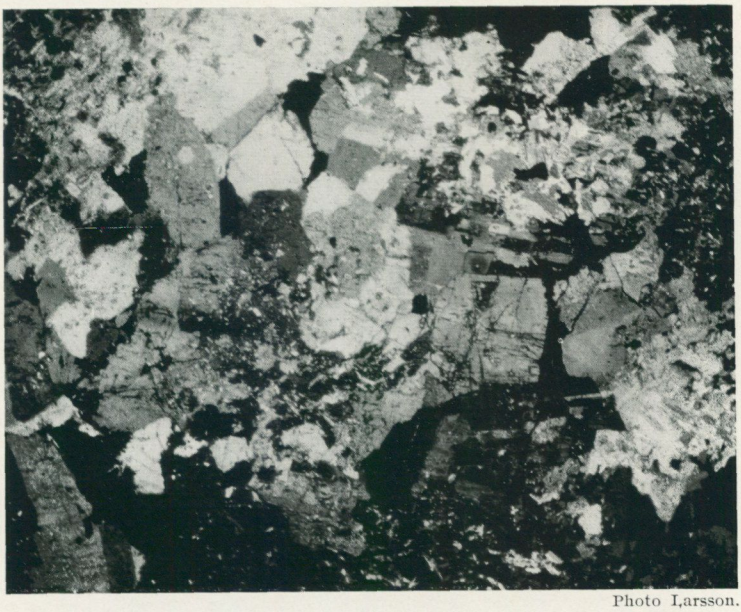


Photo Larsson.

Fig. b. Felspathized sericite schist. Footwall of Eastern Ore, Section 19, 55 m level. Thin sec., Nic. +, 22 ×.

Pl. 48.

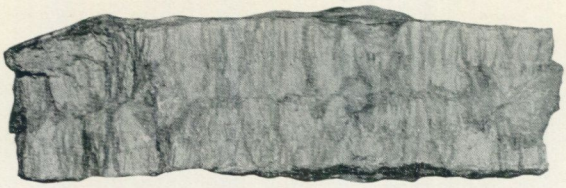


Photo Björkman

Fig. a. Fissure with apophyllite. Stope 5, 130 m level. 3/4 nat. size.

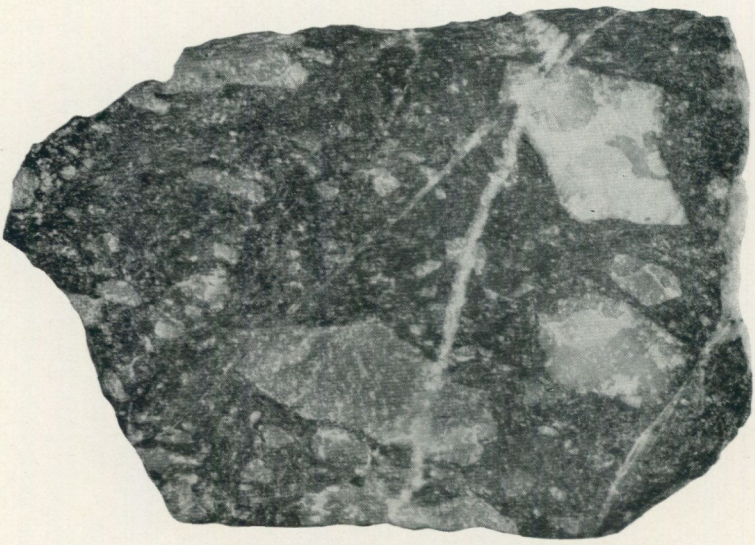


Photo Larsson

Fig. b. Fine-grained tourmaline ore with inclusions of altered wallrocks and vein-quartz. Buffalo Ankerite Mine, Porcupine District, Ontario. Nat. size.

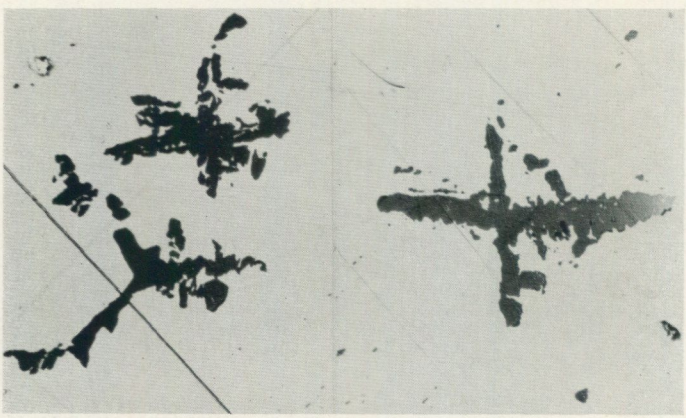
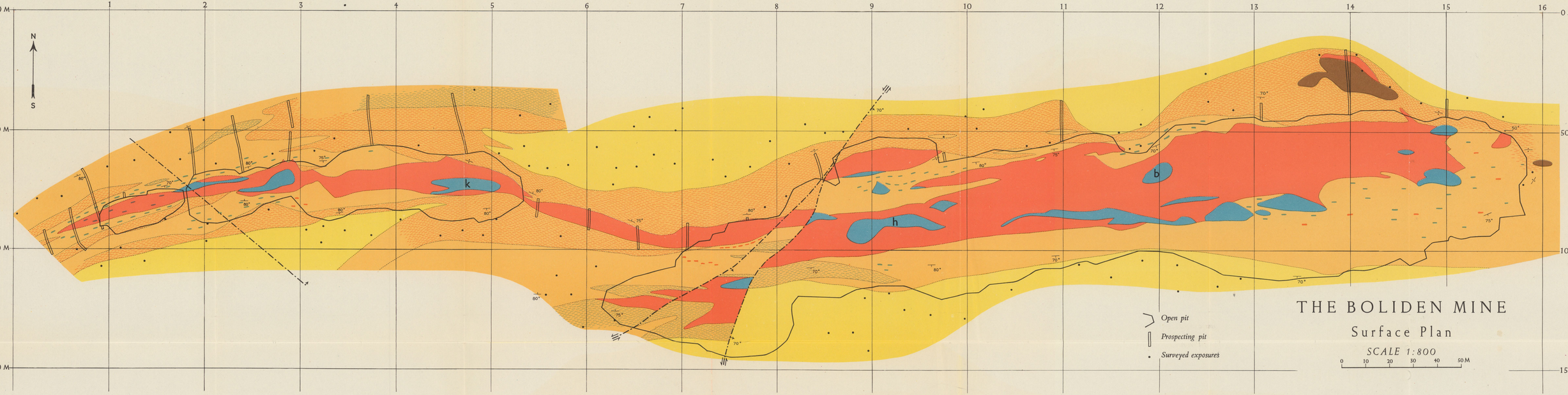


Fig. c. Star-shaped grains of stannite in chalcopyrite. Stope 20, Western Ore, 90 m level. Pol. sec., ord. light, immersion, 250 ×.



THE BOLIDEN MINE

Surface Plan

SCALE 1:800

0 10 20 30 40 50 M

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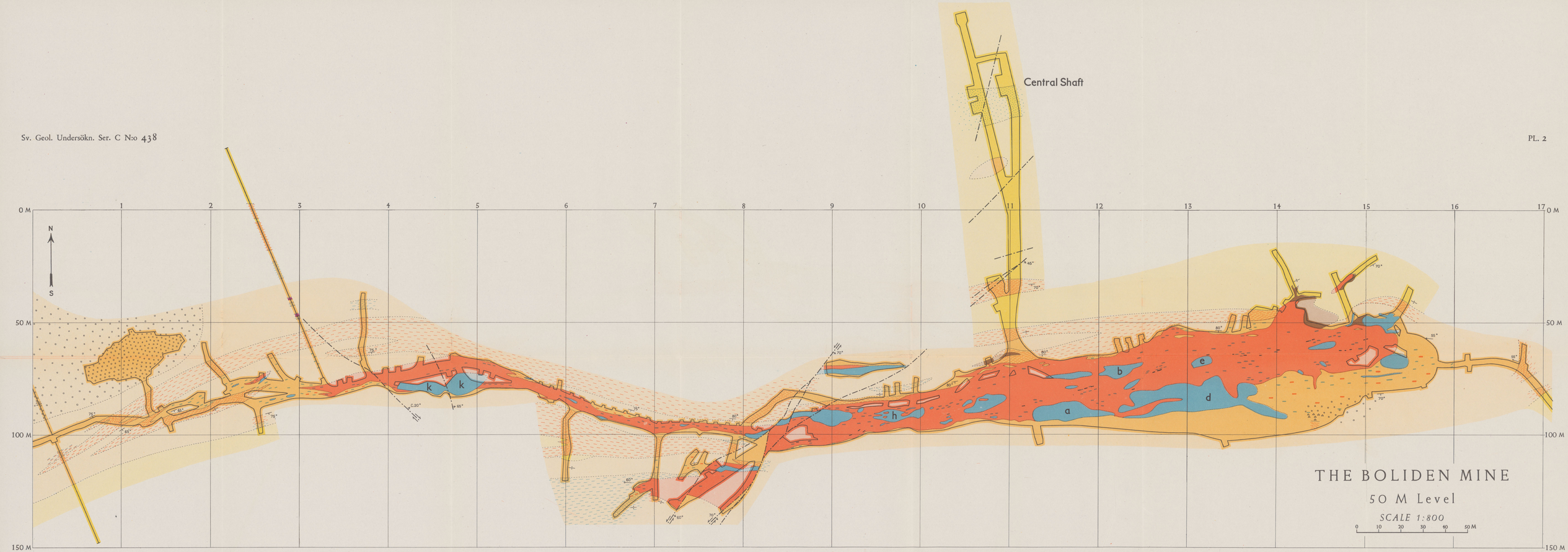

THE BOLIDEN MINE

50 M Level

SCALE 1:800

0 10 20 30 40 50 M

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THE BOLIDEN MINE

90 M Level

SCALE 1:800

0 10 20 30 40 50 M

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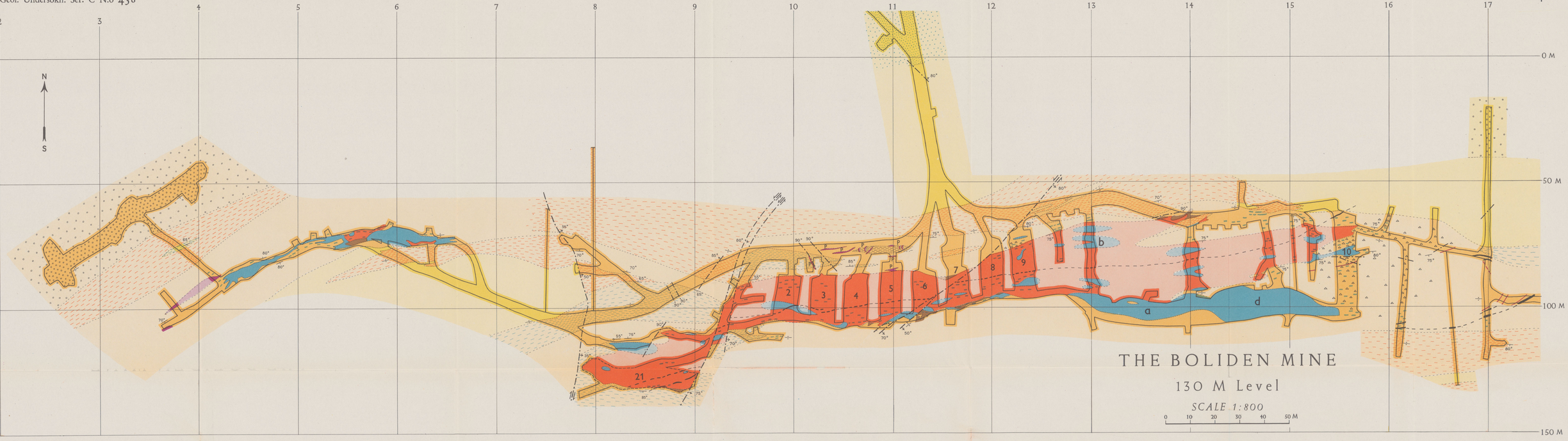

THE BOLIDEN MINE

130 M Level

SCALE 1:800

0 10 20 30 40 50 M

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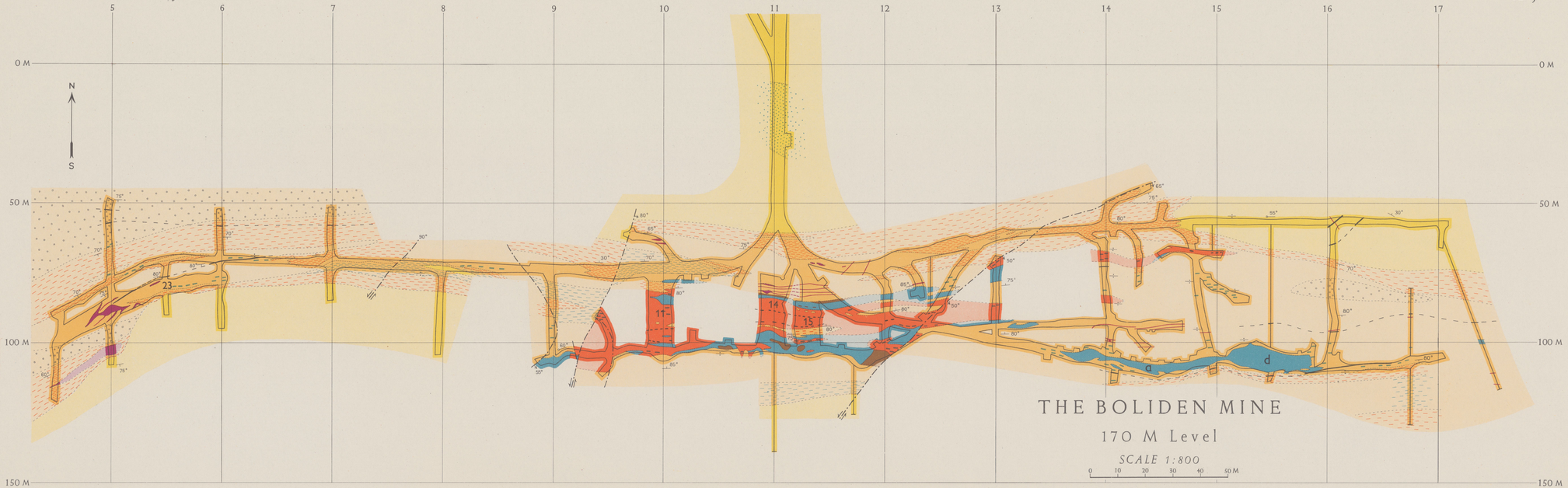

THE BOLIDEN MINE

170 M Level

SCALE 1:800

0 10 20 30 40 50 M

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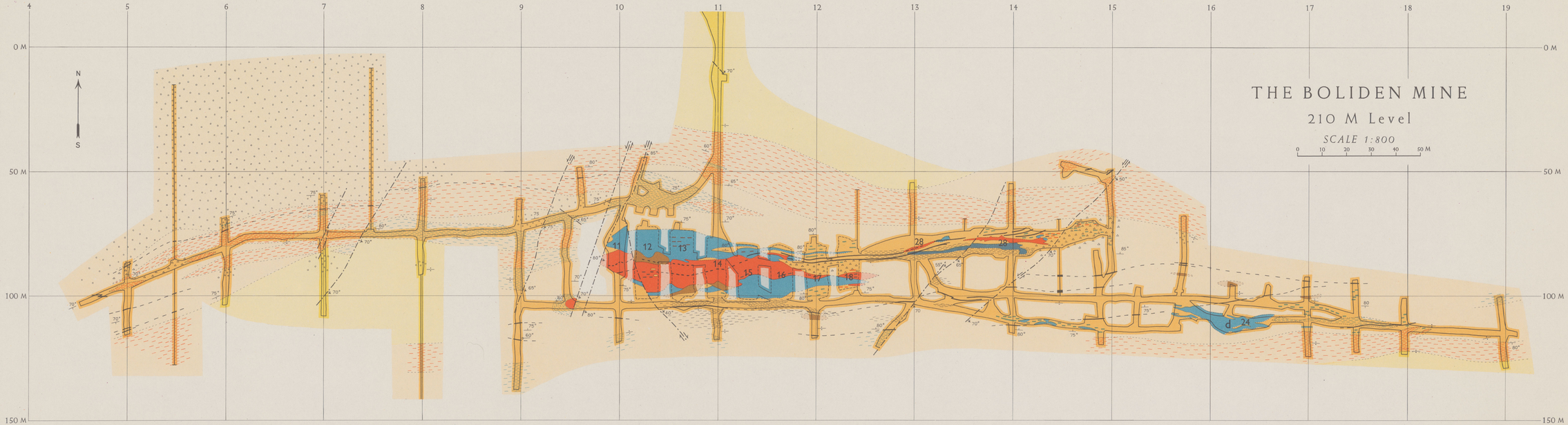

THE BOLIDEN MINE

210 M Level

SCALE 1:800

0 10 20 30 40 50 M

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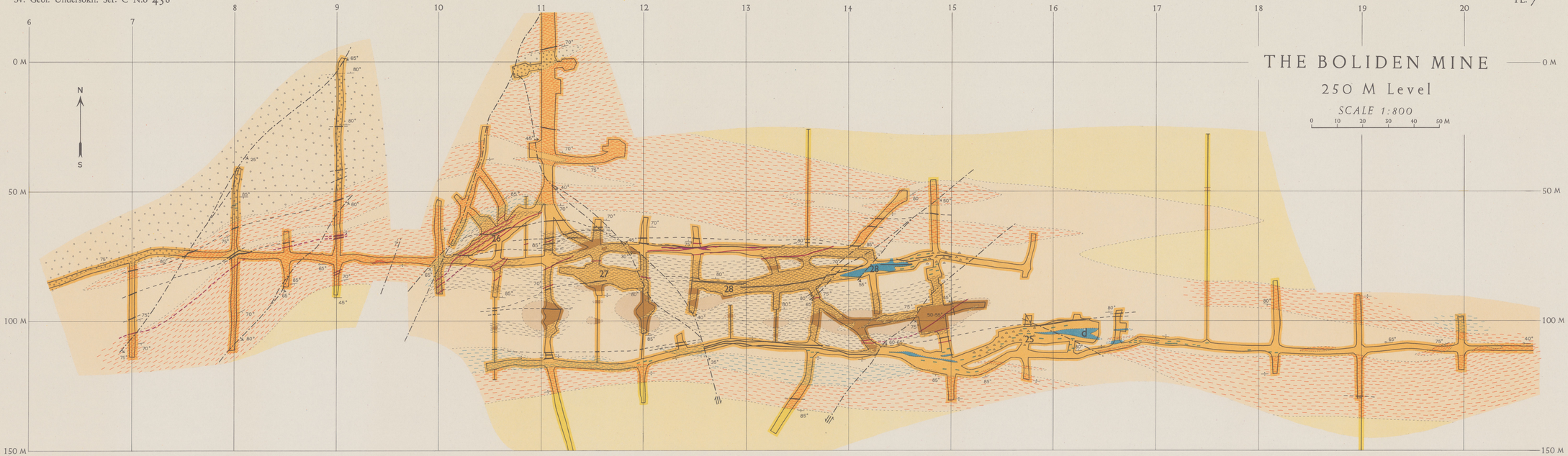

THE BOLIDEN MINE

250 M Level

SCALE 1:800

0 10 20 30 40 50 M

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THE BOLIDEN MINE

GEOLOGICAL MAPS OF STOPES Nos 23 and 28

by

OLOF H. ÖDMAN

0 — 10 — 20 M

Scale 1 : 300

LEGEND TO STOPE Nº 23

Arseno-pyrite stage

- *Sericite schist*
- *Arsenopyrite ore*
- *Disseminated arsenopyrite*

Lamprophyre-tour-maline stage

- *Tourmaline lens with ladder veins of quartz*
- *Quartz veins (with gold and sulphominerals)*
- *Pyrrhotite ore*
- *Chalcopyrite ore*

LEGEND TO STOPE Nº 28

- *Sericite schist*
- *Pyritic sericite schist*
- *Sericite rock*
- *Sericitized agglomerate*

Lamprophyre - tourmaline stage

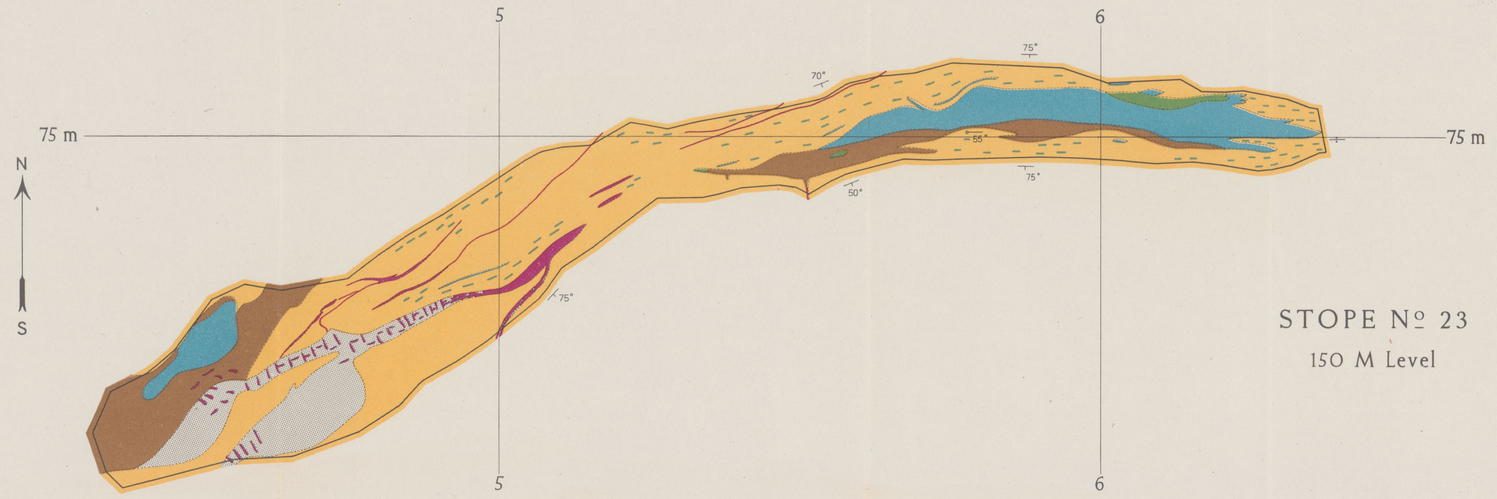
- *Lamprophyre dykes*
- *Tourmaline veins*
- *Quartz veins*

Arsenopyrite stage

- *Arsenopyrite ore*
- *Disseminated arsenopyrite*
- *Apatite*
- *Pyrite ore, including cobaltite (Co), sulphominerals, and some apatite*
- *Rutile rock*

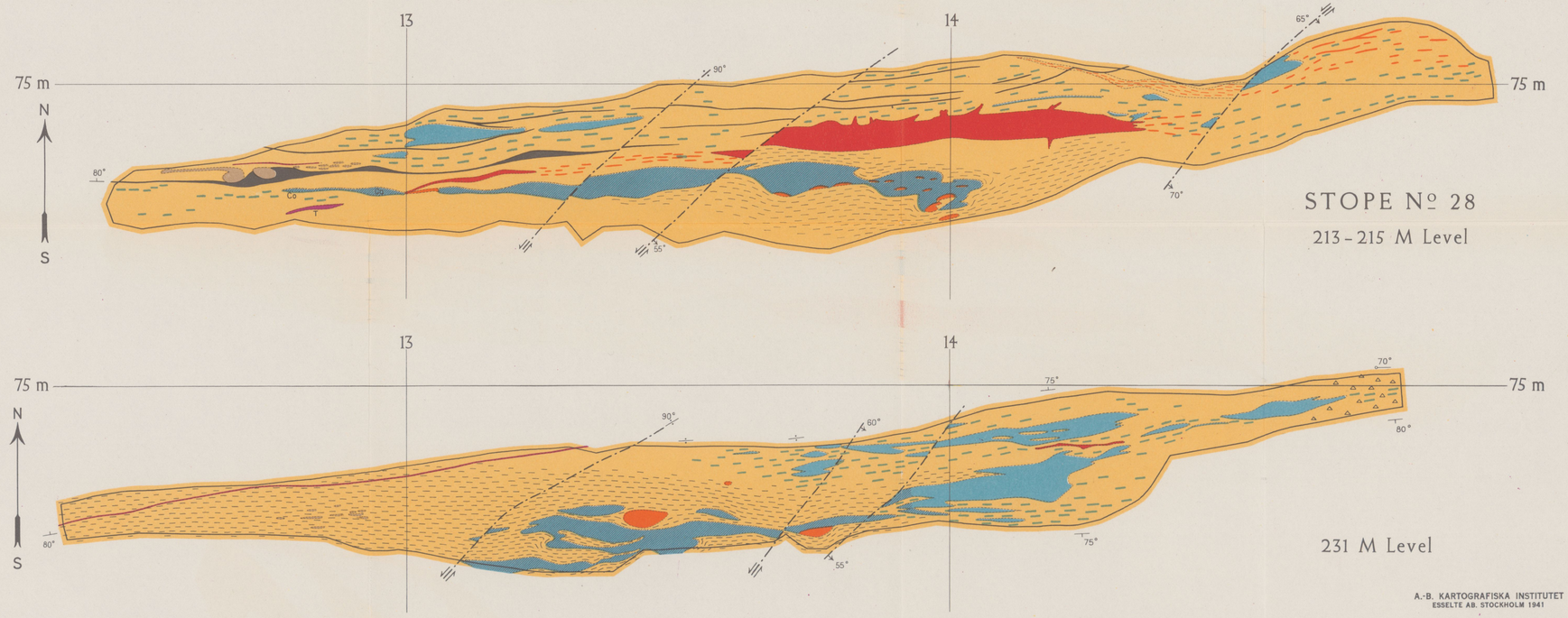
Pyrite stage

- *Pyrite ore*
- *Disseminated pyrite*



STOPE Nº 23

150 M Level



STOPE Nº 28

213 - 215 M Level

231 M Level

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