SVERIGES GEOLOGISKA UNDERSÖKNING

SER C NR 651 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 64 NR 8

ERLAND GRIP AND ÅKE WIRSTAM

THE BOLIDEN SULPHIDE DEPOSIT

A REVIEW OF GEO-INVESTIGATIONS CARRIED OUT DURING THE LIFETIME OF THE BOLIDEN MINE, SWEDEN (1924—1967)

STOCKHOLM 1970

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Editor: Per H. Lundegårdh
C. DAVIDSONS BOKTRYCKERI AB, VÄXJÖ

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ABSTRACT

After several years of systematic prospecting the Boliden sulphide deposit was discovered in 1924. Mining started the following year and continued until 1967, when the mine was exhausted and consequently closed down. The ore was complex and high-grade. It posed many new metallurgical problems for treating but these were successfully attacked. From a scientific, technological and economic point of view the Boliden Mine has been of great importance. As a matter of fact the rapidly expanding mining industry in the Skellefte District in a high degree was rendered possible thanks to the Boliden Mine. Therefore it seems expedient to give a review of all the geoscience investigations concerning the deposit which have been carried out during the lifetime of the mine before too much of its character has fallen into oblivion. The present paper is based on facts and reports not published before but a brief account is also given of material already published. Now the mine is not accessible any more. Besides its contributions to science and technology the mine has yielded 8.3 million tons of ore containing 118,000 t copper, 566,000 t arsenic, 2.1 million t sulphur, 128 t gold, 411 t silver and various quantities of several other products.

1. INTRODUCTION

After several years of prospecting, the Boliden Deposit was found in 1924. Mining began in 1925. For many years this was the only sulphide mine in production in Northern Sweden. During its entire lifetime, the mine has been of great importance in encouraging and financing further prospecting and mining development, especially of sulphide ores, all over Sweden.

During the entire period the mine was in operation, there were prospecting and development projects under way. The mine was closed November 8, 1967, when these studies had shown that there were no additional possibilities for finding new ore. The mine was exhausted.

In order to gather the most significant results together, we have surveyed all of the geological, geophysical and geochemical reports that have been presented over the 43 year period the mine was in operation and summarized them in an internal report to the Boliden Company. The Boliden Deposit is of such great interest, both from a geological and an economical point of view, that we believe the results of past investigations can be a valuable reference for further work in sulphide ore districts. Therefor we have revised our report and given it the form of the present paper. This review has been made possible through the kind permission of the Boliden Company.

The present paper is a documentation of facts and observations from the remarkable and now exhausted Boliden Mine, a deposit which probably never will be accessible again for study. As several papers about the Boliden Deposit have been published previously this one must be looked upon as a supplement which, within a reasonable frame, seeks to be as complete as possible. Facts and reports not published before will be related in detail while only a brief account will be given of material already published. A fairly large space also will be devoted to some technical problems, such as sampling, calculation of ore reserves and rock mechanics. These are facets of the problem which are often ignored in geological papers, in spite of the fact that they are very important from the point of view of economic geology.

Reports and maps, published as well as unpublished, originate mainly from the mining geologists who have been responsible for the geological survey of the mine. Basic work was carried out by Olof H. Ödman during the years 1935–1940, the results being published by him as a doctoral dissertation. Erland Grip continued the survey until 1944, at which time Åke Wirstam assumed responsibility for the project. The latter continued the work until the mine was closed.

All of the analyses presented in this paper have been made at the Research Laboratory of the Boliden Company. Drawings were prepared by the Prospecting Department. For correcting the English text we are indebted to Dr. Richard Russell. Finally we express our gratitude to the Geological Survey of Sweden which had included our paper in one of their publication series.

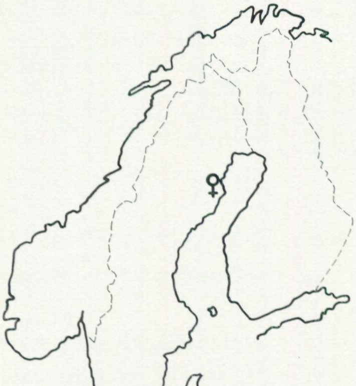


Fig. 1. Location of the Boliden Deposit (64°52′N, 20°22′E).

2. HISTORY — FROM DISCOVERY TO THE END

The first indication of ore in the easternmost part of the Skellefte District was obtained in the summer of 1921 when one of the local inhabitants exhibited a large glacial boulder, which he had found when digging a ditch at Svanfors, 5 km E of the present Boliden (Fig. 2), to one of the geologists from Central-

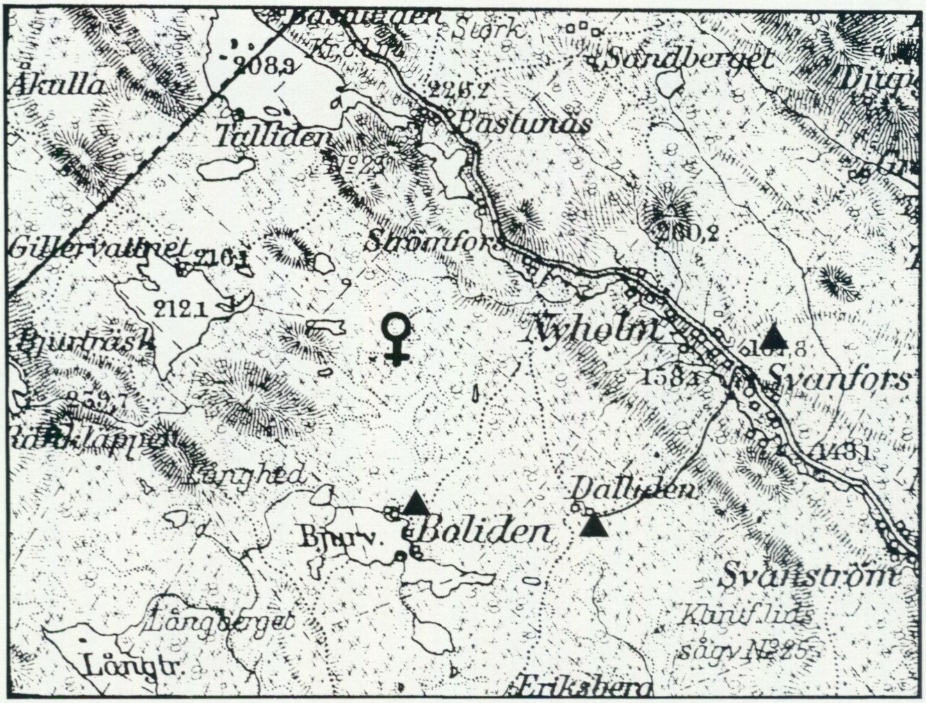


Fig. 2. Official topographic map of the Boliden area at the time of the discovery of the sulphide deposit which was to take its name, "Boliden", from the map. The copper symbol indicates the situation of the deposit. The filled triangles mark the historically important glacial ore-boulders at Svanfors, Dalliden and Bjurliden (incorrectly labelled Boliden on the map). Scale 1:100 000. (Enlargement of the original map in 1:200 000).

gruppens Emissions Aktiebolag. This company hade begun prospecting in the District a few years earlier. It is continuing the work today, although now under the name Boliden Aktiebolag.

The Svanfors boulder, which weighed one ton, consisted of compact pyrite ore, with some copper. It led to detailed geological mapping and boulder-hunting in the surrounding area and further to the NW and W. Several new boulders were found during this search. Geoelectrical measurements, starting from the Svanfors boulder, were carried out the same year.

Anomalies were located, but they proved to be caused by graphite schist disseminated with pyrrhotite. The major sulphide mineralization was expected to occur along the contact zone between the porphyry series and the overlying phyllite series. Because the critical area was covered by a thick morainic overburden, it was decided to make electrical measurements over the entire contact zone. The starting point for the survey at that time was near some boulders at Bjurliden, more to the west (incorrectly named Boliden in Fig. 2). Measurements were made continuously from the boulders lying in the phyllite area to the NW, until the porphyry contact was reached. This line appeared very sharp, as the phyllites produce very strong anomalies while the porphyries show none at all. The contact zone was then followed further to the east.

In september 1923, claims were staked around anomalies along the contact zone. The name Boliden appeared then for the first time. The name was taken from a misprint on the topographic map.

Further investigations revealed a group of remarkable anomalies about 2,5 km N of the name Boliden on the map (Fig. 2). As they seemed to be interesting from a mineralization point of view, they were investigated by diamond drilling. The first drill hole penetrated pyrite-disseminated sericite schist, an alteration rock which looked promising. The next drill hole was located on a similar anomaly. On December 10th 1924, this drill hole penetrated ore, crossing a section rich in copper-arsenic ore 10 m wide. Later tests showed it to have a high gold content. Detailed electrical investigations showed the general outline of the newly discovered ore body. Detailed drilling was carried out, so that by the end of 1925 the upper part of the deposit was known (Fig. 5). During the drilling, the deposit was found to be covered by an exceptionally thick overburden. In the eastern part, the cover exceeded 20 m in thickness. In spite of this difficulty electrical methods proved to be an invaluable tool for prospecting in the Skellefte District, where moraine, swamps and lakes cover almost the entire bedrock.

In 1925, mining development started and the Boliden Mine went into production on a small scale. After a few years of underground work, new exploratory drill holes were started from the surface. Because these holes had to penetrate the ore zone at the 250–300 m level, they were started rather far away from the ore body at the surface. Consequently the bedrock on the hanging wall side of the deposit up to the phyllites was exposed and could be studied in detail.

When the Boliden Mine was further developed for production on a larger scale in 1929, the central shaft was sunk to the 250 m level. At the same time, removal of the thick overburden was begun and an open pit opened (Fig. 3). By means of drifts and drillings, the ore body was then explored in 40 m vertical intervals from the 50 m level downwards. This allowed a detailed examination of the ore body and its immediate surroundings. Further prospecting downwards and around the deposit followed later on. This work included a blind shaft leading downwards from the 250 m level. Even though the compact ore body was thought to peater out above 330 m, the exploratory results encouraged the continuation of the blind shaft down to 570 m. Exploration levels were developed at 410, 490 and 570 m. Drifts were driven at regular intervals all along the center line of the alteration zone. Horizontal drilling was carried out on a regular grid outwards from the drifts.

This work resulted in the discovery of some gold-bearing quartz-tourmaline

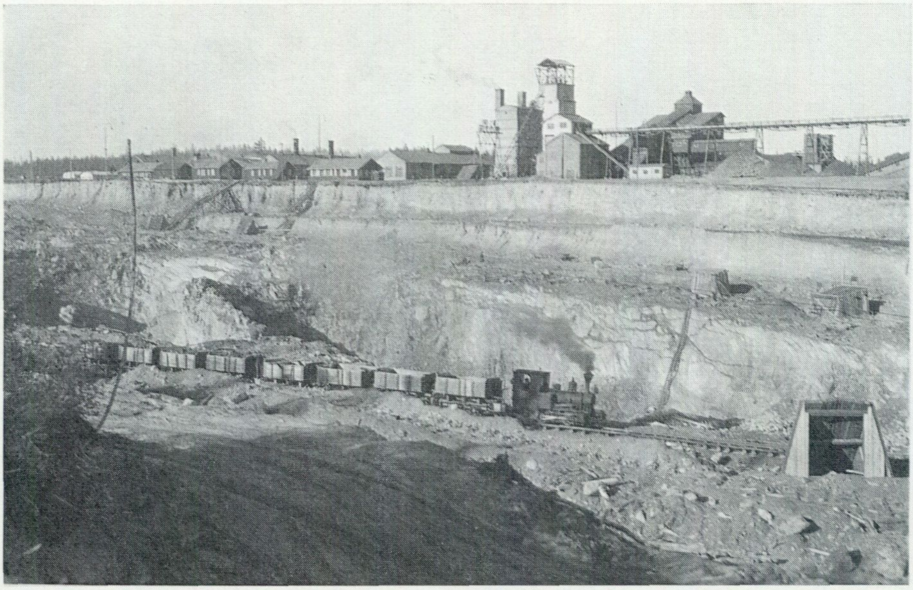


Fig. 3. Development of the open pit at Boliden. The overburden at the east end was more than 20 m thick. About one million cubic-metres were removed. Photo from 1934.

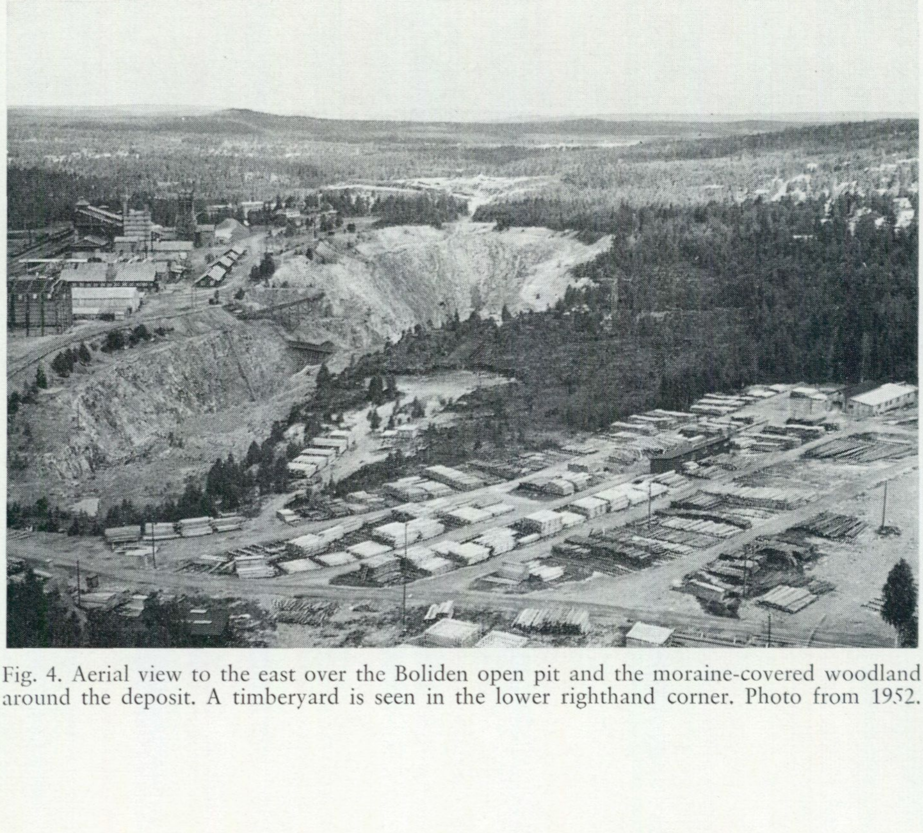


Fig. 4. Aerial view to the east over the Boliden open pit and the moraine-covered woodland around the deposit. A timberyard is seen in the lower righthand corner. Photo from 1952.

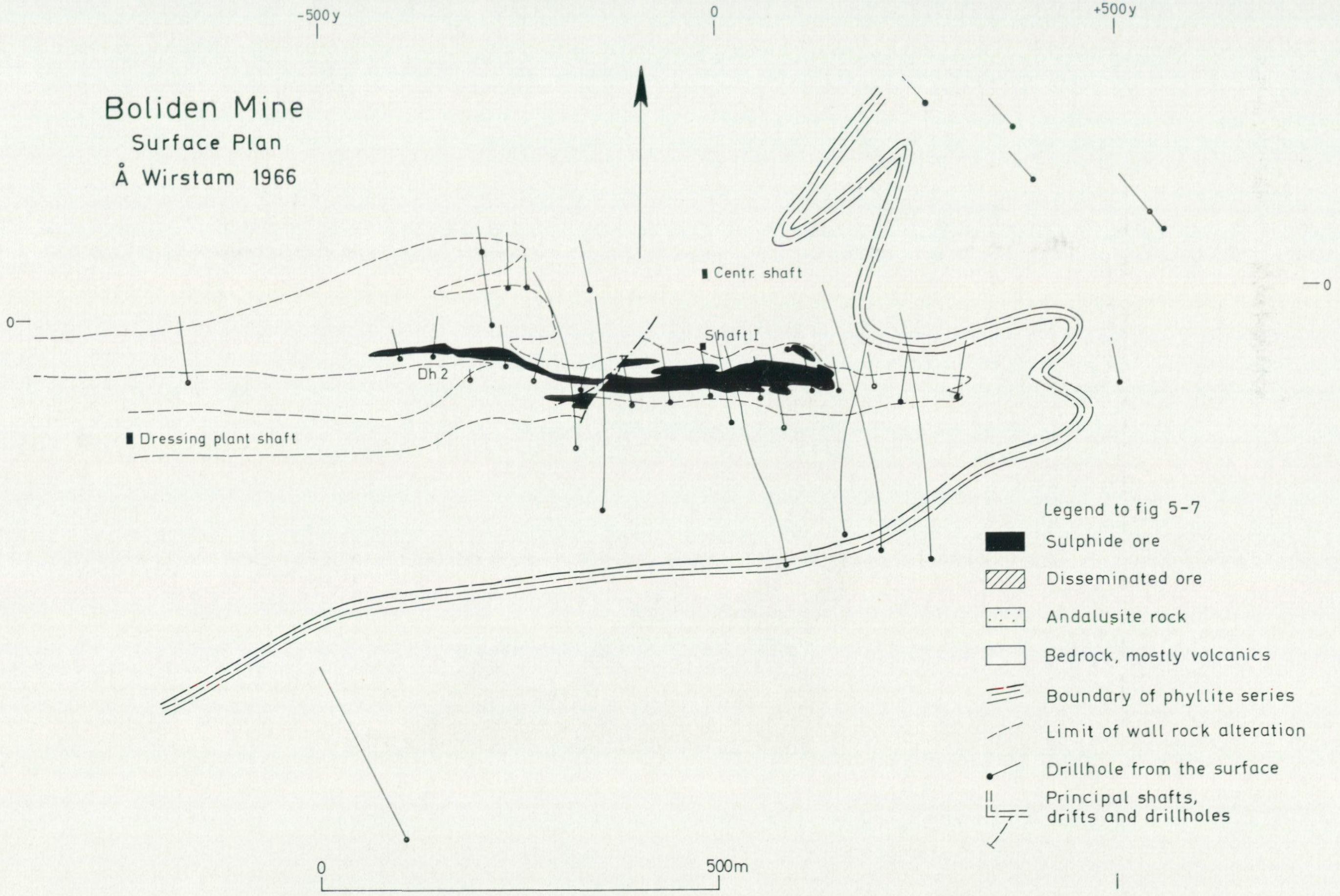


Fig. 5

Fig. 5–9. Principal plans and sections showing the extension of all the detailed work carried out in the Boliden Mine until its closing in 1967. Though similar to the corresponding figures of Ödman (1941), the present illustrations have been extended and completed. A map of the entire 410 m level has not been published previously.

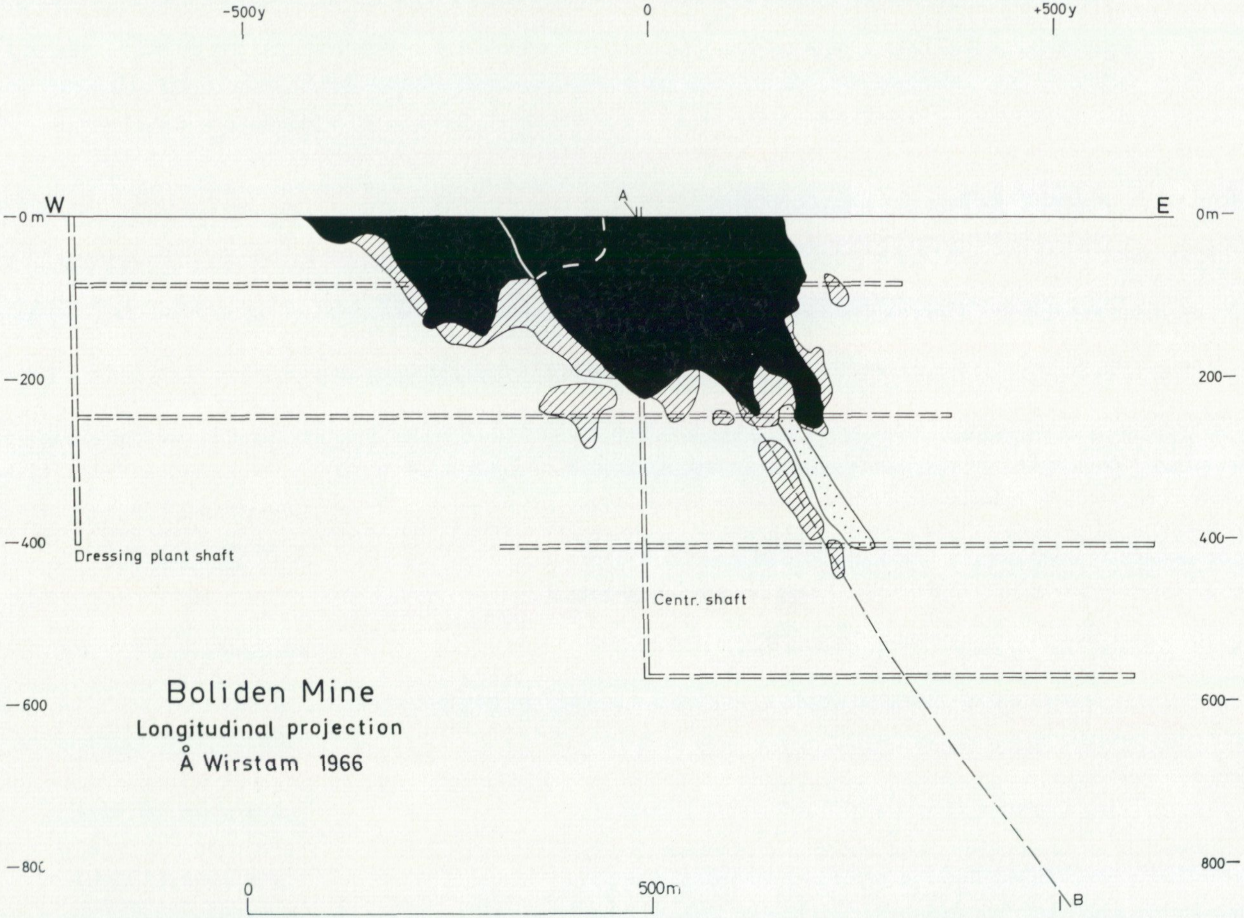

-500y
0
+500y
W
A
E
-0 m
0m
-200
200
-400
400
-600
600
-800
800
Dressing plant shaft
Centr. shaft
B
0
500m
Boliden Mine
Longitudinal projection
Å Wirstam 1966

Fig. 6

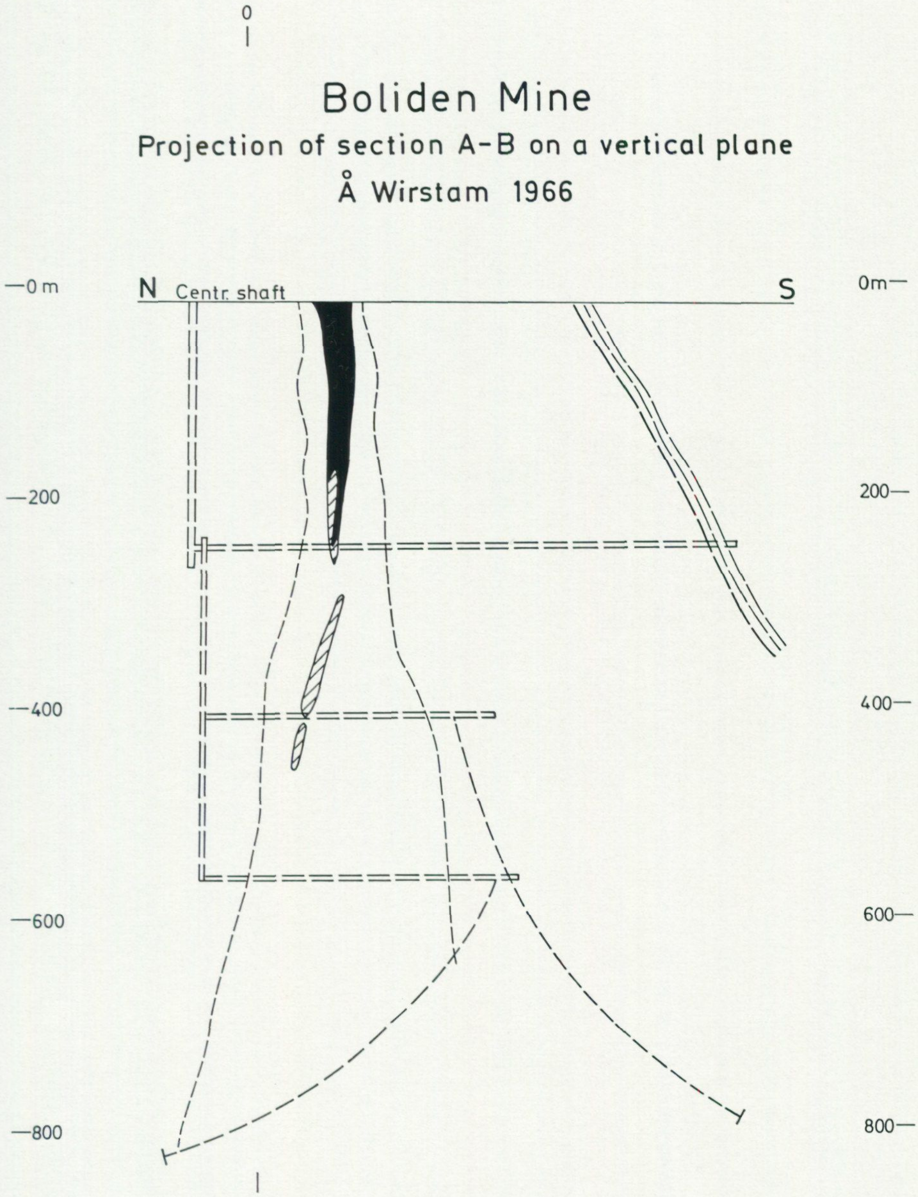

0
Boliden Mine
Projection of section A-B on a vertical plane
Å Wirstam 1966
—0 m
N
Centr. shaft
S
0m—
—200
200—
—400
400—
—600
600—
—800
800—

Fig. 7

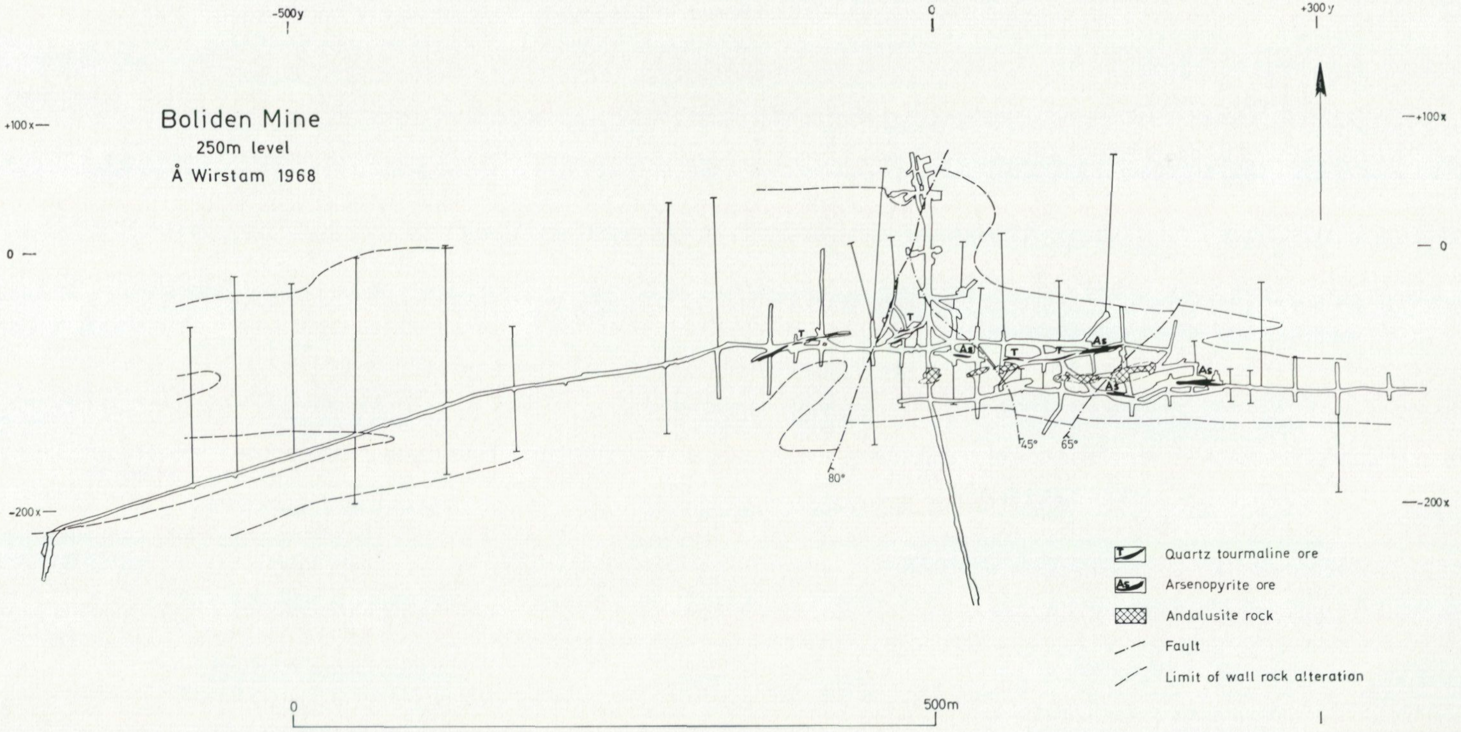

Boliden Mine
250m level
Å Wirstam 1968
-500y
0
+300 y
+100x
0
-200x
+100x
0
-200x
T
As
80°
45°
65°
Quartz tourmaline ore
Arsenopyrite ore
Andalusite rock
Fault
Limit of wall rock alteration
0
500m

Fig. 8

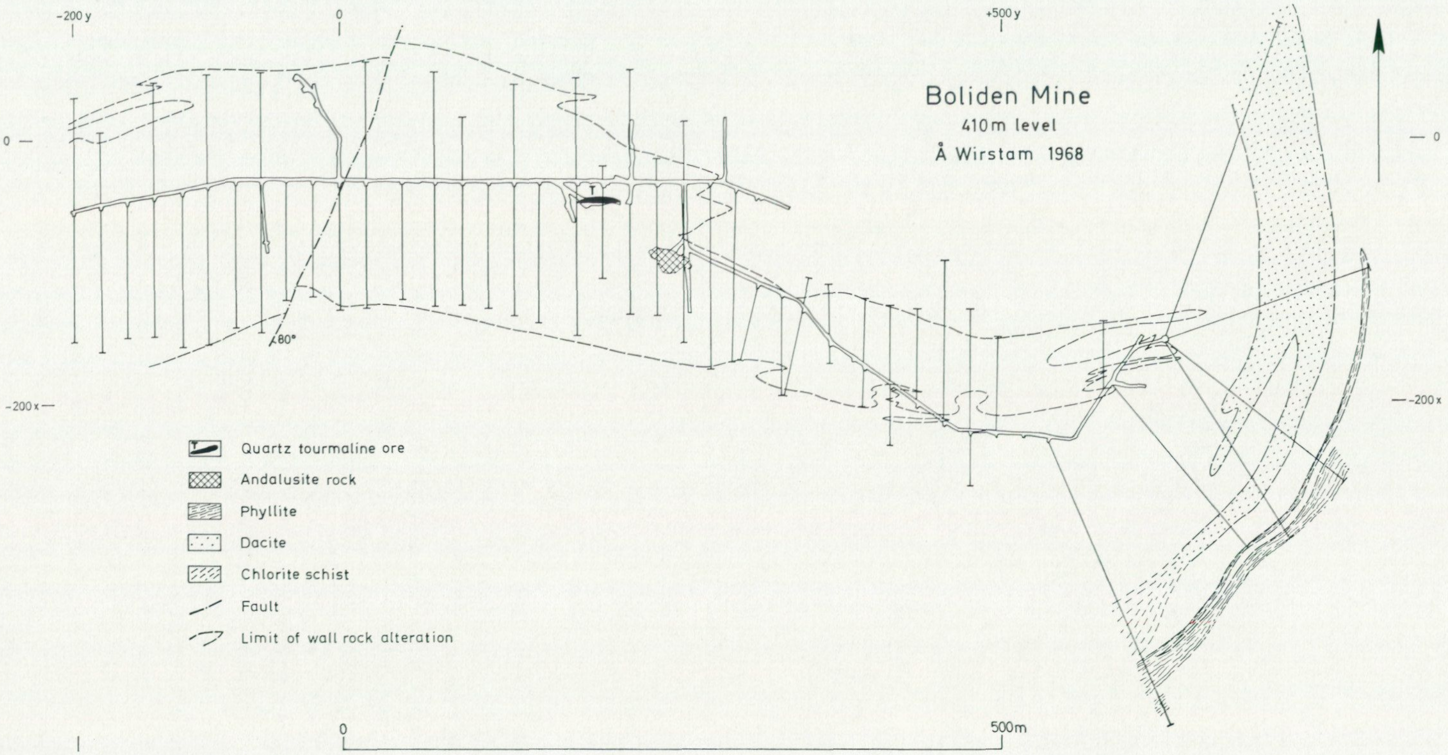

Boliden Mine
410m level
Å Wirstam 1968
-200 y
0
+500 y
0
-200 x
0
-200 x
80°
Quartz tourmaline ore
Andalusite rock
Phyllite
Dacite
Chlorite schist
Fault
Limit of wall rock alteration
0
500m

Fig. 9

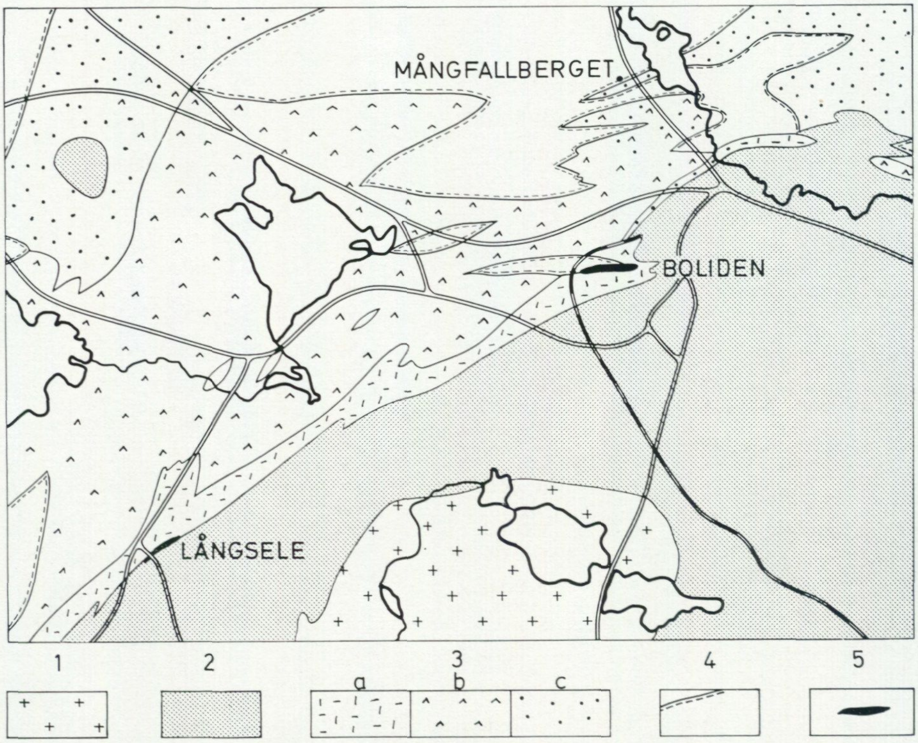


Fig. 10. Geologic map of the Boliden area. Scale 1:75 000. E. Grip, 1969.
1. Revsund granite. 2. Phyllite series. 3 Boundary series with a) quartz keratophyre, b) dacite and c) miscellaneous sedimentary rocks. 4. Oldest volcanics, mostly rhyolitic, with upper unconformity. 5. Sulphide ore deposit.

veins and some bodies of andalusite-sericite rock. In addition, a detailed picture of the entire alteration zone around the deposit down to 570 m level and even deeper was obtained. Figures 5–9 show the extension of all the detailed exploration work carried out around the Boliden ore bodies.

Additional information about the alteration zone was provided in 1953 by 500 m long drifts driven at the 90 and 250 m levels to the new central dressing plant.

Outside the alteration zone, the contact zone between the volcanic rocks and the overlying phyllite series has attracted interest. This has resulted in some additional drift constructions and drilling, both along the strike of the ore body and perpendicular to it.

As a last step before closing down the mine, one more deep test-hole was drilled from the 410 m level, in the eastern part of the alteration area. The hole reached a little more than 800 m down and gave a completely negative result. With this work, all prospecting and exploration work in the Boliden Mine and its nearest surroundings was completed.

The mean water flow in the mine during its last eight years has been 400 liters per minute. At the end of 1967, the pumps at the mine were removed. Since then the water level has risen and now reached the bottom of the open pit. In a couple of years the pit will be completely filled. Exposures around the edge will be the only parts of the mine visible.

3. GEOLOGICAL SETTING

The Boliden Deposit is situated in what is known as the Skellefte District. It is the easternmost of all the economic sulphide deposits known there. Stratigraphically the mineralization appears in the boundary zone between a volcanic rock series and a sedimentary or phyllite series unconformly overlying it. Tectonically, two ore bodies are controlled by a dragfold that is part of an unsymmetrical dome structure. In the centre of the dragford and the dome, a vertical shear zone forms the controlling structure. The shear zone widens downwards. It has provided channels for solutions which first altered the acid and intermediate bedrock and then deposited the ores. Three different stages of ore mineralization have been distinguished:

1. Arsenopyrite ore forming several ore bodies.
2. Quartz-tourmaline and lamprophyre veins with gold forming long zones subparallel to the dominant schistosity striking about E–W and dipping vertically on the average.
3. Pyrite ore with chalcopyrite forming two large bodies around the earlier mineralization partly replacing the bedrock and brecciating the earlier mineralization.

Originally the two ore bodies lay en echelon. But later they were brought together by a fault which caused the ends of the lenses to overlap.

The total length of the two ore bodies was 600 m. They were up to 40 m thick. The ore lenses dipped vertically and plunged about 55°E. The solid ore peatered out at the 270 m level; however, the gold – quartz veins get deeper. The area of the ore bodies at the surfac was 10,580 m^2. In all, 8,341,550 tons of sulphid ore were mined, containing 15.2 g/t Au, 49 g/t Ag, 1.42 % Cu, 25.1 % S and 6.91 % As. In addition to this, 61,844 t andalusite ore, containing about 50 % $Al_2 0_3$, were removed.

4. GEOLOGICAL MAPPING

In the early phase of the mining activity at Boliden, only a general geological survey of the mine was made. This was sufficient for the official map at a scale of 1:800. At that time, geological and topographical mapping were done simultaneously by the surveyor. In 1935, the method of mining was changed from shrinkage stoping and sublevel caving to cut and fill. At the same time, differentiated mining of several ore types was introduced. For this work more detailed geological mapping was needed. The first step was mapping the boundaries between the different ores distinguished in the mining. The types recognized were arsenopyrite ore, arsenopyrite ore with pyrite and chalcopyrite (for direct smelting), pyrite ore (for copper-pyrite separation) and disseminated ore of different kinds. The new mapping and studies of the deposit were to provide as complete a geological and mineralogical picture as possible.

Professor Per Geijer, consulting geologist for the mine at that time, outlined the principles by which the investigation would result in the best geological and mineralogical description of the deposit. He also recommended that a special mining geologist should be given the responsibility of carrying out the work. This recommendation was followed, with the result that Dr. Olof H. Ödman received the commission. Earlier, geological work in Swedish mines had been done by surveyors or consulting geologists. Boliden was the first mine in Sweden to employ a mining geologist of its own. The following is a brief description of how the special geological mapping methods developed at Boliden were employed in practice.

As soon as possible after blasting new exposures in the mine, the roof and the walls of the drifts or the stopes were washed. The surveyor made the topographic map and from him the geologist obtained an enlargement at a scale of 1:200. Using this map as a base, the geologist mapped the roofs and, where necessary the walls. The stopes were mapped for every slice. Boundaries between different ore types were marked with chalk on the roofs and the walls to facilitate the differentiated mining. All diamond drill cores were mapped in the same way as the exposures in the mine. Later, all the geological data were combined on 1:200 scale maps. Connections between adjacent stopes, drifts and drill holes were made both for horisontal and vertical sections. In connection with the mapping, a careful geological examination of the bedrock and the mineralization was made in the mine. This work was then followed up in the laboratory.

With some local modifications the geological mapping technique developed at Boliden has been applied to all the other mines of the Boliden Company (Grip and Ödman 1944).

5. SURVEYING AND SAMPLING

The first sampling of the ore underground was done in cross-cuts driven through the ore zone every 40 m.

In the early days, diamond drilling only was used on a small scale. Systematic studies using drilling were first begun after the extension of the ore bodies was already known. The method was mainly used in exploring their immediate surroundings.

After the one million cubic metres of overburden had been stripped and open pit mining had started, trenches crossing the ore every 40 m were made and sampled.

About 1931, when gold was found in the wall-rock surrounding the ore, a systematic and very detailed sampling of all drifts within the alteration area was carried out. Using a pneumatic chisel, channel samples were taken from the walls or the roof of the drift. Usually, sample channels in cross-cuts were taken along both the walls and in drifts, following the direction of strike along cross lines in the roof 2–5 m apart. The loose material was collected using rubber sheet on the floor.

In 1935 ”sludge sampling” was introduced, especially for control of the gold content in the walls of the gold ore stopes. These drillings, carried out with a common drilling machine, were cheap and rapid. In the beginning they only penetrated 4.8 m. By using steel extensions later on, the sludge sampling holes could reach 20 m in length.

After that sludge sampling was used on a rather large scale during the entire lifetime of the mine. During later years, however, light weight diamond drilling machines became available. Diamond drilling then more and more replaced the sludge sampling method.

During the last years the mine was in operation an increasing proportion of the ore production came from gold bearing quartz-tourmaline veins and sericite schist. Almost daily, the mining geologist had to set the cut off limits in the stopes. Chip sampling was used for this purpose. This was a simple method, but a careful surveyor could get very satisfactory results.

Many calculations of the ore reserves of the Boliden Deposit have been made. For the most part, they have been based on the analysis of samples from surface drill holes and trenches, and from cross-cuts. In some cases large stope samples have been taken out.

6. CALCULATIONS OF ORE RESERVES

The first calculation of the Boliden ore reserves is found in the annual report of the exploration of the deposit in 1925. It was made by general manager Eric Wesslau. The calculation was based on 11 drill holes cutting the upper part of the ore body. The result showed 43.000 tons of ore per vertical metre, containing 9.1 g/t Au, 41 g/t Ag, 2.09 % Cu, 6.09 % As and 36.0 % S. The calculation applied to the interval from the surface to about 30 m down, a total of about 1 mill. tons.

Twelve complete calculations of the ore reserves for the entire deposit have been made by geologists working for the Boliden Company or as outside consultants. In addition, a large number of calculations covering only gold and silver have been done. Especially important were the ore reserve calculations ordered by the owner of the company in 1931–32, Ivar Kreuger. These were carried out by the English expert, E. C. Bloomfield and by R. Marsch Jr., R. M. Overbeek and C. G. Bowers from the American firm Guggenheim Brothers. Another important estimate was ordered few years later, after the Kreuger bankruptcy, by the Swedish Government and the receivers. This was done by G. Malm, A. Gavelin and C. I. Asplund (30.4.32) resp. by S. Nauckhoff, P. Geijer, G. Malm and U. Forsberg (1.1.33). The first of these last two resulted in 6.03 mill. tons with 20.4 g/t Au, the other in 6.78 mill. tons with 18.9 g/t Au.

As early as 1935, the total original ore reserves were calculated to be 7.5 mill. tons. The final figure did not differ greatly from this estimate. It was found to be 8.34 mill. tons.

During the thirties gold was the most valuable element of the Boliden ore. The distribution of this metal in the deposit was subjected to many investigations, as this knowledge was important for planning annual production programs. The mining superintendent of that time, Håkan Abenius, argued that the gold values estimated in the remaining ore were too high. He was also the first to stress the fact that dilution should be included in the ore reserve calculations. Its effect in lowering the ore percentages must be taken into consideration.

By consistently following the values of the underground sampling and reducing the metal percentages by 10 %, with respect to dilution, Abenius calculated the gold reserves to be much lower than estimated by other experts.

As far as can be calculated now, the much debated average gold content was very near the figure stated by Abenius. All of the other metal reserves calculated in the middle of the thirties are in very good agreement with the amounts extracted from the deposit.

As a result of this experience, from the end of the thirties all the ore reserve calculations made by Boliden took the wall rock dilution of the ore into consideration. The percentages of the wall rock dilution, however, varied from one deposit to another, and also often within one and the same deposit.

The methods used in determining the ore reserve were described in detail in all calculations of the reserves in 1935. Among other things, it is mentioned there that variations in the specific gravity was taken into consideration by the calculation of the average percentage in the drifts, a rule not always followed in other ore calculations.

For the calculations made in 1935, a cut-off grade of 6 g/t Au was fixed for the disseminated ore. Sericite schist containing less gold, called ”gold bearing schist”, also was included in most of the ore reserve calculations. The cut-off grade here was set at 2.5 g/t Au. Such low grade sericite schist was mined only periodically. The schist was not only mined for the gold it contained. The rock was also useful as a flux medium at the smelter. The tonnage of gold bearing schist was not very large, only about 5 % of the total ore reserve. This explains why a reduction of the gold cut-off grade in the Boliden deposit would not have led to a significant increase in the estimate of the total ore reserves.

In 1938, a card-index of the Boliden ore reserves was set up and annually kept up-to-date with respect to mining and new contributions. The deposit was divided in blocks. Vertically, most blocks were bounded by the head levels and horisontally by the 40 m section lines of the mine map. For each block tonnage and grade of "arsenic ore", "smelt ore", "pyrite concentration ore" and "disseminated ore" was given separately.

In 1955, a final plan was drawn up for the last stages of mining out the deposit. Before that, however, all available analyses and other data were reviewed one more time and a more detailed description of each part of the mine prepared. For this final calculation, the detailed maps of the stopes at a scale of 1:200 were used. Remaining ore in the pillars could be calculated level by level and subdivided into the different ore types. The detailed geological maps and the control sampling carried out during the survey were also of a very great value in other parts of the mine. The primary card-index was revised and then used until the mine was closed.

Emphasis in the preceding discussion has been placed on reserve calculations and sampling. This is an aspect of the mining activity that often is neglected in descriptions such as this, in spite of its great importance. The methods and procedures developed at the Boliden mine have been adopted as patterns for many other sulphide mines owned by the Boliden Company, especially those mines in the Skellefte District.

7. GEOCHEMISTRY AND DESCRIPTION OF SOME IMPORTANT MINERALS AND ROCKS

The chemical composition of the ore and the wall rock has been studied in detail as well as on a larger scale. A large number of analyses were published by Ödman (1941). There, he also discussed the chemistry of the ore and the ore solutions. Since that time, many additional working and average analyses have been made, and the geochemistry of the altered rocks has been subjected to a close investigation.

7.1. THE GEOCHEMISTRY OF THE ORE

The average composition of the Boliden ore now can be calculated with a relatively high grade of accuracy. Most exact are the percentages of the elements Au, Ag, Cu, As and S. These were continuously determined in the ore throughout the productive lifetime of the mine. Other elements only have been determined in annual samples of different kinds of ore delivered to the smelter or the dressing plant. Complete analyses of all annual samples are not available; but, the quantity of ore represented by the analysed annual samples is as much as 2/3 of the total quantity of ore mined. The annual sample analyses may be considered to be quite representative for the entire deposit.

From the analyses of the annual samples, the average composition of every ore type has been calculated. Then, the analyses have been weighted against the quantities of the different ore types mined. The average composition calculated for the Boliden Deposit, including ore of all the different ore formation stages, is given in Table 1.

Ores of the three separate ore formation stages are calculated to constitute the following weight percentages of the whole Boliden deposit:

Arsenopyrite stage	23 %
Quartz-tourmaline stage	5 %
Pyrite stage	72 %

In 1941, some additional element (i. e. B, Cd, Ba, Sr) were analysed in every ore type. Calculated to represent an average for the Boliden Deposit, these analyses also are given in Table 1. These figures are certainly not as exact as those calculated for the other elements based on a larger number of analyses. However, they do indicate the order of magnitude for the elements in ques-

Table 1. The average composition of the Boliden ore as calculated from annual samples

SiO_2	24.0 %	Au	15.5 g/t
Al_2O_3	6.5	Ag	50
MgO	0.8	Cu	1.43 %
CaO	1.4	Fe total	27.0
Na_2O	0.5	Co	0.11
K_2O	1.1	Ni	0.04
BaO	0.01	Zn	0.92
SrO	0.005	Cd	0.00
TiO_2	0.4	Hg	0.001
MnO	0.01	Sn	0.006
P_2O_5	0.2	Pb	0.27
CO_2	0.6	Bi	0.04
F	0.04	Sb	0.08
B	0.04	As	6.83
		B	0.04
		Te	0.003
		Se	0.06
		S	25.0

tion. – The boron percentage is highest in the disseminated ore (0.10 % B), where it is derived from tourmaline in the quartz veins.

Table 2. Average composition of the Boliden ore as related to the total average of the ores of the Skellefte District

	Au g/t	Ag	Cu %	Zn	Pb	As	S
Boliden	15.5	50	1.4	0.9	0.3	6.8	25
Skellefte District	1.6	42	0.8	2.4	0.3	0.9	30
$\frac{\text{Boliden}}{\text{Skellefte District}}$	9.7	1.2	1.8	0.4	1.0	7.6	0.8

Table 2 shows, in round figures, the percentages of the most important elements of the Boliden ore, the average composition of all the ores of the Skellefte District in a surface cut weighted according to their respective areas, and finally the relationship between the percentages of respective elements at Boliden and in the District as a whole.

The contents of Ag, Pb and S at Boliden are about the same as the average for the Skellefte District. Copper is considerably higher than this average and Zn lower. The most striking divergences, however, are As being 7.6 times greater than the normal value and Au being 9.7 times higher.

Gavelin et al. 1960 made an investigation on "Sulfur isotope fractionation in sulfide mineralization". Also eight samples from Boliden were represented there covering all the three ore formation stages. The range of variation of the eight S^{32}: S^{34}-values was very small and no difference between sulphur from the various stages of mineralization could be discerned. Consequently it could be stated that no significant sulphur isotope fractionation occurred during the ore formation process in Boliden.

During the time the Boliden Mine was in operation, and particularly during World War II, several new minerals and rocks suddenly drew current interest. Special investigations were then carried out as to their modes of occurrence in the deposit and the prospects for their recovering. Such surveys commonly were presented as company reports or published papers. The following is a summary of special studies made on minerals belonging to the ore paragenesis.

7.1.1. ARSENIC

A high arsenic content was shown from the first drill hole proving ore in the Boliden Deposit. Further drilling showed the deposit to be unusually rich in arsenic. Analyses indicated that gold was bound to dense arsenopyrite to a high degree. It was several years though before visible gold was proved, first under the microscope, and then with the naked eye. By that time, suitable metallurgical methods hade been developed for practical, and complete, recovery of the gold, while at the some time recovering the arsenic.

Boliden soon proved to be the largest arsenic deposit in the world. We now know that its entire arsenic content was 566,000 tons. For the most part, the arsenic was bound to bodies of compact dense arsenopyrite formed during the first ore formation stage. The arsenopyrite ore rich in gold was mined separately for a long time. There were never any difficulties in determining where the boundaries to the wall-rock or to other ore zones lay. These could be followed exactly and marked on the roofs of the stopes.

The dense, steel-like arsenopyrite, which was very aboundant in the ”a-d-lens”, was of a very rare type characteristic for Boliden. Its chemical composition is given in Table 3, col. A.

Table 3. Chemical composition of the Boliden arsenopyrite ore

	A	B
SiO_2	0.30	17.8
Al_2O_3		3.63
MgO		0.63
CaO		1.17
Na_2O		0.16
K_2O		0.52
TiO_2	0.03	0.53
P_2O_5		0.39
CO_2		0.16
Au	0.0028	0.0051
Ag	0.0118	0.0085
Cu	0.06	1.22
Fe total	33.76	28.4
Co	0.15	0.30
Ni	0.00	0.040
Zn	0.00	0.36
Pb	0.27	0.40
Bi	0.13	0.09
Sb	0.33	0.10
As	44.99	20.9
Te	0.00	0.01
Se	0.28	0.15
S	19.67	19.9
	99.98	96.86

A. Dense arsenopyrite ore.

B. Normal arsenopyrite ore. Weighted average of the 323,844 t arsenopyrite ore mined during 1933–1943.

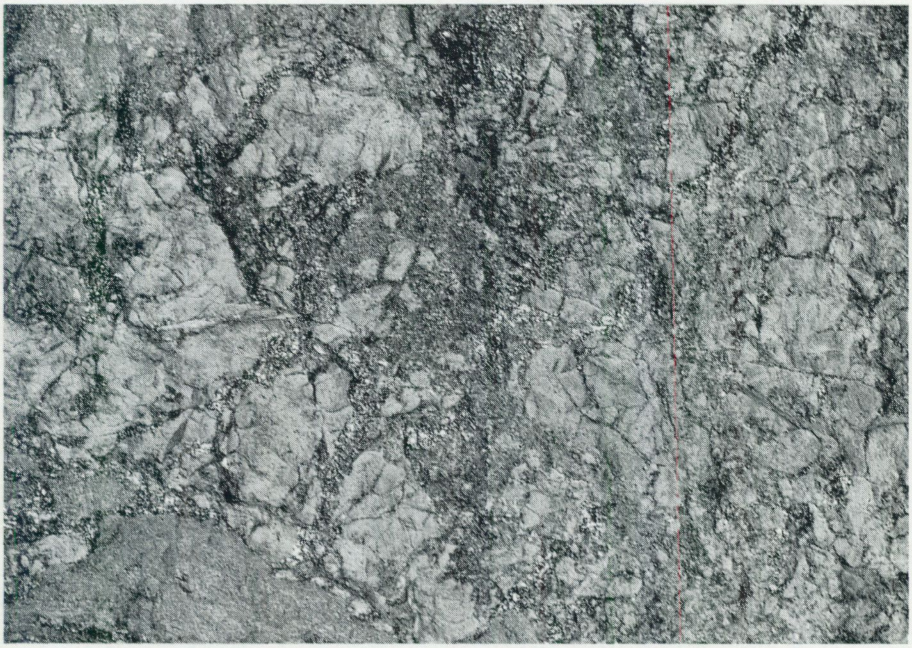


Fig. 11. Dense arsenopyrite ore brecciated by pyrite and pyrrhotite, both belonging to the pyrite ore formation stage. This type of ore was mined as "Smelt ore" and sent directly to the smelter. Scale 2:3.

The arsenopyrite, however, often was brecciated. Every transitional form, from very fine cracks to fractures cemented by other ore minerals, was found in the arsenopyrite ore (Fig. 11). The finely fractured arsenopyrite is interesting from the ore formation point of view because the cracks seem to represent shrinking structures formed when the ore solution lost its content of volatiles during solidification. Because of these primary cracks, the following brecciation must have been rather easy. (Chemical composition, see Table 3, col. B.)

The deepest arsenopyrite ore lenses petered out at the 270 m level. However, arsenopyrite stringers following the shear-planes of the sericite schist could be traced a little deeper. In the direction of strike, the arsenopyrite was even more strictly confined to the lenses.

The arsenic in the mine never have caused any health problems. The sulphides in which it is bound are dissolved with difficulty, preventing arsenic from being taken up by the human body. One observation on the risks for arsenic poisoning, however, may be mentioned. In the cross-cut below the arsenic ore at the 250 m level, there was a roof construction of logs. On the logs lying in contact with the arsenopyrite ore there developed considerable mould. In that part of the cross-cut there was a strong smell of hydroarsenic. Evidently, the arsenopyrite was affected by mouldering wood, which resulted in the formation of hydroarsenic. As the area in question was well ventilated, there never was any health risk. If a similar situation had arisen in a poorly ventilated part of the mine, however, there might have been a risk for arsenic poisoning.

The world production of arsenic in 1967 divided among producing countries is given in Table 4.

Table 4. West world production of arsenic in 1967

Sweden	20.000	tons As_2O_3
France	14.000	
Mexico	8.000	
U S A	6.000	
Belgium	4.000	
Southwest Africa	2.000	
Other countres	2.000	
West World	56.000	

From Table 4 it can be seen that Sweden was the foremost producer of arsenic in the world, with a third of the entire free-world production. Sweden has maintained this position for many years.

Most of the arsenic came from the Boliden Mine but during the last years more and more arsenic has accompanied ore from other deposits especially in the Skellefte District.

A list of the most important usages of arsenic and its compounds is given in Table 5, together with the relative amounts consumed by each.

Table 5. Commercial arsenic compounds, their use and percentage of the world consumtion

As-compounds	Use	%
As_2O_3	Glass goods	22
Na-arsenite	Weed killing	31
As-Cr-Cu-Zn-compounds	Wood impregnation	9
Pb-Ca arsenate	Insecticide etc.	9
As_2O_5	Leaf killing etc.	9
Organic As-compounds	Weed killing, food additive etc.	13
As-metal	Alloys	2
Various		5

In order to establish markets for all the arsenic being produced, already from the start of mining operations the Boliden Company began a special research and development program. Especially wood impregnation offered new markets for the arsenic compounds. The new Boliden method of wood impregnation for many purposes proved to be superior to other ones. Today this technique is used all over the world.

7.1.2. GOLD

As eraly as 1924, chemical analyses of core samples show that high gold values were associated with the arsenopyrite mineralization. A similar relationship had been found in the small Holmtjärn deposit a year earlier. For several years, the gold was thought to be submicroscopic. It was not until 1930, that visable gold was found in the Boliden ore. Mining Engineer Sture Mörtsell, later professor at the Technical University in Stockholm, made the discovery. During a microscope examination of polished sections at 300× magnifacation, he found gold grains up to 0.02 mm in size dispersed in the dense arsenopyrite (Mörtsell, 1932). Later, microscopic solid gold was found in other types of ore. It was only two years, though, before gold visible for the naked eye was found. The first discovery of such gold in the mine was made in 1932. The gold occurred in a quartz-tourmaline vein at the 210 m level (189 y, 97 x). After that, solid gold, more or less coarsely foliaceous, was found in the quartz-tourmaline veins at the deeper levels in the mine. Sometimes the gold there formed real "bonanzas".

Table 6. Chemical composition of native gold in quartz (A) and sericite schist (B). Stope 26, 250 m level

	Au %	Ag %	Hg %
A	67.11	21.15	1.2
B	68.95	23.93	1.0

The gold in the Boliden Mine never was quite pure, but to varying degrees always amalgamated with silver and mercury (cf. Table 6). The highest mercury content found in the Boliden gold was 3.5 %, the highest silver content about 24 %. Some of the richest gold concentrations are described below. Partial accounts of them have already been given by Ödman (1941). Now, further details can be presented.

"The Gold Rise Ore"

The ore in Stope 26, just W of the cross-section through the Central Shaft (cf. Ödman 1941, p. 133) contained a group of gold-bearing quartz-tourmaline veins parallel to one another. The veins were situated just north of the west end of the Eastern Ore. They followed the dominant schistosity in that area. At the 250 m level the veins were controlled by the old land surface and had a strike of about N 60°E. Higher up, the strike was more E–W. Because of its proximity to the major fault, the area was traversed by several small faults and fissures. The gold-bearing portions lay between the 170 m and 270 m levels. They were near to the goldrich scheelite-bearing part of the Eastern Ore (see p. 34) but separated from it by a few metres of barren rock. Practically always the gold was associated with sulphominerals, for the most part selenokobbelite. In addition, the Pb-Cu-Sb-sulphide mineral menighinite, new for Boliden, was found here as well as native antimony (Isaksson 1969). The wall rock of the veins consisted of sericite- and sericite-chlorite schist containing small schlieren of sericite rock which were usually intensly deformed. The gold often occurred up to several decimeters outside the quartz-tourmaline veins themselves, as thin gold leaves along schistosity planes.

The average gold value in ore from the stope was calculated to be about 50 g/t. The gold, however, was very unevenly distributed. Usually, it seemed to have been selectively concentrated to certain parts of th veins. Between the 210 and 270 m levels no unusually rich gold concentrations were detected. Between the 170 and 210 m levels on the other hand, there was a very rich portion at the west end of the gold ore, plunging 40°E. Another gold concentration was found at the eastern end of Stope 26, where a very strong mineralization with sulphominerals and gold had taken place along the slickensides of a small, steeply dipping fault plane running N–S. Here, several channel samples, each one metre long, contained about 300 g/t Au and 200–500 g/t Ag. The highest gold content in Stope 26, however, was found at the 245 m level, where a one-metre sample produced 620 g/t Au and 630 g/t Ag.

"The Big Quartz-Tourmaline Vein"

A continuous vein up to 7 m thick containing quartz, tourmaline, sulphominerals and gold was mined for distances of 10–40 m in stopes 64, 65 B and 65 C, about 150 m E of the cross-section through the Central Shaft. Mining of the vein had not been started at the time of Ödman's description, although at the 330 and 410 m levels the quartz-tourmaline ore already had been exposed. Ödman briefly mentioned the vein in his paper and drew a sketch map to show its extention.

"The big quartz-tourmaline vein" is situated about 200 m E of "the Gold Rise Ore", the prolongation of which is located 30–50 m N of the present vein. The mineralized portion was only a smaller part of the long quartz-tourmaline vein. In its upper part, between the 300–400 m levels, the vein plunged about 55°E, while between the 400–460 m levels it stood approximately vertical. The vein dipped steeply to the N. It consisted of a network of small quartz veins and quartz schlieren, which for the most part were aligned in two directions, one parallel to the direction of the big vein and the other one perpendicular to it (see Figs. 12–13). The gold was fairly evenly distributed, at least below the 330 m level, the gold percentage was about 15 g/t. The gold, however, only seldom was visible with the naked eye. As a rarity, native silver was observed in a drill-hole cutting the main vein at the 370 m level. In the same section a Pb-Bi-telluride was noted.

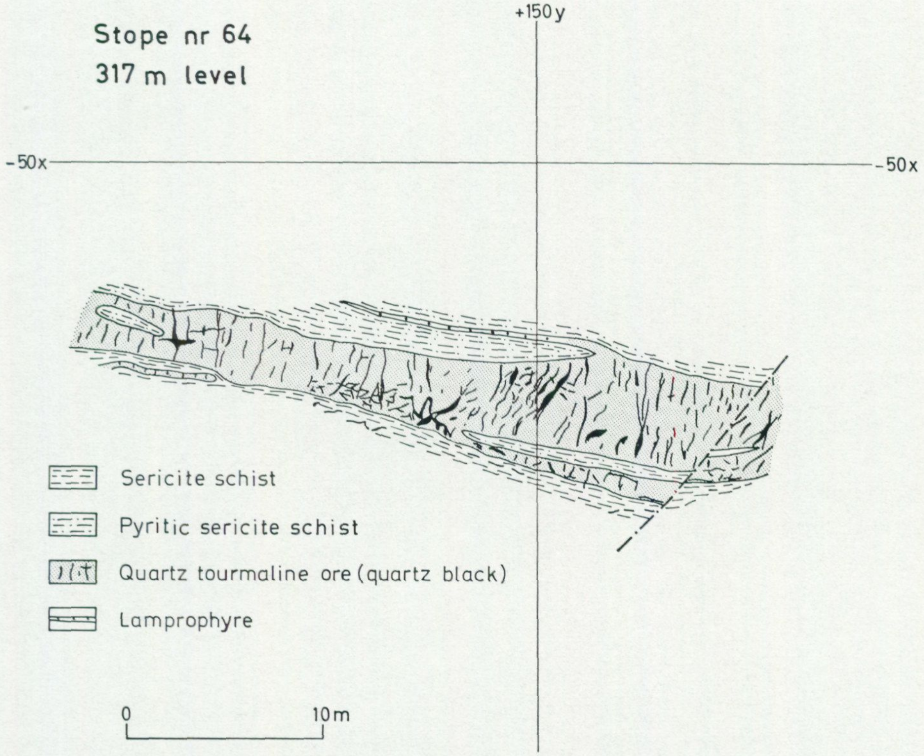


Fig. 12. Stope 64 which was mined for quartz-tourmaline ore rich in gold. In general, this type of ore showed very complicated structures with a tourmaline mass interwoven by a great many short quartz veins and the lamprophyre lying more or less isolated.

Above the 330 m level the solid gold was coarser grained, and for that reason often visible. At the same time, it was more unevenly distributed. A large stope-sample from the vein at the 330 m level gave 32 g/t Au and 470 g/t Ag.

The richest gold concentration above the 330 m level, however, occurred in a small parallel lens, a few metres long and some decimetres wide, immediately beneath the principal vein between the 295 and 310 levels. Values up to 300 g/t Au were found here in chisel samples. The gold was accompanied by sulpho-minerals very low in antimony. Among other such minerals selenolillianite, new for Boliden, was found here (Isaksson 1969).

The root-zone of the Eastern Ore

The root-zone of the Eastern Ore below Stope 27, where high gold values also appeared, was mined in Stope 27 B just E of the cross-section through the Cen-

Fig. 13. Photo of the quartz-tourmaline vein in Stope 64, S-side of the roof, cf. fig. 12. Scale about 1:20.

tral Shaft. The gold here was associated with rutile and tellurobismuthite, while quartz-tourmaline veins were lacking. To the paragenesis also belong tetradymite and joseite A (Isaksson 1969), the latter being new for Boliden. Native gold, often as plates up to several cm in size, was found in small fissures, especially in lenses rich in rutile.

The richest gold concentrations occurred in the lowest part of the section between the 255 and 270 m levels. Here, a drill hole section 210 cm wide gave 230 g/t Au, while as is common in this type of ore the content of silver was low. On the average, stope 27 B between the 250 and 270 m levels was calculated to contain 25 g/t Au but only 12 g/t Ag.

This type of ore with gold associated with rutile and tellurobismutite was found at several places in the Boliden Mine, e. g. in Stopes 30 (–95 x, 190 y, 223 m level), 46 C (–90 x, 20 y, 240 m) and 61 (–108 x, 70 y, 232 m). A common feature for all these localities was their situation in the root-zones of the arsenopyrite ore lenses, or in offshoots from these lenses.

7.1.3. PYRITE

Pyrite was the predominating ore mineral in Boliden. It constituted about 35 % of the whole deposit equal to 2.9 million tons. Consequently the pyrite filled a large place in the mining production programs.

Pyrite was found in all the three ore formation stages but only in the third stage did it occur in large quantities. There the pyrite was extremely predominating among the ore minerals. Although the content of arsenic in the pure pyrite ore of the third stage was rather insignificant, arsenopyrite as phenocrysts was the first ore mineral to have crystallized there. It was then followed by the predominating pyrite which had a grain size of about 0.3 mm or sometimes up to 1 mm. Occasionally the pyrite grains were euhedral but mostly they lacked crystal form. Small amounts of a number of other sulphide minerals were later crystallized in the pyrite ore. Among them especially chalcopyrite was of economic importance.

As mentioned before (p. 21) an investigation by Gavelin et al. (1960) of the sulphur isotopes in the sulphide minerals from various deposits also comprised Boliden minerals. In their paper they report the third stage pyrite to have the isotope ratio $S^{32} : S^{34} = 22.24$ being quite similar to the isotope ratio of several other sulphides in Boliden.

During the first years of exploitation only arsenopyrite ore was mined and sent directly to the smelter. When also other types of ore were entered into the mining program a flotation plant was constructed close to the smelter at Rönnskär. There especially ore of the pyrite stage was treated, the pyrite concentrate then being the largest product by tonnage.

In 1954 a new central dressing plant at Boliden was ready to take care of all the ore from the mines in the eastern part of the Skellefte District, and from that time also the Boliden ore was treated here. The Boliden pyrite concentrate then produced contained about 52 % S and consisted of about 93 % pyrite, 5 % pyrrhotite and other sulphides, and 2 % gangue minerals.

7.1.4. COPPER

The percentage of copper in the Boliden ore, 1,43 % Cu, was nearly double the average grade for the Skellefte District. The predominate copper mineral was chalcopyrite, which appeared in all three ore formation stages. In particular, the arsenopyrite ore was rich in copper. But partly copper was enriched during the later stages of ore mineralization. The pyrite ore was a little lower in copper; but because of the large quantities of this ore type the biggest amount of copper occurred there.

The mode of occurrence of copper in the Boliden Mine was well documentated by Ödman (1941). No additional observations of any importance have been made since then.

The economic value of the copper in the Boliden ore, ca 120,000 ton, has been greater than that of the gold.

7.1.5. ZINC

The percentage of zinc in the Boliden ore was 0.9 %. This was about one third of the average grade for the Skellefte District. Sphalerite was the only zinc mineral found. It is of interest, however, because of the relatively high content of mercury it exhibited. Analyses showed that the mercury content varied greatly; the proportion Zn : Hg ranged from 350 to 10,560. The largest amount of zinc was found in the pyrite ore where the sphalerite formed disseminations and small schlieren. But the mineral also was associated with the two other mineralization stages.

Although efforts to recover zinc from the ore have been made, production never was realized. A notable fact was that chlorite within the alteration zone contained up to 0.1 % Zn.

7.1.6. LEAD

On the average, the Boliden ore contained 0.27 % Pb. This was only a very little less than the average for the District. Lead entered into at least 12 different ore minerals and was associated with all three ore formation stages (cf. Table 11). The disseminated ore, however, had a grade of lead considerable lower than the massive ore.

The isotopic relations in galena probably belonging to the third stage of ore formation have been determined by the lead tetramethyl method and described by Wickman et al. (1963). The isotope ratios ($Pb^{204} = 1$) and model ages according to Houterman (H), Russell-Farquhar-Cumming (RFC) and Russell-Stanton-Farquhar (RSF) are presented in Table 7.

Table 7. Isotope ratios and model age of galena

206	207	208	$\frac{207}{206}$	$\frac{208}{206}$
15.24	15.14	35.12	0.993	2.304

Model age in 10^6 years:

H		2010
RFC	206:204	1820
	208:204	1870
RSF	t_{6-7}	1950
	t_{8-4}	2000

The model age from this single galena sample tolerably corresponds to the Revsundgranite, 1,790 million years, found by Welin 1969.

A new lead mineral was identified from the Boliden Mine. It was named falkmanite in honour of the president of the Boliden Company at that time, Mr Oscar Falkman. The mineral, which had the composition $Pb_3Sb_2S_6$, was investigated and described by Ramdohr and Ödman (1939).

7.1.7. ANTIMONY

Antimony was rather evenly distributed in the different types of solid ore. Analyses usually showed a little less than 0.1 % Sb. The disseminated ore on the other hand had only about half as much. Antimony entered into at least ten different minerals, several of which were complex. These complex antimony minerals tended to be associated with the quartz-tourmaline ore (cf. Table 11).

7.1.8. COBALT

The Boliden ore contained a small amount of cobalt. In 1940 the question arose of whether or not it was possible to recover cobalt from the ore. As a first step, a special survey was made of the mode of occurrence of the metal in the mine.

The study showed that cobalt was present in the minerals cobaltite and safflorite. Safflorite, however, was quantitatively of no importance. In the arsenopyrite ore up to 2.5 % Co was found, in spite of the fact that no cobalt mineral was visible, even under the microscope. The cobolt was supposed to have entered into the arsenopyrite lattice, replacing iron. Also the quartz-tourmaline ore sometimes contained a considerable amount of cobalt here bound to cobaltite.

From a mining and dressing point of view it was possible to distinguish two types of cobalt ore; massive cobalt-bearing arsenopyrite ore with or without cobaltite, and disseminated cobalt ore consisting of schlieren and lenses of fine-grained cobaltite in sericite schist often together with rutile and apatite. Both ore types were gold-bearing, especially the disseminated ore.

The massive, cobalt-bearing arsenopyrite ore appeared in the arsenopyrite lenses. High cobalt percentages were especially common along the margins and in the roots of the lenses, for example in the bottom portion of the a–d lens. The disseminated cobalt ore occurred chiefly between the 270–170 m levels, particularly in Stopes 23, 25 and 28.

After detailed dressing and smelting experiments, recovery of cobalt was begun at Rönnskär and continued for some years. Cobalt recovery then was discontinued in September, 1944, because it was not profitable.

From 1941 until 1945 about 26,000 tons of cobalt smelt ore were mined. The ore analyses showed the following percentages: 42 g/t Au, 110 g/t Ag, 1.1 % Cu, 20 % As, 22 % S and 0.6 % Co.

7.1.9. MERCURY

At the smelting works at Rönnskär in 1940 the Boliden ore was found to contain some mercury. This discovery led to a detailed investigation of the mode of occurrence of the mercury in the Boliden Deposit (Grip 1948). All minerals and ore types of any importance in the mine were analysed. This also included some rare minerals which could be expected to contain a significant percentage of mercury.

The highest mercury analysis, 3.5 % Hg, was found in native gold from Stope 12 at the 210 m level. Native gold from other parts of the mine showed about 1 % Hg. In addition, sulphominerals and sphalerite were high in mercury; but the percentage varied considerably from one place to another.

Pure arsenopyrite ore was shown to be very low in mercury, while the ore of the quartz- tourmaline stage gave a much higher percentage. The third ore formation stage, the pyrite ore, showed a mercury content intermediate between the first and second stages. The average percentage for the Boliden Deposit as a whole is calculated to have been 0.001 % Hg.

The mean mercury percentage in the different sulphide deposits of the Skellefte District ranges from a few grams per ton up to 0.025 % Hg. At the Långsele mine, only 5 km W of Boliden, the mean is 0.024 % Hg. This is one of the highest in the District, 24 times higher than that found at Boliden. Within each deposit or geological unit there, the ratio Zn : Hg appears to be rather constant. The Långsele ore is rich in zinc. There the ratio Zn : Hg is 156. The same ratio in the Boliden ore is 320, notwithstanding the much lower mean mercury percentage of this deposit.

7.1.10. SELENIUM AND TELLURIUM

Among all the ores of the Skellefte District the Boliden ore was the one richest in selenium, with the highest selenium concentrations found in the quartz-tourmaline ore. In this ore type the sulphominerals with selenium were essential constituents. In addition, there also occurred tellurides with considerable percentages of selenium as well as tellurium. The arsenopyrite ore was also rich in selenium, selenium bound to the arsenopyrite itself. The ore type in the Boliden Deposit poorest in selenium was the pyrite ore. There, selenium seems to have been bound to the pyrite.

Selenium percentages for the most important minerals in the Boliden Deposit are given in Table 8.

Table 8. The selenium content of the principal ore minerals in the Boliden Deposit

Pyrite	0.004–0.03 % Se
Chalcopyrite	0.07 –0.14
Sphalerite	0.03 –0.09
Arsenopyrite	0.04 –0.16
Pyrrhotite	0.002–0.007

The mean percentage of selenium in the Boliden ore was about 0.06 % and the radio Se : S = 0.0017.

Selenium, bismuth and antimony were usually associated and appeared in fixed proportions. Tellurium occurred chiefly in tellurobismuthite and tetradymite, minerals belonging to the quartz-tourmaline stage.

After the investigation described by Bergenfelt (1953), a complementary survey of the distribution of selenium in the Boliden Mine was made with the aim of finding out whether or not there were any selenium bearing portions in the wall rock of the ore proper. It was found, however, that no selenium percentages of interest occurred outside the boundaries of the ore. Sulphide disseminated portions of sericite schist with less than 4 g/t Au never showed selenium percentages high enough that the selenium justified changing the boundaries for mineable ore.

In the early forties, a few tons of tellurium-bismuth-minerals were picked out from the ore in Stope 28 (– 80 x, 50–150 y). Out of this portion tellurium was recovered at the smelter and used in the preparation of diphtheria serum.

For scientific purposes, an investigation of the double-beta decay of tellurium in tellurobismuthite from the 240 m level has been made at the Chicago University (Inghram-Reynolds 1950). At Max-Planck-Institut für Kernphysik in Heidelberg observations of Se^{82} and of Te^{130} double-beta decay of Se and Te from selenokobellite, respectively tellurobismuthite from Boliden were made by Kirsten et al. (1967, 1969).

Especially during certain periods, the selenium content of the Boliden ore considerably increased the value of the ore. This led to an investigation of the mode of occurrence and distribution of selenium in all of the more important sulphide deposits of Sweden (cf. Bergenfelt 1953).

7.1.11. TUNGSTEN AND MOLYBDENUM

In 1942, a large crystal of scheelite was found in the Boliden Mine. Later quite large quantities of this mineral were discovered in certain parts of the deposit. As the easiest way to recognize scheelite is by using ultra-violet light, suitable lamps were obtained and all drifts, stopes and drill-cores of the mine were surveyed in ultra-violet light. In this way, the distribution of the scheelite could be mapped in a short time, whereupon the richer portions were sampled. The percentage of molybdenum in the scheelite was estimated from the fluorescence colour, a method giving relatively exact values. As a control, chemical analyses were made of single samples (cf. p. 49).

During the regional investigation using ultra-violet light scheelite was observed in 23 of the 322 drill-cores examined. In more than half of the cases scheelite was bound to quartz veins, sometimes with tourmaline. In the rest, scheelite occurred in unaltered rocks and in a few cases in solid ore. In altered rocks scheelite has been seen only in association with sulphide minerals.

In the sulphide ore scheelite occurred in several places. It was especially concentrated, however, in the most western part of the Eastern Ore. In the sulphide ore scheelite occurred in the pyrrhotite-rich matrix of the brecciated arsenopyrite ore and commonly in parts of pyrrhotite ore. On the other hand, the mineral was never found within the solid arsenopyrite ore, nor in the pyrite ore of the last ore formation stage. Quartz veins, with or without tourmaline, often occurred close to the solid sulphide ore. Scheelite, however, was seldom found in these veins. The scheelite-bearing pyrrhotite ore belongs to the second ore-formation stage where the quartz-tourmaline ore sometimes grades into pyrrhotite ore with varying amounts of chalcopyrite. All scheelite mineralization in the mine appears to be related to this stage. At the westernmost part of the Eastern Ore at the 230–232 m level in Stopes 48 and 49 (– 90 x, – 20 y) portions were found so rich in scheelite that their exploitation was discussed. The ore also was very rich in gold. Because the scheelite-bearing parts were relatively small it would not have been profitable to treat this ore separately in spite of the high tungsten content, 1.2 % WO_3 in 13.9 m sampling channels. Everywhere, the percentage of molybdenum in the scheelite was low, 0.05 % Mo. No other molybdenum mineral has been found in the Boliden Mine (cf. Grip, 1951).

At the 250 m level about 500 m west of the ore area proper, in a tunnel driven to the Dressing Plant Shaft and situated about 150 m east of this one in unaltered bedrock, several narrow quartz veins were discovered which were rich in small scheelite grains. Channel samples taken over the drift, however, showed a maximum of only 0.03 % WO_3, calculated for the width of the drift as a whole.

7.1.12. BISMUTH

Arsenic was the first by-product to be recovered at the smelter at Rönnskär. The next one was bismuth. From the converter smoke, dust containing about 8 % Bi was collected. By 1931, 181 tons of bismuth dust were shipped to Germany. That yearly export production was maintained. In addition, between 1939–1965 an alloy containing variable amounts of bismuth was produced. From 1945 to 1949 the smelter also produced metallic bismuth and bismuth salts. The bismuth content in products from the Boliden ore amounted to 50–60 tons a year.

The mode of occurrence of bismuth in Boliden early was stated. The metal went into several different minerals in the mine. Bismuth occurred in ore representing all three ore-formation stages. although to the largest extent it was associated with the quartz-tourmaline ore. Highest bismuth contents were found in ore rich also in gold. No efforts have been made, however, to mine a bismuth ore but it has followed the other ore types to the mining operations.

7.1.13. RUTILE

In and around the root-zones of the ore bodies there occurred plenty of rutile belonging to the first, second, and to a certain extent, third ore-formation stages.

The chemical composition of a rutile-rich rock from such a complex root zone in Stope 28 (– 80 x, 50–150 y) at the 250 m level is given in Table 9.

Table 9. Chemical composition of rutile rock. Stope 28, 250 m level

SiO_2	39.90
Al_2O_3	8.45
Fe_2O_3	0.00
FeO	0.75
CaO	0.15
Na_2O	0.39
K_2O	1.66
TiO_2	44.80
P_2O_5	0.53
Y_2O_5	0.031
V_2O_5	0.1
ThO_2	<0.005
Cu	0.1
Bi	0.2

A survey of the distribution and reserves of rutile was made in 1948 in order to determine wheter or not rutile could be exploited. At the 250 m level an area of 4,900 square metres with sericite rock was localized containing 2.97 % TiO_2 and about 1 g/t Au. In Stope 30 and 61 (– 100 x, 60–200 y) small portions were found rich in TiO_2. An andalusite silt contained 2.2 % TiO_2. 43 % Al_2O_3 and 1.9 g/t Au. At the 270 m level an area of 200 square metres contained 5 % TiO_2.

None of the rutile-bearing portions found, however, had a percentage of TiO_2 high enough to warrant its recovery. For that reason no production of rutile was ever realized.

7.1.14. APATITE

The Boliden Deposit had the highest percentage P_2O_5 of all the ores of the Skellefte District, and as far as we know, of all suphide ores in Sweden. Aitik, situated only 15 km SE of the Gällivare iron ore field, shows a similar but still not so high P_2O_5 content.

The phosphorus was bound to fluor-apatite, which was especially abundant in the root-zone of the eastern ore body. In part, the apatite was associated with the arsenopyrite ore. Apatite also formed lenses and stringers in the sericite schist beneath the ore body. An additional characteristic for the milieu was an enrichment in cobalt, rutile and gold. The apatite was most closely related to the first ore-formation stage, although it also followed the second and, to a lesser degree, the third stage.

Apatite lenses in Stope 28 (– 80 x, 100 y) at the 250 m level contained more than 30 % P_2O_5. No efforts were ever made to recover apatite from the ore or the wallrock.

The chemical composition of fluor-apatite crystals is given in Table 10.

Table 10. Chemical composition of apatite crystals. Drift 689, (— 100 x, 200 y), 330 m level

SiO_2	0.9
CaO	54.0
P_2O_5	40.6
Y_2O_5	0.031
ThO_2	<0.005
F	3.5
Cl	0.05
H_2O +	0.15
	99.2

The apatite appears as milky and rose coloured crystals in sericite filled fissures close to the andalusite rock.

7.1.15. PYRRHOTITE

For the cobalt process at the smelter pyrrhotite was also needed. In the early forties a survey of the distribution of this mineral in the Boliden Mine was made. A small part of a pyrrhotite-bearing portion at the NE end of the Eastern Ore was mined. This ore contained very little gold, about 1 % Cu, 1 % As and 30 % S.

Pyrrhotite also occurred at many other places in the deposit, although it was usually found together with gold. This meant that the ore had to be treated in a way giving total gold recovery.

When cobalt production was discontinued at the smelter the demand for pyrrhotite disappeared also. No special mining for pyrrhotite occurred later.

7.2. WALL ROCK ALTERATION

By the early forties the mine had been developed down to 570 m. At every level the alteration area had almost completely been covered by parallel sections of horisontal drill-holes (Fig. 8–9). The cores had been logged and analysed, with special emphasis on the gold content. Geological maps showing the distribution of the various types of alteration rocks had been constructed. The extensive material available, however, was extremely well suited for a comprehensive geochemical study of the entire wall rock alteration problem. By and by, such an investigation was started. Ödman had already found a certain zoning in the upper parts of the deposit within the alteration area. We also found a similar zoning further down. Geological mapping of the various alteration rock types that could be distinguished by the naked eye was made in drifts and drill-cores. This was to be followed by a study of the rocks and their distribution using the microscope and chemical analyses. For that purpose in the mid-forties about twenty complete rock analyses of the principal rock types within the alteration area were made. But as the accuracy of trace element analyses at that time was not very high they were not determined. On the whole, the survey showed that Ödman's results were also valid at deeper levels.

A few years ago the entire alteration zone of the Boliden Deposit was the subject of a renewed and more accurate investigation during which previous analyses were complemented by new ones. Trace elements, using new more exact methods, were determined in all the samples. A paper by C. A. Nilsson concerning the geochemistry of the major elements was published in 1968. It will soon be followed by a second paper on the distribution of the trace elements within the alteration zone. A summary of the results obtained by Nilsson and presented in the first part of his paper follows below:

"The alteration products of the Skellefte Volcanics (quartz porphyries, keratophyres, quartz keratophyres and dacites) are: sericite rock, andalusite rock, andalusite-rich sericite-quartz schist, sericite-quartz schist including an extremely silicic type, chloritic sericite-quartz schist, and pyrite-banded sericite-quartz schist. The varieties closest to ore – i. e. sericite rock, andalusite rock and the silicic and andalusite rich sericite-quartz schists – also constitute the core of the alteration channel below the ore body. Outside the central zone and outside the light colored sericite-quartz schist a marginal envelope of chloritic and pyrite-banded sericite-quartz schists is present. This envelope shows a partial increase in femic constituents from the central and deeper portions of the conduit." –

"Width of the Alteration Envelope. – Fig. 14 illustrates the varying width of the alteration envelope and that the massive sulfide ore is localized in its narrowest part. Furthermore, the most intense alteration is below the orebody in the postulated channel of ingress." –

"The permeability of the rock (not necessarily the primary porosity) must have been the main factor determining the width of the alteration channel. The widest part of the channel is found in the rocks that primarily were the most silicic. These rocks are also the most brittle rocks of the deposit, the rocks that in response to tectonic disturbance in connection with the formation of the faulted zone, permitted the most intense shattering, thus presenting a wide permeable zone for the ascending solutions. A major fault-fracture zone, (according to Ödman, a strongly sheared drag fold) forms the prerequisite for the formation of the solution channel. An older tectonic disturbance within the present area of alteration is also indicated by the quartz phenocrysts in the

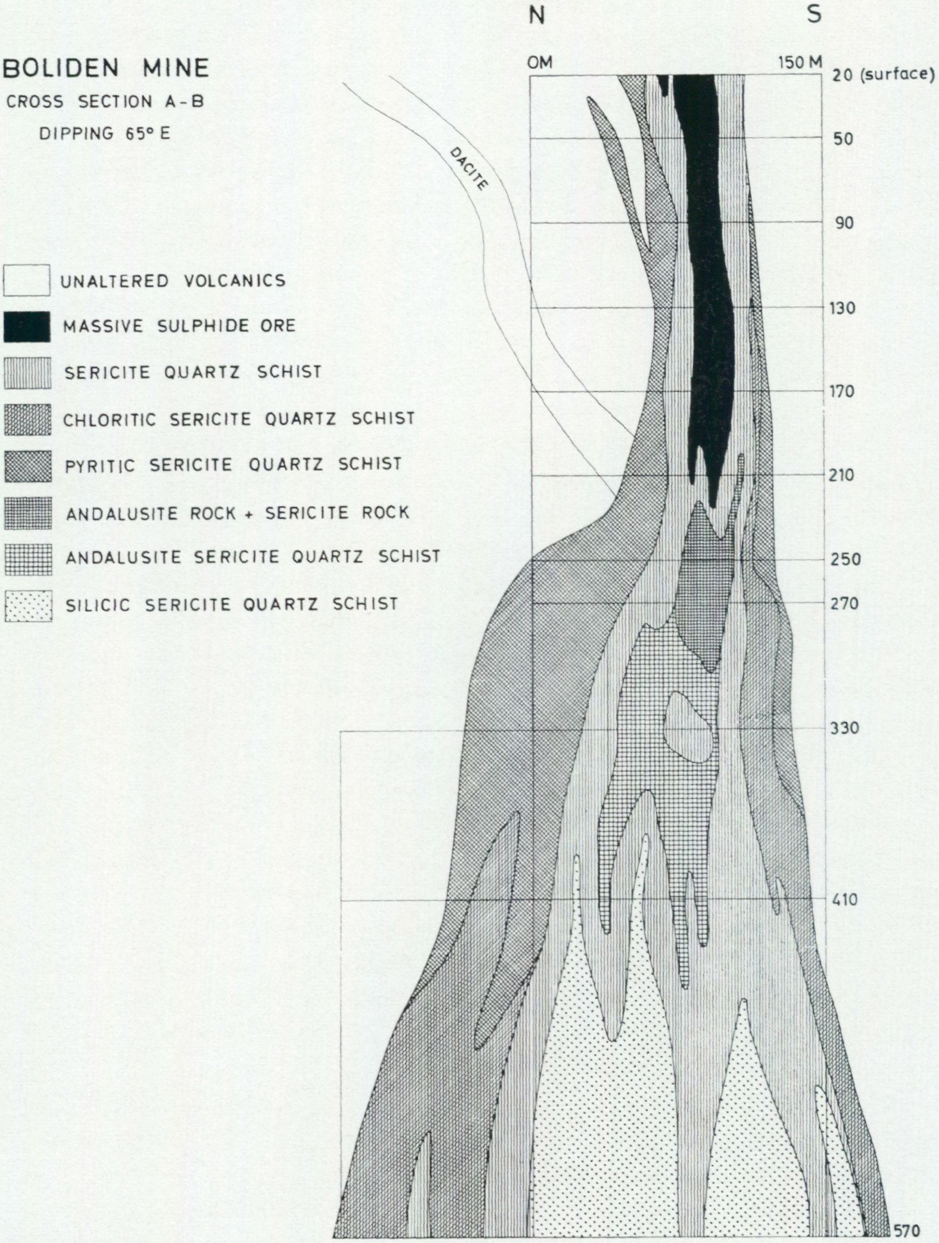


Fig. 14. Inclined cross section of the altered body. Section looking East. From C. A. Nilsson (1968, Fig. 9).

quartz-porphyritic quartz schists as these eyes show signs of a mechanical deformation. Of importance is the fact that where cracking of quartz eyes have occurred the signs of corrosion inflicted by the sericitizing solutions suggest the alteration to be later than the deformation of the wall rock. The border of the alteration zone on the higher levels is surprisingly sharp compared to the diffuse character of the contact between altered and unaltered rocks of the lower levels of the mine. The writer attributes both this clear-cut contact as well as the narrowness of the zone as depending on a narrow and equally well defined pre-alteration zone of tectonic fracturing of this more compact and dense series of intermediate rocks." –

"Convergence. – When studying rock alteration, many investigators have noted that hydrothermal action may alter dissimilar rocks to a uniform type." – "The core of the altered body at the Boliden deposit furnishes an excellent example of the same phenomenon; here intense alteration has caused dacite, keratophyre, and quartz keratophyres to become sericite-quartz schist, the chemical composition of which does not seem to be dependent on the composition of the original wall rock. However, the primary chemical composition of the wall rock is reflected in the marginal parts of the alteration envelope. It seems quite plausible that the original character of the rock to a certain extent determined the final chemical composition of the outer (chloritic) zone of the quartz schist envelope. This zone shows additions of magnesia removed from the core. In those sections of the channel where magnesia was already present in larger amounts, as in the dacite on the 250 m level, the content of this component is now abnormally high when compared to the chloritic quartz schists formed from rocks of a more silicate nature, e. g., the quartz porphyry of the lower levels of the mine. I seems evident that the original character of the rock has great influence concerning the composition of the alteration product in the early stages of hydrothermal action and in the parts of less intense chemical interchange, but if alteration continues and its intensity is increased the composition of the solution will be the determining factor as to the ultimate nature of the rock.

Zoning. – The present investigation has shown that compared to the original composition of the rock complex, the altered body (excluding the sulfide ore) has suffered a loss of Na_2O, CaO, and total Fe and gained Al_2O_3, TiO_2, MgO, K_2O, H_2O, S, and F and that a zonal arrangement of the components of the envelope exists. As evidenced by the central zone of the solution conduit, the action of the hydrothermal solutions in the core of the altered body included the complete removal of MgO, total Fe, Na_2O, and CaO. This light colored inner part of the envelope (central and intermediate zones) shows as addition of SiO_2 and/or Al_2O_3, TiO_2, K_2O, and H_2O, the proportions of which change with vertical distance from the ore. The over-all chemical pattern of the central portion of the alteration envelope, with the successive vertical increase of alumina towards the ore body and the corresponding decrease of silica, suggests that the formation of andalusite-bearing sericite-quartz schist, sericite rock, and andalusite rock was the result not of drastic changes in composition of the fluid in the channel by reason of changing conditions at the source, but of the continuous action of a solution removing alumina, liberated by the destruction of the primary feldspars, from the lower parts of the conduit and depositing it in the upper parts. It seems evident that the light colored core of the schistose zone of alteration below the Boliden sulfide ore body is the channelway of ingress.” –

”The horizontal zonal pattern, Fe-bearing chloritic zone enveloping the light colored core of the quartz schist body, has been shown to be a continuous feature from the deepest level to the surface. Ödman attributes some of the chloritic schists to the action of chloritization solutions independent of and later than the main sericitization period. It may also be suggested by some students of hydrothermal alteration that the outer zone of Mg-Fe-rich quartz schists represents an initital stage of chlorite alteration prior to a superimposed sericitization process responsible for the formation of the altered rocks of the intermediate and central zones. However, considering the spatial and chemical relations of the series of altered quartz porphyries, the original composition of which is indisputable, it does not seem logical to explain the high magnesia contents of the outer zone by assuming a mother rock of more femic composition. Most likely, the major amounts of Fe, MgO and CaO, mineralogically reflected by chlorite and secondary plagioclase in the chloritic zone originated from the deeper central portions of the solution conduit. However, the high MgO-content of the outer zone of the 250 m level must partly be explained by the corresponding high content of this component in the mother rock (dacite). Ödman includes a rock with basic plagioclase, hornblende and biotite among the altered rocks of the deposit. Its occurrence is rather irregular and is restricted to the areas outside the alteration zone proper. As the excess elements characteristic of this rock (MgO, CaO, and total Fe) correspond to those of the outer sericite-quartz schist zone, it seems likely also that the excess MgO and CaO of the ”basic keratophyre” are derived from the inner parts of the solution conduit. Thus, the present author concludes that the zonal arrangement of the altered rocks did not result from several phases of alteration, each solution differing in composition but was formed through the continuous action of one solution (or a series of solutions of similar composition).

The occurrence of chloritization including magnesia enrichment in the fringe zones of alteration areas has been emphasized repeatedly in the literature. Schwartz concludes that ”chlorite is commonly a border or fringe zone product and tends to disappear in the more intense stages.” The importance of chlorite and the mobility of Mg during the formation of the ores of the Malånäs district of Sweden has been discussed in detail by Gavelin (1939).

As has already been mentioned, the leaching of iron from the lower levels suggests that a possible source of the iron of the sulfide ore body is to be found in the parts of the country rock traversed by the solutions. Estimating the amounts of iron leached from the limited part of the altered body investigated as 466,000 tons, we find that this makes up for about one fifth of the iron of the preserved portion of the sulfide ore body – its upper part now removed by erosion – but taking into account that the alteration channel widens as far as the 800 m level and that these rocks are of the silica rich types, one does not have to extrapolate too far to explain the total iron content of the ore body. That iron is substracted from the wall rocks also when wall rock pyritization is taken into account, has been noted by McKinstry (1957) who concludes that "although it is not uncommon for iron to be introduced during pyritic alteration of wall rock, it is more common to find that the Fe content of the rock remains approximately constant or is actually reduced".

As mentioned above the investigation of the major element distribution in the altered zone around the Boliden deposit has been succeeded by a survey of the distribution of the trace elements there. Nilsson (1969) reports: "Using the 'sulphide isoformation method' the following elements in about 100 samples were determined: Zn, Pb, Cu, As, Sb, Bi, Sn, In, Ga, Mo, Ag, Tl, Ga, and Ba. In the case of Sb, Sn, In, and Tl the accuracy of the method was not considered high enough. The other elements, however, plotted in profile lines and compared with the back ground found in fresh rocks of the surrounding, showed very characteristic variations from the centre of the alteration zone outwards.

Stated briefly the trace elements have been leached from the altered area and moved outwards. Due to the different mobilities of the various elements, zoning has resulted in the following sequence, from the central zone over the marginal zone and out into the unaltered rocks: Mo, Bi, As, Cu, Pb, Zn, Ag and Ba. This order is clearly seen in a parallel alteration zone without any sulphide mineralization 150 m S of the large principal alteration zone. In the principal alteration area, the zoning of the trace elements often is obscured by precipitates of metal residues related to the ore forming solutions. It is possible, however, to correct for these admixtures. If this is done, the zoning appears clearly."

Regarding the ore proper, its altered surroundings too have been investigated because of the possibility that some of the rocks and minerals might be of economic interest. A few of them are of interest for the understanding of the entire ore formation problem in Boliden, and will therefore be treated in more detail.

7.2.1. THUCHOLITE

Thucholite was first found in the Boliden Mine in 1936. At that time, however, it could not be identified. A special study was made later by Aminoff, 1943. On the basis of its high titanium content he classified the mineral as titanothucholite.

Further investigations, based on a larger number of samples, showed the thucholite to have a variable composition, not only from specimen to specimen but also within the same individual. Because the thucholite does not have a fixed composition, it is not a mineral proper, although it may be dealt with as such. The composition of the thucholite has been determined by several analyses, giving the following average: 66.5 % C, 2.4 % H and 23.5 % ash. The ash in its turn contains 37.7 % U_3O_8, 6.2 % ThO_2, 2.2 % rare earths, 4.5 % PbO, 37.3 % TiO_2, 3.1 % SO_3 and some Si, Al, Fe and alkalies.

The thucholite occurred principally in the andalusite rock at deeper levels (192–570 m) in the mine. It was found in fissures and schlieren, which sometimes were filled with course sericite. Thucholite also occurred in veinlets and small gash-veins of quartz in the quartz-bearing andalusite rock. The thucholite was related to the second ore-formation stage, the quartz-tourmaline stage. It was strictly bound to this ore paragenesis. – Thucholite was described in a special paper by Grip and Ödman, 1944.

Thucholite was the only radioactive mineral found in the Boliden Mine. As it contains high precentages of both uranium and thorium, the possibilities for its eventual recovery have been studied. After the distribution of the thucholite had been mapped, radioactivity measurements were made over the levels and areas in question (see p. 48). Radioactivity anomalies turned out to coincide well with areas of the most intense alteration. It was possible, on basis of these anomalies, to calculate the amount of uranium in the rock. On the average, the content was 10–100 g/t U. Higher concentrations appeared especially in the andalusite rock and the root-zones of the arsenopyrite lenses. The compact ores were low grade for the most part. In the adalusite rock, the uranium content in some sections could reach 100–200 g/t U, or in some single cases even higher. These values correspond approximately to those found in Cambrian shales.

Attempts to produce a thucholite concentrate were made using hand picking or flotation. It was found possible to do so, but the costs were prohibitive. For that reason, the project to produce thucholite was dropped.

7.2.2. NATURAL GAS

In order to examine 410 m level in the Boliden Mine, a long drift was driven. From it, horizontal diamond drill holes were made on either side. A colourless gas was found to escape from some of the drill holes in the foot-wall portion of the ore zone. The gas had an intense, sickening smell and burned with a blue flame. It induced nausea when inhaled in large quantities. Clothing quickly became impregnated with the odour, which remained long after the bearer had left the mine.

The core taken from the drill holes discharging gas consisted of siliceous sericite schists with varying amounts of andalusite and even strips of andalusite rock. As was mentioned in the section on thucholite, the andalusite-rich rocks are thucholite-bearing. In the vicinity of the gas-bearing drillholes, thucholite was also found in quartz veins. Because the gas came from thucholite-bearing areas, it seemed reasonable to expect the gas to contain helium, formed in the disintegration of the radioactive uranium- and thorium-containing thucholite. This was confirmed by analyses.

The composition of the gas was found to be about the following: 60–69 % CH_4, 25–37 % N_2 + inert gases except He, 2–5 % He, 0.1–1 % CO, 0–1 % H_2.

The same gas also disharged from drillholes on the 570 m level, especially where the holes penetrated a brecciated zone, and from some fissures in the drifts on the 410 and 570 m levels. The drillholes yielded moderate quantities of water. From the water, a yellowish mud with a repulsive cadaverous odour was precipitated. The mud, which to a large extent was composed of an organic substance with about 0.5 % P_2O_5, seems to have been produced to a large extent by sulphur bacteria. The gas is assumed to have formed through the disintegration of organic substances in the phyllite series and penetrated into the ore area, particularly during the second ore formation stage when there was a plentiful influx of boron, fluorine and water. Sericitization of the andalusite rock also occurred under the influence of these solutions. The gas was then encountered in the andalusite-bearing areas.

The helium content as high as 5.4 %, was undoubtedly a radioactive disintegration product of uranium- and thorium-bearing minerals. As mentioned above, thucholite occurs in the same parts of the mine as does the gas. It seems clear that the thucholite was formed by methane, other hydrocarbons and perhaps to some extent H_2, CO and CO_2, which were polymerized under the influence of radioactive radiation of U-Th-minerals. The formation of thucholite probably still continues. Natural gas in the Boliden Mine was described in a paper by Grip and Ödman, 1944.

In 1941, the gas flow from the drillholes on the 410 m level was measured and the total gas flow from this level calculated to be 210 litres per hour. The average helium content in the gas was 2.3 %. Recovery of the gas for its helium content was discussed at that time. But since production would have amounted to only 36 cubic metres helium per year, the project was dropped. In 1945, new measurements of the gas flow from 10 drillholes on the 570 m level were made and at that time, 16.5 litres per minute, or 1 cubic metre per hour, were obtained. Although the amount of gas was considerable larger here than on the 410 m levels, recovery of the gas was not begun because the demand was then less and the price much lower than before.

7.2.3. ANDALUSITE AND CORUNDUM

Early in the geological survey, the Boliden alteration area was found to contain large amounts of andalusite-bearing rock below the ore lenses and concentrated

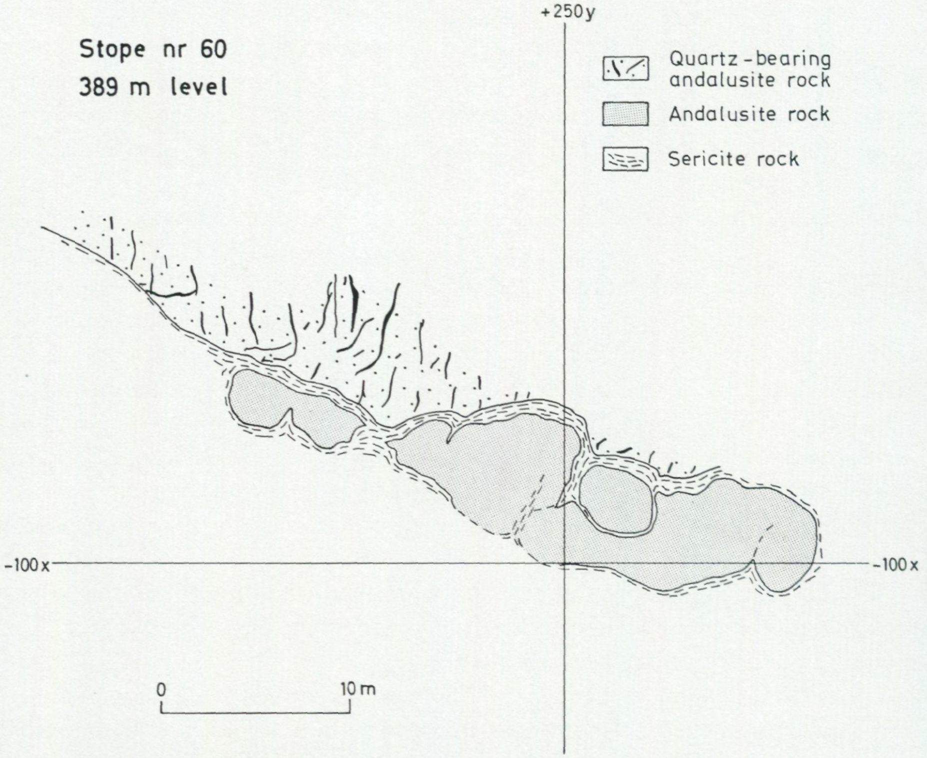


Fig. 15. Stope 60 where andalusite rock was mined. Note the round shape of the andalusite-rock bodies and the irregular quartz veins outside them. The situation and the same feature is shown in Fig. 16.

in bodies showing a high percentage of aluminium. A general survey of the andalusite reserves was made in 1938. At the 250 m level the area of andalusite rock was found to be more than 1,000 square metres, and at the 410 m level more than 4,000 square metres. The andalusite rock highest in alumina contained more than 72 % Al_2O_3; but the average was much lower. The local high percentage of Al_2O_3 was caused by a concentration of corundum and diasporite.

The structure and extension of the bodies of andalusite rock have been determined. As seen in the map in Fig. 15 and the section Fig. 16, the andalusite bodies form rounded, vertically elongated bodies lying as vertical clusters extending upwards to a line dipping about 55° to the east. They are thus coincident with the general plunge of the ore bodies. The occurrence of agglomerates here may indicate presence of tuff beds in the drag fold against which the solutions responsible for the alteration accumulated.

The vertical elongation was controlled by an older structure also found in

Fig. 16. Longitudinal section through the intensely altered lower parts of the mine with the limits of the andalusite rock bodies. Note the vertical structural control together with the 55°E pitch. Knowledge of the shape and the extension in space of the andalusite rock was rather incomplete at the time of Ödman's description. Further work, however, has given a better picture, as shown in this figure and Fig. 15. E. Grip, 1969.

the wall rock, especially on the northern side of the ore. In the walls, the sericite rock and sericite schist were more or less intensely folded in small, often sharp folds along vertical axes. This structure is seen most clearly in the western part of the open pit (see Fig. 17) although the vertical structure can be traced on most of the walls around the pit.

Because the altering solutions to a large extent have followed the vertical structure, the structural trend must have been formed very early, before the formation of the ore.

Fig. 17. The northern wall at the west end of the Boliden Mine. Note the vertical linearity and small-scale folding in the pyritic sericite schist. Photo by E. Grip, 1969.

To a certain extent the vertical structure also controlled the shape of the Eastern Ore, defining its contour to the east, while its western contour follows the direction of plunge. The pyrite ore better expresses the pre-ore-folding than the arsenopyrite ore. This is because the pyrite ore replaces sericite rock and schist while the arsenopyrite ore has a more intrusive character.

The vertical structure can be regarded as the axis for the horizontal anti-clock-wise movement which created the vertical E–W-shearing plane forming the central zone of the dragfold and the channel for rising solutions. The direction of plunge, 55°E on the other side, is the fold axis of the dragfold and coincides with the E-pitching of the E-end of the dome.

The Boliden Company tried to find a use for the andalusite rock, a very uncommon type of rock. At the beginning of World War II, the Company considered using the andalusite rock as a raw material for aluminium production, and for this purpose a cooperation with the Swedish Aluminium Company was established. A more detailed investigation of the andalusite resources was carried out, and a sufficient basis for mining aluminium ore during the crisis years found. In all about 62,000 tons of andalusite rock were mined containing 50–55 % Al_2O_3. When this mining was discontinued in 1945, 96,000 tons of aluminium ore containing a little more than 50 % Al_2O_3 remained in the mine and are still there.

7.2.4. SERICITE SCHIST

Outside the western end of the ore bodies there was a quartz-porphyritic sericite schist with a high percentage of silica (about 80 % SiO_2). During the years 1930–1932 this rock was mined at the 50, 90 and 130 m levels. Called "Quartzite A" at that time, it was used as a flux medium at the smelter at Rönnskär. Altogether, about 23,000 tons were removed containing the following approximate percentages: 80 % SiO_2, 12 % Al_2O_3, 0.5 % CaO, 2.5 % K_2O, 0.5 % Na_2O, 0.3 % MgO.

Even later on, the possibility of mining sericite schist for the smelter has been discussed, with attention being directed especially to the rock types high in silica and simultaneously containing some gold. A nearly complete recovery of the gold then was expected. The area most attractive for this purpose was located just outside the eastern end of the Eastern Ore, between the 130 and 210 m levels. After a survey made in 1962, however, only a little more than 60,000 tons with 1.4 g/t Au and 71 % SiO_2 were stated to be present. This was not enough to justify production of sericite schist. Therefore, such mining never was started.

During the early thirties a rock called "Quartzite B" was mined also. It contained 5–6 g/t Au. Later on, it was called "Hard Ore". Mining for this rock continued until the mine was closed down.

7.2.5. SERICITE ROCK

The sericite rock in the Boliden Mine was nearly monomineralic. It enveloped the ore bodies from the 210 m level downwards until they petered out and still further in the direction of the prolongation of the ore zone down to about the 410 m level. The rock contained about 44 % SiO_2, 38 % Al_2O_3, 2 % Na_2O and 9 % K_2O. Because of the high percentages of aluminium and alkalies, especially potassium, attempts have been made to find a use for this unique rock. The ceramic industry has been interested in the rock. The price offered, however, has been too low for a mining to be profitable. Accessible recoverable quantities were not very large either.

8. GEOPHYSICAL INVESTIGATIONS CARRIED OUT IN THE MINE

Various geophysical techniques have been used in prospecting for hidden ore bodies in and around the Boliden Mine. In addition, the mine has served as an experimental field for testing some new instruments. Most of these investigations have been directed by the chief of the Department of Geophysical Research, Dr David Malmqvist. The following notes 8.1–4, are extracted from his reports.

8.1. LOOP FRAME MEASUREMENTS, as tests, have been made on the 410 m and 570 m levels. Anomalies were obtained only in the easternmost part of the drift on the 570 m level, exactly where the drift intersects a pyrite-banded sericite schist. The anomaly was interpreted to have been caused by disseminated pyrite. It was noted as an interesting fact that the Loop Frame electromagnetic method, which is used extensively at the surface, could also indicate sulphide disseminations underground.

8.2. TEMPERATURE MEASUREMENTS in the bedrock at the 210 and 410 m levels were carried out already in 1938 (cf. Dahlblom 1938). More accurate values were obtained in 1951, when drillholes at several levels in the mine were measured with a more sensitive instrument, a resistivity thermometer. The results were as follows:

270 m level: 6.5–6.6°C
410 m level: 8.4°
500 m level: 9.05°

Thus, the measurements indicate a temperature increase of 1°C per 76 m between the 270 and 410 m levels and 1°C per 138 m between the 410 and 500 m levels. These temperature gradients are surprisingly low. However, in other parts of the Skellefte District the temperature gradients have also proved to be very low.

8.3. GRAVIMETER MEASUREMENTS in 1939 were made with the Boliden Gravimeter, an instrument developed by the Company, at the 410 m level. The gravimeter was to be used in prospecting for eventual deeper lying, blind ore bodies. A gravity anomaly was obtained in the drift about 300 m east of the Central Shaft. The anomaly was investigated by a drill hole directed at an oblique angle downwards and shown to be caused by andalusite which increased in abundance downwards.

8.4. RADIOMETRIC MEASUREMENTS. In 1941 an instrument for radiometric survey out in the field and underground was constructed at the Boliden Department of Geophysical Research. A detailed survey using the new instrument was made at the 410 m level in the Boliden Mine. The results showed that the altered rocks, especially the most highly altered ones rich in andalusite, had a radioactivity far exceeding the average for rocks in the Skellefte District.

Within an area of 800 square metres the percentage of uranium was calculated to be 0.004 % U_3O_8 or a little higher. Almost the entire uranium content of the rocks was found to be bound to the hydrocarbon-bearing mineral thucholite, which was especially abundant in those parts of the alteration area rich in andalusite.

8.5. FLUORESCENCE INVESTIGATIONS. As mentioned above, p. 33, ultra-violet light has been used in order to identify scheelite, to trace its distribution and to estimate the percentage of tungsten in the rock and molybdenum in the scheelite. In 1942, when this type of survey was begun in the Boliden Mine, a 220 V lamp of Swedish construction was used. Later on, however, when battery powered "Mineral Light" lamps were available, we employed these handy instruments.

The molybdenum content in the scheelite was determined on the basis of the fluorescence colour.

An investigation by R. S. Cannon Jr, F. S. Grimaldi and K. J. Murata at the U. S. Geological Survey has shown that the fluorescence colour of scheelite is directly related to the amount of molybdenum contained in the crystal lattice. The U. S. Geological Survey used this fact to develop a method by which the Mo content of the scheelite can be estimated visually in ultra-violet light: The sample to be investigated is compared with standards fixed on a card. Such a "Scheelite Fluorescence Analyzer" (Eng. Min. J. 1942), manufactured by Ultra-Violet Products, Inc. Los Angeles, was used in our survey at Boliden.

9. PARAGENESIS OF THE ORES OF THE BOLIDEN DEPOSIT

Ödman, 1941, described all the minerals which had been found in the Boliden Deposit up to that time. He summarized the parageneses of the three different ore formation stages in a mineral list. Since then several additional minerals have been found which complete the list of Ödman. Most of the new minerals could be determined only with the aid of an electron micro-probe, an instrument which as we know has been available to mineralogists only for a few years (Table 11).

All the newly discovered minerals belong to the quartz-tourmaline ore formation stage. Of the ore minerals, thucholite and scheelite have been described in detail in separate papers (Grip and Ödman, 1944; Grip, 1951; see also chapter 7). Corundum was described by Ödman (1941, p. 167), but was not included in his mineral list. The mineral, always very finegrained, was aboundant in the most alumina-rich parts of the andalusite rock. In connection with the in-

Table 11. Minerals in the Boliden ores. The mineral list by Ödman (1941), supplemented with minerals discovered later

Minerals	Arsenopyrite Stage	Quartz-Tourmaline Stage	Pyrite Stage
Arsenic[1] As	+	–	–
Antimony[4] Sb (Bi)		+	
Bismuth Bi	+	++	+
Gold[2] Au	+	+	+
Silver Ag	–	+	–
Gold-silver-amalgame[4]		+	
Bismuthite Bi_2S_3	–	+	+
Galenobismutite[4] $PbBi_2S_4$		+	
Bonchevite[4] $PbBi_4S_7$		+	
Tetradymite Bi_2Te_2S	–	++	–
Selenocsiklovaite[4] $Bi_2Te(S, Se)_2$		+	
Joseite A[4] $Bi_{4+z}Te_{1-x}S_2$		+	
Tellurobismuthite Bi_2Te_3	–	++	–
Stützite[4] Ag_4Te		+	
Sphalerite ZnS	++	+	++
Greenockite[4] CdS		+	
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[3] CuS	+	–	–
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 $Pb_2Sb_2{}_5$	+	–	+
Falkmanite $Pb_3Sb_2S_6$	++	–	+
Boulangerite $Pb_5Sb_4S_{11}$	+	+	+
Bournonite $PbCuSbS_3$	+	+	+
Meneghinite[4] $Pb_{13}CuSb_7S_{24}$		+	
"Selenocosalite" $Pb_2Bi_2(S,Se)_5$	–	++	–
"Selenokobellite" $Pb_2(Sb,Bi)_2(S,Se)_5$	–	++	–

Minerals	Arsenopyrite Stage	Quartz-Tourmaline Stage	Pyrite Stage
Selenolillianite[4] $Pb_3Bi_2(S,Se)_6$		+	
Selenogoongarrite[4] $Pb_4Bi_2(S,Se)_7$		+	
Stannite Cu_2FeSnS_4	–	–	+
Magnetite Fe_3O_4	–	+	+
Scheelite[4] $CaWO_4$		++	
Thucholite[4]		+	
Quartz SiO_2	+++	+++	+++
Rutile TiO_2	+++	+++	+
Zircon $ZrSiO_4$	+	+	+
Corundum Al_2O_3		+	
Diasporite $Al_2O_3 \cdot H_2O$	–	+	–
Fluorite CaF_2	–	+	–
Calcite $CaCO_3$	+++	++	++
Dolomite $CaCO_3 \cdot MgCO_3$	–	–	+
Copper-sulphate[3] $CuSO_4 + aq$	+	–	–
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	–	+	–
Sillimanite Al_2SiO_3		+	
Cyanite 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 $FK \cdot Ca_4(Si_2O_5)_4 \cdot SH_2O$	–	–	+
Plagioclase	+	+	+
Tourmaline	+	+++	+
Analcite $NaAlSi_2O_6 \cdot H_2O$	–	+	–
Titanite $CaTiSiO_5$	+	–	+

[1] Decomposition product in falkmanite
[2] Always contains more or less silver and mercury
[3] Formed by surface waters in the open pit
[4] Minerals discovered after 1941

+ = rare
++ = common
+++ = abundant
– = not present
? = identity of mineral not quite certain

vestigation of the andalusite-sericite rock at Mångfallberget, some cyanite and sillimanite have also been found in the same environment (Grip and Ödman, 1942).

All the other minerals in the completed mineral list, Table 11, have been found during recent detailed studies of the mineral paragenesis of the ore assemblage of the quartz-tourmaline stage, especially the sulphominerals. Greenockite and bonchevite were described by G. Eriksson (1965). Ivan Isaksson (1966) described the rest: meneghinite, selenogoongarrite, selenolillianite, selenocsiklovaite, antimony, stützite, and joseite A.

The following statistics summarize the distribution of the most important elements among various ore minerals: 47 different ore minerals belong to the ore paragenesis. Of them, 34 are sulphides, 3 are oxides and the rest metals, alloys and compounds with As, Sb or Te. Bi, which amounts to an average of only 0.04 % in the ore, enters into 13 of the ore minerals, while Sb (average 0.08 %) enters into 12, Pb (average 0.27 %) in 12 and Fe (average 27.0 %) in 11 ore minerals.

10. ROCK MECHANICS AND SUBSIDENCES

Several times during the lifetime of the Boliden Mine subsidence and collapse have occurred as a consequence of the mining. The first collapse of importance took place in the a-d-lens, where shrinkage stoping hade been started. The walls were not strong enough to allow mining by this method. Flaking off in large sheets occurred, and the ore in the magazine could not be emtied. Therefore, in 1935 this mining method had to be abandoned. The remaining ore was taken out later by a special sub-level caving method with timbered drifts.

The next important subsidence occurred in 1942 around the faulted portion of the Eastern Ore. The entire remaining part of this ore, from the surface and down to the 123 m level, sunk 1.5–2.5 m. The movement took place mainly along old fault lines and slickensides at the ore contacts.

When pillar mining was started, it began at the top of the pillars at the bottom of the open pit and proceeded downwards. Because the rock filling was rather easily compressed it could not be expected to have a stabilizing effect. The walls lost their support during the operation. Consequently, in 1943 a small subsidence of the hanging wall occurred in the open pit.

As the greatest risk for subsidences was in the vicinity of the great fault plane and a flatter branch fault extending from it, the mining of the pillars situated nearest the faults was not begun until the last stages of the pillar mining. However, when the mining of these pillars, in May, 1944, had reached the level below the branch fault, the first signs of subsidence appeared. This movement continued for several years. Houses and roads within the area most likely to

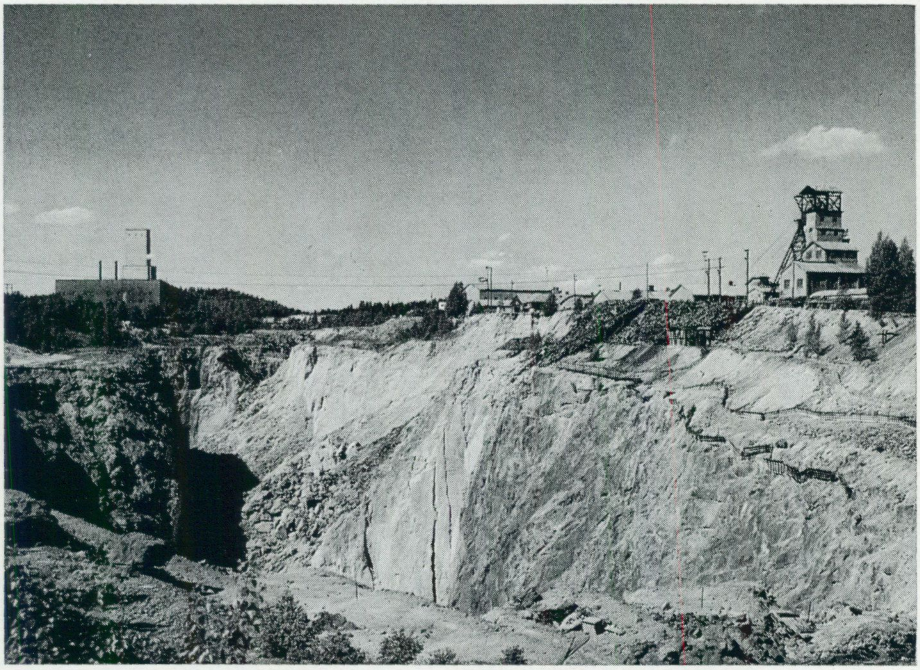


Fig. 18. The Boliden open pit. The central shaft appears to the right and the dressing plant to the left. The subsidence around the great fault and its branch-line is seen in the centre of the picture. Photo in 1962.

be affected by the subsidence were removed from the zone of danger. The subsidence then did not cause any inconveniences, except for som difficulties at the pillar mining when the area around the branch fault was passed. The drifts which lay near the ore body were also destroyed at some levels. New drifts had to be driven farther away from the ore.

Over a long period subsidences and collapsing of varying magnitudes occurred occasionally within the same subsidence area. (Cf. Fig. 18.)

In the autumn of 1951, the first signs of a subsidence were observed at the 90 m level. The main subsidence here took place only the next year during a few weeks in September. As mentioned before, the a-d-lens had been mined by shrinkage stoping at an early date. The space was then refilled by caved material. For that reason, the pillars in that part of the Eastern Ore bordering the a-d-lens were left unsupported on the southern side. In consequence of the change from longitudinal to transverse cut-and-fill mining in the Eastern Ore, the pillars were also left without support from below. A clay ”sköl” at the northern ore-contact then caused the entire pillar system within this area to be free hanging, supported only by the ore slice remaining in the bottom of the open pit. As cut-and-fill mining proceeded upwards this ore slice, however, became thinner and thinner. Finally, the remaining ore fractured, resulting in subsidence as expected. The collapse affected the area within the sections 50 y –150 y between the 90 and 130 m levels and 50 y–110 y between the 130 and 170 m levels. The maximum displacement of the subsidence was about 1 m. During the subsidence proper, all work in the area was stopped. Later on, however, it was possible to continue mining. No accidents occurred, nor did the subsidence result in a loss of ore.

During the winter of 1952–53 fractures appeared beneath the great fault plane in the southern rand of the open pit. These grew larger until finally in 1954 a mass of approximately 30,000 tons fell into the open pit. Not even this subsidence caused any interruptions of the mining, which at that time was being carried out at a secure depth below the subsidence area. In September 1954, an additional subsidence occurred comprising about 6,000 tons of rock in the eastern part of the open pit between the 30 and 80 m levels.

Otherwise, small local disturbances and subsidences due to the mining have taken place, especially during the terminal period of the production at the mine (Grip and Wirstam, 1949).

Rock mechanics measurements have been carried out only on a small scale. When microseis measurements were started in the mines of the Boliden Company in 1959, measurements were made regularly at some places in the Boliden Mine, but only by listening to clicks and without the aid of automatic registration. On account of the large number of open cracks and fissures, these measurements only were of a limited value.

When the tensile and elastic properties of the ore and the bedrock in some Swedish mines were investigated by a special research committee of the Swedish Mining Association, some large cubes were taken from the Boliden Mine and investigated at the Rock Mechanic Laboratory of the Royal Institute of Technology in Stockholm. The results were presented in a paper by Grip and Wirstam (1949, Table I).

11. PRESENT VIEW OF THE GEOLOGY OF THE BOLIDEN DEPOSIT AND SUMMARY OF GEOLOGICAL EVENTS

The geology and ores of the Boliden Deposit after detailed geologic mapping, microscopic and analytic work were described by Ödman (1941). At the time of his investigation, a large number of exposure were available within and around the two ore bodies. Additional geological mapping and other investigations have served only to modify details in the picture given by Ödman. At greater depths in the mine, however, large new exposures have been opened by drifts and diamond drillings. These have resulted in new knowledge of the alteration zone below the solid sulphide ore bodies. A detailed study of the alteration zone was published by Nilsson (1968).

In addition, the survey of new drifts and drillholes in the direction of strike, both to the east and to the west, has provided us with additional knowledge of the geology. This is true also with respect to the survey of the surface area around the deposit. Some of the results of these investigations have been published (see Bibliography), while others have been presented in the form of reports.

As a result of this work major aspects of the geology of the Boliden Deposit is very well documented and available in the work by Ödman (1941) and in other papers. Here, we will give only a brief summary of the publications, together with an account of some new observations and views of our own.

After completing a regional geological survey of the central and eastern parts of the Skellefte District, Grip (1942) published a paper summarizing the results. Since then, this work has been completed and has also illuminated some new aspects of the stratigraphy and tectonics of the Boliden Deposit and the surrounding area (Fig. 10).

The oldest rocks in the vicinity of the Boliden Deposit are an older volcanic series of acid to intermediate volcanites and sediments which have been affected by a gentle folding with nearly horizontal fold axes WNW–ESE. Some areas in the Skellefte District were intruded by an older granite called Jörn granite. Erosion partly exposed the granite and various layers of the volcanics.

Generally coarse-grained sediments, often rich in lime, were deposited on the unconformity. These were followed by dacitic volcanics and on top of them quartz-keratophyres. Some sandy units completed this "boundary zone" which altogether was about 100 m thick.

This sequence is followed by very thick series of phyllites and graywackes with occasional volcanic units. The sediments originated from an area of erosion to the north. In the southern part of the Skellefte District, the deepest parts of the complex have been granitized and partly mobilized. During a second period of folding around nearly the same fold axes as at the first, the granitization process proceeded northwards. Probably just ahead of the migmatite front, ore solutions advance to finally find suitable structures for deposition in the "boundary zone" between the volcanic and the phyllite series. The great difference in folding competence between the brittle volcanics and the ductile phyllites along with the impounding effect of sedimentary units have been of great importance for the ore deposition.

We have used this hypothesis of the ore formation for about 30 years. Recent, as yet unpublished, geochemical investigations by U. Svensson also support it. (Cf. also Gavelin 1955.)

During the later stage of the second folding, a younger granite, called the Revsund granite (1,790 mill. years according to Welin, 1969), intruded the

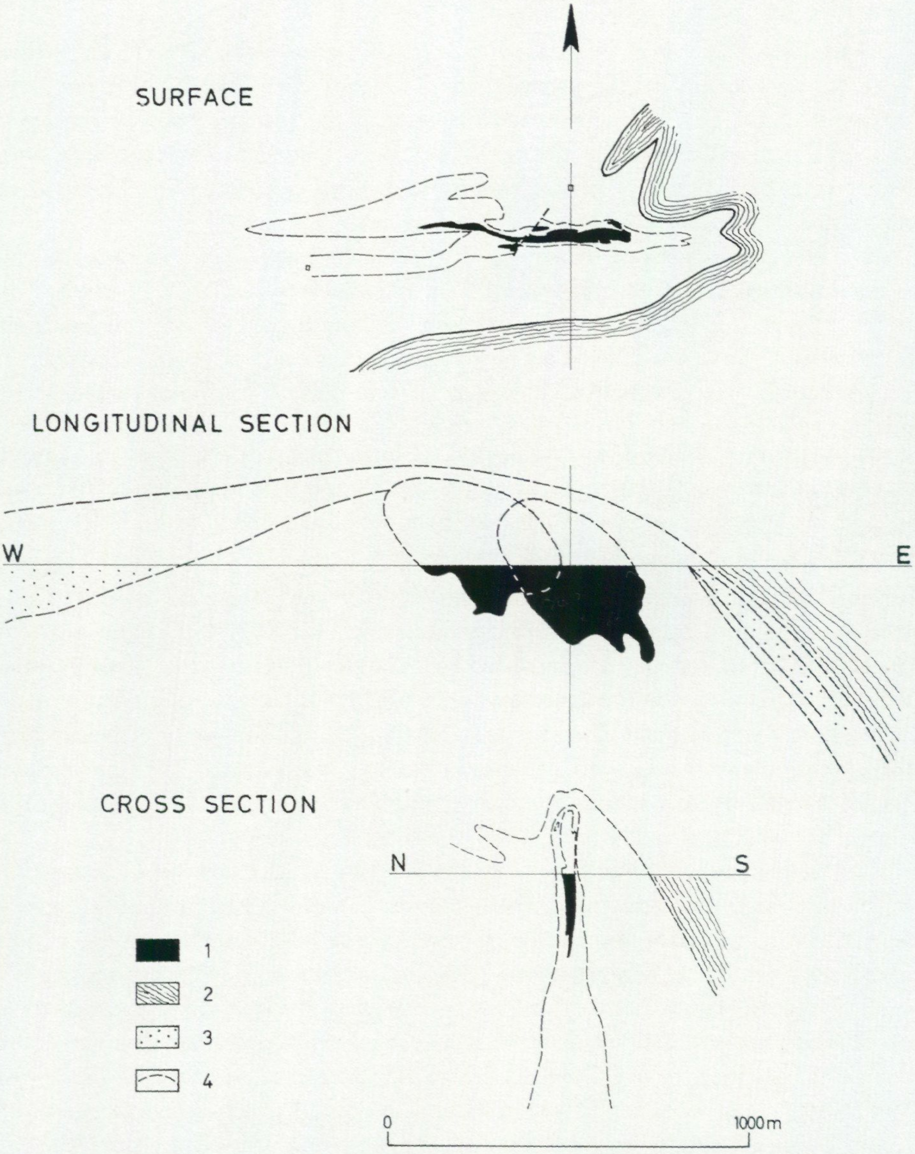


Fig. 19. Geological setting of the Boliden Deposit. Reconstruction of the dome and the ore bodies as envisioned before the erosion. 1. Sulphide ore. 2. Phyllite series. 3. Dacite. 4. Acid volcanics and sediments with alteration boundary The ore bodies were deposited in a vertical shearzone through the ridge of an asymmetric and rather complicated dome, the eastern end of which forms a dragfold plunging 50–60°E while the western end plunges gently W. Scale 1:20 000. E. Grip, 1969.

supracrustal rocks. A massif of Revsund granite is located a few kilometers S of Boliden.

In connection with the intrusion of the Revsund granite and the second folding phase, the regional stress turned counterclockwise and came more from the SSE. This stress resultet in shearing and "Schlingen" tectonics, forming steeply dipping shear-planes and linear structures. At Boliden, it produced a dragfold combined with a dome structure around a vertical shear-plane partly controlled by the old unconformity. Ore mineralization took place during this stage. (See Fig. 19.)

Looking at the geology of the Boliden Deposit in more detail, we find in the foot-wall (the N-side) of the ore bodies a quartz-porphyry. This is probably an intrusive body associated with the felsitic lavas seen in the surrounding area. The sequence called the "boundary zone" with detrital breccia, conglomerate and agglomerate containing fragments of underlying bed-rocks overlies an old unconformity. The Boliden Ore follows a shear-zone in these beds just above the unconformity. In the mine, the "boundary zone" is represented by fragment-bearing sericite schist which occurs in the direction of strike both to the east and to the west. It may also be mentioned that in the Eastern Ore a thin fragment of graphite schist has been found.

Further upwards, the sequence is composed of dacite and quartz keratophyre which to the west has been more or less completely replaced by dacite. A dacite bed also bends around the eastern end of the ore body. (See Fig. 9, the 410 m level.) In the hill called Tjälamyrberget, 1 km WSW of the Boliden Deposit, amphibolized rocks are exposed. Originally, these appear to have been lime-rich conglomerates or dacitic tuffagglomerates. Directly upon the quartz keratophyre and at places upon the dacite, rests the phyllite series.

The shear-zone controlling the Boliden ore bodies strikes E–W and dips vertically. It has several parallel counterparts to the North, both in the form of geophysical anomalies and as shearing structure in the rare outcrops. The Mångfallberget Deposit is situated in one of them (Grip and Ödman, 1942).

On the basis of our new observations it appears that the Boliden Deposit is situated on a major fracture zone, along which a flexure striking NE and dipping 45°SE has been formed in phyllites overlying flat lying volcanics. Although much more flat-lying, the lime-rich zone at Tjälamyrberget and also north of it seems to correspond to the Boliden ore zone.

Thus we find the Boliden Deposit situated in a structure which may be interpreted as the eastern limb of a dome. The western limb is much wider and here it does not extend deep enough for the phyllite to be preserved. Five km W of Boliden, however, a mountain N of Bjurvattnet is capped by flat-lying phyllite.

The sedimentary and the structural control of the Boliden Deposit has been described in detail by Ödman (1941 and 1942). New exposures and observa-

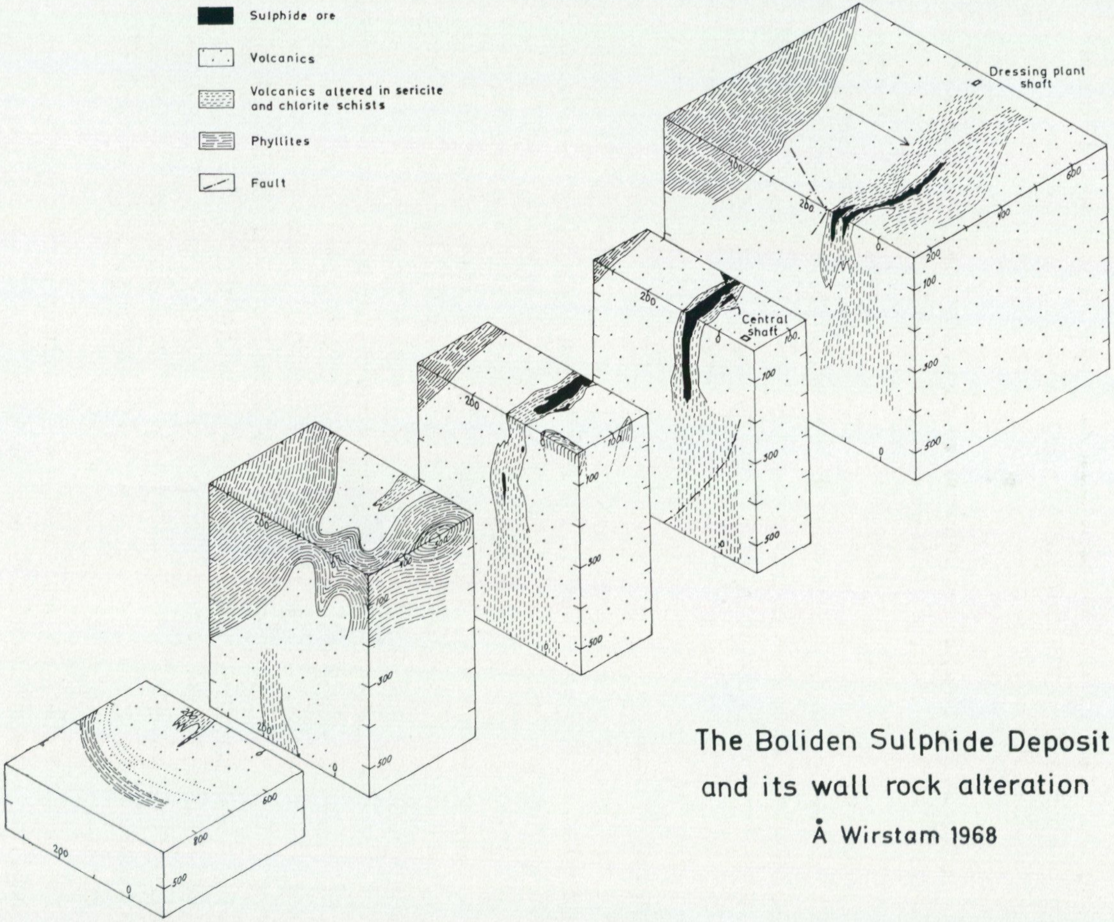


Fig. 20. Block-diagram of the Boliden Deposit and its surroundings. Å. Wirstam, 1968.

tions, however, complete and modify the picture. The stereogram in Fig. 20 shows clearly how the ore and the alteration zone are controlled by the structure throughout the mine and its surroundings investigated by drifts and drillings.

Fig. 19 is a reconstruction showing the two ore lenses of the Boliden Deposit dipping vertically in the shearing zone but pitching 50°E. The phyllite forms a dragfold around the ore lenses and along a fold axis parallel to the pitch of the bodies. Above the ore lenses, however, there is a culmination of the fold axis which towards the west then is dipping flat W. The dome-shaped structure thus formed appears extremely well suited for the collection of ore solutions which penetrated along the vertical, strongly sheared, center zone of the dome.

Most of the following summary is taken from Ödman (1941). Here and there we have added complementary remarks based to later observations and opinions.

"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 11).

The development of an independent dragfold in the contact between the volcanic and the sedimentary rocks "– combined with a dome-shaped structure –" is of fundamental importance for the ore deposition. The dragfold was caused by a shearing stress, acting in the counter clockwise direction. The axis of the dragfold pitches 50–60°E and this direction has exercised a structural control on the deposition of the ores. "– Together with it, an early vertical linearity also is of importance. –

"In the dragfold the stress formed suitable channelways for ascending hydrothermal solutions which brought about an alteration of the bedrocks. 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" – Nilsson (1968) found that "compared to the unaltered rocks the central zone shows addition of Al_2O_3, K_2O, TiO_2, SiO_2, and H_2O. The proportions of these components are shown to change with vertical distance from the sulfide ore. The outer zone shows a

Fig. 21. View looking west from the east end of the Boliden open pit. Note the steeply dipping hanging wall on the left side, along which the a-d-arsenopyrite ore lense (Fig. 22) lay. There the altered rocks extended for only a few metres outwards from the ore contact before being followed by fresh quartz keratophyre. This wall was very strong and stood practically undisturbed down to the bottom of the pit at the 90 m level. Around the fault line crossing the ore to the right in the photo there have been subsidences for a long time, cf. chapter 10. In the distance one can see a glimpse of the dressing plant. The section shown in Fig. 23 cuts the water-filled part of the pit. Photo by E. Grip, 1969.

definite addition of MgO, total Fe, H_2O, and S. Throughout the alteration envelope there is a remarkable loss of CaO and Na_2O. The central zone has lost total Fe and MgO. Compared to the calculated original composition of the rock complex, the whole altered body (not counting the sulfide ore) has suffered a loss of Na_2O, CaO, and total Fe and gained Al_2O_3, TiO_2, MgO, K_2O, H_2O, S, and F. The over-all loss of Fe (accentuated at depth) may indicate

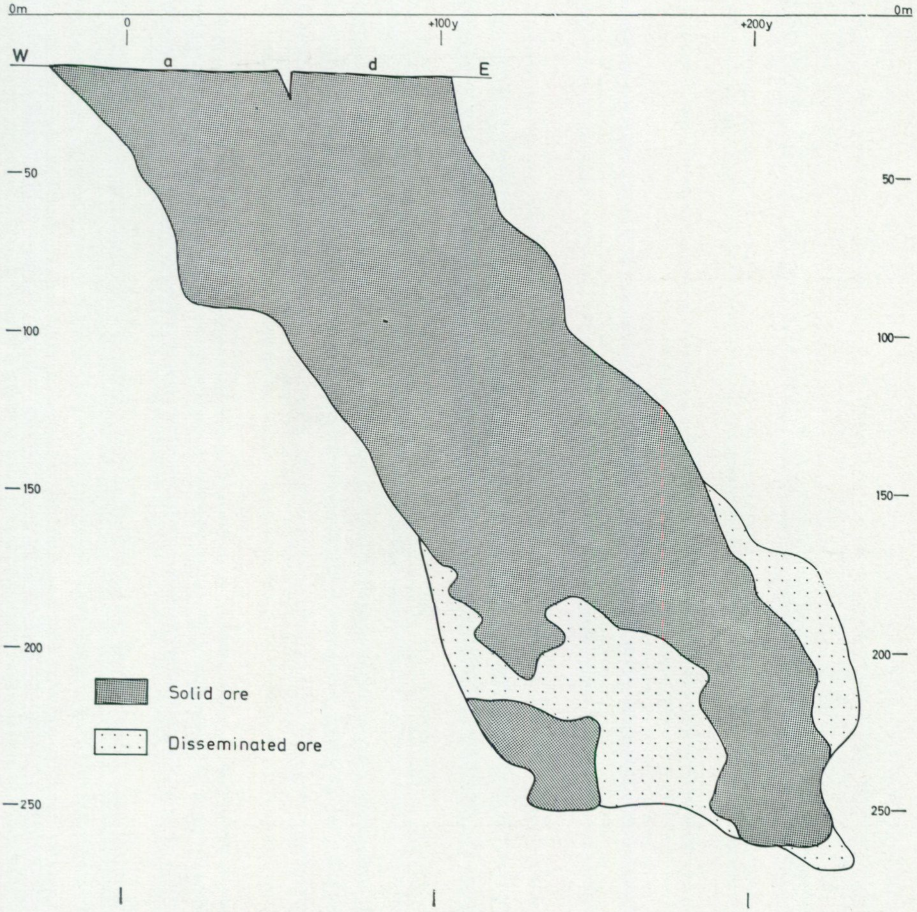
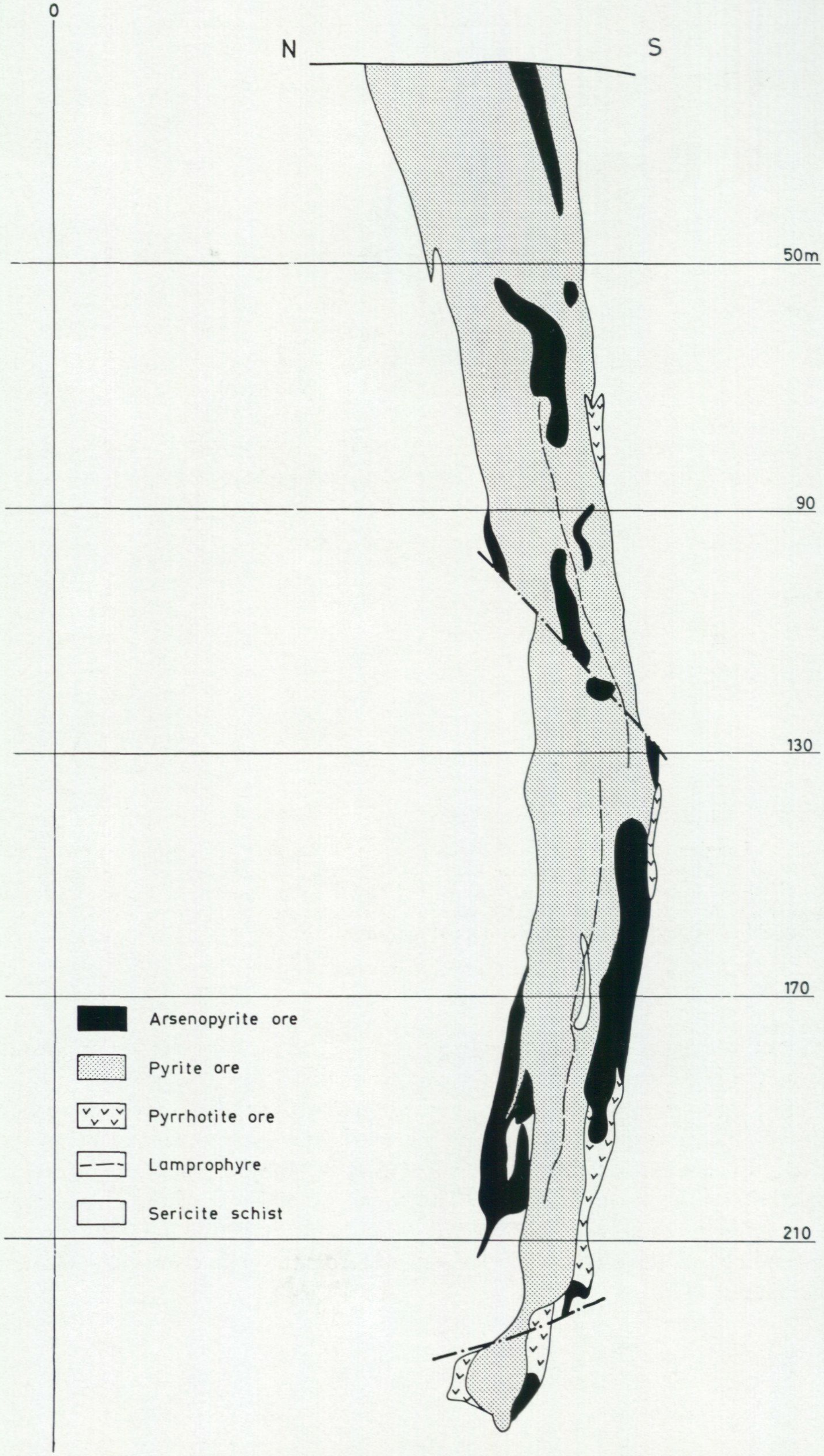


Fig. 22. Longitudinal projection of the a-d-ore lens, the largest of the arsenopyrite ore lenses at Boliden. Though seen as separate bodies at the surface the lenses grow together downwards. 0–170 m level according to Ödman (1941 Fig. 22). The extention of the section downwards was done by Wirstam. At these lower levels disseminated arsenopyrite ore with copper and gold as an envelope enclose the roots of the lenses.

that at least parts of the Fe now fixed as sulfide of the compact ore originated from the Fe-bearing silicates of the country rock.

The high values of MgO found in the outer portions of the envelope as well as the concentrations of alumina in the central zone, accentuated just below the ore body, are explained by the removal of these components from the deeper portions of the solution conduit. The zonal arrangement of the altered wall rocks is believed to have been formed as the results of continuous action of an ascending solution on the wall rock outward from the main channel." – Ödman continues:


0
N
S
50m
90
130
170
210
Arsenopyrite ore
Pyrite ore
Pyrrhotite ore
Lamprophyre
Sericite schist

"The altering solutions are considered to have been hydrothermal and from the beginning weakly acid or alkaline; in the final of the alteration the solutions were probably of a decidedly acid nature. The shearing "– during the entire pre-ore alteration period formed vertical lineations and small foldaxes (cf. Fig. 17). –" In combination with the alteration it 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 or 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.

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" – See Figs. 21–23. "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" – including gold and silver in rather high amounts – "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" – which have arisen through shrinkage – "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 association, 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.

The second stage was initiated by the intrusion of lamprophyres on fissures

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Fig. 23. Cross section through the Eastern Ore just in the front of the Central Shaft (0 y). The upper portion was published by Ödman (1941, Fig. 28). It has been revised by Wirstam, who also completed the section from the 200 m level to the bottom of the ore.

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 sericitication 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" – gold, however, being comparatively high. Arsenic on the contrary – "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" – Ödman believes that the intimate relationship between the lamprophyres and the ores suggests that they are differentiates from a common magma. But according to our view of ore formation briefly mentioned above, the lamprophyre has been a transport medium for elements dissolved and mobilized by the hot basic magma as it rose through rocks containing ore elements. Thucholite and natural gas occurring in the paragenese of the second ore formation stage also indicate on origin from bituminous supracrustal rocks.

"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." – Its eastern end, however, follows the primary vertical linearity while the western end of the Western Ore follows a rather flat east dipping line representing the crosscut between the old landsurface and the vertical shearing plane. –

”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.”

Ödman finishes his summary by stating ”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.”

Contrary to Ödman, we do not believe that an arsenopyrite melt, or ”Speiss” according to the metallurgical nomenclature, necessarily originated from a magma. It could have been formed from disseminations in older rocks through a metasomatic concentration process preceeding a migmatite front. Final mineralization was then restricted to suitable structures.

Boliden is not the only deposit in the Skellefte District which was formed in several different stages. Similar differentiations, always related to tectonic movements, have been reported from several other deposits, even if the composition of the ores varies. The sequence of events usually follows the same pattern, although one or several steps in the sequence may be missing.

Table 12 gives some examples of the types of succession of the ore formation stages found in the deposits of the Skellefte District (cf. Grip, 1951 b).

Table 12. Ore formation stages in some of the deposits of the Skellefte District

Deposit	As	QTL	Py	Cu	Zn	OP
Kristineberg		×	×	×	×	
Rakkejaur	×		×	×		×
Mensträsk	×		×	×		×
Holmtjärn	×		×			
Åkulla		×?	×	×		
Långsele		×?	×			×
Boliden	×	×	×			

As, arsenopyrite stage. QTL, quartz-tourmaline-lamprophyre stage. Py, pyrite stage. Cu, chalcopyrite stage. Zn, sphalerite stage. OP, ”ore pegmatites” (latest crystallization).

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GFF – Geologiska Föreningens i Stockholm Förhandlingar
SGU – Sveriges Geologiska Undersökning

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