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GEOLOGICAL STUDIES  
ON THE CALEDONIAN PYRITIC  
ZINC-LEAD OREBODY  
AT BLEIKVASSLI, NORDLAND,  
NORWAY

By  
F. M. VOKES

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*State geologist  
Fredrik Hagemann*

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Part 1.

The geological setting, mineralogy and petrology of the ore.

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## Abstract.

This paper is the first of a series dealing with various aspects of the Palaeozoic pyritic zinc-lead-(copper) orebody at Bleikvassli, Northern Norway (lat.  $65^{\circ}50'N$ ). The deposit is a typical representative of the conformable class of pyritic deposit, lying in highly micaceous, quartz-rich schists and mica-quartz feldspar gneisses of the Nordland facies of metasediments above the Rødingfjell thrust plane. Considerable thickness of metalimestones occur structurally higher in the succession above the ore horizon, while minor thicknesses of amphibolitic schists, quartzites and graphitic schists occur in the footwall country.

The massive ore, as defined in the text, comprises two main types, the dominant one a heavily pyritic type comprising pyrite, sphalerite, galena, pyrrhotite, chalcopyrite, the other a pyrrhotite-rich type comprising pyrrhotite, sphalerite, galena, chalcopyrite and minor or no pyrite. A numerous suite of minor ore minerals has been identified. Some of these are unusual or unique for such deposits in Norway, especially stannite and cassiterite. The mineralogy-petrology of the two main ore types is described and discussed in detail. It is concluded that the forms exhibited by the pyrite granules are in the main due to metablastic recrystallisation during the Caledonian orogeny. Similar relations are exhibited between the various matrix sulphides, especially the pair sphalerite-galena. Further metamorphic characteristics are shown in directed textures, interfolding of ore and schist bands, folding of ore mineral banding. All transitions are shown from undisturbed ore to ore in which considerable movement has taken place, with disruption of the folding, rotation of schist fragments, etc. The pyrrhotite ore shows a pseudo-breccia texture as the result of «Durchbewegung».

The relations between the two ore types are discussed and it is concluded that they were both present in their present relation to each other before the folding and metamorphism. The original form of the sulphides or their mode of genesis cannot be reconstructed from the present study.

The Bleikvassli orebody mineralogically belongs to the Fløttum class of C. W. Carstens, together with a few other lead rich ores in central Nordland. The class shows considerable mineralogical differences from the normal Norwegian Caledonian pyritic orebodies, even though certain transitional examples may be found among these.

## Introduction.

The Bleikvassli mine lies in Nordland county, Norway, at latitude  $65^{\circ}50'N$  and longitude  $13^{\circ}50'E$ . (Fig. 1). It is situated about 50 kilometres due south of the town Mo in Rana, to which it is connected by some 75 kilometres of all-weather unpaved roads. The area is hilly to mountainous and the mine lies at an altitude of about 450 metres a.s.l. on the lower western slopes of the mountain of Kongsfjell, 1060 metres.

The ore outcrops at Bleikvassli were first discovered in 1914, but although a certain amount of exploratory work was carried out at various times subsequent to this, it was not until 1948 that serious exploratory and development work was commenced. Surface drilling, trenching and shaft sinking were used to outline an ore reserve of 2.4 million tons of pyritic zinc-lead ore and in 1957 a concentrator with a yearly capacity of about 100,000 tons was brought into operation. Up to the end of 1961 500,000 tons of ore had been milled to yield 20,500 tons of lead concentrate, 43,500 tons of zinc concentrate and 148,000 tons of pyrite concentrate. The concentrates are trucked by road to the loading quay at Andfiskåga on Ranafjord, just west of Mo.

## Present investigation.

The writer first visited the mine in November 1958, when samples for mineralogical and geochemical investigations were taken. Following this, detailed examination, sampling, and surface and underground mapping were carried out during the summers of 1959, 1960, 1961 and 1962. The laboratory investigations have been undertaken at the Mineralogisk-Geologisk Museum of the University of Oslo at times during the intervening months.

The investigation was designed to provide a detailed mineralogical, geochemical and geological study of a Norwegian massive sulphide body and, as such, it must be considered as still being in progress. The present report is in the nature of an introduction to the geology of the mine and it also gives a fairly detailed description of the sulphide mineralogy and petrology of the Bleikvassli ore.

The two succeeding parts (later in this volume) deal with, respectively, the supergene alteration of the ore and with the abundances of Cu, Zn and Pb within it. It is hoped to be able to follow the present publication with others dealing with other aspects of the geology of the orebody, as well as of the surrounding area.

### Acknowledgments.

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Professor T. F. W. Barth and Dr. H. Neumann of the Mineralogisk-Geologisk Museum have never failed to give their support, advice and encouragement during the course of the investigation, and the writer is grateful to them and his other colleagues both in the Museum and elsewhere for fruitful discussions of the problems involved. To Direktør H. Fangel, Teknisk direktør I. Jonsson and the staff of A/S Bleikvassli Gruber the writer wishes to express his sincere thanks for permission to work at the mine, for hospitality and help received during the field work and for permission to publish the results.

### Previous work.

Very little work has been published regarding the geology of Bleikvassli mine and its surroundings, but the mining archives of the Geological Survey of Norway (NGU) contain a number of reports concerning the earlier investigations of the orebody, mainly written during the years of the Second World War.

The present writer recently published short accounts of the occurrence of cassiterite and gahnite in the Bleikvassli ore (Vokes 1960, 1962 b) and Geis (1961) gives a certain amount of information regarding the structure of the orebody in a publication dealing with several of the Caledonian massive sulphide deposits.



## General geology.

Figure 1 shows a general geological map of a part of southern Nordland county and the adjacent part of Västerbotten county, compiled from the map-sheets «Hattfjelldal» (Rekstad, 1924) and «Rana» (Holmsen, 1932) from the map published by Bugge (1948) and, to the east of the international boundary, that published by Kulling (1955).

The following account of the general geology of the area is based on the above sources and on the summary accounts by Strand (in Høltedahl, 1960, and 1961).

One of the main geological features of the Palæozoic fold mountain belt of southern Nordland is a major, northerly-trending thrust-plane, forming a boundary between the rocks of the Nordland facies to the west and those of the Trondheim region facies to the east. Apart from the rather marked lithological differences between the rocks of the two facies, there is also a considerable difference in their metamorphic grades. The Nordland facies rocks consist of a very thick succession of pelites with minor quartzites, and, especially in the upper parts, great thicknesses of limestones and dolomites. Rocks of apparent volcanic derivation are present, but as far as is known at present, these are minor in amount. The metamorphic grade in these Nordland facies sediments is normally high, corresponding to the epidote-amphibolite or amphibolite facies of regional metamorphism. The low grade metamorphic rocks of the Trondheim region facies to the east of the thrust plane contain very high proportions of acid, and especially basic, volcanic members, both lavas and pyroclastics as well as many intrusive bodies of varying sizes — peridotites-serpentinites, gabbros and trondhjemites.

Thus the Bleikvassli zinc-lead orebody in common with a number of sulphide prospects in Nordland, lies in a nappe (Rødingfjell nappe) of fairly high-grade metamorphic rocks which is thrust to the east over rocks of lower metamorphic grade. These latter rocks, mainly in Sweden, also contain relatively small massive sulphide orebodies, which carry varying amounts of copper, and also of zinc and lead, as their base metal components.

There are very few known sulphide deposits in the immediate vicinity of Bleikvassli, and none of obvious economic importance.





## The Bleikvassli ore deposit.

### THE COUNTRY ROCKS

The immediate country rocks of the Bleikvassli orebody comprise gneisses, schists and minor quartzites, with related pegmatites. The dominant minerals are quartz, mica (muscovite, biotites of various types, and light brown mica, possibly phlogopite), microcline, and albitic plagioclase. Graphite-bearing schists and quartzites play an important role, particularly in the foot-wall of the ore deposit. Garnet, staurolite and spinel (gahnite) are constituents of certain, rarer, rock types, while in places epidote-(clino)zoisite appears in notable quantities. Sphene and calcite are sometimes present as accessory minerals.

The grain size is predominantly fine to medium. The quartzo-feldspathic constituents in any rock type are normally of finer grain than the micaceous ones, the latter often range up into the coarse grain size. The texture is dominantly schistose, due to the parallel arrangement of the mica flakes, or gneissose due to the parallel banding of the quartzo-feldspathic, and the micaceous constituents, respectively. As far as can be ascertained, the metamorphic foliation is parallel to the primary sedimentary banding of the rocks.

The strike of the country rocks at Bleikvassli is dominantly NE, ranging between  $30^{\circ}$  and  $40^{\circ}$ \*. In places local folding produces deviations from this general strike direction, but otherwise it is quite constant over relatively large areas. Dips are to the NW, varying between  $40^{\circ}$  and  $90^{\circ}$ . In most exposures there is an apparent conformity between the schistosity of the country rocks, the walls of the orebody and the schist inclusions in the ore, though locally, crosscutting relations do exist.

The schists and gneisses normally show a marked lineation, defined by a parallel arrangement of the minerals and by minor folds and corrugations. A stereographic plot of one hundred of these lineations taken in the immediate vicinity of the ore deposit, on the surface and underground, indicates that the fold axes and other linear elements plunge dominantly in a westerly direction, ranging between about  $370^{\circ}$  and  $330^{\circ}$  true bearing. The amount of the plunge is usually fairly low, between  $20^{\circ}$  and  $40^{\circ}$ .

\*400 degree circle.

About 7 km SE of the mine, on the southern slopes of Kongsfjell, there is an area showing weak chalcopyrite-pyrrhotite and galena-sphalerite-pyrite mineralization which has not been investigated in detail. On Rostafjell, 30 km due north of Bleikvassli, lead-zinc showings have been known for some time (Torgersen, 1928, pp 30-34) and on the eastern side of the Hemnes peninsula at Svalengen, there are both lead-zinc and copper-pyrrhotite prospects. (Torgersen, *op. cit.*, pp 34-36).

Further north, in the Rana area, is the producing zinc-lead-copper mine of Mofjell as well as many prospects of varying promise. The nearest known sulphide deposit southwards from Bleikvassli is at Ravnåsen, about 37 km SW of the mine. Here lead and zinc sulphides occur in a long narrow zone of calcsilicate rocks (Torgersen, *op. cit.*, pp 14-18). Grip (1952, p. 369) has briefly described the Swedish sulphide deposits lying generally to the east of the Bleikvassli area. (see also Wickman et al, 1963).

Although the detailed geology of the Bleikvassli area is little known at present, the larger relationships are clear, as shown in Figure 1. The area is underlain dominantly by metamorphic rocks of apparently sedimentary origin, with none of the large bodies of gneissose granitic rocks which are a feature of the geology of the Nordland region further towards the coast.

To the west of the mine area is a N-S striking belt, perhaps 5 km wide, dominated by considerable thicknesses of crystalline metalimestones, with occasional lenses of quartzo-feldspathic gneiss. To the east of this belt the rocks are mainly mica schists and mica-feldspar gneisses with lesser amphibolitic rocks, green schists and minor metalimestones.

The general strike of the rocks in the vicinity of the mine is NE, with dips to the NW. Further east, along the shores of Bleikvatn, the strike becomes E and then ESE. The structure of the Kongsfjell area, east of the mine, appears to be in the form of a large syncline. Areal mapping is now in progress to elucidate the regional stratigraphy and structure.

In detail the structure of the area around the Bleikvassli orebody is much more complicated than just indicated. However, the subject will not be enlarged upon in the present publication.

At the present state of development of the mine, underground exposures of the country rocks, away from the immediate vicinity of the ore, are rather limited, so that it is often not possible to determine the true extent and structure of any one rock unit. In general the foot-wall rocks are much better exposed than the hanging-wall ones, due to the crosscuts to ore from the main inclined shaft at the various levels, and to the foot-wall transport drives. Up to the time of writing little diamond drilling has taken place from the underground workings and the cores from the original surface drilling are not available.

*Foot-wall rocks.* The rocks exposed along the foot-wall of the ore zone show differing characteristics in different parts of the mine, and, especially on the upper levels, there are marked differences between the foot-wall rocks in the northern part of the mine as compared with the southern part.

From the surface downwards for a vertical depth of about 120 m the northern part of the ore zone is structurally underlain by an apparently homogeneous body of fine-grained, grey microcline-quartz-biotite gneiss. This body has an outcrop strike length of at least 250 m and a maximum width across the strike of about 150 m, but it appears to narrow down in depth and may have the form of a boat-shaped body lying in the schists. In the northernmost part of the mine this microcline gneiss immediately underlies the ore, but southwards a variable thickness of white muscovitic quartzite comes in between the gneiss and the ore. Further south both the gneiss and quartzite swing away from the ore zone into the foot-wall country and their place is taken by a variable thickness of highly micaceous schists and gneisses.

The microcline gneiss appears on *both walls* of the orebody in places in the northernmost stopes, where the ore begins to thin out, but the exposures are too limited to allow any structural conclusions to be drawn.

The highly micaceous schists and schistose gneisses along the foot-wall in the southern part of the mine do not lend themselves readily to any clear-cut lithological-stratigraphical divisions and no definite units have been defined in them.

The limited exposures of the foot-wall schists on the lower two levels (280 m and 230 m) reveal to a large extent highly micaceous schists and gneisses of the types seen in the southern part of the mine on the higher levels. Bands of quartzitic rocks occur frequently interbanded with the schists and gneisses. These quartzitic bands range in thickness from less than a metre to perhaps 2 to 3 m in thickness though in several cases it is obvious that tight, often isoclinal, folds have repeated and thickened up the beds to the widths exposed.

The quartzitic rocks are of two main types. One comprises grey to white, fine- to medium-grained, banded quartzites not too different from the quartzite overlying the microcline gneiss, though without its, often high, muscovite content. The second type of quartzite is dark grey to black, the colour being due to finely divided graphite in varying amounts. Iron sulphide, mainly pyrrhotite, is abundant in this rock type. Transitions appear to occur between hard, highly siliceous types and more or less graphite schists. It may be mentioned here that, while the graphite-sulphide quartzites have not so far been recognised in surface outcrop, graphite schists are exposed at several places on the surface both east and west of the ore zone.

In addition to the above-described rock types, coarse garnet-mica schists are strikingly exposed in several places, especially near the foot-wall of the ore. They occur as concordant bands or lenses in the other schists, varying in thickness from some few centimetres to perhaps one or two metres. The garnets, which are from 0.5 to about 2 cm in diameter, occur in a coarse grained, lustrous groundmass of both muscovite and dark-brown biotite. Sulphides are usually richly disseminated throughout these bands.

*Hanging-wall rocks.* Exposures of the hanging-wall rocks, underground at least, are much more limited than is the case with the foot-wall rocks. They bear great similarity to the foot-wall rocks in the southern part of the mine—heavily micaceous schists and schistose gneisses, with an occasional band of coarse-grained garnet schist. During surface mapping great difficulty was experienced in distinguishing rock units, and the few that were defined could not normally be followed for more than a few tens of metres along the strike.

As previously mentioned, microcline gneiss appears on both the hanging- and foot-walls of the ore zone towards its north end. In places this gneiss takes on a streaky and contorted appearance, in which the micaceous constituents are segregated into lenses, bands,

or «schlieren» of irregular and indefinite shape. Chlorite is developed in small quantities in this rock.

In the central part of the mine, a hanging-wall crosscut exposes 3—4 m thickness of a microcline-quartz-biotite gneiss, petrographically identical with the large body of this type of rock which occurs in the foot wall. There is at present no means of deciding the size and extent of this gneiss body, no rock of similar character has been seen so far in surface exposures of the hanging-wall rocks.

At a couple of localities in the mine, staurolite is an important mineral constituent of the hanging-wall rocks. It occurs as coarse, irregular grains in the biotite-quartz schist on the hanging-wall of the orebody. In thin section the staurolite appears as large, anhedral, poikilitic plates, showing a very well developed sieve texture with quartz grains.

## THE FORM AND STRUCTURE OF THE DEPOSIT

Although it is not intended to deal with the structure of the Bleikvassli orebody in detail in this publication, a summary is given here of its main features.

At the time of writing (late 1962) the orebody has been developed along a strike length of some 400 m on three main levels, the 430, 380 and 330 m levels. (The figures denote height above sea level, the highest point of the outcrop being around 450 m). The main incline shaft has been sunk below the 230 m level and crosscuts have been driven from it to intersect the ore zone on the 280 and 230 m levels. Foot-wall drives north and south have been driven from these crosscuts for varying distances. On the 280 m level stoping has been commenced for distances up to about 80 m north and south of the shaft crosscut.

The orebody as developed consists of a series of interconnected and branching plates or lenses of massive sulphides lying apparently concordantly in the schistose and gneissose country rocks. This concordance is especially marked in the southern part of the orebody, where the country rocks are dominantly schists. However, there is a suggestion that the orebody is crosscutting its wall rocks slightly towards the north, but this is something which has yet to be proved or disproved.



The individual plates or lenses of massive sulphides vary greatly in thickness along both strike and dip directions. The maximum width of ore so far encountered underground is about 10 to 15 m. Surface drill hole logs record widths of the same order, including barren schist partings of subordinate thicknesses. At the other extreme, the orebody is represented in places by strips of sulphides only a decimetre or two in thickness.

Within the ore zone as a whole individual plates and lenses of sulphides thin out and disappear along both strike and dip and new lenses appear in an apparently *en echelon* fashion. The ore plates also frequently branch and divide and it is a matter of great importance in underground development work to be able to predict which branch is the main one. During the mapping emphasis has therefore been laid on determining any possible regularity in the system of lenses and plates which would assist the management in planning a more rational development system.

The mapping seems to show that the *en echelon* arrangement is such that, northwards along the strike, the new lens or plate appears in the hanging-wall of the former one. Similarly the new plate appears down dip in the hanging-wall of the old one.

So far it has not been possible to work out corresponding regularities in the branching of the individual ore-plates. Geis (1961) maintains that such a regularity is observable, with the branches on the hanging wall diverging in a southerly direction, while those on the foot-wall split off to the north. The present writer has, however, mapped a large branch of the ore in the foot-wall of the stopes above the 330 m level N which splits off in a southerly direction. More detailed work is needed to clear up this point. The latest mapping, however, seems to indicate that the detailed form of the orebody is often governed by very tight, often isoclinal, overturned folds, in which both the ore and its wall rocks are involved. Interpretation of these fold structures awaits further mapping as the mine is developed.

The ore zone as a whole, to judge from the somewhat limited amount of development to date, appears to pitch at  $100^\circ$ , i.e., down the dip of the enclosing schists. Since the plunge of the fold axes and lineation in the area is SW or WSW at between  $20^\circ$  and  $40^\circ$ , there is thus no apparent correlation between this structural feature and the form of the ore zone. In many deposits in the Caledonian orogenic zone there is good coincidence between the plunge of the

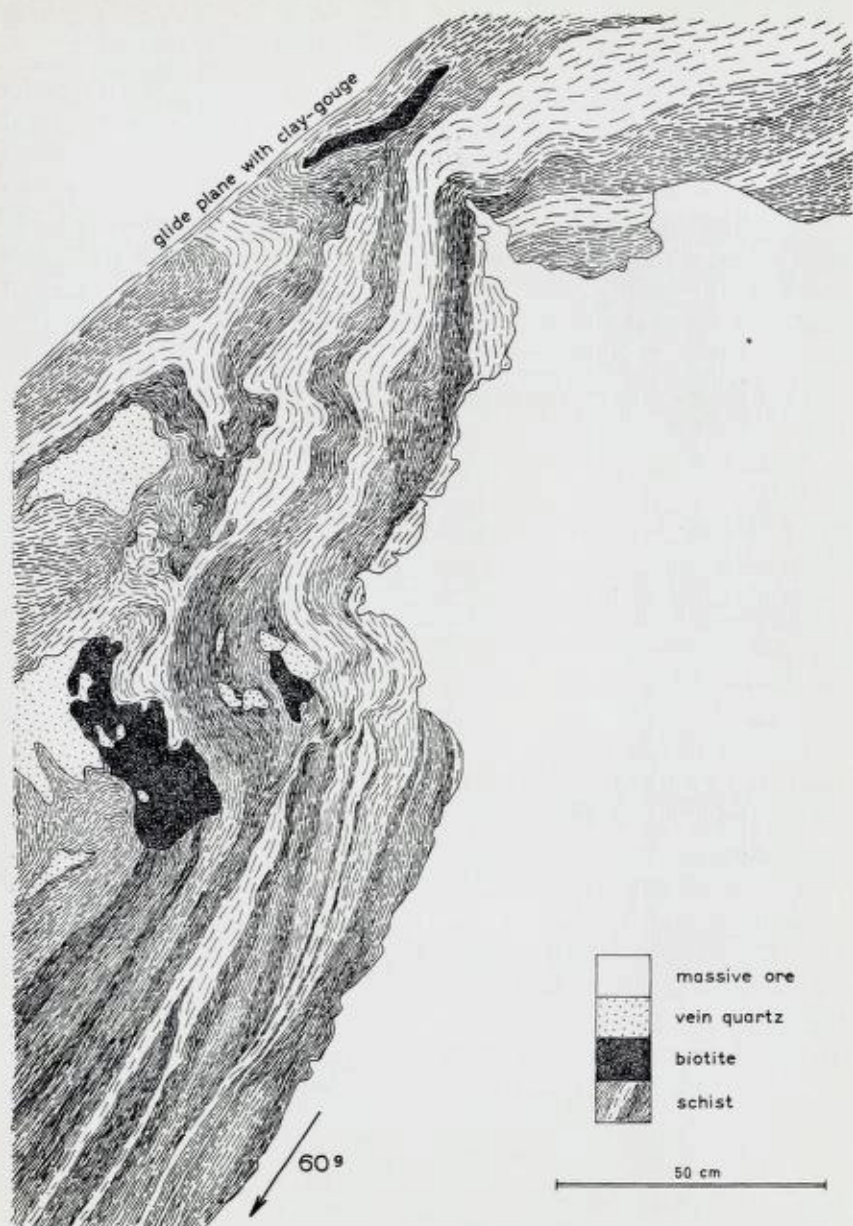


Figure 2. Sketch (from photograph) of hanging-wall of ore in 330 m level south stopes, showing local crosscutting of schistosity by sulphides in crest of larger fold.  
 Fig. 2. Skisse etter foto fra malmens henggrense på 330 m nivå S, som viser hvordan malmen lokalt overskjærer skifrene i en foldestruktur.

longer axes of the orebodies and of the fold axes and/or lineation in the country rocks (see Vogt, 1944, 1952, Vokes, 1957).

However, as the ore is developed in depth a truer picture of its form will be obtained and a more accurate correlation with structural features will be possible.

The ore walls in general are conformable to the schistosity in the surrounding rocks, but often crosscutting relationships are seen in connection with fold structures. (see Figure 2). The wall rock contacts are normally quite sharp, but occasionally there is a transitional gradation from the massive ore by way of a pyritic impregnation in the wall rock schists.

Thus the picture of the orebody as a whole is one of apparent conformability between the massive ore, the immediate wall rock schists, schist inclusions in the ore (see below) and isolated bands or strips of sulphides. This conformability is in places much disturbed by the fold structures mentioned above. Along strike and dip the ore plates or lenses appear to thin out gradually, preserving the apparent conformability with the immediately enclosing schists.

## TYPES OF ORE

The ore within the above-described plates or lenses is a more or less heavily sulphidic type in which the content of gangue minerals varies within fairly wide limits, but is always under 40 wt. percent. For the purposes of the present description this will be referred to as the «massive ore» even though a good deal of it is probably not sulphidic enough to deserve this term when used in a general sense (See the remarks of Gunning, 1959). In addition, the wall rock schists, especially on the hanging-wall, are often mineralized to a lesser extent. By far the greater bulk of the ore is of the massive variety, but the disseminated wall rock mineralization can be quite rich, especially in lead, and is often stoped in considerable quantities together with the massive ore.

### MASSIVE ORE

This is of two types. By far the greater part is a medium-grained, pyrite-sphalerite-galena ore, usually with small amounts of pyrrhotite and lesser amounts of chalcopyrite. The less abundant type consists

dominantly of pyrrhotite and more or less the same amounts of sphalerite and galena as the pyritic type, but usually a good deal more chalcopyrite. The pyrite content varies from zero to a few percent.

### Composition of the massive ore.

The relatively homogeneous texture and generally medium grain size of the Bleikvassli massive ore, especially the pyritic type, lend themselves to modal mineralogical analysis by point counting in polished section. This method has been utilised intensively in the present study to investigate the general mineralogical composition of the ore, to see if systematic relationships exist between the various

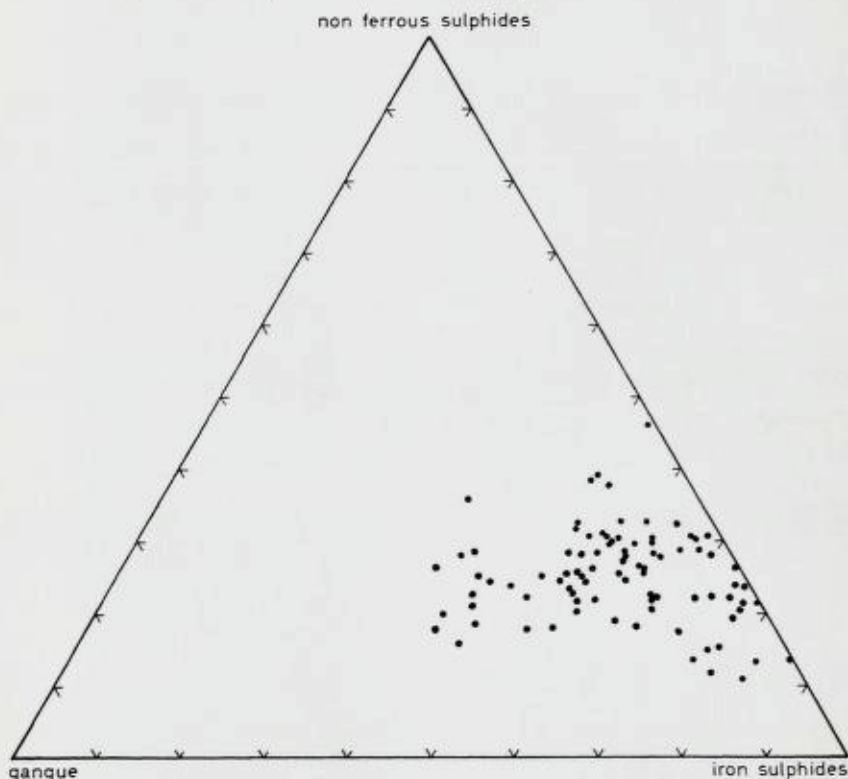


Figure 3. Triangular compositional diagram showing mineralogical composition of Bleikvassli massive ore.

Fig. 3. Trekant-diagram som viser den mineralogiske sammensetning av Bleikvassli-malmen.

components and to detect any possible variations in composition along any dimension of the orebody.

The general mineralogical composition of the ore is depicted in Fig. 3, a triangular plot showing the relative proportions of iron sulphides, non-ferrous sulphides (sphalerite + galena + chalcopyrite) and gangue minerals. The diagram shows that the points fall in a relatively limited part of the field, indicating in general a rather homogeneous mineralogical composition. The greatest variation is seen in the gangue mineral content, while the content of non-ferrous sulphides shows the least variation.

The points represent the mineralogical modes of 92 polished sections counted on a Swift Automatic point counter,  $\frac{1}{16}$  mm spacing between points, 1 mm spacing between lines, 1000 points per section.

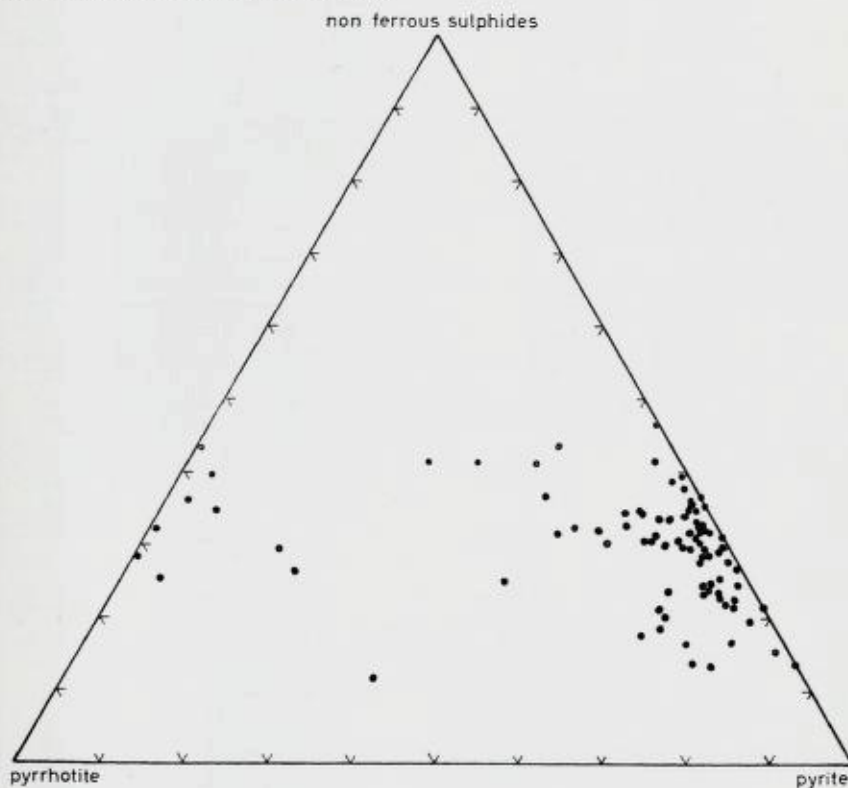


Figure 4. Triangular compositional diagram showing the ganguefree mineralogical composition of Bleikvassli massive ore.

Fig. 4. Trekant-diagram som viser malmens mineralogiske sammensetning uten gang-mineralene (kvarts, glimmer osv.).

In order to investigate the relations between the various sulphide components of the ore, the figures used in plotting Figure 3 were recalculated to 100 percent, free of gangue minerals. The resulting data were then plotted on another triangular diagram as pyrite, pyrrhotite and non-ferrous sulphides (Fig. 4). This diagram brings out the mineral compositional differences between the pyritic ore and the pyrrhotite-rich type. As can be seen, the majority of the points, representing the pyritic ore, is concentrated towards the pyrite — non-ferrous sulphides join, showing low pyrrhotite contents, usually below 15 percent. Grouped fairly close to the pyrrhotite — non-ferrous sulphides join are seven points representing the typical pyrrhotite rich ore, showing less than 5 percent pyrite. The diagram reflects very well the division into the two types of ore which is readily made on the basis of megascopic and microscopic observations. There is a short spread of a few points from the pyritic field towards the left, indicating an increased pyrrhotite content, but on the whole the two fields are well separated. Examination of those specimens, the points for which fall between say, 15 and 30 percent pyrrhotite, shows that they come from either the junction between the two ore types, or from certain thinner bands of sulphides, usually along the margins of the thicker ore lenses.

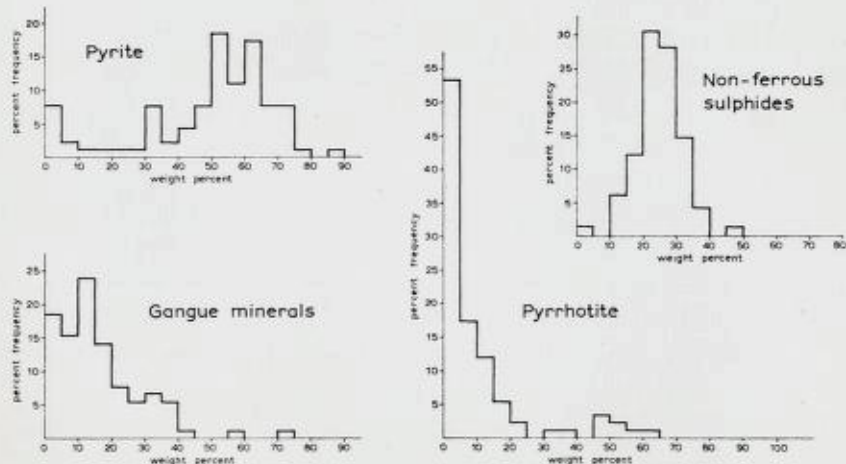


Figure 5. Histograms showing the frequency distributions of the mineral contents of the Bleikvassli massive ore.

Fig. 5. Histogrammer som viser frekvens-fordelingene av mineralinnholdet i Bleikvassli-malmen.

The histograms in Fig. 5 show the frequency distributions of the main mineral components of the massive ore. The most striking feature is the normal distribution of the non-ferrous sulphides and their limited spread, nearly 60 percent of the points lying between 20 and 30 weight percent.

Plots of the relations of pyrrhotite against chalcopyrite and pyrrhotite against sphalerite plus galena, (not reproduced) showed a general sympathetic trend in the former case, but no correlation in the latter. A sympathetic variation was also found in a plot of the sphalerite against the galena contents of the ore, though this is not as significant as the one between pyrrhotite and chalcopyrite.

Further graphical examination of the modal data fails to reveal any significant relationships between other pairs or groups of minerals.

Of the other opaque minerals in the ore, only magnetite and arsenopyrite have ever been found in quantities sufficient to figure in modal analyses. Their distribution is discussed below, p. 22.

Mineralogical variations *across the width* of the Bleikvassli orebody find macroscopic expression in the transition from the pyrrhotite-rich bands which, when present, occur preferentially along the foot-wall, to the massive, rather homogeneous pyrite ore which forms the bulk of the orebody. Within the latter, mineralogical variations are seldom very noticeable on a macroscopic scale and a series of sections were sampled for microscopic examination in order to see if significant mineralogical variations could be detected.

In all twelve sections were sampled in varying detail and polished sections prepared for point counting. The sampling covered wide sections of massive ore, both where the pyrrhotite rich band was present and where it was lacking, narrow sections of massive ore, and sections where the ore was split into separate bands by significant widths of schist. In all cases no mineralogical variations were seen in the massive ore when taking the samples, which can be considered to be quite random.

Examination of the mineralogical modes of specimens taken across these sections showed systematic variations in the case of pyrite and, to a lesser degree, non-ferrous sulphides and gangue minerals. Considering for a moment variation of pyrite content across sections of the massive pyritic ore only, in eight out of nine cases there was a marked to moderate *increase* from foot-wall to hanging-wall. The percentage differences in pyrite contents between the two walls ranged from 10 to 52, with an average for the eight sections of

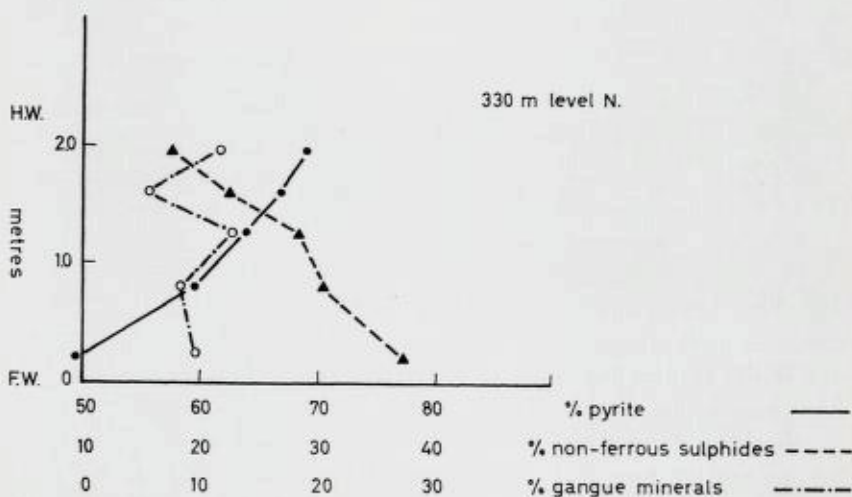
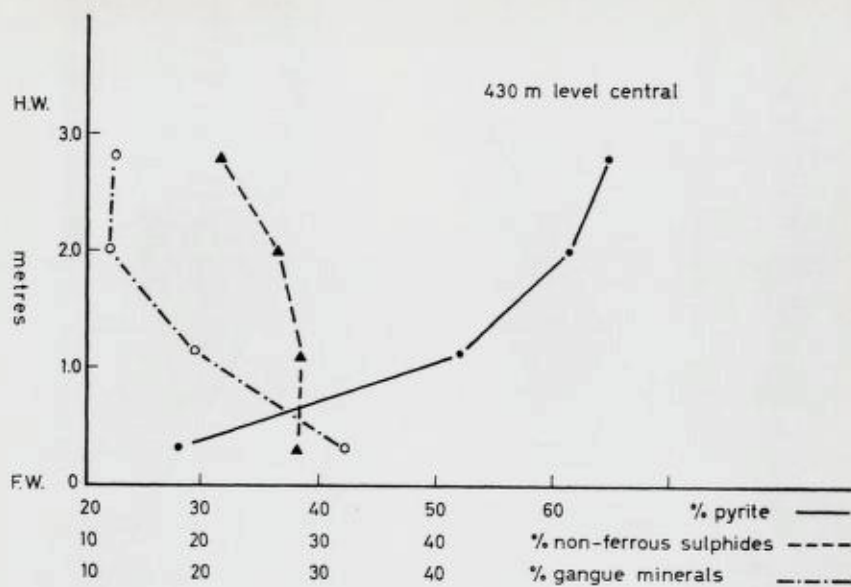


Figure 6. Graphs illustrating variations in contents of pyrite, non-ferrous sulphides and gangue minerals across the width of the Bleikvassli ore-body.

Fig. 6. Grafiske fremstillinger av variasjoner i innholdet av svovelkis, bly-, sink- og kopper-sulfider og gangmineralene på tvers av Bleikvassli-malmen.



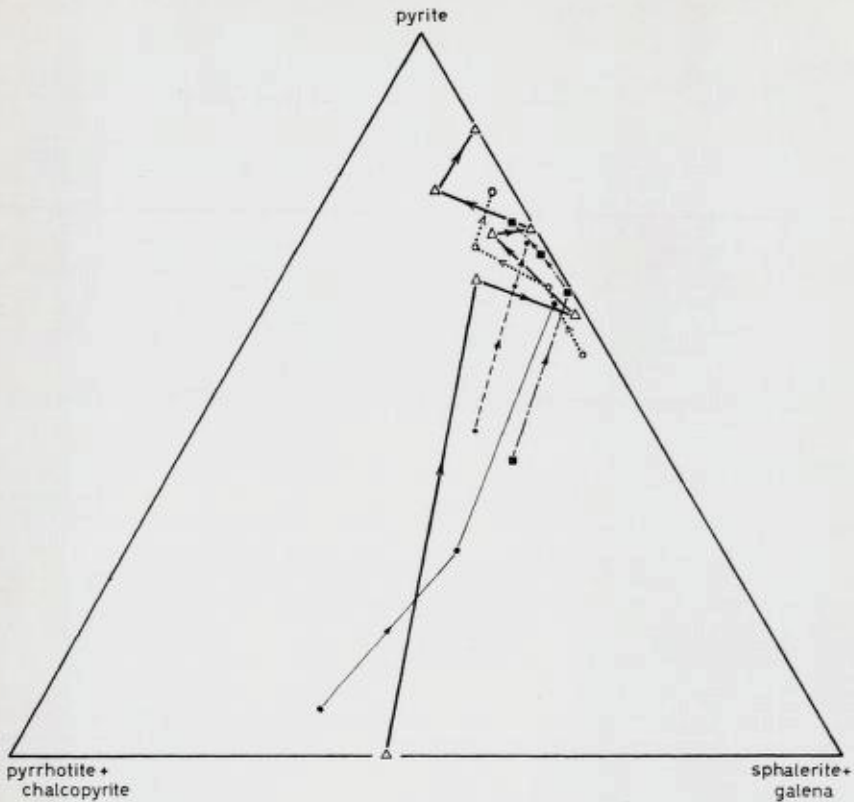


Figure 7. Triangular diagram illustrating mineralogical variations across the width of the Bleikvassli orebody. Arrows are drawn from foot-wall to hanging-wall.  
 Fig. 7. Trekant-diagram som viser mineralogiske variasjoner på tvers av Bleikvassli-malmen. Pilene er tegnet i retning ligg til heng.

28. The type of variations is shown in Figure 6, where the vertical coordinate shows the position of each sample with respect to the ore walls, and in Fig. 7, where the modal analyses of sections have been plotted on a triangular diagram. No complimentary decrease in pyrrhotite content from foot-wall to hanging-wall of the pyritic type of ore can be discerned from the modal figures, but it seems significant that, where present, the pyrrhotite-rich ore, in which pyrite is practically absent, nearly always occurs as a foot-wall zone. Thus there seems to be a definite change from a sulphur-poor to a sulphur-rich assemblage in the direction foot-wall to hanging-wall. In the case of composite ore sections there is an abrupt increase in sulphur

content at the change from pyrrhotitic to pyritic ore, but within the pyritic ore there is also a general, steady increase in sulphur up to the hanging-wall. The following data illustrate the trends of pyrite content across the orebody.

*Variation in pyrite content from F.W. to H.W. (All sections).*

Steady decrease.	Steady increase.	Higher in centre.	Lower in centre.
1	9	1	1

The trends exhibited by the non-ferrous sulphide contents across the measured sections are not as consistent as those shown by the pyrite, but in seven out of the twelve sections there was a definite, though not numerically large, *decrease* in non-ferrous sulphide contents from foot-wall to hanging-wall (See also Figs 6 and 7). In the case of the individual non-ferrous sulphides, values show a steady decrease across the sections from foot-wall to hanging-wall more often than any other form of variation. The strongest tendency is shown by galena, followed by chalcopyrite and then sphalerite, e.g.

*Variation of non-ferrous sulphides from F.W. to H.W. (All sections).*

	Steady decrease	Steady increase	Higher in centre	Lower in centre	Irregular
Galena . . . . .	7	1	3		1
Chalcopyrite . . . . .	4	3	2	1	2
Sphalerite . . . . .	3	1	3	2	2
Total n.f. sulphides	7		2	3	

In the case of the content of gangue minerals in the massive ore, the data show more often than not a decrease in amount from foot-wall to hanging-wall. This applies to the gangue minerals actually intergrown with the sulphides, independently of the schist inclusions and partings.

*Variation of gangue minerals from F.W. to H.W. (All sections).*

Steady decrease	Steady increase	Higher in centre	Lower in centre	Irregular
7	1	3		1

The above-described variations across the sections of the Bleikvassli massive ore may be summarized as follows.

Along the foot-wall there is present in places a zone or band of pyrrhotite ore in which pyrite is typically absent, but in which there may be a slightly higher than average non-ferrous sulphide content, mostly due to increased chalcopyrite. The gangue mineral content is usually high. From the junction with the overlying pyritic ore, or, where the pyrrhotitic band is absent, from the foot-wall upwards, there is a steady increase in pyrite content and complementary, though less well-marked, decreases in non-ferrous sulphides and gangue minerals.

These variations across the width of the orebody are discussed later in this publication, pp. 81–82.

There is very little statistical evidence regarding variations in the contents of other minerals across the width of the Bleikvassli orebody. Arsenopyrite and magnetite are met with relatively rarely in the massive ore and only in isolated cases has any instance of a distinct concentration with respect to the ore walls been noted.

Arsenopyrite has only once been present in sufficient amounts to figure in modal analyses. In a section taken across about  $6\frac{1}{2}$  m of ore at about the 420 m level, central, arsenopyrite appeared in specimens from the  $2\frac{1}{2}$  m nearest the hanging-wall. The average content, as counted, was just under 0.2 percent. Such sparse data do not allow any conclusions to be drawn regarding the general distribution of arsenopyrite, but it is worthwhile remarking that arsenopyrite is a prominent constituent of the disseminated mineralization in the hanging-wall rocks of the mine, especially in the southern half.

Magnetite is also a minor and apparently erratic constituent of the Bleikvassli ore and only two instances of it being present in sufficient quantities to be recorded in modal analyses have so far been met with. In a section across  $7\frac{1}{2}$  m of «solid» pyritic ore in the stopes above the 330 m level, south, an average of 0.5 weight percent magnetite occurred in the two metres nearest the foot-wall. In this section, no pyrrhotite ore was present along the foot-wall, and it may be remarked here that no magnetite has as yet been identified in the pyrrhotitic ore from Bleikvassli.

The second occurrence of notable quantities of magnetite was in ore exposed in the prospecting winze below 330 m level, central, at approximately the 310 m elevation. The ore zone here consisted of

two bands of sulphide separated by one metre of tightly folded mica schist. The upper band, 0.75 m in thickness, showed the following modal analysis: (weight percents).

pyrite .....	65.8
pyrrhotite .....	15.8
non-ferrous sulphides .....	3.3
magnetite .....	9.0
gangue .....	6.1

This analysis is quite atypical of the Bleikvassli pyritic ore, the pyrrhotite content is rather high and, especially, the base metal sulphide content is very low. In no other section analysed does the content of base metal sulphides fall below 10 percent. It would thus appear that with such an unusual composition it would be unwise to place any general significance on the occurrence of magnetite in this hanging-wall band. The lower band at this locality, 0.5 m thick, shows an almost average composition for the pyritic ore and contains no magnetite.

The other minor metallic minerals in the Bleikvassli ore do not lend themselves to quantitative estimation by modal analysis due to their fine state of division and erratic distribution. However, close study of polished sections fails to give any indication that their presence or absence is in any way related to distance from either of the ore walls.

At the present state of development of the mine, insufficient data are available to enable definite mineralogical variations along the strike and dip dimensions of the orebody to be determined. The few data which are applicable indicate a rather even distribution of pyrite and total non-ferrous sulphides, for example.

As the mine is developed in depth any such trends, if present, will become more determinable.

### Composition of the gangue.

The non-opaque minerals of the Bleikvassli ore are dominantly quartz and mica. The latter is usually a colourless muscovite or less frequently a pale brown phlogopitic type. Quartz normally constitutes between 70 and 90 percent of the gangue minerals, while mica accounts for between 10 and 20 percent. Plagioclase feldspar is present

in some of the thin sections examined, but nowhere makes up more than 10 percent of the total gangue. Other non-opaques observed in thin section in the ore comprise cassiterite, gahnite, (clino)zoisite-epidote, chlorite, apatite and carbonate. Of these all but the last-named occur in amounts of the order of about one percent or less. Carbonate was observed as sparse grains in only a few sections.

Quartz occurs typically in fine- to medium-grained allotriomorphic aggregates showing an intimately recrystallised texture with sutured grain boundaries. The grain size of the aggregates varies over fairly wide limits, often in any one thin section, but mostly this seems to be due to granulation and crushing rather than to marked differences in the grain size of the original material. The quartz grains in general show a weak to marked preferred orientation in most sections, though this is often markedly disrupted. No signs of grain size banding have been noted in the quartz of the gangue to the massive ore.

The dominant mica is a colourless muscovite which occurs in individual flakes and shreds or in more or less parallel oriented books and aggregates. In the heavily sulphidic ore muscovite is on the whole a minor constituent, occurring as a few isolated flakes. It is an abundant constituent of the schist partings and inclusions in the massive ore, and in the less sulphidic mineralization towards the ore walls in certain localities. In these latter cases the muscovite occurs in parallel orientation, usually in almost monomineralic bands, alternating with bands of almost pure quartz mosaic.

A light brown, moderately pleochroic, mica is present along with the muscovite in a few of the specimens examined. Much more rarely this mica is the only type present in the ore. Biotite (brown, markedly pleochroic) is a lesser constituent. The relations between the various types of mica in the Bleikvassli ore have not become apparent during the present investigation. The different types are all present in the wall and country rocks of the ore deposit and they seem in no way to be unique to the ore.

Plagioclase feldspar is a minor constituent of the massive ore. In many thin sections examined no identifiable plagioclase is present. Otherwise it occurs as odd grains in the quartz mosaic with the same general grain size as the quartz. In a few sections the plagioclase grains seem to be concentrated along a definite band or layer in the ore and in such instances show a slightly larger grain size than the quartz. Such bands are, in addition, usually quite rich in muscovite. Often

the plagioclase in these bands shows a remarkable intimate intergrowth with the sulphides, which takes the form of a crude semigraphic texture, with small, irregular, though generally rounded, bodies of the sulphides distributed throughout the feldspar, apparently controlled by its cleavages. The plagioclases in such zones also frequently show included skeletal flakes or blades of white mica.

The plagioclase in the Bleikvassli ore is either weakly twinned (albite law) or else is free from twin lamella, and it is difficult to find enough grains on which to obtain a value for the maximum extinction angle. Those measurements that could be carried out indicate that the mineral is an albite, around  $An_{10}$ .

This is in agreement with the type of plagioclase feldspar found in the wall rock schists. No microcline has been observed in the ore.

The zinc spinel, gahnite, and garnet are rare constituents of the massive ore. The occurrence of gahnite forms the subject of a separate paper (Vokes, 1962 b). Garnet, though rather abundant in the wall rock schists, is seldom observed in the massive ore. In thin sections of impregnation type ore from near the walls of the ore body, garnets are often abundant as normal rock-forming constituents showing a typical poikilitic texture. Often, besides quartz and micas, opaque minerals form inclusions in these garnets.

A dirty green epidote is present as individual, often euhedral, grains scattered sparsely throughout the gangue in some specimens. In most cases the grains are enclosed by a shell of clear, later (clino)-zoisite. The latter mineral by itself is extremely rare in the massive ore, contrasting strongly with the wall rocks where it is often abundant.

Chlorite has been rarely observed in the quartz mosaic as greenish fibrous aggregates. It does not appear to be replacing an earlier formed mineral.

Apatite is also a very rare constituent of the gangue as individual, widely scattered subhedral to euhedral crystals associated with the quartz.

Carbonate, probably calcite, occurs as irregular to ragged patches in a few of the specimens examined.

Tourmaline has not been observed in thin sections of the Bleikvassli massive ore, but one stubby crystal of the mineral about one centimetre long, was collected from pyrrhotite-rich ore in the zone intersected by the 280 m level crosscut from the shaft. In this connection it



may be mentioned that tourmaline occurs as a constituent of some pegmatites in the country rocks surrounding the orebody.

Thus the gangue minerals at Bleikvassli are minerals which are present in the surrounding schists and gneisses, i.e. mainly quartz, micas and lesser albitic plagioclase. There is nothing to suggest that the gangue minerals are «introduced», they seem to form an integral part of the non-sulphide metamorphic assemblage of the area as a whole.

### The pyritic ore.

This type of ore, forming the vast bulk of the Bleikvassli deposit is a dominantly equigranular, medium-grained ore with, locally, bands or zones of fine- or coarse-grained types. The texture of the ore is determined by the closely crowded granules of pyrite, the shapes of which vary from euhedral (cubes) to anhedral. Apart from the very minor arsenopyrite, and to a lesser extent the pyrrhotite, pyrite is the only ore mineral which does show crystal outlines. The other sulphides, sphalerite, galena and the less abundant chalcopyrite, together with the non-sulphide gangue minerals, occur interstitially to the pyrite granules, often in quite intimate intergrowth with each other.

Modal analyses of polished sections of the Bleikvassli pyritic ore show the following mineralogical compositions (weight percentages).

Mineral	Average	Range
Pyrite .....	55.6	30 to 85
Pyrrhotite ....	5.4	0 to 15
Spahlerite ....	17.4	10 to 30
Galena .....	6.1	0 to 12
Chalcopyrite ..	0.8	0 to 5
Gangue .....	14.7	0.2 to 40

In addition the following ore minerals have been identified, usually in trace amounts and always less than one percent: molybdenite, cassiterite, magnetite, tennantite-tetrahedrite, stannite, boulangerite, valleriite, arsenopyrite, cubanite, gudmundite, breithauptite, bournonite and ruby silver. Marcasite, supergene pyrite and covellite, as well as anglesite and native sulphur have been identified in the weathering zone.

The Bleikvassli pyritic ore is, on the whole, rather uniform in grain size, texture and mineralogical composition and at first sight there is

very little megascopically apparent ore mineral banding. In certain places, for example, the rich ore worked at the southern end of the open cut, a very vague and indefinite banding was observed, in the form of streaks and lenses much richer in galena than normally. These lead-rich streaks were of the order of a few centimetres wide at a maximum and had little continuity in either strike or dip directions.

In certain areas of the mine, apparently only at the extremities of the orebody, where it is thinning out, a more clearly recognisable ore mineral banding is present. The banding so far observed is due to variations in the proportions and amounts of the non-ferrous sulphides occurring in the matrix between the pyrite grains. In particular, bands rich in both galena and sphalerite, up to a centimetre or two in

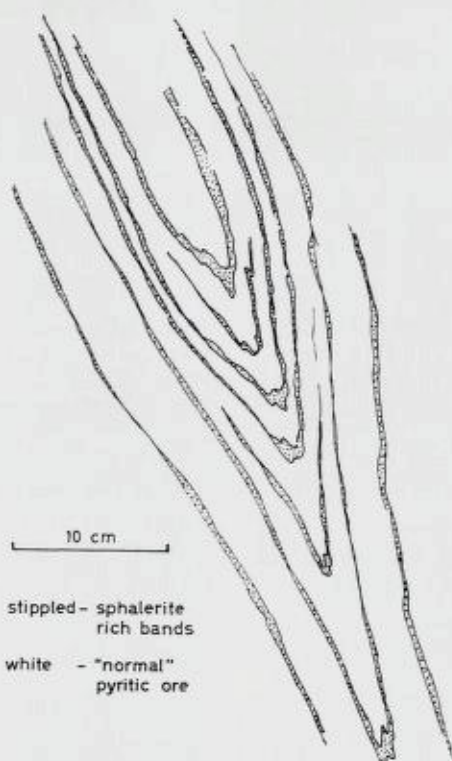


Figure 8. Sketch of part of stope back on 350 m level south, showing almost isoclinal folding of sphalerite-rich bands in the ore.

Fig. 8. Skisse fra en del av en strosse på 350 m nivå S, som viser nesten isoklinal-foldning i sinkblenderike bånd.



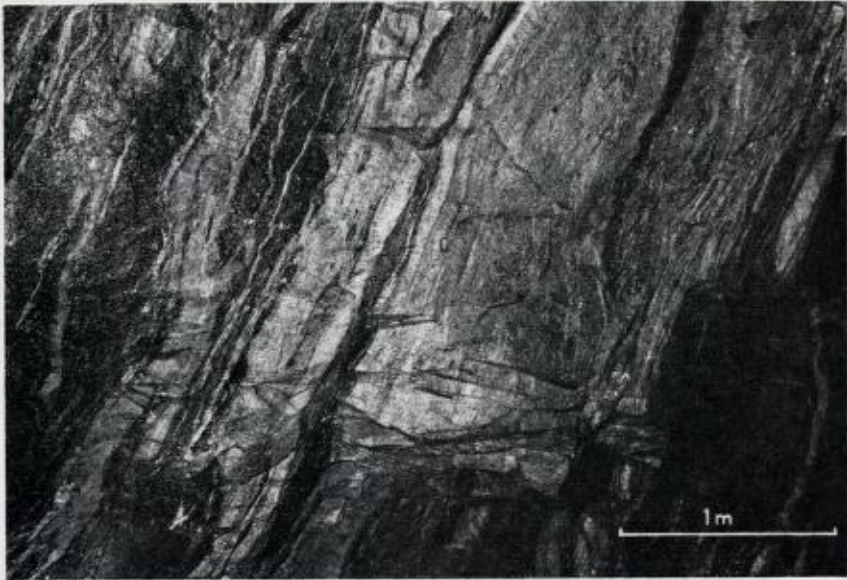


Figure 9. Photograph of face in 280 m stope north, showing banded nature of the pyritic ore.

Fig. 9. Foto fra strosse, 280 m nivå N, som viser bånding i malmen.

thickness, could be discerned in the ore at about the 350 m level in the extreme south end of the mine. In places these bands were clearly seen in tight folds of the order of a decimetre or so in amplitude (see Fig. 8).

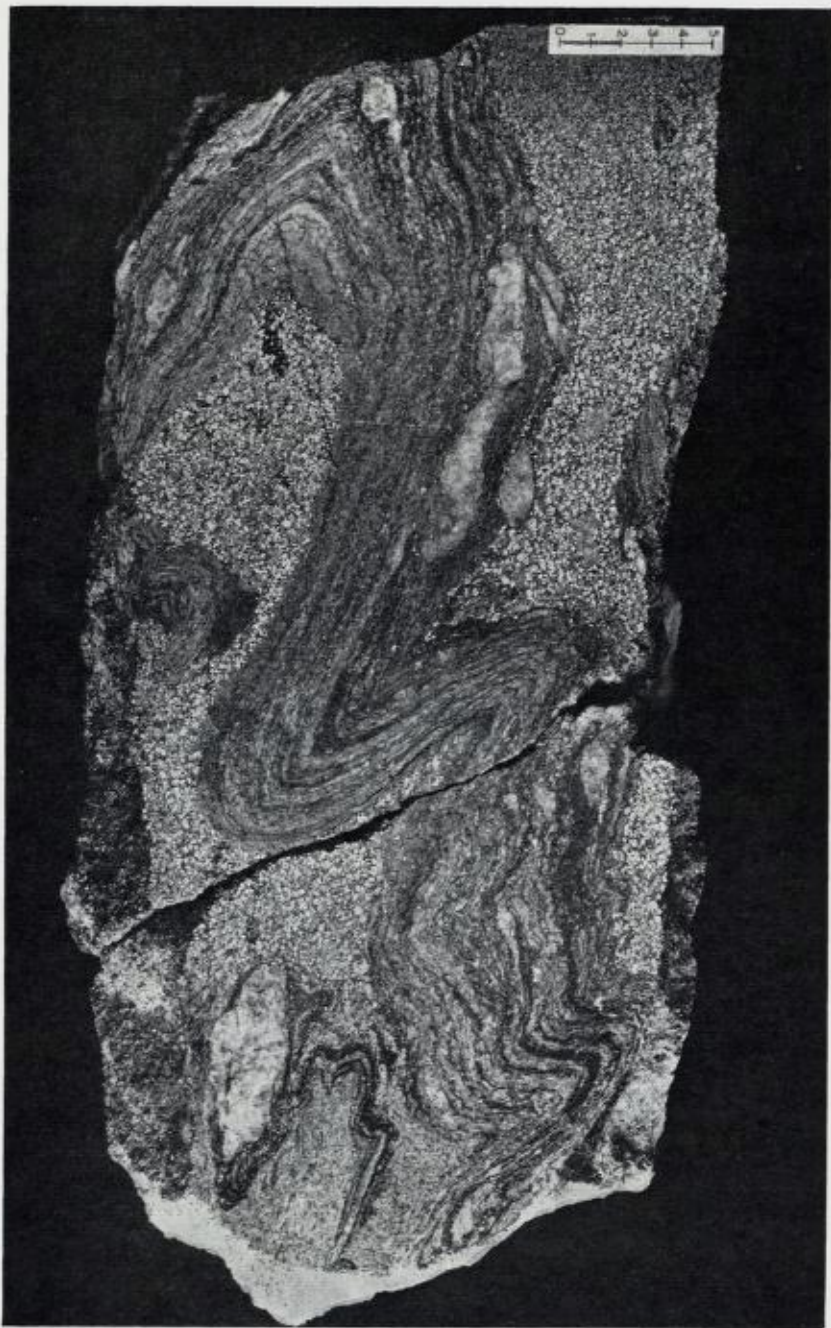
However, in the main sections of massive ore the texture and composition appear quite uniform and on the whole it may be said that ore mineral banding is very subordinate in the Bleikvassli deposit.

However, as regards the relations between the ore minerals and the gangue minerals, the Bleikvassli pyritic ore may definitely be described as being banded.

The banding consists of variations in the sulphide to gangue mineral ratio, which may vary fairly rapidly across any one section of the ore, though thicknesses of several metres of solid compact ore with no visible banding are the rule in the wider parts of the orebody.

Figure 10. Photograph of polished surface of slab of ore showing tight folding of the schist interbands. Scale is in centimetres. ➤

Fig. 10. Polert malmstykke som viser tette folder i skifer og sulfider. Målestokk i cm.



3 — Vokes.

Very often bands or lenses of schist occur within the orebody. The junctions of such schist intercalations are on the whole sharp, though they may often show evenly disseminated pyrite grains throughout their thicknesses. This pyrite is usually of a greater grain size than that in the compact or massive ore bands. The more prominent schist bands are seldom more than a decimetre or two in width and may often have the form of flattened, very elongated lenses, dying out in both strike and dip dimensions. Fig. 9 is a photograph showing an underground exposure of the gangue mineral banding in the pyritic ore.

In many places the schist bands have been folded, normally into folds with an amplitude of only a few centimetres to one or two decimetres (see Fig. 10). However the folding varies considerably in intensity from place to place within the orebody and in many exposures the folds approach an isoclinal type. In places the folds appear to have been disrupted and detached so that a series of schist fragments, often tightly folded, occur strung out in the massive ore. (Fig. 11.)



Figure 11. Photograph of stope face at 340 m level north showing detached folds of schist in massive pyritic ore.

Fig. 11. Foto fra strosse på 340 m nivå N, som viser avbrutte, oppdelte og foldete skiferlag i massiv sulfidmalm.

Where measurable, the fold axes in the schist inclusions, even the most isolated fragments, have always the same general direction of plunge as the fold axes in the country rocks surrounding the orebody. The ore forming processes therefore do not appear to have involved any significant disturbance of the fold axes in the schists if they took place subsequent to the folding. On the other hand such relations would also exist if the folding took place after the emplacement of the sulphides. This problem will be discussed more fully in a later section.

In places irregular patches of vein quartz occur in bands which are also roughly parallel to the general strike and dip of the ore zone and its enclosing rocks. These could represent detached remnants of originally coherent quartz lenses which have become ruptured during the folding movements in a manner identical with that described for the schist fragments above. On the other hand they could also represent local metamorphic segregations of quartz.

The generally even, medium-grained texture of the Bleikvassli massive pyritic ore is only interrupted by the above described partings and inclusions of schist and, less frequently, by irregular streaks and zones of coarser or finer grain size.

The average grain size of the typical pyrite granules has been determined in polished sections by measuring the dimensions of the cubic or rectangular outlines exhibited in the planes of these sections.

The data obtained from 200 such measurements, are:

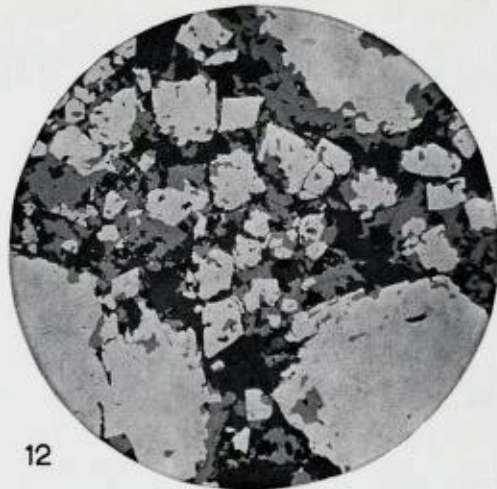
Longer dimensions, range 0.2 to 4.0 mm, arith. mean 1.54 mm.

Shorter dimensions, range 0.2 to 3.3 mm, arith. mean 1.23 mm.

Frequency diagrams of the grain size data showed very irregular distributions, but the data for the shorter dimensions showed a much smaller spread than for the longer ones, with over 50 percent of the measurements falling between 0.75 and 1.50 mm.

Thus within the vast bulk of the Bleikvassli pyritic ore, the pyrite has an average grain size in the range 1.25 to 1.50 mm.

In addition there are in places within the «normal» ore irregular coarse-grained patches or streaks in which the grain size is of the order of 1 to 2 cm or more. These patches have been mostly observed towards the southern end of the orebody. In places the pyrrhotitic ore shows isolated idiomorphic pyrite grains up to 5 mm in dimensions. There is no readily apparent reason for these coarser grain sizes.



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Figure 12. Photomicrograph of Bleikvassli pyritic ore showing pyrite granules of two distinct grain sizes. Reflected light. air. 52x.

Fig. 12. Foto av Bleikvassli-malmen som viser to tydelig forskjellige kornstørrelser av svovelkis. Reflektert lys, luft, 52x.

Massive ore of a grain size markedly less than average is even rarer than the coarser grained type and has only been observed at one locality in the mine. However, in certain polished sections pyrite grains of two distinctly different grain sizes were observed. The larger grains, of the same order of size as the «normal» ones, occurred fairly evenly spaced and were generally rounded in outline, while in between them were scattered much more numerous, much smaller, euhedral to subhedral crystals. (See Fig. 12).

#### *Mineralogy.*

**Pyrite.** In polished section the Bleikvassli pyrite shows a weak, though distinct, anisotropism under crossed nicols, the colour varying from a dark red brown to a dull greenish grey. This feature is normally regarded as an anomalous one. Uytengaardt (1951) states that it is «probably due to internal tensions caused by some FeS-surplus or As-admixture». More recently, however, Stanton (1957) has put forward the opinion that the optical anisotropism of pyrite is a normal feature of the mineral, only being revealed after polishing

which does not disturb the surface layers. Arnold (1962) has reached similar conclusions as regards synthetically produced pyrites. The majority of polished sections of the Bleikvassli ore were prepared by «hand methods» involving rotating nylon-cloth covered laps and diamond paste abrasives. A certain number were prepared for the writer on the Rehwald machine at the Mineralogisch-Petrographisches Institut of the University of Heidelberg. In these latter sections the pyrite appears isotropic on rotation between crossed nicols.

The above facts are put on record without the expression of any opinion as to whether the anisotropism shown by the hand polished pyrite is «abnormal» or «normal».

The crystal forms exhibited by the pyrite granules are mostly cube faces, or parts thereof, with, occasionally, some rare octohedral forms. However, euhedral grains are the exception rather than the rule, and typically the pyrite shows complicated outlines in detail, while exhibiting a general, often vague, cubic outline. The pyrite grains show no sign of internal structure, either through the already described anisotropism or after etching with acidified potassium permanganate.

Certain specimens, mainly those in which the groundmass consists almost wholly of sphalerite, show fairly simple cubic forms and a greater tendency towards euhedralism, but even in these examples, the crystals are seldom complete. The sections exhibited vary from L-, or hook-shapes in which parts of only two crystal faces are shown, through «channel sections» showing parts or all of three faces, to more or less complete cubes, interrupted only by «embayments» of the surrounding mineral(s). These embayments resemble strongly the so-called «caries texture» usually taken as indicative of replacement of the pyrite by the surrounding minerals. (Fig. 13).

More typically the groundmass to the pyrite granules consists of an intergrowth of all the non-ferrous sulphides plus the gangue minerals in varying proportions (Fig. 14). The pyrite then shows much more complex outlines. Embayments of the «caries» type are very numerous as well as apparent «inclusions» of both the matrix sulphides and of the silicate gangue minerals. Obviously some of the apparent inclusions represent chance intersections of embayments by the plane of the polished section. However, they are present in such large numbers in all or nearly all the grains present in a single polished section (which represents a random intersection through

differing «depth zones» in the crystals present), that it is clear a proportion of them at least are really true three-dimensional inclusions.

The sulphide embayments and inclusions are mainly convex against the pyrite and have generally smoothly rounded outlines and elongated or oval shapes. The sphalerite embayments and inclusions show this type most frequently. The outlines are in many cases composite in nature, being made up of alternating curves and straight lines. It is frequently clear that the straight parts of the outlines lie parallel to

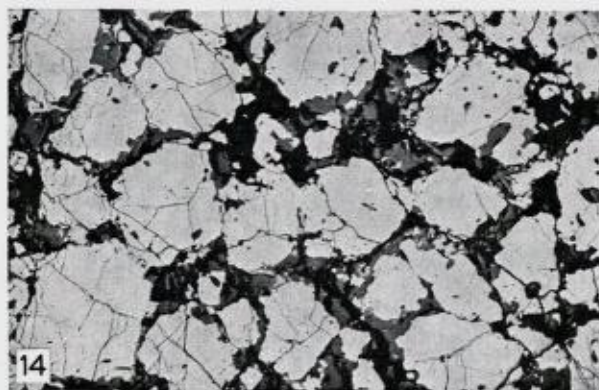
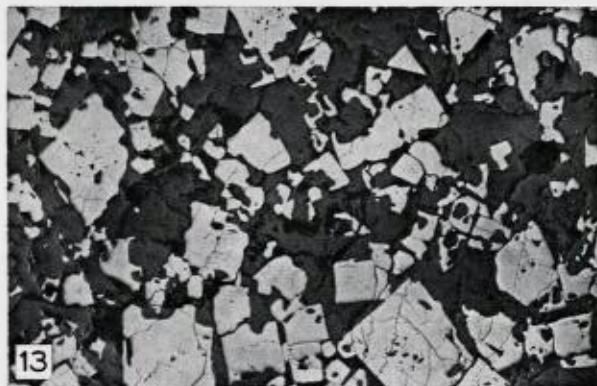


Figure 13. Photograph (12x) of polished section of sphalerite-rich pyritic ore. Anhedral to euhedral pyrite grains in matrix of sphalerite (dark grey).

Fig. 13. Foto av polerslip av sinkblende-rik svovelkis malm. Anhedrale til euhedrale svovelkis korn i grunnmasse av sinkblende (mørkgrå). 12x.

Figure 14. Photograph (12x) of polished section of pyritic ore showing subhedral pyrite granules.

Fig. 14. Foto av polerslip av svovelkis malm som viser suhedrale svovelkis korn. 12x.

the cube faces of the pyrite granule as a whole, or else at  $45^\circ$  to these (i.e. parallel to 110 faces). Another rather common shape for the inclusions of matrix sulphides is more or less perfectly circular. In infrequent examples extremely small circular inclusions, often composite, of all the matrix sulphides, can be seen clustered together in a group almost at the centre of the pyrite grains.

On the other hand the larger, elongated sulphide inclusions occur distinctly in a zone or belt around the circumference of the pyrite grain and are thus transitional into the similarly shaped embayments in the outer surface of the pyrite. In sphalerite-rich ore this mineral is commonly seen as single, large, rounded inclusions towards the centre of the pyrite grains.

To obtain an idea of the mineralogical composition of the inclusions in pyrite 4500 of them were counted, in ten polished sections which included specimens showing a wide range of pyrite to pyrrhotite ratios. The results of the counting revealed a marked difference as between sphalerite and galena (plus gangue) on one side and pyrrhotite and chalcopyrite on the other.

#### *Results:*

Sphalerite	formed from 25 to 78 percent of total, av. 57.6 %
Galena	» » 10 to 37 » » » av. 24.4 %
Pyrrhotite	» » 0 to 5 » » » av. 1.6 %
Chalcopyrite	» » 0 to 4 » » » av. 1.4 %
Gangue minerals	» » 6 to 35 » » » av. 15.0 %

Perhaps the low figure for chalcopyrite as inclusions in pyrite is not so surprising, considering the generally low abundance of chalcopyrite in the ore, but the infrequency of the pyrrhotite is surprising, especially in the high pyrrhotite specimens in which the mineral formed up to 50 percent of the section.

This seems to be just another expression of the close association between chalcopyrite and pyrrhotite on the one side and sphalerite and galena and also pyrite on the other which has already been discussed. Sphalerite and galena also form the majority of the sulphide embayments around the edges of the pyrite grains, whereas it is noticeable that pyrite nearly always presents straight crystal edges to surrounding pyrrhotite.

If one estimates the «availability» of each matrix sulphide in the



specimens used for the counting (by calculating them pyrite free) it can easily be seen that both sphalerite and galena are present as inclusions to an extent greater than they are «available», whereas pyrrhotite is present to a much smaller extent. The figures for chalcopyrite seem to be about the same.

A typical pyrite granule showing partly developed crystal faces, embayments and internal inclusions is shown in Fig. 15. It can be seen that the inclusions consist mainly of sphalerite, while this mineral and quartz forms many of the embayments. The generally smooth nature of the outlines of the granule and of the embayments can be seen, these being made up of either straight crystal faces or regular curves. Only occasionally is there a suggestion of an uneven contact towards the surrounding sulphides. Truly ragged borders are almost wholly lacking around the Bleikvassli pyrite granules. (See p. 45 and Fig. 27 for exceptions).

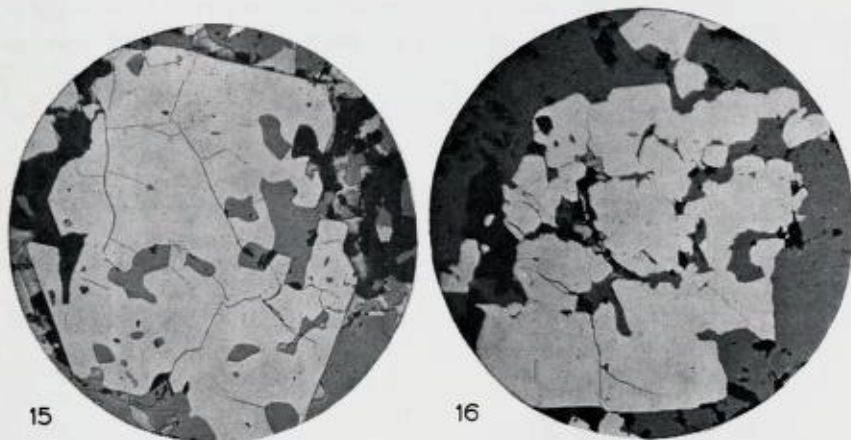


Figure 15. Photomicrograph of a typical pyritic granule showing partly developed crystal faces, embayments and inclusions. Matrix minerals are sphalerite (grey), galena (light grey, relief), and gangue minerals, (black). Reflected light, oil. 54x.  
 Fig. 15. Foto av et typisk svovelkis korn som viser delvis utviklete krystallflater, innbuktninger og inklusjoner. Mineraler i grunnmassen er sinkblende (grå), blyglans (lys grå, relief) og gangmineraler (sort). Reflektert lys, olje, 54x.

Figure 16. Photomicrograph of a complex pyrite granule apparently the result of the coalescence of several smaller grains. Matrix, sphalerite, (grey) and gangue minerals, (black). Reflected light, oil. 54x.

Fig. 16. Foto av et sammensatt svovelkis korn som synes å være dannet ved sammenvoksning av flere, mindre korn. Grunnmassen er sinkblende (grå) og gangmineraler (sort). Reflektert lys, olje-immersjon, 54x.

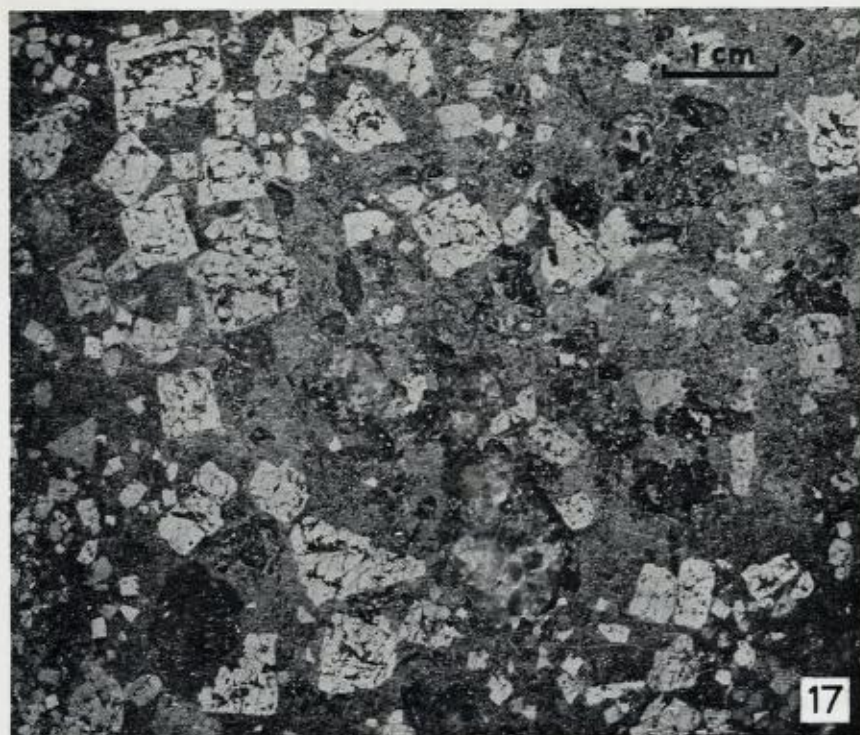


Figure 17. Photograph of polished surface of pyrrhotite rich ore showing idiomorphically developed pyrite crystals. Rounded quartz and schist inclusions indicate «Durchbewegung» of ore, which must have preceded growth of pyrite crystals.

Fig. 17. Polert flate av magnetkis-rik malm som viser idiomorft utviklete svovelkis krystaller. Avrundete kvarts- og skifer inneslutninger tyder på «Durchbewegung», som må ha funnet sted før svovelkis-krystallene ble dannet.

The forms shown in Fig. 15 are typically developed when the pyrite granules are fairly evenly spaced in the matrix, which is the general case. However in less frequent cases the granules show much more complex outlines, as illustrated in Fig. 16. This complex granule appears in effect to be the result of the close proximity of several semi-independent pyrite grains which were so near to each other that they mutually interfered with each others' growth processes. In this case only the outer grains have had the opportunity to develop the typical partially idiomorphic outlines, as shown by Fig. 15.

Furthermore it may be noted that as the groundmass becomes more

and more homogeneous, the tendency to idiomorphism on the part of the pyrite granules becomes stronger. This has been already illustrated in the case of sphalerite-rich specimens. The phenomenon is perhaps shown even better where the pyrite grains are totally enveloped in pyrrhotite, in such cases the crystal outlines are almost completely developed and free from embayments. Internal inclusions are however still present. (Fig. 17).

Such considerations suggest most strongly that the forms exhibited by the majority of pyrite granules are due to processes of growth and are not the result of a «caries-type» replacement by the surrounding sulphides. This does not exclude the local, limited replacement of the pyrite by the matrix sulphides, as indicated by the more, uneven, corroded-looking junctions which can occasionally be seen in polished section.

However, the majority of the embayments and inclusions in the pyrite granules seem to represent partially and fully enclosed grains of the groundmass in which the pyrite grew.

A point which seems to argue against replacement is that not only sulphides are present in the inclusions and embayments, but also grains of the non-sulphide gangue minerals, especially the quartz. As described elsewhere these grains are identical with the quartz grains of the quartz-mica schist forming the inclusions in the ore, as well as its wall rocks. They were either constituents of a pre-ore schist which has subsequently been partly replaced by the sulphides, or they were introduced contemporaneously along with the sulphide components of the ore before the processes causing the growth of the pyrite came into play. They are not later introductions of quartz (e.g. hydrothermal quartz) and cannot have replaced the pyrite. The inclusion of quartz grains in the pyrite granules is illustrated in Figs. 18 and 19. In the first of these a quartz grain can be seen partly enclosed in a pyrite granule, with another, small, pyrite grain almost blocking off the neck of the embayment. Only a slight further growth of the smaller pyrite would have completely sealed off the quartz and made it appear as an «inclusion». This is what appears to have occurred in Fig. 19. Part of a quartz grain, together with some adjacent sphalerite has been isolated from the rest of the groundmass by the growth of a smaller pyrite grain in the opening in the centre of a partly developed, hollow grain.

Not infrequently the Bleikvassli massive pyritic ore shows weak,

though distinct, gneissose textures. Though much more clearly shown in the pyritic impregnation ore (see below) such textures are not at all uncommon in the massive type. A polished surface showing such a texture is illustrated in figure 20. This figure shows a distinct parallel elongation of the pyrite grains in the direction shown by the arrow. A distinct mineral banding is also observable and in the plane of the photograph this lies parallel to the black line in one corner of the specimen.

In less massive ore the gneissose texture is often much more clearly marked. Fig. 21 shows how both the pyrite grains and the gangue fragments form a directed texture in less massive ore.

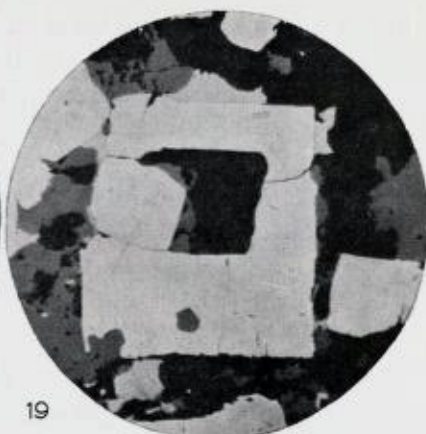
However, the extreme manifestations of directed textures are shown in the minor bands of «disseminated» pyritic ore which often occur in between the more massive plates and, especially, along the hanging-walls of such. In this disseminated ore, pyrite grains of a somewhat larger size than normal occur scattered profusely in the schist. These pyrite grains show markedly elongated forms and lie with their long axes parallel to the foliation and to the lineation direction in the schist (Fig. 22). In section the longer dimensions of these crystals vary between  $\frac{1}{2}$  and 1 cm, while their shorter dimensions are of the order of a half to one third of the longer. Examination of polished hand specimens of such ore shows all transitions from only slightly distorted cubes to clearly elongated, lenticular pyrite grains in which little, if anything is left of the original crystal outlines. The process of elongation of the pyrite grains seems to have involved a combined rotation and distortion under the influence of shear stress (a couple) which also impressed the marked schistosity on the wall rocks. The probable steps in such a process are illustrated schematically in Fig. 23.

The pyrite cubes appear to have resisted this stress to a considerable degree, so that along their borders «stress shadows» were created in which stress became minimal or lacking and into which the more plastic or mobile sulphides (preferentially pyrrhotite) have migrated and crystallised. This process has given rise to borders and «tails» of pyrrhotite and lesser galena.

The elongated pyrite grains in this «disseminated» ore show rounded inclusions of the type described from the massive ore and it seems clear that these inclusions were in place before the above described distortion and elongation of the grains took place. This may be inter-



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Figure 18. Pyrite granule partly enclosing grain of quartz (black) in matrix of sphalerite (grey) and galena (light grey). Photomicrograph. Reflected light, oil. 63x.  
 Fig. 18. Svovelkis korn som delvis inneslutter et kvarts korn (sort) i en grunnmasse bestående av sinkblende (grå) og blyglans (lys grå). Reflektert lys, oljeimmersjon, 180x.

Figure 19. Composite pyrite granule apparently enclosing inclusion of quartz (black) and sphalerite (grey), in matrix of sphalerite and gangue. Some pyrrhotite, (off-white, slightly darker than pyrite). Photomicrograph. Reflected light, oil. 180x.  
 Fig. 19. S sammensatt svovelkis korn som synes å inneslutte kvarts (sort) og sinkblende (grå). Grunnmassen er sinkblende, gangmineraler og litt magnetkis (nesten hvit, mørkere enn svovelkis). Reflektert lys, olje-immersjon, 180x.

Figure 20. Polished surface of massive pyritic ore showing weak gneissose texture.  
 Fig. 20. Polert flate av massiv svovelkis-malm som viser en svak gneiss-tekstur.

Figure 21. Distinct oriented texture of pyrite granules and schist fragments in less massive ore. Photograph of polished section. 12x.

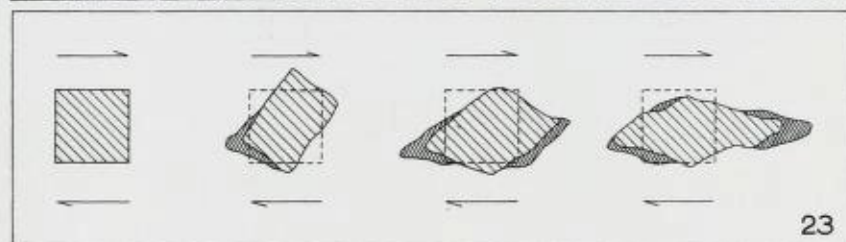
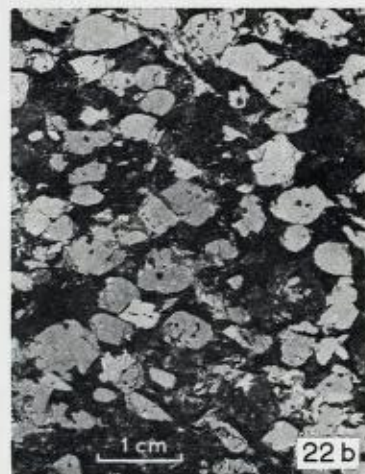
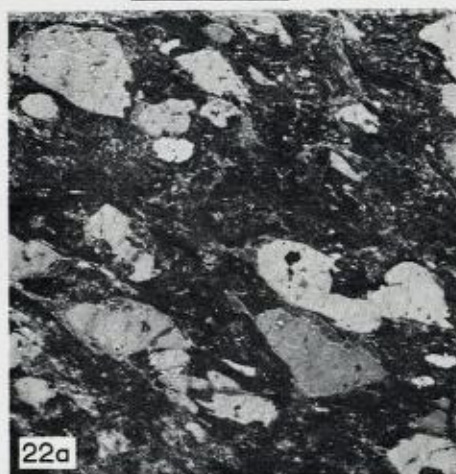
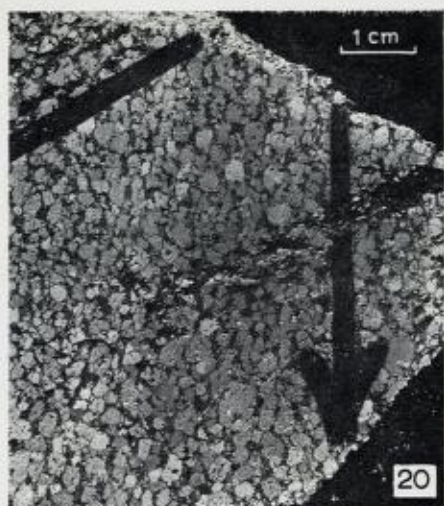
Fig. 21. Tydelig orientert struktur bestående av svovelkis korn og skiferstykker. Prøve av mindre massiv malm. Polerslip, 12x.

Figure 22a and b. Elongated pyrite grains in schist along the borders of the main ore lens, 330 m level stopes south. a) is parallel to the elongation direction of the grains and shows 'tails' of pyrrhotite in the strain shadows of the pyrite, while b) is almost at right angles to a). Photograph of polished surface.

Fig. 22, a og b. Utstrukkete svovelkis korn i skifer langs grensen av hovedmalmen, 330 m nivå S. a) er parallelt med lengderetningen av svovelkis kornene og viser «haler» av magnetkis i svovelkisens «strain skygger». b) er nesten rettvisklet på a). Polert flate.

Figure 23. Sketches to illustrate the possible mode of formation of the elongated pyrite granules illustrated in Figure 22.

Fig. 23. De utstrukkete svovelkis korn i Fig. 22 kan være dannet slik skissene viser.



preted as meaning that the pyrite grains began to grow in the schist before the shearing stress made itself felt.

The fact that such unequivocal evidence of the lengthening of pyrite grains under stress is mainly found in the «disseminated ore» on the margins of the massive plates may indicate either that the stress was greater along the margins of the massive ore, or that this massive ore was able to resist the stresses to a greater degree than the disseminated type.

In one or two polished sections of the pyritic ore the pyrite granules have been cracked or shattered and the cracks infilled by sulphides from the matrix. (Fig. 24). The walls of such cracks have been replaced only to a minor extent, if at all, by the infilling sulphides. However a minor instance of undoubted replacement of pyrite by pyrrhotite has been observed in a specimen from the stope drive on the 330 m level central. (See below under pyrrhotite)..

*Matrix sulphides.* While the main texture of the Blikvassli pyritic ore is determined by the generally subhedral pyritic grains, against which the matrix sulphides are moulded, these latter show, among themselves, an order of decreasing euhedral tendencies which is only revealed after study of the polished sections. The matrix sulphides exhibit a generally intimately intergrown allotriomorphic texture, which also includes the grains and aggregates of the gangue minerals. Very little tendency to euhedralism is seen in these matrix sulphides, and what there is, is shown only by the pyrrhotite. However there is an apparent constancy of textural relationships between pairs of the various minerals which would appear to be of significance in deciphering the history of the ore. These relations are shown most clearly and consistently between the pair sphalerite-galena and they will be thus considered first.

*Sphalerite and Galena.* Sphalerite is the most abundant matrix sulphide in the Bleikvassli pyritic ore and is the most abundant non-ferrous sulphide in the massive ore as a whole. On the average the ratio sphalerite to galena in the massive ore is as 3 to 1. Thus normally sphalerite is dominant over galena in any one polished section, so that is the former mineral which to a large extent determines the textural relations between the pair.

Sphalerite normally occurs as a fairly even-grained allotriomorphic mosaic disposed in somewhat irregular patches and normally showing no ordered, e.g., banded, arrangement in any one polished section. However as already described megascopic observations show, the zinc sulphide occasionally is dominant in bands up to a centimetre or so in thickness towards the ends of the orebody.

Polished sections of sphalerite-bearing ore, etched by  $\text{KMnO}_4 + \text{HCl}$  reveal the secondary lamellar twinning which is a well known feature of the mineral and which has been discussed by, among others, Edwards (1954, pp. 36–37) and Stanton (1960). The latter considers that it is «at least possible that such secondary twinning in sphalerite . . . . . is due to the final movements of the folding in which the ores were involved». The present writer can only concur with this view. The Bleikvassli sphalerite reveals an even, red-brown colour in thin sections of normal thickness and no suggestion of more than one generation has been observed. The Fe content of the sphalerite appears to vary very little from place to place in the orebody. A total of twenty-five separated and carefully cleaned samples of sphalerite from all parts of the orebody (270 m elevation and above) were analysed for their iron contents (analyst, B. Bruun, Mineralogisk-Geologisk Museum). The iron contents ranged from 6.25 to 8.00 wt. percent, with an arithmetical average of 6.90 percent. There were no differences of significance in the figures for the sphalerites from the pyritic and pyrrhotitic types respectively. It is hoped to discuss these figures more fully in a later publication.

When sphalerite and galena occur together, as is the general case, the texture they exhibit is a fairly constant one in which the sphalerite appears as generally rounded (convex) grains, while the galena occurs as interstitial or intergranular (concave) forms between the sphalerite grains. Where, as is usual, the sphalerite is in excess, the galena occurs as an irregular network of disconnected interstitial fillings, which often seems to outline or encircle areas (probably grains) of the zinc sulphide (Fig. 25). In patches where the galena is in local excess, the rounded sphalerite grains are partly or entirely enclosed in the lead mineral (Fig. 26). In almost all cases, however, the relationship between granular sphalerite with convex boundaries and interstitial galena with concave boundaries holds.

Both the sphalerite and the galena contain minute, variable amounts of one or other of the minor ore minerals.



It is noteworthy that the trace mineral contents of galena, on the one side and sphalerite (with chalcopyrite) on the other are distinct and characteristic. Galena shows sparse «fahlerts» (possibly tennantite) and boulangerite, while the sphalerite (to a much lesser extent the chalcopyrite) contains minor amounts of stannite. Thus during the crystallisation of the ore trace elements such as As, and Sb have separated with the galena, perhaps to form the minor As- and Sb-bearing minerals by internal unmixing on falling temperature, while the Sn has been taken up by the Cu- and Zn-sulphides and later has exsolved in the form of the Cu-Fe-Sn-sulphide which then most likely segregated to the sphalerite grain-boundaries or the sphalerite-chalcopyrite interfaces, in which positions it is found at the present time. (See also below under stannite, p. 66).

*Pyrrhotite.* In the pyritic ore pyrrhotite is present in varying proportions along with the non-ferrous sulphides and the gangue minerals forming the matrix to the pyrite granules. The mineral occurs as irregular anhedral grains or groups of grains and as allotriomorphic patches. Pyrrhotite has not so far been seen to take part in any banding texture in the pyritic ore.

Optically, the mineral shows the «normal» characteristics of pyrrhotite. It has a weak to distinct reflection pleochroism, especially noticeable across grain boundaries in aggregates. The marked anisotropism of the mineral reveals clearly the anhedral form of the grains forming the mosaics, and in addition frequently it shows the development of secondary (strain?) twinning in the mineral.

The majority of the pyrrhotite grains shows a flat, featureless polished surface, but some few sections have revealed a lamellar texture in the mineral, of the type described by the writer from the Birtavarre ores and more recently produced artificially and described by Kullerud and Yoder (1959) and by Arnold (1962). The distribution of the specimens showing this lamellar structure does not appear to be other than quite random.

The pyrrhotite shows often quite intimate intergrowths with the non-ferrous sulphides, preferentially with the chalcopyrite, but it generally retains its convex outlines against the softer sulphides. It is also noticeable that pyrrhotite in places shows euhedral or subhedral-prismatic outlines, but only where it occurs in fields of galena. Pyrrhotite is the hardest of the matrix sulphides while galena is the

softest. Thus the iron monosulphide only shows crystal outlines when the hardness difference between it and its adjacent, or enveloping, sulphide is at a maximum.

Replacement relations are generally lacking between the pyrrhotite and the other sulphides. As already mentioned, the pyrite grains tend to show their best developed crystal faces against pyrrhotite. However, in one specimen from the 330 m level central, a clear replacement relation is shown between the two iron sulphides. As Fig. 27 shows the pyrrhotite has replaced certain pyrite grains to varying degrees, the replacement proceeding from the edges of the grains inwards and taking on a most ragged form, apparently controlled by the cleavage of the pyrite.

It is not clear whether a fracturing of the pyrite took place first or whether the texture is solely the result of replacement. It is however perhaps significant that the pyrite grains generally in this specimen are rather heavily shattered, the fractures being infilled by the matrix sulphides. As can be seen from Fig. 27 the pyrrhotite is pseudomorphing the pyrite only and inclusions of other minerals originally present in the pyrite are not affected. For example, in the southwest quadrant an embayment of sphalerite originally present in the pyrite is preserved intact while the surrounding iron sulphide has been changed to pyrrhotite. The same specimen also shows a more or less complete pseudomorphing of grains of magnetite by the pyrrhotite (see below p. 68) and it is reasonable to suppose that the same general process has been operative in both cases. The pyrrhotite replacing both the pyrite and the magnetite appears extremely fine-grained and its polished surface shows a slightly darker colour and distinctly porous appearance compared with the smooth pyrrhotite which occurs as a «normal» constituent of the ore.

The replacement is a strictly volume for volume process and appears to have started from a network of microscopic cracks and cleavages in the host minerals. There are no obvious veinlets leading to the replaced minerals by which the replacing agent could have been admitted. The replaced grains appear to be closed systems and in the case of the pyrite it would not be unreasonable to suggest a breakdown  $\text{FeS}_2\text{--FeS}$  had taken place to varying degrees. The case of the magnetite is not explicable in this manner, though perhaps the excess sulphur released during the supposed breakdown may have effected the sulphidization of the magnetite.

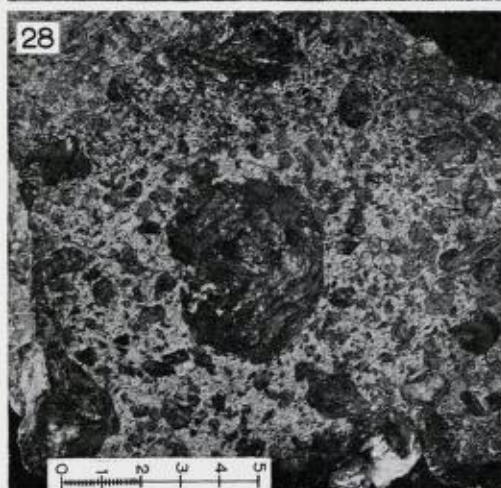
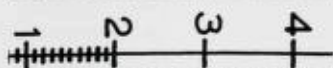
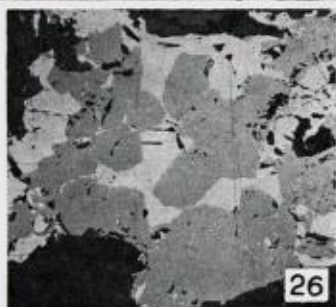
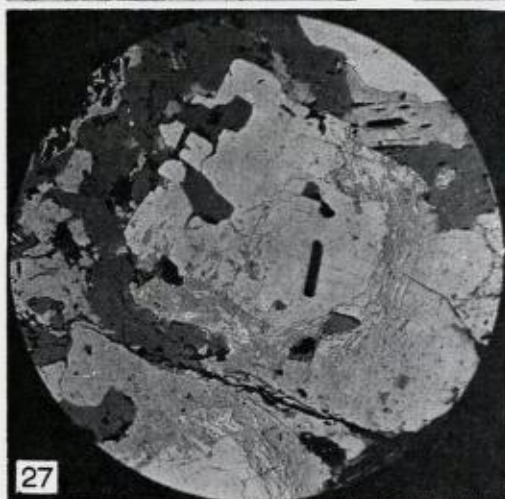
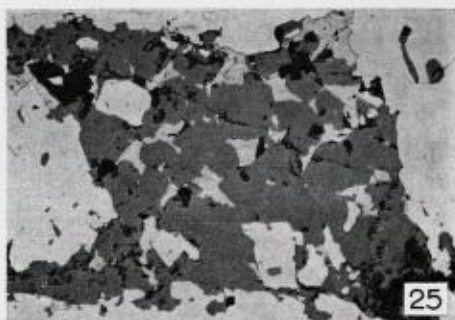
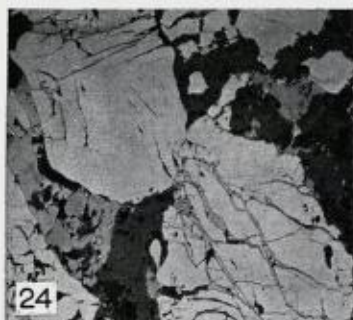


Figure 24. Fractured grains of pyrite with mainly chalcopyrite (light grey) as fracture fillings. Other matrix sulphides: sphalerite (dark grey), pyrrhotite (light grey) and galena (light grey, scratched). Reflected light, oil. 55x.

Fig. 24. Oppsprukket svovelkis-korn, hvor hovedsaklig kopperkis fyller sprekkene. Kopperkis (lys grå), sinkblende (mørk grå), magnetkis (lys grå) og blyglans (lys grå, ripet). Reflektert lys, olje-immersjon, 55x.

Figure 25. Intergrowth of sphalerite (dark) and galena (light) interstitial to pyrite grains. Galena appears to be «filling in» against convex sphalerite bodies. Reflected light, oil, 120x.

Fig. 25. Sammenvekning mellom sinkblende (mørk) og blyglans (lys) som grunnmasse mellom svovelkis korn. Blyglansen synes å utfylle plassen mellom konvekse sinkblende korn. Reflektert lys, olje-immersjon, 100x.

Figure 26. Round, subhedral sphalerite grains (medium grey) surrounded by galena. Gangue minerals black. Reflected light, oil, 120x.

Fig. 26. Runde, subhedrale sinkblende korn (middels grå) omringet av blyglans (lys grå). Gangmineralene er her sorte. Reflektert lys, olje-immersjon, 120x.

Figure 27. Granules of pyrite (light grey) heavily replaced by pyrrhotite, (slightly darker). Note that inclusions and embayments of sphalerite (dark grey) are not affected by the replacement, which pseudomorphs the original pyrite outlines. A patch of normal «matrix» pyrrhotite (light grey) occurs in the northeast quadrant. Reflected light, oil. 75x.

Fig. 27. Svovelkis korn (lys grå) som for en stor del er opppist (replaced) av magnetkis (noe mørkere). Inneslutninger og «innbuktninger» bestående av sinkblende (mørk grå) er helt uforandret, og magnetkis danner en pseudomorfose av det opprinnelige svovelkis korn. Reflektert lys, olje-immersjon, 75x.

Figure 28. Typical pyrrhotite rich ore showing the pseudobreccia texture; inclusions mainly of schist, showing extremely contorted foliation. Matrix mainly of fine-grained pyrrhotite and sphalerite. Photograph of polished surface. Scale in centimetres.

Fig. 28. Typisk magnetkis-rik malm, som viser en pseudo-breksiert struktur. Inneslutningene er hovedsaklig skifer, med meget deformert skiffrighet. Grunnmassen er hovedsaklig finkornet magnetkis og sinkblende. Polert flate, målestokk i centimeter.

Figure 29. Pyrrhotite rich ore with numerous pyrite granules and semirounded inclusions of vein quartz. Photograph of polished surface. Scale in centimetres.

Fig. 29. Magnetkis-rik malm med mange svovelkis korn og avrundete inneslutninger av gangkvarts. Polert flate, målestokk i centimeter.

These phenomena will not be enlarged upon here since they constitute such a minor detail in the general picture of the massive ore.

*Chalcopyrite.* This minor sulphide occurs somewhat erratically distributed throughout the massive pyritic ore, usually in rather intimate intergrowth with the sphalerite.

The rather weak anisotropism of the mineral between crossed nicols reveals a lamella twinning in the mineral which may possibly be a form of strain twinning similar to that shown by both the sphalerite and pyrrhotite.

### Cataclastic effects in the pyritic ore.

On the whole the Bleikvassli pyritic ore shows little evidence of any pronounced cataclasis subsequent to the crystallisation of the sulphides. The apparently cataclastic textures seen in polished section vary from specimen to specimen, but mostly they indicate movements of a rather mild nature, showing that the greatest tectonic disturbances took place before and during the final crystallisation of the ore.

The most widely observed cataclastic texture, which is present in practically all the sections studied, to various degrees, is a sub-regular to highly irregular network of fractures. These can be seen clearly in the photographs of pyrite grains, and especially in Figs. 14 and 15.

Often the fractures appear to be controlled by the cleavage directions in the pyrite, but irregular, often curving, fracturing is very noticeable, the curves often being roughly concentric with the outer surfaces of the pyrite grains.

These fracture cracks appear to be most frequent within the pyrite granules, though they are by no means confined to them. The more prominent of them can be seen to intersect both pyrite grains and the intervening matrix sulphides and gangue minerals. The greater concentration of fractures in the pyrite is most likely ascribable to the relatively brittle nature of the mineral.

As far as can be observed at high magnification under the microscope, cracks of this type are not filled by later deposited mineral; though they seem occasionally and locally to grade into somewhat wider openings in which the matrix sulphides have been deposited.

In one or two polished sections the pyrite shows the effect of a

mild fracturing or shattering in which the walls of the fractures and the individual mineral fragments have moved apart to varying degrees, up to a maximum of perhaps 0.1 mm. The openings so formed are now filled by one or other of the matrix sulphides, most frequently by chalcopyrite (see Fig. 24).

The relations between these very infrequent, filled fractures and the ubiquitous network of unfilled cracks already described, are somewhat variable. In some instances the unsealed cracks appear to have occasionally opened up slightly and to have received infilling of non-ferrous sulphide, usually chalcopyrite, less frequently of pyrrhotite. This would indicate that both these effects are differing expressions of one continuous process. However, very often the unfilled cracks can be seen to cut across the filled fractures in the pyrite, indicating that there was a later stage of slight cracking of the ore unaccompanied by any sulphide deposition.

A similar and related cataclastic effect which may often be observed is a slight opening-up or widening of the cleavages of the pyrite from the edge of a grain inwards, the resulting wedge, or dagger-shaped, opening being now filled with one or other of the matrix sulphides.

The sulphides filling the fractures and widened cleavages in the pyrite grains have most likely migrated there from the groundmass of the ore. Careful observations of the fracture fillings in polished section show them to be continuous with areas of the same minerals in the matrix between the pyrite grains. No instance has been seen of veinlets of sulphide cutting the sulphides of the matrix. There thus seems to be no reason to postulate the introduction of any late generation of sulphides. The fracture fillings have been derived from the apparently closed system of the orebody by local remobilization and migration.

The other, matrix, sulphides in the pyritic ore show considerably fewer cataclastic effects than the pyrite, in particular no fracture effects of the type just described. The pyrrhotite shows frequent wavy or irregular extinction between crossed nicols in polished section (analogous to the «strain shadows» seen in thin sections of quartz) and, less frequently, strain twinning. The already mentioned secondary twinning in sphalerite (see p. 43) and a similar texture in chalcopyrite are most likely strain effects of a similar character.

The relative scarcity of cataclastic effects observable in the matrix

sulphides as compared to the pyrite is probably ascribable to the former's relatively more ductile nature.

As has already been noted, the gangue components of the Bleikvassli ore, especially the schist partings and inclusions, have undergone considerable tectonic disturbances in places. While the amount of disruption and movement did not approach that which pyrrhotite rich ore zones appear to have suffered (see below, pp. 52-54) in places there has been produced a «pseudo-breccia» type of structure.

There is abundant microscopic evidence of the disruption and deformation undergone by the non-opaque minerals and rock fragments in the pyrite ore. The quartzite patches or fragments in most of the thin sections show marked shearing and granulation of the quartz grains and strain shadows are a marked feature of this quartz. Many of these fragments exhibit a schistose or streaked-out texture, parallel to the long axes of the fragments, or disposed in broad waves or folds. The mica flakes are very frequently either bent, folded or broken. Books of mica show splitting or opening-up of cleavages, especially at the crests of tight crenulations, with deposition of sulphides in the openings so formed. The schistose alignment of the mica-rich bands in the immediate country rocks and in the undisturbed schist partings in the ore is often completely disrupted, so that in many sections of the massive ore the micas are disposed without any suggestion of parallel orientation.

### **Pyrrhotite-rich ore.**

Pyrrhotite-rich mineralization of apparently two different types has been observed in the Bleikvassli mine. Of these only the first type belongs under the category of «massive ore» (in the sense used in this paper) and it is this type which will be discussed in detail below. However, in various parts of the mine, mainly towards both the north and south extremities of the orebody, but also occasionally within the massive ore, occurs a variety of this type of ore which has a distinctly different appearance, as well as grain size and relative mineral contents. This second type of pyrrhotite-rich mineralization occurs in very irregular bodies which are often highly quartz-rich. In contrast with the massive variety of this type, it may be described as a «brittle» type, the sulphides often occurring in a loose, sugar-grained quartz gangue, the whole lying in a heavily

crushed zone in the schists. The mineralization is distinctly coarser in grain than that of the massive variety and has a fresh, shining appearance when newly fractured. The non-ferrous sulphides in it occur characteristically in very coarse-grained, erratic «splashes»; in particular, the chalcopyrite content is much higher than in the massive pyrrhotite-rich variety and this type of mineralization may well be designated the chalcopyrite-pyrrhotite type. In places there occur coarse crystals of arsenopyrite, closely associated with the galena patches.

It is tentatively suggested that this looser, coarser grained type of chalcopyrite-pyrrhotite mineralization represents a local remobilization of the massive pyrrhotite rich ore. The question of remobilization of the minerals of the Bleikvassli deposit as a whole will be taken up in a later publication.

In the following the term «pyrrhotite-rich» or «pyrrhotitic» ore will refer exclusively to the massive, fine-grained variety.

As a rule this variety occurs as a band or strip along the foot-wall side of the more abundant pyritic ore. These pyrrhotite-rich bands are an integral part of the massive ore, the junction between the two types being either quite abrupt or else transitional over some few centimetres. No structural break of any kind has been noticed at the junctions. In the transitional zones the normally tightly packed pyrite grains of the pyritic ore become more widely spread and pyrrhotite forms the dominant sulphide in the matrix between them. In the fully developed pyrrhotite ore pyrite is usually almost completely lacking.

The texture of the pyrrhotite-rich ore is not at all regular, so that it is by no means easy to give a reliable average modal mineralogical composition based on the point counting of polished sections as has been done for the pyritic ore. However, such data as can be obtained do indicate ranges of composition (weight percentages).

	Average	Range
pyrite .....	2.5	0—12
pyrrhotite .....	49.0	33—63
sphalerite .....	19.3	9—24
galena .....	6.5	3—9
chalcopyrite .....	1.8	0.5—3
gangue .....	20.8	11—39



The following minerals also occur in the pyrrhotite-rich ore, usually in minor quantities, molybdenite, tennantite-tetrahedrite, stannite and marcasite (supergene). Arsenopyrite, boulangerite, gudmundite, and breithauptite have each been observed in single polished sections.

As can be seen by comparing the data on p. 26 with the foregoing, the average mineralogical compositions of the two ore types are generally similar, apart from the relation between pyrite and pyrrhotite. The non-ferrous sulphides are rather more abundant in the pyrrhotite-rich type, as is also the content of gangue minerals. The total iron sulphide is correspondingly slightly less.

The modal figures also show that the pyrrhotite-rich type carries roughly about twice as much chalcopyrite as does the pyritic type. The true ratio may be slightly higher, since the copper sulphide tends to occur somewhat erratically, in rather rich «splashes». In a recent publication the present writer commented on the general tendency for the pyrrhotite-rich types of ore in the Norwegian Caledonides to be preferentially copperbearing in comparison with the massive pyritic types. (Vokes, 1962 a). At Bleikvassli the pyrrhotitic type is also rich in zinc and lead, in keeping with the general geochemistry of the ore. (See also Part 3 of this publication).

The foot-wall strip or zone of pyrrhotite-rich ore, while not being completely continuous over the whole area of the orebody, has been observed at all levels in the mine and at several places along the strike. In the thicker parts of the orebody, it may reach a maximum thickness of 1 to 2 m, out of a total ore width of perhaps 10 to 15 m. There is, however, no apparent relation between the total width of an ore plate and the width of the accompanying pyrrhotitic band, if present. In places, where the ore is quite narrow, as on the 380 m level N, the foot-wall pyrrhotitic band forms perhaps one-third to one-half of a total ore width of about 1 to 1½ m.

In addition there is apparently a plate or thin lens of the pyrrhotitic ore forming the complete width of the orebody in the central part of the mine working. The ore here reaches a maximum thickness of about 2 m, but shows great variations due to apparent squeezing-out and thickening controlled by folding in the wall rock schists.

In texture the pyrrhotitic ore shows considerable differences from the pyritic type. Banding of any kind is completely lacking and the mineralogical composition is extremely variable. The ore is best described as a «breccia» in most cases, without assigning any definite

genetic significance to this term. The fragments comprise schists, of the types forming the immediate wall rocks or the partings in the ore, as well as medium to coarse-grained quartz or quartzite. These fragments, which are cemented together by a fine- to medium-grained matrix of pyrrhotite and base metal sulphides, vary in size from a fraction of a mm to a dm or two. They are characteristically rounded and sharp edges are seldom if ever observed. The degree of rounding varies according to the material forming the fragment. Schist fragments are usually elongated or ovoid in shape, whereas many of the quartz fragments are spheroidal. Figures 28 and 29 show photographs of typical examples of the Bleikvassli pyrrhotitic ore.

The schist fragments, especially the smaller ones, present a pebble-like external appearance and their surfaces are often highly polished. Internally the mica flakes are severely bent or folded, sometimes to the extent that they form an almost continuous, «onion-like» structure. In other instances they show tight double, or S-folds. This evidence shows that the fragments were subjected to rather intense tectonic movements, producing a «rolling» action, which accounts for both the highly polished outer surface and the distortion of the schistosity.

The quartz fragments also exhibit a polished outer surface, but internally they present an allotriomorphic aggregate of quartz grains, in which any signs of textural deformation are not distinguishable.

Examination of the casts of the «breccia» fragments show highly polished films of the matrix sulphides, especially galena, and occasionally these films are seen on the outer fragment surfaces. The «breccia» fragments usually present their highly polished outer surfaces to the enveloping sulphides, and normally little corrosion or penetration by the latter can be seen. The schistosity planes of the larger fragments have in some cases been penetrated by sulphides, but only to a small extent. The coarser granular quartz fragments more often show sulphides deposited between the grains, but signs of actual replacement are notably lacking.

All the above mentioned characteristics seem to point to a thorough kneading (*Durchbewegung*) of the zones now occupied by the pyrrhotitic ore. Whether the whole of this movement took place while the sulphides were *in situ* cannot be ascertained from the evidence available, certainly some movement must have taken place after the *mise en place* of the ore-forming minerals, to judge by the «smeared out» films of sulphides around the fragments.

Somewhat conflicting evidence is afforded by a polished section study of the sulphides occurring between the breccia fragments. Cataclastic textures are rare, which is surprising considering the megascopic evidence that movement must have taken place while the sulphides were present.

The main textural feature of these sulphides is a fine- to medium-grained intergrowth of dominant pyrrhotite with lesser sphalerite and smaller amounts of galena and chalcopyrite. This intergrowth, especially as between sphalerite and chalcopyrite, can be very intimate and can vary considerably in grain size across any one polished section.

The pyrrhotite is the only mineral which shows evidence of having been subjected to stress. In this type of ore it invariably exhibits strain (wavy) extinction between crossed nicols. Often distinct strain twinning is also present. Etched sphalerite shows twin lamellae of the type already described from the pyritic ore.

Rather contradictory evidence is afforded by the pyrite when it occurs in the pyrrhotitic ore as isolated grains or groups of grains. In this «mixed» type of ore pyrite appears as individuals of varying crystallographic development. In the majority of cases studied the mineral shows all the features of the pyrite grains in the pyritic ore, as described elsewhere in this report, i.e., partial or complete development of perfect crystal faces, skeletal growths, embayments, and inclusions of other sulphides. Even in ore where the pyrrhotite shows marked straining, the pyrite seems to be practically undisturbed. The only effects noticed are the ubiquitous network of subregular cracks and the occasional opening-up of a cleavage, but these effects have been noticed in the pyritic ore, which, on the whole, shows fewer tectonic effects than does the pyrrhotitic type.

Occasionally, sections exhibit rounded pyrite grains where any crystal faces appear to have been broken off by a rolling action similar to that proposed for the country rock fragments. These grains otherwise show the typical inclusions of other sulphides and gangue minerals and would seem to be originally more euhedral grains which have been subsequently affected by movements in the ore. The question then arises as to why more pyrite grains do not show this effect, especially in ore showing marked straining of the pyrrhotite. This question will be taken up for discussion later.

The minor opaque minerals in the pyrrhotitic ore show a generally similar mode of occurrence to that in the pyritic ore, as is described

elsewhere. Here it is perhaps sufficient to point out the almost ubiquitous occurrence of tennantite-tetrahedrite and stannite in this type and the virtual absence of magnetite, cubanite, valleriite and arsenopyrite. Molybdenite is also probably less abundant in the pyrrhotite-rich type of ore.

## WALL ROCK MINERALIZATION

The massive sulphidic ore at Bleikvassli normally shows sharp contacts with its wall rocks. However in many places schist partings in between the plates or bands of massive ore, as well as the immediate hanging-wall schist, show scattered sulphides of varying denseness, most prominent among which is pyrite, occurring in often elongated crystals up to a centimetre or so in greatest dimension. Other sulphides occur scattered less regularly in the schist between the pyrite crystals. This pyritic type of wall rock mineralization is dealt with more fully in the section on pyrite. (p. 39).

In addition to this there occurs another, very irregular sulphide mineralization in the schists surrounding the plates of massive ore. This takes the form of veins, patches and impregnations mainly, but not exclusively, in the rocks on the hanging-wall side of the orebody. The sulphidic minerals found in this irregular wall rock mineralization comprise all those which have so far been identified in the massive ore, as well as one which has not so far been found there.

There is, however, a very marked difference in the relative orders of abundance in the massive and «disseminated» ores, respectively. Due to the wall rock mineralization's extremely irregular character, it is not possible to give any quantitative data for the abundances of the various minerals in it, but a qualitative inspection of underground exposures and of wall rock specimens readily shows that galena is by far the most abundant sulphide present. Of the other sulphides present in the massive ore, pyrrhotite, chalcopyrite and sphalerite all occur in the wall rock mineralization, but sphalerite, for example, is much less abundant, proportionally, than in the massive ore. Pyrite is a minor constituent of this wall rock mineralization. In addition, certain minerals that are only present as «traces» in the massive ore are in places very prominent in the wall rock mineralization. These are, notably, arsenopyrite and tennantite. In certain exposures geo-

cronite makes its appearance in coarse vein fillings and irregular patches.

The detailed mineralogy of the wall rock mineralization will be dealt with in a separate publication and the subject will not be touched on further here, except to discuss its possible relation to the massive ore in a later section. (p. 79).

### MINOR ORE MINERALS

Several minerals have been identified in the Bleikvassli ore in minor or even trace amounts. They comprise sulphides (with antimonides, etc.) sulphosalts and oxides, and may be classified as

<i>Sulphides, etc.</i>	<i>Sulphosalts.</i>	<i>Oxides.</i>
Arsenopyrite	Tetrahedrite-tennantite	Magnetite
Molybdenite	Boulangerite	Cassiterite
Cubanite	Stannite	
Valleriite	Bournonite	
Marcasite	Ruby silver ores	
Gudmundite		
Breithauptite		

This suite of minor ore minerals must, at the present state of knowledge, be regarded as exceptional for Norwegian massive sulphide ores, though this is no doubt due in part to the lack of detailed mineralogical investigations on these ores. A comparable mineral assemblage has been described from the Jakobsbakken mine in Sulitjelma by Ramdohr (1938), occurring in a quartz-rich zone a short distance in the hanging-wall of the massive pyrite-sphalerite-chalcopyrite ore of this mine. According to Ramdohr (personal communication) some at least of the minerals occurring in his «antimonreiche Paragenese» in the hanging-wall schist are also present in the massive sulphide ore, but no details about these have been published.

All the minor minerals present in the Bleikvassli ore were reported in Ramdohr's 1938 paper from Jakobsbakken, with the exception of the tin minerals and breithauptite. However, in the index of the latest edition of «Die Erzminerale . . . .» (Ramdohr, 1960), stannite and breithauptite are stated as being present at «Sulitjelma, Norwegen».

Otherwise this present report provides the first published record of the presence of stannite in the massive Caledonian ores of Norway, and in the country as a whole. Recently Jøsang (personal communication) has also detected the tin-copper sulphide in specimens of the ore from the Fløttum mine, Sør-Trøndelag, ore which otherwise shows considerable similarities to the Bleikvassli ore (See later, p. 81).

### Sulphides.

The minor sulphides of the Bleikvassli ore, arsenopyrite, molybdenite, cubanite, valleriite and marcasite, are normally widespread, if «trace» constituents of the massive sulphide ores of Norway which have been subjected to detailed mineralogical examination.

**Arsenopyrite**,  $FeAsS$ , occurs sparsely and sporadically in the massive sulphide ore, almost exclusively in the pyritic type. The mineral occurs normally as subhedral to euhedral crystals of the order of size of 0.1 to 1 mm, scattered singly or in small groups. Most frequently the mineral occurs as individual idiomorphic forms set in the matrix sulphides or in the gangue. The tendency to idiomorphism is very strong in the case of arsenopyrite, much stronger than, for example, that of the pyrite. The crystals exhibit a clear, homogeneous surface under ordinary light, and seem to be free from inclusions of any kind. Complicatedly twinned aggregates are revealed between crossed nicols.

In the sections where arsenopyrite is more abundant, the mineral often appears crystallised together with pyrite in composite grains or crystals. Such forms seem to indicate that the two minerals crystallised together and thus occupy the same position in the crystalloblastic sequence. The much stronger tendency to idiomorphism in the case of the arsenic mineral is shown by the fact that it very often exhibits crystal faces against adjacent pyrite, a fact that might be taken to indicate that arsenopyrite crystallised earlier than pyrite. The other cases of intergrowth, however, show that the two minerals are essentially contemporaneous.

**Molybdenite**,  $MoS_2$ , is a very minor, but ubiquitous, constituent of the Bleikvassli massive ore. It shows no definite relationship to any other sulphide and does not seem to prefer either of the two main ore types. The characteristic occurrence of the mineral is as



isolated, single flakes, appearing in polished section as highly elongated cross-sections, which may be either perfectly straight, i.e., flat, or may be bent, either singly or doubly.

The dimensions of typical flakes as seen in cross-section, are of the order of 0.1 to 0.5 mm. The molybdenite has been observed bedded in all the major sulphides present in the ore, as well as in the silicate gangue. The flakes may be completely surrounded by one particular mineral or they may lie across the border between two minerals. This mode of occurrence resembles strongly that of the cassiterite, as has been noted previously by the present writer (op. cit. 1960) and would suggest that the molybdenite is one of the earliest crystallised minerals in the ore.

The problem of the bent molybdenite flakes is somewhat puzzling. Several instances have been noted where highly bent molybdenite flakes occur entirely enclosed in grains of other sulphides, including subhedral grains of pyrite. Presumably the bending of such flakes is a tectonic phenomenon. If the molybdenite were already enclosed in its host sulphides when the supposed movements took place, these latter should be expected to show some evidence of the movements. This they do not do, especially the pyrite crystals. Such considerations may possibly point to some tectonic action before the final crystallisation of the pyrite grains.

Molybdenite flakes of a similar form and mode of occurrence have previously been reported from the pyrrhotite-chalcopyrite ores of the Birtavarre district (Vokes, 1957) and have been noted in hand specimens from the Vaddas ore district, north of Birtavarre. The ore at the Mofjell mine, near Mo, which has a similar mineralogy to that of Bleikvassli, is also reported as containing molybdenite.

Thus, although molybdenite is not usually regarded as being a typical mineral of massive sulphidic ores, and has so far not been reported from many such ores in Norway, it is present as a trace constituent in some of these deposits and its presence may be suspected in others.

**C u b a n i t e,  $CuFe_2S_3$ .** This copper-iron sulphide shows a very restricted distribution in the Bleikvassli massive ore and has, in fact been detected in only two polished sections, both of which must be considered as showing exceptional mineralogical compositions and relations. Both are extraordinarily rich in magnetite for Bleikvassli

and show this mineral in various stages of being replaced by pyrrhotite (see p. 68). Both sections are from specimens taken in the central part of the mine, almost along the same vertical coordinate (ca. 50S), one at an elevation of about 350 m, the other at 310 m. There is no reason to suspect that this magnetite-cubanite bearing band is anything other than an integral part of the massive ore and has had the same geological history as the ore as a whole.

The cubanite occurs in typical lamellæ of varying form and thickness, within the areas of chalcopyrite, and also as irregular fine-grained aggregates and elongated grains along with the fine grained pyrrhotite which is apparently replacing the magnetite. The individual cubanite lamellæ mostly show the typical internal twinned structure of the mineral which is brought out well by the anisotropic colours. Ramdohr (1960, p. 581) suggests that this texture is due to the fact that the cubanite, at the temperature of its unmixing from the chalcopyrite, was originally hexagonal, but that it reverts to a rhombic pseudo-hexagonal form on cooling.

Close examination of the cubanite lamellæ in one of the sections showed that they were made up of two components. One is normal anisotropic cubanite, the other a darker component showing no pleochroism and no detectable variation during rotation under crossed nicols. In colour this second component is much darker (with a yellowish-brown tone) than the lightest position of cubanite and almost indistinguishable from cubanite in its darkest position. It appears completely homogeneous even under the highest magnification. This isotropic component appears to resemble the «cubanite II» of Ramdohr (1960, p. 585), which Borchert (1934) has identified as «chalcopyrrhotite». Meanwhile Uytenbogaardt (1951, pp. 210–211) has criticised the use of the name chalcopyrrhotite for this material on which «no chemical, crystallographic or röntgenographic investigations have so far been made».

In one instance a broad composite lamellæ of the two components was seen to be intersected by irregular wavy or flame-like forms of pyrrhotite. These resemble strongly the forms exhibited by the minor component of the two-component pyrrhotite which has been described elsewhere (see p. 44). The pyrrhotite cuts across the lamellar texture of the cubanite with apparently complete disregard for any crystallographic directions.

The chalcopyrite containing the cubanite is in places heavily replaced



by irregular areas of pyrrhotite of the type which is also replacing magnetite in the same section. Often the replacement appears to begin from the edges of the cubanite lamellæ, or a thin lamella of chalcopyrite intergrown with the cubanite may be completely replaced by the pyrrhotite.

The occurrence of cubanite in the Bleikvassli ore is so minor that very little of a general genetic nature can be concluded from its appearance. According to Ramdohr (1960, p. 581) the unmixing of cubanite from chalcopyrite occurs at from 250° to 300° C. From independent evidence the Bleikvassli ore as a whole has been at least 100° to 200° C higher than this at one stage of its history so that there has been opportunity for  $\text{CuFeS}_2$ -FeS solid solution and subsequent unmixing to take place as a general feature. The explanation of the scarcity of cubanite must be that unmixing, if it occurred, produced normally chalcopyrite plus pyrrhotite which later mostly segregated to an intergrowth of the type seen in the ore at the present time. The production of cubanite as an exsolved mineral would seem to be the result of some localized special conditions, and it may be significant that cubanite has only been observed in polished sections containing partly replaced magnetite.

Valleriite,  $\text{Cu}_3\text{Fe}_4\text{S}_7$ , is a very rare mineral in the massive ore, though it is quite widespread and has been observed from over half the polished sections examined.

The mode of occurrence of the mineral is quite characteristic, as small, irregular, «lance-like» or «gash-like» forms, often branching, in areas of chalcopyrite. Similar forms have been previously described and illustrated by the present writer (Vokes, 1957, pp. 126-131) from the chalcopyrite-pyrrhotite ores of the Birtavarre district. In agreement with the weight of evidence from the literature, the valleriite at Birtavarre was interpreted as a breakdown or replacement of the chalcopyrite. This interpretation would seem to hold in the case of the Bleikvassli example too. There is nothing in these textures to suggest they are a result of the unmixing of the valleriite from a solid solution in the chalcopyrite.

Marcasite,  $\text{FeS}_2$ . The dimorph of pyrite is not a usual constituent of the normal Bleikvassli massive ore, but is present in the upper parts of the mine as a product of the supergene alteration of the

pyrrhotite. As this will be dealt with in the second part of this publication, nothing further will be said here regarding this supergene marcasite.

No other type of marcasite has been observed in the Bleikvassli ore.

### Antimonides.

*Gudmundite*,  $FeSbS$ , is fairly widespread in the massive ore in minute quantities, having an apparently random distribution. Where observed it shows a fairly constant and characteristic mode of occurrence and mineral association. The gudmundite occurs as aggregates of very small sub- to euhedral crystals, often tabular or prismatic in outline, intimately intergrown with pyrrhotite and lesser chalcopyrite. Usually there are also present fine «flecks» or «specks» of a highly tarnished (blackish) mineral which possibly is native arsenic.

This association usually occurs in small patches along the grain boundaries of the more abundant minerals. The edges of the pyrite granules seem to be a common place of occurrence, as does the junction between chalcopyrite and quartz. Very often these patches occur alone; sometimes they are associated with larger patches of galena. A clue to their mode of formation is given by one or two instances in which these patches occur associated with the galena-«fahlerts» semi-graphic intergrowths (see below) in such a manner as to suggest that they are replacing part of the «fahlerts» composing these intergrowths (Figure 30). Ramdohr has figured and described intergrowths of gudmundite, chalcopyrite, pyrrhotite, etc. from Jakobsbakken which show great similarity to the Bleikvassli occurrences. He ascribes the intergrowths to the breakdown of «fahlerts», and it would be reasonable to ascribe the apparent partial replacement of the galena-«fahlerts» intergrowths to the same process. The patches consisting wholly of the gudmundite-pyrrhotite-chalcopyrite- (native arsenic) intergrowths would then represent original grains of «fahlerts» which had completely broken down. The reason for such a breakdown, if this is the mode of formation, is not easy to see. It may have occurred under the influence of falling temperature late in the metamorphic history of the ore.

*Breithauptite*,  $NiSb$ . The identification of this mineral is by no means certain, due to its extremely infrequent occurrence and fine state of division. It is possible that the mineral so identified is

wholly or in part niccolite, NiAs. The mineral has been observed in only three of the polished sections examined so that it is an extremely insignificant component of the ore.

In one instance it occurred in galena along the boundary between this mineral and chalcopyrite as a narrow zone of pink, pleochroic, prismatic or skeletal crystals intergrown with small grains of a darker, brownish mineral, which was tentatively identified as stannite, though its fine state of division made a certain identification difficult.

In the other two instances the mineral, or one almost identical, was seen in very small irregular patches apparently replacing «fahlerts» which was semi-graphically intergrown with galena. Under extremely high magnification the patches could be seen to be made up of an intimate, complicated intergrowth of ? breithauptite and, probably, pyrrhotite. These identifications must be considered for the present as highly tentative.

### Sulphosalts.

**Tetrahedrite-Tennantite.** A mineral of the tetrahedrite-tennantite group ( $\text{Cu}_3(\text{As}, \text{Sb})\text{S}_4$ ), is a widespread, though somewhat irregular, mineralogical constituent of the Bleikvassli massive ore. Due to its fine state of division, it has not been possible to determine its definite position in the series and the term «fahlerts» will be used for the mineral in the present description.

In reflected light the mineral is medium grey in colour, considerably lighter than sphalerite, and is completely isotropic between crossed nicols. These optical properties rather indicate it is near the tetrahedrite (Sb-rich) end of the series. However, coarse-grained accumulations of fahlerts in the wall rocks have proved, from their chemistry and x-ray data, to be tennantite. The possibility remains that there are two members of the series, one in the massive ore and one in the wall-rock mineralization.

The fahlerts in the massive ore is almost invariably associated with galena. Only on extremely rare occasions can it be seen crystallised together with other sulphides, mostly chalcopyrite. Within the patches of galena, the fahlerts shows variable grain size, form and mutual relations. Very frequently the mineral occurs as small, rounded grains or patches, of the order of 0.01 mm diameter, within the areas of galena, most typically at or near the boundaries with adjacent mineral grains.

It is seldom that anything resembling crystal outlines can be seen in these small fahlerts bodies.

In specimens in which the fahlerts is rather more abundant, the size of the individual grains may approach the order of 0.1 mm, but at this stage it would be more correct to speak of a mutual intergrowth of galena and fahlerts. As an extreme example of such intergrowth the two minerals on occasions form semigraphic intergrowths with each other. (Fig. 31).

The almost constant association of the fahlerts with the galena, together with the mutual textures of the two minerals indicate that they have been intimately associated together during the history of the deposit. The texture suggest simultaneous crystallisation, while the frequent occurrence of the fahlerts at the grain boundaries of the galena might be taken as indicating that it had migrated there during cooling and annealing, perhaps from an initial solid solution. Textures usually taken as indicative of the unmixing of solid solutions of the two minerals are lacking and as Ramdohr points out, (1960, p. 525) the dissimilarity in the crystal structures of the two minerals is rather against the possibility of solid solutions.

However this may be the fahlerts and galena must be regarded as strictly contemporaneous and to have crystallised from some mutual component in the ore.

Intergrowths possibly resulting from the breakdown of the fahlerts have been described above in the sections dealing with gudmundite and breithauptite.

*Boulangerite*,  $Pb_5Sb_4S_{11}$ . A sulphosalt of the «plumosite» type is a very rare constituent of the massive ore. It is normally much less abundant than the fahlerts mineral, but like the latter it is almost invariably associated with galena.

The mineral has a hardness slightly less than that of galena and shows (in oil) a whitish body colour, with a distinctly green tint, having a markedly lower reflectivity than galena. Reflection pleochroism is distinct, white with a greenish tint (near galena) to light green-grey. Anisotropism is distinct to strong, light grey to darker brown-grey. It is tentatively identified as *boulangerite*.

The *boulangerite* occurs in irregular, often elongated to tabular patches in the galena, occasionally by itself, of the order of 0.1 mm maximum dimensions. Less often it occurs in rather intimate, semi-

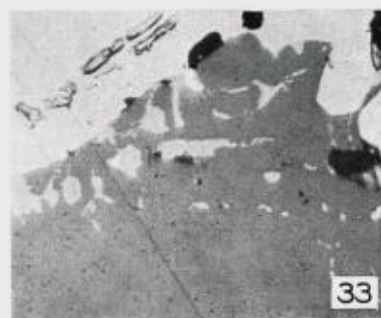
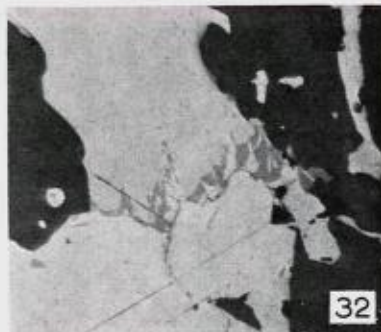
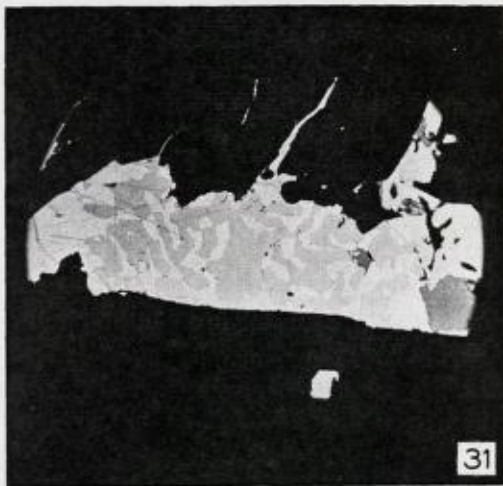
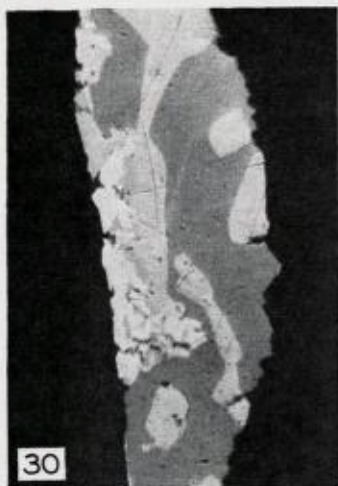


Figure 30. Part of semigraphic intergrowth between galena (medium grey, scratched) and «fahlerts» (dark grey) with fine-grained intergrowth of gudmundite (lightest) and pyrrhotite (slightly darker than galena). Reflected light, oil. 720x.

graphic textures with galena and/or fahlerts. Fahlerts is often present along the grain boundaries between the larger grains of boulangerite and the surrounding galena (Fig. 32). Less commonly the boulangerite grain is surrounded by a semigraphic intergrowth of the other two minerals.

Thus the remarks regarding the close association of fahlerts with galena must be extended to include the boulangerite. Thus, of the minor sulphosalts present in the Bleikvassli massive ore, fahlerts and boulangerite seem invariably to accompany the galena, as contrasted with the almost invariable association of stannite with the sphalerite and chalcopyrite.

Fig. 30. Del av en «semigrafisk» sammenvoksning mellom blyglans (middels grå, ripet) og fahlerts (mørk grå), med finkornig gudmunditt (lysest) og magnetkis (noe mørkere enn blyglansen). Reflektert lys, olje-immersjon, 720x.

Figure 31. Semigraphic intergrowth between galena (lighter) and «fahlerts» (darker) interstitial to fragments of gangue minerals (black). Reflected light, air. 75x.

Fig. 31. «Semigrafisk» sammenvoksning mellom blyglans (lysere) og fahlerts (mørkere). Finnes som grunnmasse mellom stykker av kvarts (sort). Reflektert lys, olje-immersjon, 75x.

Figure 32. «Fahlerts» (medium grey) in small patches along boundary between boulangerite (light grey, upper half) and galena (slightly lighter, lower half). Also present sphalerite (very dark) and pyrrhotite (light grey, relief). Reflected light. Oil. 265x.

Fig. 32. Fahlerts (middels grå) i små områder langs grensen mellom boulangeritt (lys grå, øvre del) og blyglans (noe mørkere, nedre del). Det forekommer også sinkblende (meget mørk) og magnetkis (lys grå, relieff). Reflektert lys, olje-immersjon, 265x.

Figure 33. Small irregular bodies of stannite (medium grey) in sphalerite (dark grey) near its grain boundary with chalcopyrite (light grey). Reflected light, oil. 740x.

Fig. 33. Små, uregelmessige stannitt-kropper (middels grå) i sinkblende (mørk grå) nær dens korn grense mot kopperkis (lys grå). Reflektert lys, olje-immersjon, 740x.

Figure 34. Almost complete pseudomorphs of pyrrhotite after magnetite in ground mass of sphalerite (dark grey) and pyrrhotite (light grey, smooth). Remnants of magnetite (medium grey) and unreplaced inclusion of pyrite (lightest) occur within the pseudomorphing pyrrhotite. Reflected light. Oil. 300x.

Fig. 34. Nesten fullstendige pseudomorfoser av magnetkis etter magnetitt i en grunnmasse av sinkblende (mørk grå) og magnetkis (lys grå, glatt). Rester av magnetitt (middels grå) og en uforandret svovelkis-inneslutning (lysest) opptrer i den nydannede magnetkis. Reflektert lys, olje-immersjon, 300x.

Stannite,  $Cu_2FeSnS_4$  is a widespread, but trace, constituent of the massive ore at Bleikvassli\*, and has been observed in over 50 percent of the polished sections examined. The stannite shows a generally characteristic and uniform association and normally occurs in extremely minute individuals which exhibit few, or no crystal outlines. These individuals take the form of rounded blebs or elongated «worm-like» bodies and irregular branching shapes showing a combination of the first two. When present these stannite bodies very seldomly occur singly, but rather in «swarms» of individuals of varying numbers.

The most common place of occurrence by far is in sphalerite at or near the grain boundaries, very often when the zinc sulphide is in contact with chalcopyrite. Figure 33 illustrates a typical occurrence of this type in which the irregular nature of the stannite bodies is well shown. It can be seen that the stannite bodies which occur at the actual grain boundary present a mutual junction with the sphalerite. No instances have been noticed of the stannite sticking out into the chalcopyrite, and the tin mineral does not seem to occur at all in the chalcopyrite at its grain boundaries with sphalerite, it is always the reverse relationship which holds.

In less frequent cases the minute rounded stannite bodies occur at the contacts between sphalerite and galena, and here it is not uncommon for them to protrude out into the galena or to occur wholly on the galena side of the mutual contact.

The stannite exhibits normal optical properties. In ordinary light the mineral shows an olive brown colour, clearly darker than chalcopyrite and pyrrotite, but lighter than sphalerite. The stannite bodies are normally so finely divided in the massive ore that it has not been possible to determine the mineral's absolute reflectivity. Similarly, pleochroism is normally difficult to detect in most instances. Under crossed nicols the stannite shows a marked to strong anisotropism, but here again only the larger bodies show this effect clearly. The anisotropic colours in the diagonal position are a characteristic deep violet and a slaty green. These colours often reveal that the mineral is twinned.

The mode of occurrence of the stannite, particularly its very close association with the sphalerite and its preference for the border zones of this mineral indicates a close genetic connection between the two

\* The content of Sn as stannite in the Bleikvassli ore does not exceed 100 ppm (0.01 percent).

sulphides. The texture is that of an «emulsion» resulting from the unmixing of a solid solution, which has incompletely segregated toward the grain boundaries of the host mineral. In this case there would seem to have been small quantities of Sn and Cu originally in solid solution at elevated temperatures in the dominant zinc-iron sulphide, which during cooling have been precipitated as  $\text{Cu}_2\text{FeSnS}_4$ , probably as a fine emulsion texture which has subsequently coagulated and moved towards the sphalerite borders.

The crystal structures of sphalerite, stannite and chalcopyrite are very similar, being based on the face-centred cubic, ZnS structure, so that extensive solid solutions between these minerals (and others of similar structures) are possible.

Exsolution textures between stannite and chalcopyrite are extremely common and would appear to be more usual than stannite-sphalerite (in cases where stannite is the minor or «guest» mineral). In the case of the Bleikvassli massive ore there seems little doubt that the stannite was originally in solid solution with the sphalerite and not with the chalcopyrite.

The origin of the tin in the sulphide phase in the ore is not too clear. It may have originally been present in the mixed sulphides, in whatever form they were, which crystallised or recrystallised to give the ore as observed today. There is the possibility, however, that this sulphide tin was derived from the tin oxide, cassiterite, present in the ore by a process of corrosion during the elevated temperature conditions of the metallization. As described in a separate publication the cassiterite appears as subrounded to irregular grains, often enclosed in sulphides, and a certain amount of corrosion might be expected under elevated conditions. There is, however, no observable spatial relationship between the cassiterite grains and the occurrence of stannite.

**Bournonite**,  $\text{CuPbSbS}_3$ , has only been identified with certainty in one polished section of the Bleikvassli ore. In a section of massive pyritic ore from about the 420 m level, bournonite occurred with galena in a fine myrmekitic intergrowth surrounding an elongated core of boulangerite. The myrmekite and the core together seem to make up a prismatic crystal outline which may have been the original outline of a complete boulangerite crystal. The mineral surrounding this compound crystal is galena.



In other places in this same section were seen elongated bladed forms made up of the same galena-bournonite myrmekitic texture, one of them also with a small unreplaced core of boulangerite, which seems to strengthen the idea that the myrmekite has resulted from an alteration of boulangerite.

Ruby silver ore has been certainly identified in only one polished section. The mineral is normally easily recognizable due to its characteristic blue-grey colour in normal light and its deep red internal reflections under crossed nicols. In the instance observed the ruby silver ore occurred intimately intergrown with galena surrounding a small patch of boulangerite. It was not possible to determine whether the mineral was a proustite or a pyrargirite.

### Oxides.

Magnetite,  $\text{Fe}_3\text{O}_4$ , is very restricted in its occurrence at Bleikvassli, as has already been described in the section on the composition of the massive ore. The only two localities in which magnetite has been observed in polished section are a) in the wide section of solid ore on and above the southern end of the 330 m level, b) in the central part of the mine, in the neighbourhood of coordinate 50S, at elevations of 310 m and 350 m. In specimens from locality a) the iron oxide occurred randomly distributed in small grains showing both anhedral and euhedral outlines. These grains occurred in both the sulphides and in the non-sulphide gangue and presented both well-developed crystal faces and rounded outlines to all the surrounding minerals. In places the section showed rounded forms of sphalerite apparently entirely surrounded or enclosed in the magnetite. To judge by the complete lack of embayments or caries of the sulphides around the edges of the magnetite, these seem to be true three dimensional inclusions and not just chance intersections of the plane of the section. This texture may suggest the magnetite has grown blastically in the ore, but since it is of infrequent occurrence it will not be stressed here.

In the second locality the magnetite, which occurs much more abundantly than in the first locality, shows a remarkable brecciated and partly replaced texture. (see Fig. 34). The magnetite apparently occurred originally as granular aggregates in the sulphides or as individual grains showing, in places, crystal outlines, a mode of

occurrence identical with that in the first locality. However the iron oxide in locality b) has subsequently been fractured or even shattered and the fragments have been replaced to varying degrees by fine-grained pyrrhotite, which appears to be of a different nature from that normally occurring in the ore (see above, p. 45). The degree of replacement varies from a mere corrosion of the edges of the magnetite fragments to an almost complete pseudomorphing of the original subhedral grains. It is clear that the replacing pyrrhotite has only affected the magnetite. It has not attacked the sulphides which were originally adjacent to or surrounding the magnetite grains, nor has it affected sulphides originally present as apparent inclusions in them. This mode of replacement is identical to that affecting the pyrite grains in the same sections (see above, p. 45).

As has already been mentioned, cubanite has been observed intergrown with the fine-grained pyrrhotite between the magnetite fragments and occurs as lamellae in the adjacent chalcopyrite.

Cassiterite,  $\text{SnO}_2$ , occurs in trace amounts apparently scattered at random throughout the massive ore. Its occurrence and distribution have already been dealt with in detail in a previous publication (Vokes, 1960). The cassiterite occurs as rounded to subhedral grains sometimes showing poorly developed crystal faces. The maximum dimensions of the grains range from 0.03 to 0.50 mm, with an average of about 0.20 mm.

In thin section the grains shown mainly subhedral to irregular cross-sections, with a greater tendency to euhedral forms where they occur in patches of the quartz-mica gangue. Kneeshaped twins were observed in a few instances. A few grains show short prismatic forms, but the majority tend to be equidimensional and rounded in outline.

The cassiterite may be colourless or may show irregular streaks or patches of a light brown colour. A common form for the coloured patch is an indefinite annular ring with a colourless centre and rim.

The cassiterite is associated with all the main minerals of the ore, but most grains appear to occur in the quartz-mica gangue. They usually occur in an area of allotriomorphic quartz mosaic and in most cases it is very noticeable that the grain size of the cassiterite is several times larger than that of the quartz enclosing it.

Less often the grains of cassiterite occur isolated within much larger grains of sulphide minerals, especially within the pyrite granules.

## Discussion.

### METAMORPHISM OF THE ORE

The present investigation of the mineralogy and petrology of the Bleikvassli ore does not, in the writer's opinion, afford conclusive evidence concerning the original derivation and emplacement of the sulphides, but it does enable the later history of the ore to be worked out in some detail and, the writer believes, enables the metamorphic (or metamorphosed) character of the ore to be established.

The sulphides occur in the main in the form of concordant bodies whose areal dimensions are many times greater than their thicknesses. They lie interlayered with the country rock schists at all scales, from mere strings of sulphide grains to massive bands of sulphides several metres wide. The interrelations of the sulphides and interlayered schists are completely reversible, i.e., it is often not possible to say whether any particular cross-section of the orebody is a series of bands of sulphides in schist or a series of schist layers in sulphides. Both the schist and the sulphide layers seem to be equal members of the rock sequence, at least within the actual ore zone.

The gangue minerals of the massive sulphide bands are qualitatively the same as those forming the schist bands; they are merely «diluted» by the sulphide minerals. In the relatively minor cases where there is a transition from ore to country rock, the continuity of the gangue minerals from ore to non-ore is easily followed.

Not only are the two members, schist and ore, interlayered with one another, but they also take part in fold structures together. These structures are at all scales, from hand specimen size to folds of many metres amplitude and wave-length. Within the orebody as a whole examples may be found showing all transitions from «undisturbed» interlayered schist and sulphide through mutually folded areas to places where the folds (as shown by the schist) have become disrupted and detached so that isolated pieces of the folded schist lie entirely surrounded by massive sulphide.

Such features, it would seem, are capable of one of two possible interpretations:

a) the sulphidic ore as a whole has invaded and partly replaced a zone of previously folded and disrupted schists at a fairly late stage

in the history of the Caledonian orogeny. Thus the ore itself would be post- or late-tectonic in time of emplacement.

While this possibility cannot be discounted, the present writer feels that the weight of textural, structural and tectonic evidence is against it. In the case of the pyritic ore at least, the fold axes in the schist partings and, especially in the detached folds, show the same directions as in the surrounding country rock. This argues against there having been any large scale open space filling by, for example, a «sulphide magma» or by hydrothermal solutions. In this case the fold axial directions in the ore zone would have been greatly disturbed by the pushing aside of the ore walls and the intervening schist partings to form orebodies of the thickness encountered.

A more gentle *in situ* replacement mechanism is however not excluded, whereby already folded and metamorphosed schist were partly replaced, by sulphide bearing emanations «soaking» through the ore zone.

b) the sulphides were *in situ*, interlayered with the non-sulphide members, before the orogeny and were subsequently folded and metamorphosed together with the latter. Independently of the form of the sulphides before the orogeny, they recrystallised under the PT conditions of the metamorphism to produce the textures observed at the present day. This interpretation is favoured not only by the interfolding of the ore and schist layers, but by the folding, where present, of the ore mineral banding.

However, perhaps the most important single piece of textural evidence favouring a metamorphic nature of the ore are the forms exhibited by the pyrite granules which, as has already been intimated, seem to indicate that they are dominantly the result of growth rather than of replacement.

The writer considers that this process of growth is one which has taken place under the influence of the Caledonian regional metamorphism, in other words it is a process of *metablastic recrystallisation* from a milieu in which all the components of the sulphides were present (as well as the gangue minerals). Because of the well-known idioblastic tendencies of pyrite (high force of crystallisation) this mineral has preferentially formed sub- to euhedral grains, whereas the matrix sulphides, as has been described, have not done so. Such a growth process is well-accepted in non-ore petrology in the case of minerals like garnet and staurolite. If one compares a pyrite from the Bleikvassli

ore with a garnet from the immediate wall rock, it can be seen that such features as inclusions, embayments and partially developed crystal faces are common to both minerals and a common, blastic, mode of formation must be ascribed to both.

Thus the textures shown in polished section by the Bleikvassli pyritic ore are not the results of a depositional sequence but of metablastic recrystallisation in which minerals with the strongest idio-blastic tendencies (pyrite, and where present arsenopyrite and magnetite) have grown to form the most euhedral crystals.

This conclusion has already been reached by other workers on similar pyritic ores. The most recent expression of this is a publication by Stanton (1960) who has described similar textures from the metamorphic pyritic Pb-Zn-Cu ores of the Bathurst area of New Brunswick. Stanton envisages a process of expulsion of entrapped matrix sulphides during the blastic growth of the pyrite grains. The rounded inclusions near the centres of the pyrites thus represent «trapped» inclusions which had not migrated outwards to any appreciable degree. The elongated inclusions around the circumferential belt of the pyrite grains would represent areas of sulphides which had been almost expelled, while the embayments are the inclusions which had succeeded in breaking out. This mechanism is somewhat different from the one proposed by the writer earlier in this paper which was based on the blastic growth of the pyrite crystals whereby the inclusions represent entrapped embayments.

However, composite granules of pyrite formed by the near coalescence of grains growing from several centres have also been described and it is easy to envisage that grains of matrix sulphide, which became so entrapped during the blastic growth of the pyrite, would tend to be expelled towards the margin due to the dissimilarities in the crystal structure and crystalloblastic strength of the pyrite and the matrix sulphides respectively. The mechanism of the growth of the pyrites may therefore well be a combination of skeletal growth of the crystals and subsequent expulsion of the inclusions of «foreign» matrix sulphides so incorporated in an attempt to form a perfect, inclusion- and embayment-free pyrite crystal.

The possibility of blastic growth of pyrite in massive sulphide ore bodies has not, in recent years at least, been considered in the rather sparse literature dealing with Norwegian examples.

The most recent, published, study of the mineralogy of a Norwegian

Caledonian pyritic orebody is that of Gjelsvik (1960) on the Skorovass deposit. In this publication Gjelsvik does not consider the mode of formation of the sub- to euhedral pyrite cubes, but considers that they have been «extensively replaced by chalcopyrite and, particularly, by sphalerite». However, this writer does discuss the effects of the Caledonian metamorphism on the Skorovass ore and implies that the replacement phenomena may possibly be a result of this metamorphism.

It has already been remarked that limited replacement of the pyrite in the Bleikvassli ore has taken place and this, too, must have occurred at some time during the metamorphism subsequent to the blastic growth of the mineral.

Some years ago, C. W. Carstens (1941, 1944) discussed the metamorphism of the Norwegian pyritic ores. Among other aspects of this, Carstens described and figured photographs of large pyrite crystals from Charlotta Grube, Sulitjelma and Nordre Grube, Folldal, showing inclusions of non-sulphide minerals. Carstens interpreted these crystals as being «typically developed porphyroblasts with inclusions of several different groundmass minerals». The example from Folldal appeared to have been rotated, since the inclusions showed a circular or bow-shaped arrangement, in the same manner as inclusions of quartz, etc., in helicitic garnets.

Since so few pyrite grains show signs of any really violent disturbance after they were formed, this blastic growth must have been mainly completed at a period succeeding that of the folding, a period of relative quiescence and perhaps mainly static pressure, although one at which the temperature of the metamorphism was maintained with the result that the minerals adjusted to the metamorphic facies conditions. The recrystallisation has been so complete that all signs of any preexisting texture have been lost completely. The frequent occurrence of almost perfectly idiomorphic crystals of pyrite in the thoroughly tectonized (*durchbewegt*) pyrrhotite-rich ore is another indication that there was a period of pyrite growth subsequent to the more violent tectonic movements.

However, the directed, or gneissose, textures observed in the ore, especially in the less massive parts, show that pyrite metablasts either grew under stress or were subsequently deformed by such stress arising from the folding.

It thus appears that growth of pyrite granules took place both simultaneously with and subsequently to the folding of the ore.

The mutual relations shown by the sphalerite and the galena seem also to be the result of the segregation of the minerals under the metamorphic temperatures attained. Such a conclusion is in accord with that of Stanton (1960, pp. 4-5) regarding the crystalloblastic sequence of minerals in metamorphic ores of this type. The reader is referred to Stanton's fuller, more generalized, discussion of these topics, based on the examination of ores of generally lower metamorphic grade than Bleikvassli. In these ores the process of segregation can be followed stage by stage towards the production of textures of the type exhibited by the Bleikvassli ore in which the process of segregation seems to have been completed to a large degree.

In this connection the photographs of artificially recrystallised lead and zinc sulphides published by Nixon et al. (1961) are interesting. A photograph of a recrystallised zinc sulphide-lead sulphide mixture shows a texture resembling many observed in the Bleikvassli ore.

It has already been remarked that true exsolution textures, e.g. between sphalerite and chalcopyrite, are generally absent in the ore. It is of course rather obvious that in an ore which has been subjected to regional metamorphism, both the heating up and the cooling down processes would be of relatively long duration so that any emulsion textures which existed would have had the opportunity to segregate into the type of intergrowth now exhibited by these two minerals. Comparatively rapid quenching is required in order to retain emulsion textures and such a process is likely to be more characteristic of hydrothermal vein deposits than of metamorphosed massive ores.

Thus the cusped forms exhibited by the galena, and to a lesser extent by the chalcopyrite, around the edges of larger grains of sphalerite appear to be the end result (or nearly so) of the segregation of the mineral pairs from an originally finer grained intergrowth — most likely, in the case of the copper and zinc sulphides, from an exsolution texture.

This recognition of the metamorphic nature of the ore does not necessarily imply that the original *mise en place* of the sulphides took place prior to all orogenic movements. The Caledonian orogeny stretched in time from Cambrian to Devonian and embraced several distinct phases of movement.

The main folding and metamorphism occurred during the Ardennian phase which took place during the late Silurian or at about the boundary

between the Silurian and Devonian. Thus it would appear reasonable to conclude that the Bleikvassli sulphides had been emplaced in their present position before the onset of the Ardennian phase and that they are of a Silurian or earlier age. In such highly metamorphosed, non-fossiliferous rocks such as those of the Bleikvassli area, classical geological methods are of little help in determining the ages of the formation represented. Meanwhile, geochemical methods of age determination may be used to try to date at least the age of the metamorphism. One such determination (K-Ar) on muscovite from the Bleikvassli ore by L. T. Kulp gave an age of 395 m.y. (Neumann, 1960).

According to the latest time scales of Holmes and Kulp, reported by Davidson (1960, p. 318) such an age would fall in the early Devonian, within 5–15 m.y. of the Devonian–Silurian boundary. This is, at least, in keeping with the geologically most probable age of the main Caledonian metamorphism.

Lead isotopic ratios of three samples of galena from Bleikvassli (see Moorbath and Vokes, 1963) gave anomalously young ages and cannot be used to date the actual ore minerals.

#### PREVIOUS VIEWS ON THE METAMORPHIC CHARACTER OF MASSIVE SULPHIDE ORES

The regionally metamorphosed character of massive sulphide ores of types similar to that of Bleikvassli has been established for some decades now. Among the earliest workers to deal with the subject were certain German ore geologists, of whom one may mention G. Berg in 1927. Berg put forward the opinion that the large rounded pyrite crystals at Sulitjelma were porphyroblasts. The following year P. Ramdohr (1928) described the mineralogical and textural changes which he considered the Rammelsberg ores had undergone during regional metamorphism. Ramdohr also mentioned the Sulitjelma ores in the same paper and considered that they had been metamorphosed under katazonal conditions, whereas the Rammelsberg ores had been subjected to lower, epizonal conditions. Contemporary and later workers described further examples of this type, for example, Frebald (1927), the Meggen and Rammelsberg ores and Maucher (1940), the ore at Grube Bayerland, Oberpfalz, an ore which strongly resembles many of the Norwegian massive pyritic ores. Among publications



dealing with the metamorphism of pyritic ores in other countries one may mention those of Zavaritsky (1950) and, more recently, T. Schadlun (1959) dealing with Russian examples. R. L. Stanton (1959, 1960) has described similar features in ores from the Canadian Appalachians.

In 1931 C. W. Carstens published a paper dealing with the Precambrian pyritic deposits in the Porsanger district of Finnmark. In this, Carstens put forward the view that the copperfree layered pyrite deposits of this district must be regarded as metamorphosed representatives of a type of mineralization similar to the sedimentary Leksdals type of the Trondheim region. The metamorphic grade of the Porsanger district is considerably higher than that prevailing in the Trondheim region, basic rocks which appear as greenstones in the latter region are metamorphosed to amphibolites in the Porsanger district. Correspondingly, the dense micro-crystalline pyrite of the Leksdals type in the Trondheim region is represented by a recrystallised, fine-grained type in Porsanger.

The first printed Norwegian reference to the metamorphism of the Caledonian massive sulphide deposits of which the writer is aware, is in the report of a discussion in which S. Foslie (1938) forwarded the view that the massive sulphide deposits, in a similar manner to the rocks in which they occurred, had been subjected to regional metamorphism. Foslie pointed to the fact that those deposits which occur in rocks showing low grade metamorphism (greenschist facies) are as a rule characterised by a very fine-grained texture and very intimate intergrowth of their mineral constituents, e.g., Løkken, Grong, etc. In regions of higher metamorphic grade, as for example, parts of Nordland and Troms, where the rocks have often been metamorphosed under conditions of the amphibolite facies, the massive sulphide deposits everywhere show a coarse grain size.

This theme was later taken up and enlarged upon by C. W. Carstens in the two publications (1941, 1944) to which reference has already been made in the present paper. Carstens pointed to the extremely fine grain size (ca  $5\mu$ ) of the sedimentary sulphide layers of the Leksdals type in the low grade metamorphic rocks of the Trondheim region. The more massive ores of Løkken itself and the Grong area deposits show a somewhat coarser grain size, in the range 50 to  $200\mu$ . However these are still very fine-grained as compared with such ores as those of Follidal, Røros and especially Sulitjelma, which lie in areas

of increasing metamorphic grade. Carstens suggested also that there was a somewhat different mineralogical composition in these higher metamorphic ores.

The present writer from his studies of the Bleikvassli and other Norwegian Caledonion massive sulphide ores is in complete agreement with Carstens' 1944 conclusions that «the pyritic deposits — in the same manner as other rocks and ores — have to different degrees been subjected to a regional metamorphism which has altered the ore both mineralogically and structurally».

#### THE RELATIONSHIP BETWEEN THE TWO MASSIVE ORE TYPES

The differences of texture and mineral and chemical composition between the two ore types prompt one to enquire into the possibility that they have different genetical histories.

It is clear that both types of ore have been tectonically affected to a greater or lesser extent, but that, on the whole, the pyrrhotite-rich ore shows evidence of a more intense deformation, a true «Durchbewegung». Indeed, it may be considered whether the pyrrhotite-rich ore may possibly be a product of the process, being formed along zones of more intense deformation by metamorphism (loss of sulphur) of the pyritic ore. However, in parts (particularly the highly folded areas towards the foot-wall) the pyritic ore also shows rather intense deformation and still retains its mineralogical character. This makes it somewhat unlikely that there has been a change from pyrite to pyrrhotite due to more intense deformation.

A second alternative which must be considered is that the pyrrhotite rich ore was introduced later than the pyrite ore, along zones, particularly along the foot-wall, where movement (post-pyrite ore) had given rise to crush zones which provided the host structures. At the same time the movements caused the pyrite ore to be deformed to varying degrees. This alternative seems possible from a structural point of view, but the often transitional junctions between the two massive ore types and the not infrequent presence of undisturbed, blastic pyrite grains in the pyrrhotite ore would seem to argue against this.

A further alternative is that the pyrrhotite-rich ore was, like the pyrite ore, *in situ* before the orogeny — a foot-wall layer of relatively

sulphur-poor ore — which on metamorphism would give rise to pyrrhotite as the dominant iron sulphide, although in parts, especially in the junction zone between the two types, some pyrite was able to crystallise. During the orogenic deformation either the mechanical properties of the pyrrhotite-rich layer were such that it deformed more strongly (plastically) than the pyritic type ore, or, less likely, there were localised parts of the orebody which were more intensively deformed, these parts coinciding with the pyrrhotite-rich ore on the whole.

The writer believes that the weight of the evidence is in favour of this last alternative, that both massive ore types at Bleikvassli were emplaced in more or less their present stratigraphic position by a common ore forming process before the onset of the deformation and recrystallisation to which they have undoubtedly been exposed. It is not possible to say from the present study in what form the Bleikvassli sulphides existed prior to the orogeny.

A single period of deformation seemingly produced the fold structures in the pyrite ore and its wall rocks, in places causing the folds to become disrupted and detached, as well as the pseudo-brecciated structures in the pyrrhotite-rich ore.

The possible origins of the pyritic and pyrrhotitic ores, respectively, in the Caledonides of Norway have been discussed in more general terms in a recent paper by the present writer (Vokes, 1962) and it must be said that the Bleikvassli study has not given much support to the view put forward in that paper of a late, epigenetic (granitization) derivation of the pyrrhotite-rich ore type. In the case of Bleikvassli, at least, the evidence is strongly in favour of the structural-textural features of this ore type being the result of «Durchbewegung» and not of an epigenetic introduction into an existing breccia zone. This leaves the possibilities that either the pyrrhotite-rich mineralization is the result of the metamorphism of a preexisting pyrite ore, or that it was present *per se* prior to the period of orogeny. The writer considers that this latter possibility is the more likely.

The recognition of two types of pyrrhotite-rich mineralization at Bleikvassli (see pp. 50–51) may help to reconcile the evidence of undoubted epigenetic emplacement of this type of ore at mines such as Joma and Jakobsbakken, cited in the writer's 1962 paper just mentioned. What has been termed on p. 51, the chalcopyrite-

pyrrhotite type, seems to be due to a partial remobilization of these minerals under the conditions of metamorphism and their emplacement at comparatively short distances away.

It is possible that this is the origin of the rich chalcopyrite-pyrrhotite ore cementing a breccia of fine-grained pyritic ore at Joma, for instance. At the present state of knowledge it is not possible to say how widespread this remobilized type may be in the Coledonides, i.e., just which representatives of the pyrrhotite-rich mineralization are the result of remobilization.

There is also reason to ascribe the irregular wall rock mineralization (see p. 55) to remobilization during the orogeny. This, it is hoped, will form the subject of a separate study and will not be touched on again here.

However, it may just be mentioned that Maucher (1940) in his study of the ore at Grube Bayerland, suggested a remobilization origin for mineralization similar to that in Bleikvassli wall rocks. It is also of interest that T. Schadlun (1960) has recently described almost identical phenomena from massive sulphide deposits in the region of the Urals.

### Conclusions.

In general the Norwegian Caledonian ores may be divided into two main groups based on geological associations, texture and form. The first group, the Løkken-Grong type of Carstens, occurs in massive to schistose volcanic rocks, generally in the green-schist facies of metamorphism and shows an extremely fine- to fine-grained texture. The orebodies are normally thick lenses of very massive sulphide, analysing around 50 % S. The second group, which is usually further subdivided, occurs in more schistose rocks of a generally higher degree of metamorphism. The ores show a generally coarser texture and occur as plates or flattened lenses, often greatly elongated in one direction, which lie generally concordantly with the layering of the enclosing schists. They may be classed as «conformable ores» in the sense of Stanton and Russel (1959). Bleikvassli shows many similarities to orebodies of this second type.

Normally these ores may be best described as pyritic Zn-Cu ores, less frequently as Cu-Zn ores. Bleikvassli and the few related ores (see below) are best described as pyritic Zn-Pb-(Cu) ores.

Mineralogically, the Bleikvassli massive ore shows the following main differences from most of the ores of the second group:

- 1) The presence of a high percentage of galena, such that this mineral appears as one of the major mineralogical constituents of the ore.
- 2) A rather higher than normal sphalerite content.
- 3) A considerably lower chalcopyrite content.
- 4) The presence of a large number of minor ore minerals, which so far have been found in very few of the other deposits of this group. (Notable exceptions are Sulitjelma and Røros).

Within the Caledonian province as a whole, lead-bearing deposits are most abundant in certain sub-provinces, especially in parts of Nordland county and in particular in the Vefsn-Rana area and the Ofoten-Southern Troms area. The only other mine in Norway which produces lead concentrates at the present time is that at Mofjell on the outskirts of Mo i Rana. Although not all the ore mined at this mine can be classed as «massive pyritic ore», the deposit contains many bands which resemble the massive Bleikvassli ore in composition and texture.

In the Plurdalen area, ENE of Mo, several small prospects show irregular bodies of a pyritic zinc-lead ore, which in hand specimen is indistinguishable from that of Bleikvassli, though little detailed mineralogical work has yet been done on them.

The other lead-bearing deposits in central Nordland (Helgeland) (Torgersen, 1928) and in the rest of northern Norway (Torgersen, 1935) are on the whole seldom pyritic, yet on the other hand there occur within the lead-rich sub-provinces pyritic ores of the more usual Caledonian type containing only trace amounts of lead, e.g. Båsmo, Malmhaug, Mosgruven, Bjørkaasen. The reasons for this distribution of metal values are little understood at the present time.

Grip (1950) briefly mentions the lead and zinc-bearing deposits in the Caledonides of Västerbotten at about the same general latitude as those of Helgeland. In their discussion of the lead isotope ratios of Swedish galenas, Wickman et al (1963) also mention these deposits and refer them to the Flöttum type of Carstens. This point will be enlarged upon below.

In the rest of the Norwegian Caledonian province, lead-bearing ores are very infrequent. Two small, insignificant prospects in the Grong

area are mentioned by Oftedahl (1958), while two others are known in Nord-Trøndelag county, near Steinkjer and Levanger respectively.

The pyritic ore at Killingdal mine, SE of Trondheim, is a «normal» Zn-Cu ore of the second type, but fourteen bulk analyses made available to the writer showed an arithmetical mean of 0.40 percent Pb, with a range from 0.20 to 1.40 percent. The ore at Nordre gruben, Folldal, shows occasionally small grains of galena in polished section. These last two deposits are of interest in suggesting that there may be transitions from the more usual Zn- and Cu-bearing pyritic ores to the Zn-Pb-(Cu) ores of the Bleikvassli type.

Probably the most interesting deposit in the present context is the hitherto economically unimportant one at Flöttum, between Løkken and Røros. Carstens (1935) cited this deposit as the type example of his fourth class of Caledonian massive sulphide ores. The mineralogy comprises pyrite, pyrrhotite, sphalerite and galena, with occasionally small amounts of tennantite-tetrahedrite. As previously mentioned, Jösang has reported the presence of stannite in the Flöttum ore, though a detailed mineralogical study has yet to be carried out.

Until such time that this has been done, it seems reasonable to class Bleikvassli and the small deposits in Plurdalen, with possibly Mofjell, in the same mineralogical group as Flöttum. However, the above mentioned instances of a lead component in some of the more usual Caledonian pyritic ores show that there are gradations from this Flöttum-Bleikvassli type to the dominantly zinc-copper ore of the second type outlined above.

The Bleikvassli massive ore shows distinct mineralogical trends across its width, in which pyrite increases from footwall to hanging-wall and the non-ferrous sulphides generally diminish.\*

Very few data on such variations are available from other similar ores. Page has found that the ore at Nordre grube, Folldal, shows similar trends. Here there is no pyrrhotite-rich ore as at Bleikvassli, but the pyrite content of the massive pyritic ore does increase from foot-wall to hanging-wall. A foreign example of a mineralogically stratified ore which comes immediately to mind is that of Grube Bayerland, which has already been mentioned in another connection. Here the increase in sulphur content from foot-wall to hanging-wall is very well marked, the succession being: magnetite-rich layer — pyrrhotite ore — pyrite ore, from the foot-wall upwards. The small and erratic magnetite content at Bleikvassli does not fit in with any trends of this

sort, being at one place concentrated near the foot-wall, at the other near the hanging-wall. At Grube Bayerland the mineral stratigraphy is interpreted as being a primary (sedimentary) feature, being due to an increased sulphur supply during the later stages of sedimentation, i.e., to a change in the sedimentary facies from oxidic to sulphidic. As already discussed, the Bleikvassli evidence indicates that the pyrrhotite-rich foot-wall layers of the ore were already in situ prior to the Caledonian orogeny, though there is no evidence from the present study that this layering was necessarily sedimentary in origin.

The ore-forming materials appear to have been emplaced in their present position prior to the orogeny and metamorphism. They were recrystallised under metamorphic conditions which at their maximum corresponded to the epidote-amphibolite or lower amphibolite facies of regional metamorphism and the ore as seen at the present has a coarseness which seems to correspond with this facies.

The original derivation of the sulphides is a problem which a purely mineralogical-petrological study of the ore cannot solve unequivocally. Indeed, it may well be doubted if this problem will ever be solved in deposits which have undergone such a high degree of metamorphism.

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Part 2.

The supergene alteration of the pyritic ore.

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## Abstract.

The supergene changes which have taken place at the outcrop of this pyrite- sphalerite-galena-pyrrhotite-chalcopyrite ore are described and discussed. The present day climate is sub-arctic with a high annual precipitation, (ca. 1500 mm) most of which runs-off as surface waters. The area was glaciated during the Pleistocene and very little detectable weathering has occurred since then.

The ore outcrops are in parts ice-scoured, in parts remnants of an apparently preglacial zone of weathering are preserved. This zone consists uppermost of a porous gossan, the texture of which strongly reflects that of the pyritic ore from which it is derived. Goethite is the only oxidized mineral formed in the gossan, apart from anglesite which is very abundant in the lower parts. Beneath the gossan is a 20—30 cm zone of highly decomposed ore in which native sulphur plays a prominent role. This element appears to represent a temporary phase in the breakdown of the sulphides which is later oxidized and removed in solution as sulphate. Apart from thin films of covellite there is no sign of a copper cementation zone beneath the gossan.

Beneath the decomposed zone the ore quickly resumes its primary state and in polished section the only detectable effect is alteration of the pyrrhotite. Even this ceases within about 20 m of the surface.

The lack of a cementation zone is ascribed to the impermeable nature of the country rocks coupled with the climate, which led to little penetration by ground waters, most of the metals being carried away in solution by the run-off.

## Introduction.

The first part of this publication has described the detailed mineralogy of the Bleikvassli pyritic ore. This second part describes and discusses the supergene processes which have affected the pyritic ore at and near the present day outcrop.

Studies of the weathering processes affecting the pyritic orebodies of the Norwegian Caledonides have been few and far between, since it is usually considered that the Pleistocene glaciation has been instrumental in removing most or all evidence of the zones of weathering and cementation. Foslie (1950) and Sæbø, Sverdrup and Bjørlykke

(1960) have described the effect of weathering processes on pyrrhotite-bearing ores in the Caledonides, while Bjørlykke (1960) attributed enrichments of chalcopyrite in the upper parts of certain massive sulphide bodies to supergene processes. Bjørlykke's views have been queried by the present writer (Vokes, 1961) who pointed out the unusualness of chalcopyrite as a supergene mineral of copper.

It would appear however that instances of the supergene alteration of sulphide ores in Norway are not as scarce as the literature might suggest. The effects produced (or preserved) are obviously not as pronounced as those met with in countries which have escaped the planing effect of the Ice Age, or where the post-Pleistocene climate has been milder than in northern Norway\*). However detailed mineralogical investigations of those phenomena which are present would be rewarding in that the effects produced under the different climatic and palæoclimatic conditions could be compared in order to see if the course of weathering is any different in each of them.

Bjørlykke (op.cit.) pointed to three examples of pyritic ores which had apparently escaped the eroding action of the Pleistocene ice. These were Rauhammer mine, north of Røros, Bjørkåsen mine in the Ofoten area and Skorovass mine in the Grong district. Other examples which may be added to this list are Båsmo mine near Mo i Rana and Bleikvassli.

The present study of the weathering effects on the Bleikvassli pyritic ore is offered as a contribution to the problem of sulphide weathering in glaciated areas in high latitudes in the hope that it will stimulate others to similar contributions.

### The outcrop of the Bleikvassli ore.

The Bleikvassli orebody has a surface outcrop which has a strike length of about 400 m (Fig. 1), the width of ore subexposed under the overburden varying considerably. The greatest widths, up to 20 m, occur near the middle, and the southern part, of the outcrop. Overburden is variable in thickness but never more than a metre or two in thickness.

\*) At Mo, i Rana, about 50 km due north of Bleikvassli the average July temperature is 13.8° C and the average January temperature —5.8° C. The highest temperature recorded was 29.2° C in June and the lowest —30.4° in January. The mean annual precipitation is 1496 mm, the greater part falling in the winter months.

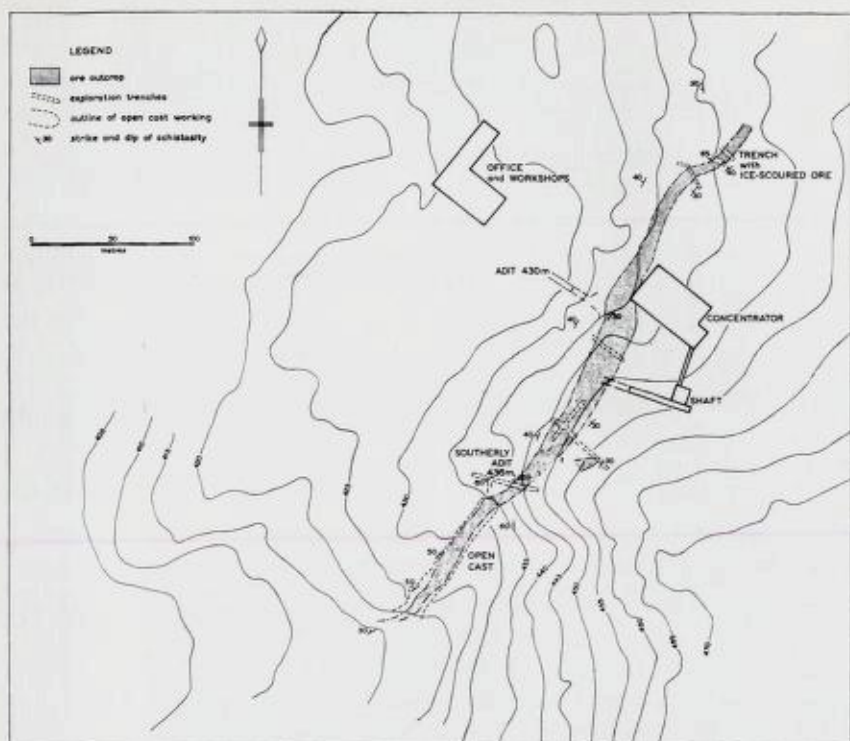


Figure 1. Map of the outcrop of the Bleikvassli ore zone to show some of the localities mentioned in the text.

Fig. 1. Kart over Bleikvassli-malmens utgående som viser en del av stedene nevnt i teksten.

The field investigations which form the basis for the present publication were only started after the exploitation of the ore had been in progress for some time. By then the surface outcrop had been considerably disturbed, especially by the excavation of a large open pit in the southern third of the orebody.

In places, however, sufficient of the preexisting surface has remained undisturbed to enable a qualitative study of the original nature of the weathered outcrop to be made.

Along the northern part of the ore outcrop, about 100 m long north of the concentrator building, the terrain has a fairly even and gentle slope to the west. The ore is covered by a mixed sandy-gravelly

transported glacial or fluvioglacial overburden, which varies in thickness from 0.5 to about 2 metres. The vegetation is a semi-tundra type comprising grass and low creeping shrubs and bushes with occasional small stunted birch trees. Several old exploration trenches through the overburden to solid ore enable the nature of the suboutcrop in this area to be studied. One of these trenches shows the overburden resting directly on an ice-scoured surface of massive pyritic ore. The only apparent weathering effect has been the formation of ox-blood red clay less than a centimetre in thickness. This presumably developed after the scouring of the ore by the ice.

However, in the next trench, only about 10 m along the outcrop to the south, there is evidence of much deeper weathering effects. The ore appears to have been the normal solid banded type, with partings of schist between the sulphide bands. These latter are now represented by bands of brown, porous gossan, or iron-hat, while between these, lighter coloured strips represent the original schist partings, now often reduced to a loose, granular mass of iron-stained quartz grains. The unaltered ore was not exposed in this trench, but the gossan bands could be followed down dip for at least 1.5 m.

Along the ore outcrop south of the concentrator, the thickness of the overburden appears to have been much less and there is more surface expression of the weathering zone. However along this part of the ore zone a considerable amount of surface working has taken place, so that the picture is very incomplete.

Southwards from the concentrator the westward slope of the ground along the ore outcrop steepens considerably and this steepening reaches a maximum in the area around the north end of the open pit. (See Fig. 1). The westerly dip of the ore is in places not very much greater than the slope of the ground surface, so that there was comparatively little rock cover to the sulphides for several metres down the dip. Thus the weathering processes have been able to affect the ore for considerable distances below the actual outcrop and it is in this area that the effects of these processes are best preserved.

At about the 436 m elevation a level has been driven along the strike of the ore zone, in the southerly portal of which it was possible to make a detailed study of the change from the gossan to the apparently unaltered ore. This locality was studied in detail in order to determine the mineralogical and chemical changes taking place in the ore due to the supergene processes.

## The dating of the weathering zones.

The question naturally arises as to whether these weathering remnants on the Bleikvassli ore are survivals from a pre-Pleistocene weathering epoch, or whether they have developed since the Ice Age.

The evidence from the northerly trench seems conclusive that where the ore has been scoured by the ice, no gossan development has taken place since. Supergene effects are a mere «rusting» of the surface of the ore. From a general point of view, one would not expect any deep weathering, since the glacial period, in the sub-arctic or cold northern climatic conditions which have prevailed in the area under consideration. Observations away from the ore zone show that unaltered copper, zinc and lead sulphides are not infrequent on glaciated pavements under a shallow cover of gravel or bog. Thus the gossan zones must be considered as survivals from a pre-glacial period of weathering. The reasons for their survival are not too clear. The glacial map of Norway (Holtedahl and Andersen, 1960) shows a general direction of ice-movement from east to west in the area under consideration, i.e., at right angles to the local «grain» of the topography. In the area around the orebody glacial striæ are hard to detect, but two observations on the foot-wall microcline gneiss to the east of the ore outcrop show a local movement, at least, from NNE to SSW. This direction of movement is down the valley from Bleikvatn towards Kongsdalen and may be related to a late stage of valley glaciation, probably emanating from a centre around Oksfjell-tindene, a mountain group some 15 km NE of Bleikvassli, which even today carries ice-fields.

For some reason, perhaps local unevenness of the preglacial surface, parts of the Bleikvassli outcrop were eroded to greater depths than others. In the southern half of the outcrop the steep westerly slope of the ground may have caused overriding by the ice, with a consequent lessening of pressure, and therefore, scouring effect.

Gjelsvik (1956) has discussed the preservation of preglacial weathering zones over copper deposits on Finnmarksvidda in the extreme northeast of Norway. He considers the effects of the paragenesis, the thickness of the ice sheet, the rate of movement of the ice and the possibility of preservation by depression due to earth movements. Gjelsvik is unable to come to any definite conclusions regarding the deposits studied by him, and for the time being this must be the state

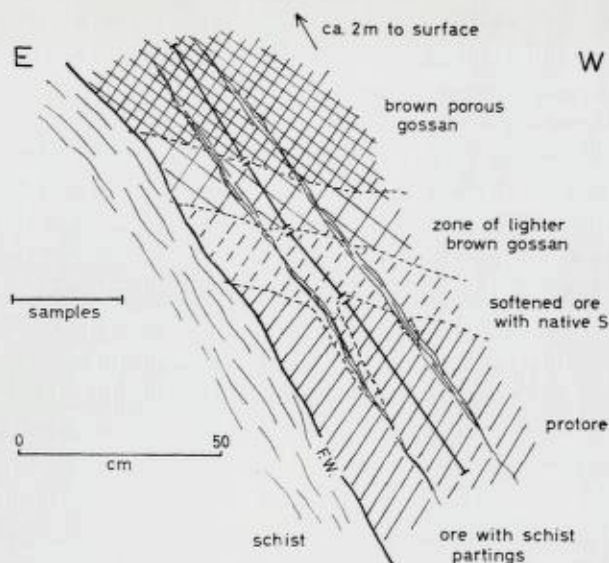


Figure 2. Sketch section of base of weathered zone near the portal of the southerly adit along the 436 m level showing the various weathering zones and the samples taken. Fig. 2. Skisse som viser tverrsnitt gjennom nedre del av forvitringssonen i nærheten av stollåpningen langs 436 m nivået. Forskjellige forvitringssoner er avmerket, likeledes hvor prøver ble tatt.

of affairs regarding Bleikvassli. One can only say that along parts of the outcrop the pre-glacial weathering zone is preserved, without being able to offer any detailed explanation.

### The mineralogy of the weathering zones.

The place chosen to study the various zones produced by the weathering of the ore was near the portal of the southern adit on the 436 m level, just north of the open cast. The locality was studied in detail and samples and specimens were collected for mineralogical and chemical investigation. Fig. 2 is a sketch of this locality locating these samples and specimens. As can be seen from this sketch, the ore bands dip to the west at 50–60°, while the surface of the ground above slopes at about 30–40°. The various weathering products form zones which are roughly parallel to the present ground surface, except where alteration has followed a schist parting to greater depth.



The gossan, from the outcrop to within 20 cm of the ore is a very uniform chocolate-brown, cinder-like substance. Fig. 3 is a photograph comparing a «typical» piece of gossan with a «typical» piece of sulphide ore from which it was derived. The similarity in texture between the two is striking. In a zone about 10 cm thick above the top of the ore the gossan is coated with powdery bright orange goethite. The total thickness of the gossan zone at this locality is about  $1\frac{1}{2}$  m measured at right angles to the surface of the ground.

The ore beneath the gossan has been strikingly altered to a depth of some 10–20 cm, though in places this alteration extends down dip for some distance along the schist partings. The ore has been softened due to the partial decomposition of the lead and zinc sulphides and of pyrrhotite. The pyrite grains apparently remained unaltered. Beneath this markedly decomposed zone the protore is at first slightly softened and leached, but soon assumes the megascopic appearance of the normal granular pyritic ore. The detailed mineralogical changes which have taken place in this section are described below.

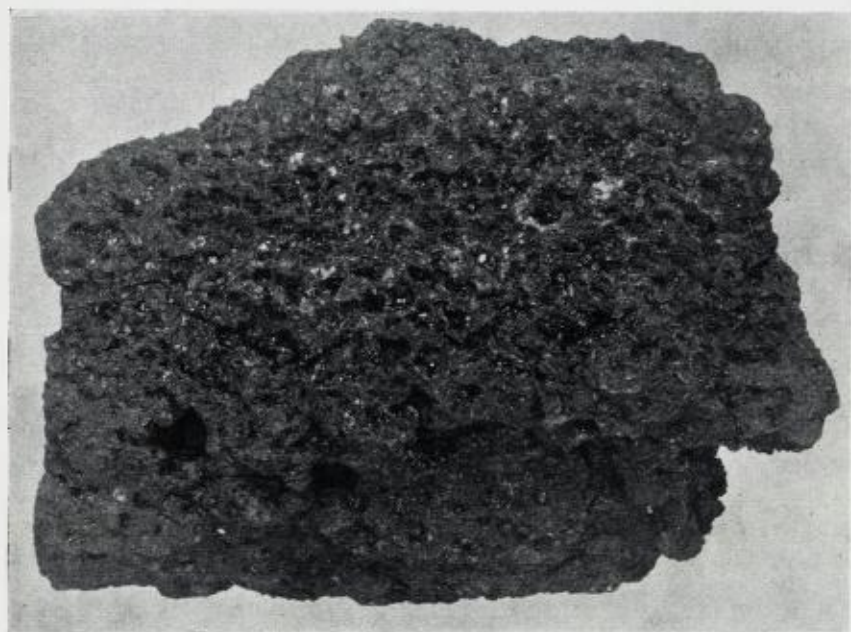
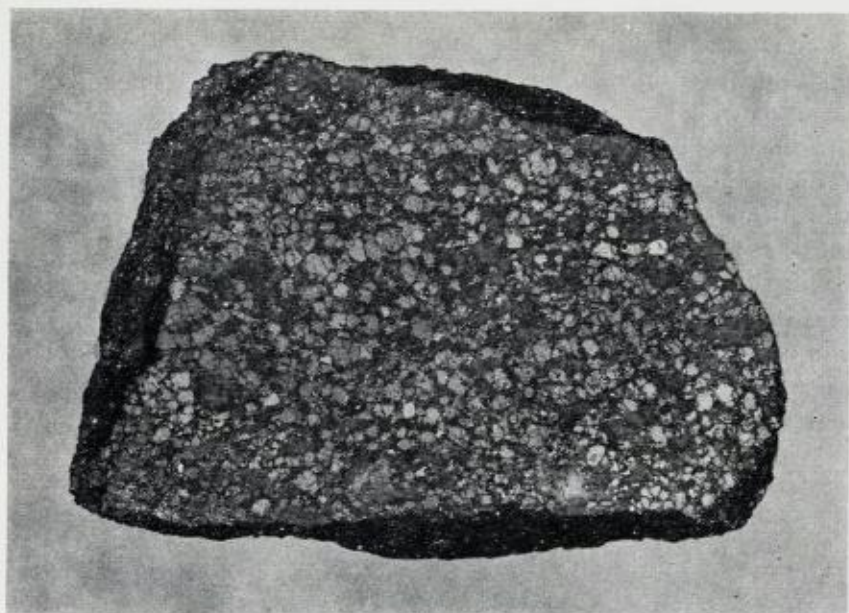
### THE GOSSAN

The gossan derived from the pyritic type of ore at Bleikvassli has a very uniform and characteristic appearance, which seems to reflect the texture of the unweathered ore, see Fig. 3. It is considered that it will be possible to recognise any eventual new discovery of ore of the Bleikvassli type by means of the gossan, if present. In hand specimen the gossan is brown to dark brown, porous, cinder-like mass, which, when dry, is quite strong and does not easily crush. No collapse or shrinkage structures have been noted in connection with the gossan formation at Bleikvassli. The pores or openings in the gossan are of the order of about 2 to 5 mm across and are regularly spaced — simulating the size and spacing of the pyrite grains in the unweathered ore. The walls of the pores are

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Figure 3. Photographs of hand specimens of (above) typical Bleikvassli pyritic ore and (below) typical gossan. The interiors of the pores in the latter are coated with a dark brown, shiny goethite.  $X\frac{1}{2}$ . ▶

Fig. 3. Håndstykker av typisk Bleikvassli svovelkis malm (øverst) og typisk «jernhatt» (nederst). De indre deler av porene i jernhatten er belagt med brun-sort, glinsende goethitt.  $\frac{1}{2}x$ .



7 - Vokes.

normally lined with dark chocolate brown botryoidal goethite. In section (see Fig. 4) it can be seen that this lining is of the order of 0.1 to 0.2 mm thick, and is made up of many rhythmically alternating bands showing varying reflecting powers. X-ray powder determinations indicate that goethite is the only mineral phase present. This crustiform goethite forms a coating to a more massive, light brown goethite which acts as the cementing medium in the ribs or septa between the pores. In polished section this goethite sometimes shows a coarse banded texture, the banding conforming to the fine banding in the crustiform goethite. Otherwise the massive goethite is quite textureless and takes a bad polish due to its softness. Embedded in it are the original gangue minerals of the ore which seem to be entirely unaffected by the weathering processes — chiefly quartz, mica and

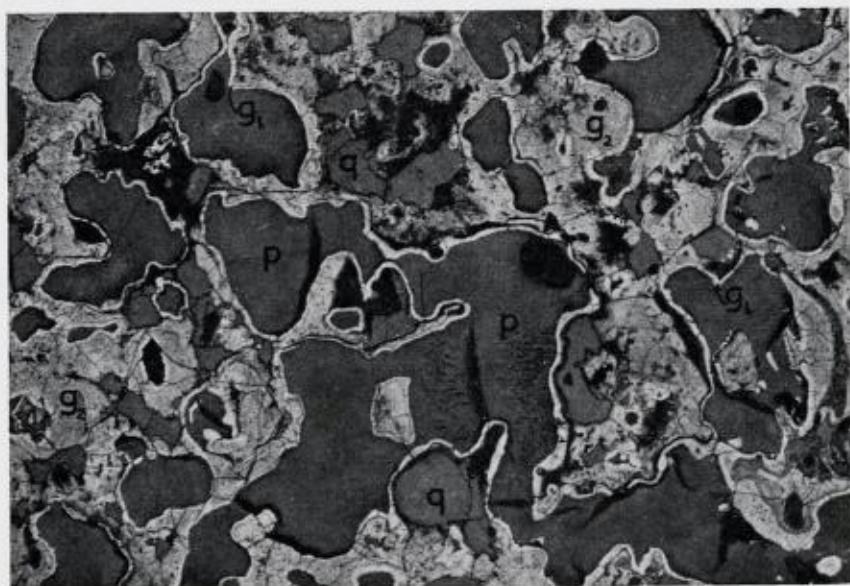


Figure 4. Photograph of polished section of the Bleikvassli gossan. p — pore spaces now filled with plastic,  $g_1$  — lighter coloured rim of harder goethite lining the pores,  $g_2$  — softer, massive goethite, q — residual quartz grains from the original gangue of the ore. Reflected light, X7.

Fig. 4. Polerslip av Bleikvassli jernhatt. p = porerom, i bildet er disse fylt med plastikkmasse,  $g_1$  = lysere farget rand av hårdere goethitt som beleg i porene,  $g_2$  = bløtere, massiv goethitt, q = uforandrete kvarts korn, opprinnelig som gangmineraller i malmen. 7x.

cassiterite. No supergene minerals of the base metals occurring in the ore have been recognised in the gossan. The primary sulphides have almost completely disappeared in the process of gossan formation, but occasional small grains of pyrite can be detected in polished section. These are invariably enclosed in quartz grains or aggregates and have thus been protected against the weathering.

In the lowermost 10 cm or so of the gossan, immediately above the weathered ore, a bright orange, pulvurent or ochreous goethite is very conspicuous, occurring beneath the botryoidal crust of dark goethite. Euhedral crystals of anglesite also appear in large numbers embedded in the goethite. These anglesite crystals are of the order of size 0.25 to 0.5 mm, usually well formed, showing typically 011 and 210 faces. They are white to yellowish white in colour, with a characteristic resinous lustre.

A careful mineralogical examination of specimens from the upper part of the gossan failed to reveal any anglesite; it seems definitely to be confined to the lowermost 10 cm or so, immediately above the weathered ore. No other supergene minerals could be found in the lower gossan zone; residual sulphides were pyrite, a little galena and an occasional flake of molybdenite.

### THE ALTERED ORE

For a depth of about 10 cm below the sharp lower junction of the gossan the ore shows a marked alteration. It has been completely softened, such that it can be scraped away easily with a knife or crushed to a granular mass between the fingers.

Megascopically this altered material consists of apparently fresh and unattacked granular pyrite bound loosely together by a dirty white interstitial matrix consisting of quartz and pulvurent, greenish-white native sulphur. Also embedded in this matrix are partly replaced remnants of the original base-metal sulphides of the ore, mostly sphalerite and a little galena. Coating these latter sulphides are usually thin films of blue covellite. The powdery nature of the sulphur makes it extremely difficult to study in polished or thin section. During polishing it is invariably plucked away from the surface of the section, so that its relations to the sulphides of the ore can only be inferred by the pits which are formed. Examination of polished sections shows

that the pyrrhotite has completely disappeared, except for some small inclusions in other sulphides, and that sphalerite and galena have both been heavily replaced, their ragged remnants being surrounded by pits from which the native sulphur and possibly other supergene minerals have been removed by polishing. Small quantities of chalcopyrite in the ore do not appear to have been altered or replaced, but covellite appears as a supergene copper mineral. It is on the whole quite scarce and occurs as irregular grains and films in the decomposed areas between the sulphides, and also along fractures and cleavages in some of the grains of sphalerite and galena. The covellite replaces the galena preferentially to the other sulphides and in many places can be seen as rims to the very ragged grains of the lead sulphide. No instances were noted of the covellite replacing either sphalerite or chalcopyrite. Presumably the displaced lead from the galena combined with sulphate to form anglesite, small grains of which appeared quite abundantly in heavy, non-magnetic fractions of the crushed samples, but could not be identified in hand specimen, due to the coating of native sulphur. Crushed fractions also showed that the sphalerite in particular has been very heavily corroded, practically all the grains of this mineral showing ragged or pitted, dull surfaces. They were often coated with a film of a white-blue, apparently translucent, alteration product which it was not possible to isolate for X-ray identification. It could possibly be hydrozincite. In contrast to the sphalerite, the pyrite grains were practically all clean and uncorroded, supporting the polished section evidence that the supergene processes have not affected this mineral to any extent. Other minerals appearing in the crushed fractions were corroded galena, unaltered chalcopyrite and molybdenite and the unaltered non-sulphide minerals, notably quartz and cassiterite.

Beneath this altered zone, the ore rapidly assumes its «normal» appearance. Megascopically visible supergene effects are confined to very thin coatings of fine-grained, white, crystalline melanterite on surfaces of joints and fractures, the ore away from such cracks being apparently unaffected.

In polished section it can be seen that the pyrrhotite has been severely altered and is now almost completely absent from the ore (see below). Occasionally the grains of galena appear to be slightly replaced along their cleavages, possibly by anglesite. Much of the sphalerite shows very accentuated cleavages, which may be an expression of slight leaching. No secondary copper minerals could be detected, and, with the

exception of the alteration of the pyrrhotite, supergene effects appear to have disappeared already within about half a metre of the base of the gossan.

The weathering effects on the pyrrhotite appear to persist for some distance down the dip of the orebody and have been observed generally in polished sections of ore from localities in upper levels of the mine at vertical depths up to a maximum of 20 metres below the outcrop. The effects, however, diminish rapidly with depth and complete replacement of the pyrrhotite is only observed in the uppermost metre or so.

This behaviour of the pyrrhotite is in keeping with the known instability of the mineral under near-surface conditions. (cf. Schneiderhöhn and Ramdohr, 1931 pp. 138—141, Ramdohr, 1960, pp. 554—559). Norwegian examples of the supergene alteration of pyrrhotite have been described by Foslie (op.cit.), Vokes (1957, pp. 116—117) and Sæbø et al (op.cit.). The latter workers describe and figure examples of so-called «birds-eye» textures resulting from the alteration. In the cases described by the two first named authors, no such textures were found, the alteration spreading out along the cleavages of the pyrrhotite from irregular cracks intersecting it.

In the case of the Bleikvassli ore, although incipient examples of «birds-eye» are seen the mode of alteration more often resembles closely the examples of Foslie and Vokes.

The first signs of supergene action is the development of alteration rims along the grain boundaries of the pyrrhotite and along irregular cracks in the mineral. The alteration appears to spread inwards from the grain boundaries or outwards from the cracks along the very closely-spaced parallel 0001 cleavages of the pyrrhotite. The alteration front is irregular or ragged, having, as Foslie puts it, a seismogram-like contact with the pyrrhotite.

The first mineralogical change in the alteration is the formation of a grey to blue-grey, slightly pleochroic mineral, showing a very marked anisotropism, bright orange-yellow to dark grey or black. This is probably the mineral described Schneiderhöhn and Ramdohr and by Ramdohr as «zwischen-produkt» and seems to correspond to the mineral in the «light grey marginal zone» of Foslie (op.cit. pp. 147—148). Sæbø et al (op.cit. p. 208) suggest that the mineral «shows many similarities to the new rhombohedral iron sulphide mineral, smythite,  $Fe_3S_4$ , described by Erd, Evans and Richter (1957)». However, the

description of the optical properties of smythite by these latter authors seems to make it clear that there are considerable differences. Smythite has optical properties very closely resembling pyrrhotite; the supergene mineral under consideration has quite different optical properties.

The true nature of this «zwischen-produkt» does not yet appear to have been determined. According to Ramdohr (*op.cit.* p. 556), G. Frenzel obtained marcasite powder patterns of varying intensity from samples of this material showing very varying properties. The same authority reports that Saksela was able to analyse an «especially favourable» sample of the «zwischen-produkt» which showed  $\text{Fe:S} = 1:2.27$  and  $7.95\% \text{H}_2\text{O}$ .

In many cases this initial supergene alteration manifests itself in a marked accentuation of the basal cleavage of the mineral, and hair-like veinlets of the grey alteration mineral may extend right across large grains along these cleavage cracks.

The supergene processes do not appear to have penetrated to any great extent beneath the present outcrop. A specimen of ore, containing 58 percent pyrrhotite, was taken from the foot-wall side of the orebody near the southern end of the open pit, not more than two metres below the surface. Although the joint- and other fracture-planes were heavily coated with rust, polished sections revealed that the alteration of the pyrrhotite was confined to borders of the grey alteration product, not exceeding 0.01 to 0.02 mm in width, along cracks. Again the alteration could be seen to spread out into the pyrrhotite along the 0001 cleavage planes, irrespective of the direction in which the fractures cut the pyrrhotite grains. In places these cracks formed a ramifying network, and along the centres of some of the wider ones was located a thin veinlet of iron oxide, probably goethite. However, other goethite-filled fractures were seen to intersect the sulphide without any accompanying alteration rim. Where these fractures intersect galena they occupy the cleavages of this mineral, frequently showing sharp, right-angled bends and often bifurcating, enclosing a block of galena which appears to have been twisted or displaced. The widths of these iron oxide-filled fractures are usually not more than a fraction of a mm wide and do not represent any great disturbance of the ore. Such narrow, iron oxide-filled cracks have been observed sparsely in specimens taken up to 20 m below the outcrop, where they were unaccompanied by any form of alteration of the pre-existing sulphides. Such specimens seem to show that

10 to 15 m down dip below the original outcrop is the limit for supergene alteration of the pyrrhotite.

As the alteration of the pyrrhotite proceeds, marcasite begins to form — apparently from the grey alteration product — along the sides of the original crack whence the alteration first started. The marcasite so produced is extremely fine-grained and it is not easy in every case to detect its anisotropism. It shows a crustiform, rather pitted, texture and normally takes a poor polish. The original crack can usually be seen as a thin vein of iron oxide running down the middle of the marcasite veinlet or rib, which often rims a cavity in the polished section from which the residual remnant of pyrrhotite, or grey alteration product, seems to have dropped out, (cf. Sæbø et al, op.cit. p. 207).

As has been mentioned previously, some parts of the Bleikvassli ore outcrop appear to have been scraped clean by the Pleistocene ice and show no gossan at all. Instead there is developed a thin layer of iron oxide — often nothing more than a rusting of the sulphides. A specimen of this type of ore was taken in one of the prospecting trenches at the northern end of the ore outcrop. A polished section was made of the topmost 5 cm of this specimen to study the effects of weathering since the Ice Age. For about 3 mm below the surface the sulphides, especially the pyrite, have been shattered, most probably by frost action, and in the network of cracks so formed iron oxide (? goethite) has been deposited and has partly replaced the sulphide fragments. Iron oxide also occurs in larger amounts filling in unevennesses in the surface of the sulphides. This effect decreases rapidly and has ceased within 3–5 mm of the surface. Chalcopyrite grains included in the pyrite have been shattered along with it, but the fragments appear clean and show no sign of replacement by the iron oxides. Supergene copper sulphides could not be detected in the polished section and a mineralogical examination of specimens from this locality failed to reveal any other supergene minerals. On the other hand, the pyrrhotite originally present had been completely replaced by fine-grained aggregates of marcasite, often with central residuals of the grey alteration mineral, which exhibit a closely spaced parallel cleavage inherited from the 0001 cleavage of the pyrrhotite. Towards the lower end of the specimen occasional small, rounded inclusions of pyrrhotite in pyrite were seen to be unattacked, but otherwise there appeared to be no decrease in the intensity of the alteration. Just how deep the pyrrhotite alteration



descends could not be ascertained due to lack of exposures, but specimens from the 430 m level, about 15 m vertically below the outcrop in question, do not show any sign of alteration of the pyrrhotite. If the above-described alteration is solely due to post-glacial weathering, one would expect it not to penetrate so deeply as alteration due to the combined effects of pre- and post-glacial weathering. However there is no knowing if the ice did remove all the pre-glacial alteration zone, so it would be unwise to ascribe all these effects to post-glacial weathering alone.

### SUMMARY OF MINERALOGICAL CHANGES

The accompanying table presents in a generalised form the mineral parageneses which have been identified in the various zones of weathering of the Bleikvassli ore. The totally resistant minerals which appear in all the zones are essentially the silicate and oxide gangue minerals of the ore, notably quartz and cassiterite. Mica appears to be less resistant, though its behaviour-picture is less complete since it was not at all abundant in the exposures which could be studied. The other gangue minerals such as garnet and spinel are also totally resistant, but do not figure in the scheme because they are normally present in minor amounts. Pyrrhotite is unstable in all the weathering zones — indeed its appearance in an unaltered state is taken to mark the base of the supergene zone.

The study reveals a point worthy of especial mention. This is the shallow vertical extent of the supergene zone beneath the base of the gossan and the sparsity in it of supergene sulphides, in particular those of copper. Covellite is the only supergene copper sulphide which has been detected, and even this is in quite minor amounts. The Bleikvassli ore is admittedly not copper-rich, averaging around 0.5 % percent Cu, but this is not lower than the protore of many deposits in other parts of the world which show marked supergene cementation zones. It would seem that a true cementation zone is lacking at Bleikvassli (see also pp. 105—106).

### CHEMISTRY

Garrels (1954, pp. 153—4) has summarized the chemistry of the zones of oxidation and secondary enrichment thus;

	Resistates	Residual sulphides	Supergene minerals
Upper gossan	Quartz, cassiterite, etc.	((pyrite)) ((galena))	goethite
Lower gossan	do.	((pyrite)) ((galena)) molybdenite	goethite anglesite
Intensely weathered ore	do.	pyrite (galena) ((sphalerite)) molybdenite	sulphur anglesite covellite
Less intensely weathered ore. Effects decrease rapidly downwards.	do.	little replacement except of pyrrhotite	marcasite grey alteration mineral anglesite? melanterite

Brackets indicate degree of replacement of sulphides.

Double bracket - - intense replacement.

Single bracket - - less replacement.

No brackets - - - no apparent replacement.

Order of appearance indicates rough order of abundance of minerals.

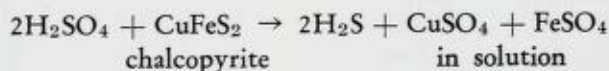
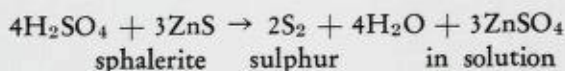
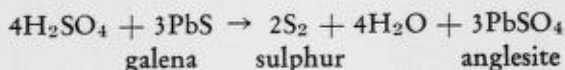
«A typical primary ore deposit may consist of galena (PbS), sphalerite (ZnS), and chalcopyrite (CuFeS<sub>2</sub>) disseminated in a limestone or igneous rock matrix. This association is stable in the environment found beneath the ground-water table — mildly alkaline and moderately reducing — and remains without change indefinitely. But when erosion exposes such a deposit at the surface, oxidation and solution take place. Lead remains at or near the surface, but the sulphide is converted into sulphate or carbonate. Zinc goes into solution and tends to move downward; some of it may remain near the surface as the silicate or as the carbonate, but most of it seems to move entirely away from the original deposit. The behaviour of copper is perhaps the most complex; it moves downwards, precipitating en route in a wide variety of minerals . . .

Very broadly, the changes in the zone of oxidation involve freeing the metal ions by oxidation of sulphide to sulphate, and reprecipitation of the metals by reaction with carbonate, hydroxyl, silicate or sulphate ions. For copper additional reactions occur; some copper travels downward to the water table and is reprecipitated nearby as a sulphide.»

The mineralogy of supergene zones at Bleikvassli shows that this «orthodox» behaviour has been followed there. However the following remarks may be made concerning the behaviour of lead. Garrels shows that from a calculation of the activity of Pb<sup>2+</sup> ion, it can be predicted that lead could not be transported in ground waters. Normally one finds a lead sulphide core, surrounded by a lead sulphate shell, in turn surrounded by a lead carbonate shell, except that where galena occurs in a silicate rock it is the sulphate, anglesite, which is the sole oxidation product. Such is the case with the Bleikvassli ore, there is little or no carbonate in the gangue to neutralise the acid produced during oxidation. The typical occurrence of anglesite as a shell surrounding galena is, however, not encountered at Bleikvassli. The supergene mineral occurs in discrete, euhedral crystals which seem to have formed in situ from solution. There must therefore have been solution of the galena and movement of the lead sulphate, if only for a few centimetres, before its recrystallisation as anglesite. This seems to bear out Garrels' prediction (*op.cit.* p. 159), that «if lead moves at all in solution, it should do so when it occurs in non-carbonate rocks in areas of high rainfall and good drainage». All these conditions are fulfilled in the area under consideration.

The reactions taking place in the weathering zone may be represented as follows. The weathering of the pyrite and/or pyrrhotite produces sulphuric acid and ferrous sulphate, the latter changing readily to the ferric salt and the hydroxide. It is the hydroxide, now in the form of goethite, which forms the cementing medium to the gossan.

The other sulphides are attacked with the formation of their sulphates and free sulphur:



The sulphur appears to be a temporary phase only present in the upper few centimetres of the altered ore. With continued weathering it is itself oxidized and does not appear in the gossan. The copper seems to be partly precipitated at the top of the sulphide zone as covellite, but also in part to be removed in the ground waters along with the zinc.

### The chemical changes due to weathering.

The samples of the weathering zones in the 446 m adit were also analysed for Cu, Zn, Pb and S in order to trace the chemical changes due to the weathering of the massive ore. The samples correspond to the various zones already described and which are shown in Fig. 2.

The following tabulation gives the results of the chemical analyses (Analyst: Bleikvassli mine laboratory).

	Cu	Pb	Zn	S
upper gossan . . . . .	0.08	2.53	0.39	1.65
lower gossan . . . . .	0.08	6.53	0.31	2.96
heavily altered ore . . . .	0.18	1.61	0.47	46.72
less altered, to fresh, ore	0.22	1.09	8.46	43.10

These figures seem to reflect very closely the above described mineralogical changes. The lowest line of figures may be taken as a close approximation to the composition of the ore being weathered (protore), since, apart from the alteration of pyrrhotite, little mineralogical change was detected in this sample.

In the upper gossan copper, zinc and sulphur have been mostly removed in solution, while lead has tended to remain behind, probably in the form of relatively insoluble anglesite. The same relations are observed in the lower gossan zone, except that the lead content is still higher. It was in this zone that the abundant anglesite crystals appeared and the lead content must be due to this mineral. Above, it was suggested that the euhedral forms of the anglesite implied a certain, limited, movement of the lead sulphate. This seems to be substantiated by the analysis figures. The more than doubled content of lead in the lower gossan zone indicates a strong downward concentration of lead from the upper zone.

In the zone of heavily altered, softened, ore the figures for copper and lead approach those of the protore beneath. Copper may or may not have been slightly leached. It is seen that there is no question of a copper cementation zone here. Lead is probably rather high still, showing that the slow downward movement of lead as sulphate has continued into this zone, as was also shown by the presence of anglesite. Sulphur is not much higher than in the protore. This sulphur content is due partly to residual pyrite and partly to the native sulphur present as a temporary phase in this zone. It is clear that practically none of the sulphur which was present in the now completely oxidized (gossan) zones has accumulated in this zone as the native element. It has nearly all been apparently removed in solution as sulphate. The native sulphur in the heavily altered ore must therefore represent a temporary stage in the breakdown of the sulphide minerals, which is itself later further oxidized and removed as sulphate.

Thus, in summary, the different elements in the ore appear to have the following behaviour during the supergene alteration:

*Copper.* Copper is almost completely removed in solution, probably as sulphate, from the gossan zones, but in the heavily altered ore the content seems to be little changed from that of the protore.

*Zinc.* This appears to be the most mobile of the three non-ferrous metals, which is in keeping with its known behaviour. Zinc is very low in all the altered zones above the protore and does not appear to have been concentrated at all. The metal must have been taken into solution as the sulphate and been removed in the run-off.

*Lead* shows a different behaviour from that of the other two metals. It is concentrated preferentially at the base of the gossan zone as the new-crystallised sulphate, anglesite, but is not completely removed from the upper parts of the gossan, where it is also probably present as anglesite. The heavily altered ore is slightly concentrated in lead due to introduction of the sulphate from the gossan above.

*Sulphur* is almost entirely removed from the gossan zones in the form of sulphates, probably of iron, copper and zinc. The slight sulphur contents of the gossans most likely are due to fixation as lead sulphate. There is a slight increase in sulphur in the heavily altered ore as compared to the protore, but this may not be significant. As previously mentioned the native sulphur in this zone does not appear to represent an enrichment of the element, but rather a stage in the breakdown of the sulphides.

### Summary and discussion.

This limited study of the supergene changes which have taken place immediately beneath the outcrop of the Bleikvassli pyritic ore raises certain points of interest.

In the first place, there seems to be quite definite evidence that, in places, at least, the preglacial iron hat or gossan is preserved. The maximum depth of this gossan which has been observed is of the order of 3-4 metres, measured parallel to the dip of the ore body. This gossan exhibits a texture which reflects that of the massive pyritic ore from which it is derived, even though all the sulphides have been completely removed. The dominant oxidized mineral in the gossan is goethite of various forms.

The point of greatest interest seems to be the absence beneath the gossan of a supergene copper cementation zone. Apart from some few films or rims of covellite replacing primary sulphides no secondary copper minerals were found. The copper content in the zone immedi-



ately below the gossan appears to be lower than that of the protore. Zinc has been completely removed from all the weathered zones, which is to be expected from its general behaviour under supergene conditions. Lead has been slightly mobilized and recrystallised in the lower parts of the weathering zone, so that one may perhaps speak of a lead cementation zone towards the base of the gossan. The secondary mineral involved is the relatively insoluble sulphate, anglesite.

These observations all point towards an almost complete and rapid removal of the elements Cu and Zn following their liberation as soluble sulphates due to the break-down of the primary sulphides. This must be explained by the fact that the greater part of the rainfall runs off as surface water rather than percolating downwards to join the ground water table. This is confirmed by the numerous small lakes, bogs, and waterlogged areas which are to be found in the area; Bleikvassli is on the whole a «dry mine». Thus the sulphate bearing waters run off rather than percolate downwards and do not come into contact with the primary ore. Under these conditions little cementation of supergene sulphides can be expected.

The reason for the prominence of run-off rather than percolation is to be sought in the «tight» nature of the country rock schists and gneisses, the relative steepness of the terrain and in the coolness of the climate. Certainly present climate conditions are not conducive to chemical weathering. The absence of a cementation zone would also indicate that since the ore was first exposed by erosion, relatively little chemical weathering has taken place .

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Part 3.

The abundances of copper, zinc and lead in the ore.

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## Abstract.

Copper, zinc and lead abundances in the Bleikvassli ore are discussed on the basis of the analyses of 60 samples of diamond drill core and 90 underground chip samples. The statistical and graphical treatment of the data follows closely that used in recent abundance studies of similar ores from North America and Australia. Comparisons are drawn with the ores investigated in these studies. The three metals are investigated separately, as pairs and as the ternary group. No correlation is found between the pairs of metals, except for a very weak sympathetic variation in the case of lead-zinc. A triangular plot of the atomic proportions of the three metals shows a preponderance of points towards the zinc apex ( $>65$  atom per cent zinc) with only weak spreads of a few points along the zinc:copper and zinc:lead joins. The distribution pattern is typical for the Palæozoic pyritic Cu-Zn-Pb ores which have so far been investigated. Comparisons of analyses from the Bleikvassli pyritic and pyrrhotitic ore types, respectively, confirm the mineralogical data that the latter is considerably enriched in copper.

The average Cu-Zn-Pb content of the Bleikvassli ore (atom basis) is compared with the averages of 21 orebodies recently published and comparisons are made. A tentative three-fold division is suggested, based on the metal contents. The division appears to cut across the general geological grouping of the orebodies.

## Introduction.

This third part of the report on the Bleikvassli orebody presents the results of a study of the abundances of copper, zinc and lead in the «massive» ore and their mutual interrelations, based on 150 chemical analyses of diamond-drill core and underground chip samples.

The paper is intended to supplement previous studies of metal abundances of similar ores in Palæozoic and Precambrian fold mountain belts previously published by Stanton (1958, 1962) Wilson and Anderson (1959), Kilburn (1960) and Stanton and Richards (1961). Such studies have already shown their importance in illuminating world-wide trends in the base metal abundances of massive sulphide ore deposits, trends which promise to be of importance in helping to elucidate the genesis of such ores.

The Bleikvassli data are on the whole in good agreement with those already published for ores of the same general class, thus emphasizing the already well-known geological and mineralogical similarities.

### Sampling.

The samples analysed to provide the data for this study fall into two classes. The first class comprises the cores from the original diamond-drilling of the Bleikvassli orebody, the results of the analyses of which were obtained from the diamond-drill profiles kept by the company. The second class comprises random chip samples taken in the mine by the writer in the course of his study of the Bleikvassli ore during the summers of 1959 to 1962. These samples were normally taken over sections of the massive ore in order to study possible metal variations across its width. The sampling avoided the schist inclusions and partings which occur within the ore, wherever possible. These samples are, therefore, of the massive sulphides only and do not give a true picture of the mineable orebody as a whole, since dilution by the schist inclusion and wall rock will lower the metal contents of the «pure» sulphides.

In all 60 analyses of diamond drill cores and 90 of mine samples were available for the study.

The samples were analysed at the Bleikvassli laboratory or at the laboratory of A/S Bergverkselskapet Nord Norge, Andfiskåga, Mo i Rana. The writer is grateful to the Director and staff of the two companies for the analyses and for the diamond-drill core information.

### Treatment of data.

In order to facilitate comparisons with similar deposits in other parts of the world the statistical treatment of the Bleikvassli data follows closely that of Stanton (1958) for fourteen deposits of parallel types from localities in Canada, Ireland and Australia. The same calculations have been made for the Broken Hill, N.S.W., deposits by Stanton and Richards (op. at) and for the Black Star orebodies, Mt. Isa, by Stanton (1962).

The behaviour of the Cu, Zn and Pb in the Bleikvassli ore is treated as 1) individual metals, 2) pairs of metals and 3) as the group of three. The following table gives the data for the individual metals and the parameters calculated therefrom. These correspond to those

given in the above-cited publications, though it may be objected that the distributions of the Bleikvassli metal data are not normal ones (as shown by the frequency curves) and that the calculation of variance and standard deviation for such non-normal distributions is not strictly valid.

Table 1. Abundances and behaviour of copper, zinc and lead in the Bleikvassli ore\*.

	n	z	x	$S_x^2$	$S_x$	y	c		
							Cu value as unity present	Stanton's average	
Copper	149	62.52	0.42	0.130	0.360	0.0066	0.86	1.00	1.00
Zinc	150	1022.15	6.81	11.376	3.373	0.1041	0.49	0.57	1.16
Lead	150	550.41	3.67	18.078	4.252	0.0177	1.16	1.35	1.61

\* n, number of analyses; z, sum of analyses; x, sample mean;  $S_x^2$ , sample variance;  $S_x$ , sample standard deviation; y, sample mean expressed as atom percent; c, coefficient of variation.

## Individual metals.

### COPPER

The frequency distribution of the copper analyses is shown by the histogram, Fig. 1a. It can be seen that the distribution is positively skewed and has a regular J-shape, a feature which appears to be common in deposits of this type. In particular the Bleikvassli copper distribution pattern shows marked similarities with those published for the Broken Hill ores and for the Captain's Flat, N.S.W., deposit.

The arithmetical mean of the copper analyses is 0.42 weight per cent, the median value is 0.25 percent, while the range is from 0.06 to 1.72 weight percent. The skewness may possibly be accounted for by the fact that the analyses include both types of ore comprising the Bleikvassli body, the pyritic and the pyrrhotitic type. The latter is notably richer in copper (see below) but constitutes a minor portion of the bulk of ore. The median value may therefore approach rather more closely the mean weight percent of copper in the pyritic type of ore.

As is the case in nearly all the deposits of this type which have been studied, copper is the least abundant of the three base metals in the Bleikvassli ore. The Bleikvassli ore is lower in copper than the four-

teen similar pyritic orebodies studied by Stanton (1958), the mean of 0.42 weight percent comparing with an overall mean of 0.84 weight percent for the fourteen. Only one of Stanton's fourteen deposits showed a mean copper value less than that of Bleikvassli.

On the other hand the Bleikvassli copper content is much higher than that in the pyritic lead-zinc ore zones of the Black Star orebodies, Mt. Isa (0.18 and 0.09 percent) and slightly higher than the mean value of 0.31 percent reported for the various non-pyritic ore lenses at Broken Hill.

## ZINC

The frequency distribution of the Bleikvassli zinc analyses is shown in the histogram, Figure 1 b. It can be seen that the distribution, while approaching more nearly a normal type than the copper one, is bimodal, with the main peak in the range 7 to 9 weight percent and another, much smaller one at 2-3 percent. Similar bimodal distributions of zinc values have been noted by Stanton and Richards for certain of the Broken Hill orebodies. They suggest that this supports an idea previously advanced on geological grounds that the orebodies at Broken Hill are not homogeneous lenses but rather groups of sublenses. So far the geological study of the Bleikvassli orebody has not revealed any such grouping of sub-lenses of different zinc contents. The difference in zinc content between the two ore types at Bleikvassli also seems insufficient to account for the bimodal distribution.

Stanton's study of the Black Star orebody, Mt. Isa also shows a bimodal distribution of the zinc values in the No. 2 lead-zinc ore zone. Stanton suggests that this may possibly represent two sub-zones with differing zinc values.

Zinc is the most abundant base metal in the Bleikvassli ore, the arithmetical mean of 6.81 weight percent exceeding the means of copper and lead by factors of 16 and almost 2, respectively. The major median value is 8.5 percent, the minor one 2.5 percent. The range in individual analyses is from 0.34 to 14.30 weight percent.

Published values for the zinc contents of base metal ores of the type under consideration are more variable than those of the copper contents, but the Bleikvassli figure is the same order of size as most. For example, Stanton's average value for the fourteen pyritic orebodies sampled by him was 5.70 weight percent, with a range from 0.50 to 15.42 weight percent. The pyritic lead-zinc ore zones of the Black Star orebodies,

Mt. Isa approach very closely to the Bleikvassli ore in zinc contents (No. 2 zone 6.51 percent, No. 5 zone 6.73 percent). The zinc contents of the Broken Hill ore lenses are all higher than the Bleikvassli average, in most cases by factors of two or more.

### LEAD

The frequency distribution of the Bleikvassli lead analyses is shown in Figure 1 c. It is readily seen that the distribution is much

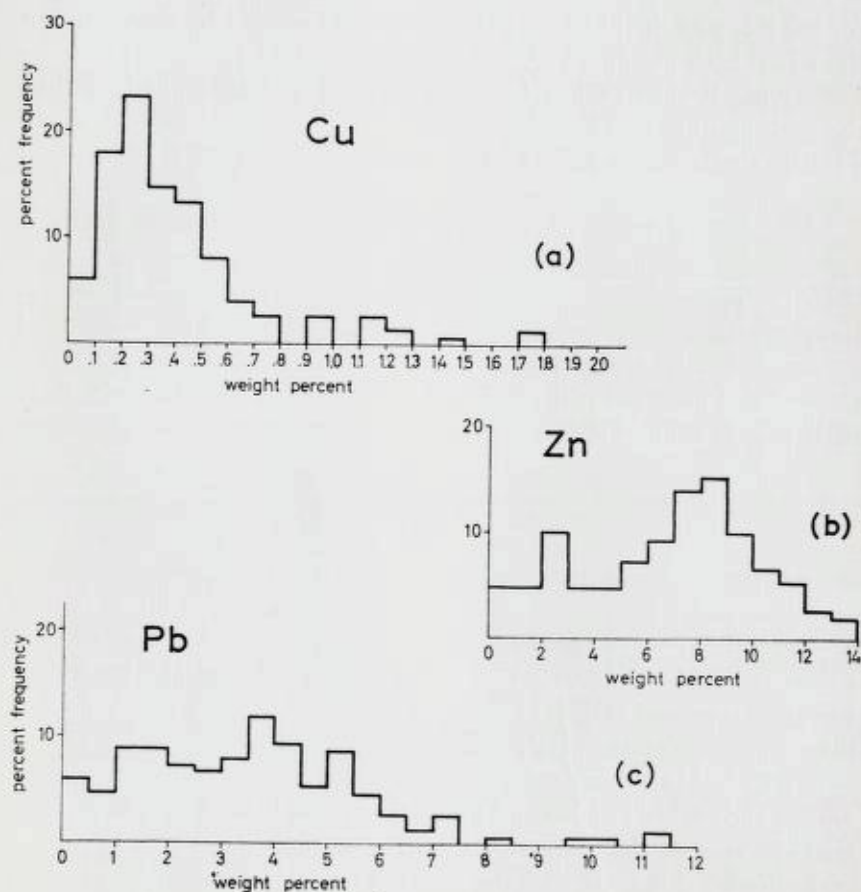


Figure 1. Histograms to show the frequency distributions (weight percent) of a) Cu, b) Zn and c) Pb in the Bleikvassli ore.

Fig. 1. Histogrammer som viser frekvens fordelingene (vekt-prosent) av a) Cu, b) Zn og c) Pb i Bleikvassli-malmen.

less regular than those of copper or zinc and that no definite peak is shown, though there is a suggestion of one at 3.75 percent.

The Bleikvassli lead frequency distribution is unlike most of those published in the works already referred to; these show either quite normal, unimodal distributions or regular J-shaped skewed distributions.

The mean value of the Bleikvassli lead analyses is 3.67 weight percent, the median value, in so far as one can be expressed, 3.75 percent and the range of individual values 0.10 to 16.81 percent.

The Bleikvassli mean compares with a figure of 2.71 weight percent for the mean of the fourteen pyritic orebodies studied by Stanton. On the whole both the pyritic Black Star, Mt. Isa lead-zinc zones and the non-pyritic Broken Hill orebodies are a good deal richer in lead than the Bleikvassli ore. The Rhodonitic zinc lode at Broken Hill shows a closely similar mean value of 3.46 weight percent.

### Pairs of metals.

In the rest of this paper when comparing the lead values against those of the other two metals, atomic percentages have been used because of the much higher atomic weight of the lead atom. Copper and zinc are still compared on a weight percent basis, since their atomic weights differ but little.

### COPPER AND ZINC

The frequency distribution of the Cu/Zn weight percentage ratios in the Bleikvassli ore are shown in Figure 2 a. It shows a distinctly skewed distribution with over 50 percent of the values falling below 0.05. The mean ratio is 0.1 and the individual values range from 0.008 to 2.01. Values higher than 0.3 form less than 5 percent of the total.

In Figure 3(a) the weight percents for the two metals are plotted against each other and it can be seen that there is no apparent correlation. In view of the frequent association of copper and zinc in pyritic orebodies of this type and the often intimate intergrowths of their sulphides, this lack of correlation is rather surprising. However it appears to be a general feature of those orebodies so far investigated, with the exception of two deposits in Newfoundland studied by Stanton (1958).

## ZINC AND LEAD

The frequency distribution of the Bleikvassli Zn/Pb atom percent ratios are shown in Figure 2(b). Again, the distribution is a skewed one, but it shows a distinct peak. The mean ratio is 7.60, the median value 7.50 and the range of individual values 1.14 to 53.40.

Stanton (1953, p. 494) figures a plot of the mean Zn/Pb atomic ratios for each of the fourteen pyritic deposits studied by him. All the points fall on or very near a straight line defining a ratio of nearly 6.0, showing a remarkable uniformity of this ratio in these deposits. However the Zn/Pb ratios in pyritic lead-zinc ore zones of the Black Star, Mt. Isa, orebodies are of the order of 3.0, while at Broken Hill the ratios vary between 2.2 and 8.3.

In Figure 3(b) the atomic proportions for the two metals are plotted on a scatter diagram. The plot seems to suggest a vague sympathetic variation between the values for Zn and Pb, though the correlation appears rather weak. This latter impression is confirmed by a calculation of the correlation coefficient between the two sets of values. The value obtained is  $+0.22$  which shows that the suggested correlation on the scatter diagram is not substantiated.

Stanton found that generally the zinc:lead correlation in the ores he studied, although not good, was markedly better than for copper:zinc. In the present case it is perhaps only justified to say that the zinc:lead correlation, while poor, is at least better than that for the pairs copper:zinc and copper:lead.

Little correlation is apparent in the published scatter diagrams for both the Broken Hill orebodies and the Black Star, Mt. Isa, ore zones.

## COPPER AND LEAD

The frequency distribution of the Bleikvassli Cu/Pb atomic ratios is shown in Figure 2(c). It can be seen that the distribution shows a distinctly skewed form, closely resembling that for the Cu/Zn ratios. Over 67 percent of the values fall below 0.5, while the average ratio is 0.72. Individual values range from 0.02 to 14.75.

The scatter diagram, Figure 3(c), shows the atomic proportions of copper and lead in the Bleikvassli samples plotted against each other. No correlation can be discerned.

Thus of the pairs of metals in the Bleikvassli ore, only one, zinc:lead, shows any sign of correlation at all.



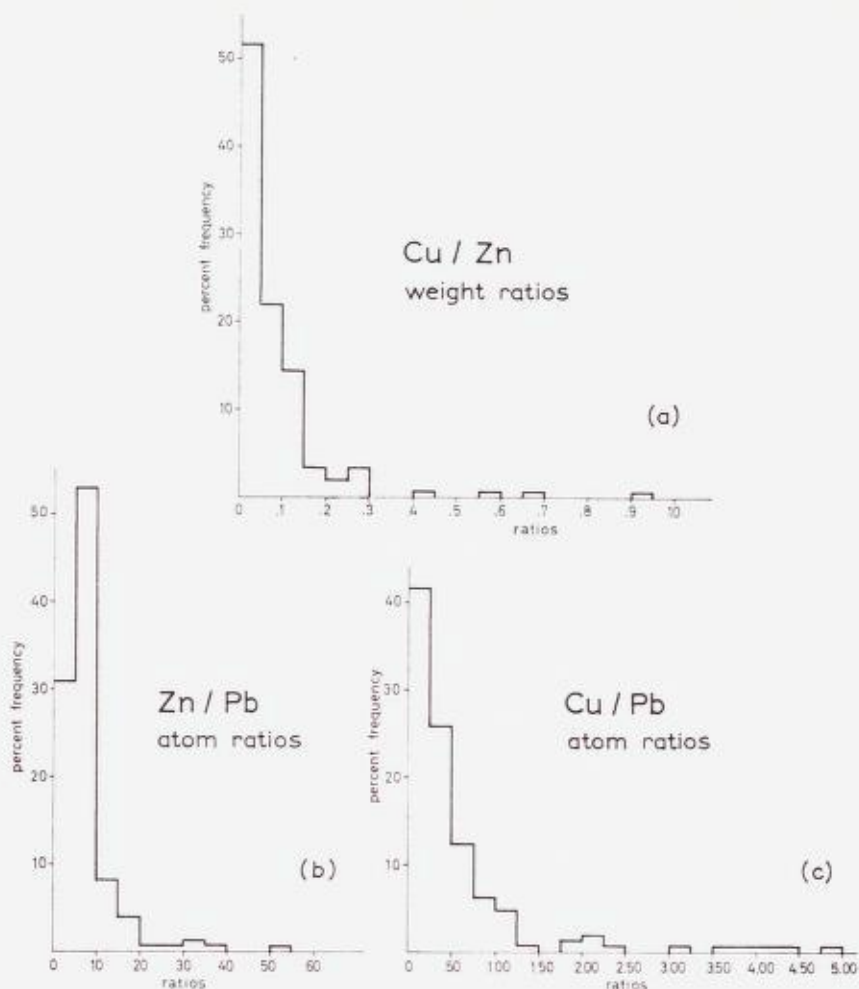
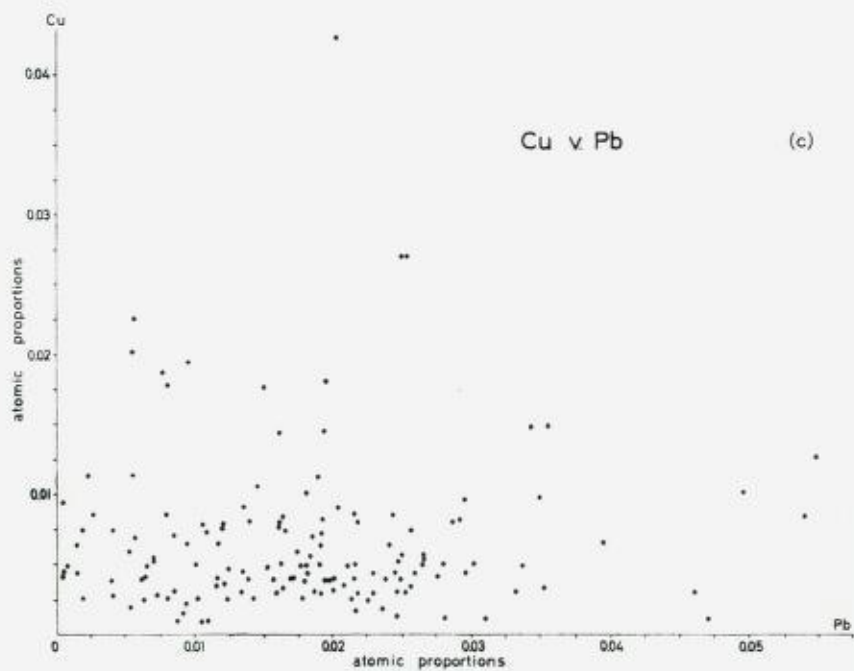
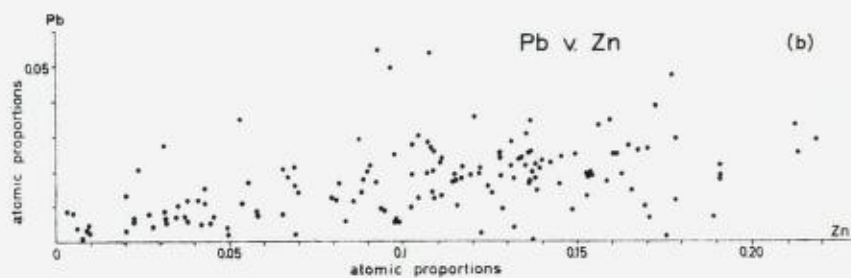
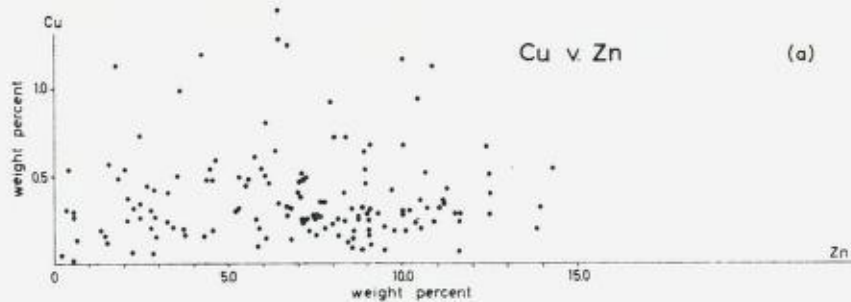


Figure 2. Histograms to show the frequency distributions of the ratios a) Cu:Zn (weight ratio), b) Zn:Pb (atom ratio) and c) Cu:Pb (atom ratio) in the Bleikvassli ore.

Fig. 2. Histogrammer som viser frekvens fordelingene av forholdene a) Cu:Zn (vekt-forhold), b) Zn:Pb (atom-forhold) og c) Cu:Pb (atom-forhold) i Bleikvassli-malmen.

Figure 3. Scatter diagrams to show the relations between a) Cu and Zn (weight percents), b) Zn and Pb (atomic proportions) and c) copper and lead (atomic proportions) in the Bleikvassli ore. ➤

Fig. 3. Grafiske fremstillinger av variasjoner mellom a) Cu og Zn (vekt-prosent), b) Zn og Pb (atom-proporsjoner) og c) Cu og Pb (atom-proporsjoner) i Bleikvassli-malmen.



### Relations between the three metals.

In Figure 4 the atomic proportions, recalculated to 100 percent, of Cu, Zn and Pb in each of the 150 analysed samples of the Bleikvassli ore are plotted on a triangular diagram. The main feature of this plot is the crowding together of the majority of the points towards the zinc apex of the triangle, with rather weak spreads of only a few points along the Zn-Cu and Zn-Pb joins.

Similar distributions of points have already been noted from certain of the other orebodies of this type investigated by Stanton (1958)

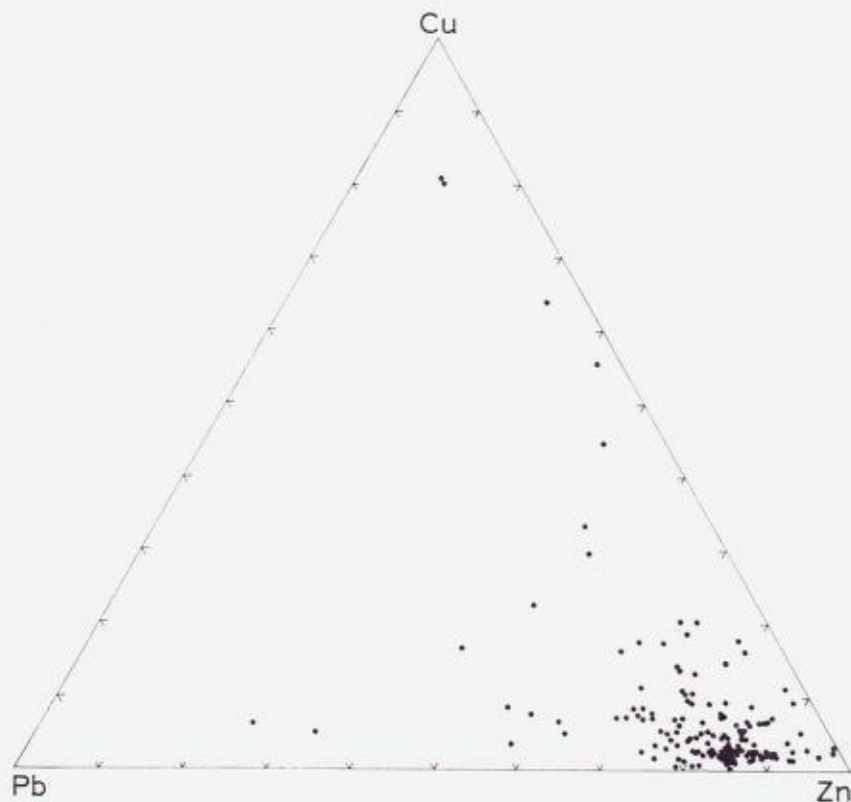


Figure 4. Triangular plot of the atomic proportions (recalculated to 100 percent) of Cu, Zn and Pb in the Bleikvassli ore.

Fig. 4. Trekant-diagram som viser atom-proporsjonene av Cu, Zn og Pb i Bleikvassli-malmen.

notably Rothermere I and Oriental II, Newfoundland and Captain's Flat, N.S.W. (see also below, p. 121).

The strong zinc component is a marked feature of the Bleikvassli ore, all but 17 points (i.e. ca. 89 percent) fall in the zinc apex with over 65 atomic percent Zn. Only four analysis points show a copper content of more than 50 atomic percent, while only two points show more than 50 atomic percent lead.

However the Bleikvassli plot does not wholly support Stanton's (1958) point that «almost all» the points in the analyses fall below the 20 atomic percent lead line. However, Stanton has later (pers. comm.) pointed out that more complete data from ores of this type show that the compositional field does extend symmetrically towards both the copper and lead apices and that the «20 percent lead line» is in fact of no significance.

Wilson's and Anderson's figure (op. cit., p. 626) for the copper, zinc and lead contents of 125 Canadian sulphide orebodies also show the same general features of distribution as does Figure 4. In this case however deposits of several different geological ages and types are included, so that the comparison is not wholly valid.

The distribution pattern of points shown in Figure 4 seems to be rather characteristic for the pyritic zinc-lead-copper deposits of the conformable type, especially from Palaeozoic fold-mountain belts. This point is discussed more fully below.

### Difference between the two ore types.

In previous publications the present writer has pointed to the generally increased copper contents in ores of the «pyrrhotitic» type as compared with those of the «pyritic» type in the «conformable» deposits of the Caledonian fold mountain belt in Norway (Vokes, 1962, and Part I of this report). Similar conclusions have also been reached by Stanton (1959) and other workers for other regions.

In order to test this, the analysis data for the 90 underground chip samples were divided up according to the type of ore they represented and the average metal contents were calculated for each. (The data from the diamond drill records could not be used as the type of ore was not specified). Twelve samples of the pyrrhotitic ore were available. The mean metal values are as follows (weight percents).

	Cu	Zn	Pb
Mean of 90 underground samples . . . . .	0.50	8.06	3.81
Mean of 12 «pyrrhotitic» samples . . . . .	1.03	6.98	4.11
Mean of 78 «pyritic» samples . . . . .	0.42	8.22	3.76

These figures at least indicate that there is a markedly higher content of copper in the pyrrhotitic type ore, even though the amount of data is probably not sufficient to determine the exact numerical increase. It is not possible to attach any significance to the differences in the figures for zinc and lead. These figures do however show that the pyrrhotitic ore at Bleikvassli is still a decidedly Zn-Pb rich type in keeping with the general geochemistry of the ore as a whole. There is no question of the copper-enriched pyrrhotitic ore being completely depleted in zinc and lead as, for example, is the case in the Black Star, Mt. Isa, orebodies investigated by Stanton (1962).

Other data from the Norwegian Caledonides show that in areas where the sulphide deposits are lead-free or lead-poor, the pyrrhotitic ore types tend to be significantly enriched in copper, such that the average copper:zinc ratio becomes greater than one. There is however still a very strong zinc component and no example is known to the writer of an orebody where copper is the sole metal present. It is hoped to deal more fully with the metal distributions in the Norwegian Caledonian sulphide ores in a later publication.

### Comparisons and discussion.

In Table 2 are given the mean atomic proportions and percentages (recalculated to 100) for Cu, Zn and Pb in twenty-one orebodies for which data have already been published and for the Bleikvassli orebody.

The percentage figures have been plotted on a triangular diagram, Figure 5, in order better to bring out the similarities in metal content between the various deposits. The diagram shows, as has already been pointed out in the literature, that the points are concentrated towards the Zn apex of the diagram, with a marked spread along the Zn-Cu join and a much less marked spread along the Zn-Pb join. The Bleikvassli data seem to fall into a fairly close group of nine which have the following characteristics: Cu, 4–11 at. percent; Zn, 14–15 at. percent; and Pb, 9–17 at. percent. The data most similar to those

Table 2.

	at.			at. %		
	Cu	Zn	Pb	Cu	Zn	Pb
1. Rothermere I, Nfld. . . . .	205	2359	420	6.9	79.0	14.1
2. Oriental II, Nfld. . . . .	119	1528	317	6.1	77.8	16.1
3. B.M.S. 6, N.B. . . . .	78	588	85	10.4	78.3	11.3
4. B.M.S. 12, N.B. . . . .	58	1243	165	3.9	84.8	11.3
5. Kennco, N.B. . . . .	178	293	47	34.4	56.6	9.0
6. Texas Gulf and Sulphur, N.B. . . . .	80	957	102	7.0	84.0	9.0
7. Heath. Steel A, N.B. . .	108	794	180	10.0	73.4	16.6
8. » » B, » . . . . .	105	740	98	11.1	78.5	10.4
9. » » C, » . . . . .	137	126	7	50.7	46.7	2.6
10. Vermillion, Ont. . . . .	238	793	67	21.7	72.2	6.1
11. Errington, Ont. . . . .	248	583	53	28.1	65.9	6.0
12. East Avoca, Eire . . . . .	72	147	18	30.4	62.0	7.6
13. West Avoca, Eire . . . . .	107	76	4	57.2	40.6	2.2
14. Captains Flat, NSW. . .	116	1987	355	4.7	80.8	14.5
Broken Hill (means)						
15. Siliceous Zinc lode . . . . .	32	1953	208	1.5	89.0	9.5
16. Rhodonitic Zinc lode . .	24	1367	168	1.5	87.7	10.8
17. No. 1 lens . . . . .	21	2485	306	0.7	88.4	10.9
18. No. 2 lens . . . . .	23	1562	702	1.0	68.3	30.7
19. No. 3 lens . . . . .	33	2095	616	1.3	76.3	22.4
Black Star, Mt. Isa.						
20. No. 2 orebody . . . . .	28	996	334	2.1	73.3	24.6
21. No. 5 orebody . . . . .	14	1030	361	1.0	73.3	25.7
B. Bleikvassli . . . . .	66	1041	177	5.1	81.1	13.8

of Bleikvassli are the ones for the Captain's Flat, N.S.W., deposit (14), and to lesser degrees those for Rothermere I (1) and Oriental II (2), Newfoundland, and for B.M. and S. 12, New Brunswick (4).

Fairly well separated from this group are a string of six deposits along the Zn-Cu join with Pb contents under 9 atomic percent and with Cu, 21-57 at. percent; Zn, 41-73 at. percent.

Strung out along the Zn-Pb join, with Cu contents of 2 atomic percent or less, are plots for seven deposits, exclusively from Broken Hill and Mt. Isa. These apparently fall into two groups, one (15, 16, 17) with 9-11 atomic percent lead from Broken Hill, and another

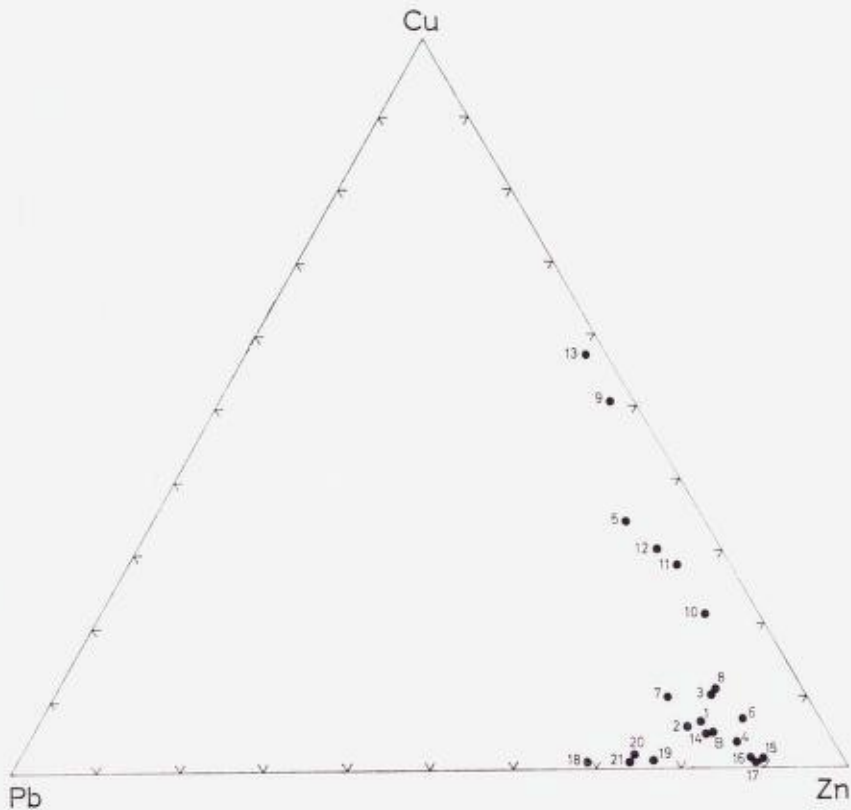


Figure 5. Triangular plots of the mean atomic proportions (recalculated to 100 per cent) of Cu, Zn and Pb in the 22 orebodies listed in Table 2.

Fig. 5. Trekant-diagram som viser de gjennomsnittlige atom-proporsjoner av Cu, Zn og Pb i 22 malmkropper fra forskjellige deler av verden, se lister, tabell 2.

(18, 19, 20, 21) with 22–31 atomic percent lead from Broken Hill and Mt. Isa.

	Cu	Zn	Pb
Group A .....	4–11	74–85	9–17
Group B .....	21–57	41–73	< 9
Group C .....	$\leq 2$	68–88	9–31

There seems to be little geological reason for this apparent grouping; *if it is at all valid*. The copper-poor points along the Zn-Pb join all represent Precambrian ores from Australia, but even here the apparent

grouping cuts across the geological features. The non-pyritic ores of Broken Hill are split between the lead-richer and lead-poorer groups, while the pyritic Black Star orebodies come in the lead-richer group. The rest of the points represent orebodies from Palæozoic (Caledonian?) fold mountain belts with the exception of points 10 and 11, which are from deposits in the Precambrian of Canada. They are all of the pyritic type of lead-zinc ores and, as does the whole group, belong in the «conformable class» of deposit as defined by Stanton.

Thus as far as general geology is concerned, there seems little reason for any grouping of metal content such as seems to be detectable in Figure 5.

It is worth noting that within the Caledonian orogenic belt of Norway, pyritic ores of this same general class are dominantly zinc-copper or less often copper-zinc types in which lead is absent or present in only minor amounts. Most of the Norwegian Caledonian pyritic ores would plot along the zinc-copper join of Figure 5, i.e. they would fall in group B. A few deposits, notably Bleikvassli and the deposit at Mofjell, Mo i Rana, have notable lead contents and belong in group A. Non-pyritic lead-zinc ores, having a negligible copper content, i.e. of the group C type, also occur in the Caledonides of Norway. They are mostly small and of no economic significance and systematic analyses are not available. Examples coming readily to mind are the deposits in the Ofoten basin of Nordland and Troms, as well as certain minor deposits in Central Nordland.

There are no readily apparent geological differences between the lead-rich and the lead-poor (or lead-free) pyritic ores. Their differences in metal contents seems to depend on the regional availability of the various elements, a feature which is also revealed by the data for the deposits plotted in Figure 5.

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## Sammendrag.

Avhandlingen gir resultatene av mineralogisk-geologiske undersøkelser av den kaledonske svovelkisrike sink-bly-(kopper) malmkroppen ved Bleikvassli i Nordland. Undersøkelsen i feltet foregikk somrene 1959 til 1962. De mineralogiske og andre undersøkelser av malmen og dens sidebergarter ble utført mellom feltsesongene, ved Mineralogisk-Geologisk Museum, Oslo. Formålet med undersøkelsene har vært å oppnå et fullstendig geologisk bilde av en noe egenartet norsk kisleforekomst. Forholdene i Bleikvassli er nemlig noe anderledes enn i de fleste norske kisleforekomster som hittil er beskrevet i noe detalj. Foreliggende avhandling gir en del resultater, og det er å håpe at senere avhandlinger vil belyse andre sider av feltets geologi.

Avhandlingen er delt opp i tre deler. Den første del (Part I) gir en detaljert beskrivelse av Bleikvassli malmens mineralogi og petrografi, og malmens geologiske historie forsøkes tolket ved hjelp av dens mineralstrukturer og teksturer.

Malmkroppen er et typisk eksempel på den såkalte «konkordante» klasse av kisleforekomster. Den ligger parallelt med skifriheten i meget glimmer og kvartsrike skifre og i glimmer-kvarts-feltspat gneisser som begge tilhører den nordlandske fasies i den kaledonske fjellkjeden.

Malmen viser to hovedtyper. Den første og viktigste består av svovelkis (hovedbestanddel), sinkblende, blyglans, magnetkis og kopperkis, mens den andre typen inneholder magnetkis (hovedbestanddel), sinkblende, blyglans og kopperkis, med lite eller ingen svovelkis. Dessuten forekommer en hel rekke sulfider, sulfosalter og oksyder i meget små mengder, som oftest bare som «spor». Disse omfatter arsenkis, molybdenglans, cubanitt, valleriitt, gudmunditt, fahlerts, boulangeritt, stannitt (tinnkis), bournonitt, magnetitt og cassiteritt (tinnsten). I de fleste norske kisleforekomster er en del av disse meget sjeldne, eller mangler helt. Det gjelder særlig stannitt og cassiteritt.

Etter detaljerte beskrivelser av mineralenes innbyrdes forhold, konkluderes det med at malmen har gjennomgått regional metamorfose

under den kaledonske orogenesisen for ca. 400 millioner år siden. Særlig viser svovelkiskornene former som må skyldes omkrystallisering under denne metamorfosen. Andre metamorfe trekk er bl. a. følgende: forekomstmåten av mineral-paret sinkblende-blyglans, orienterte teksturer og strukturer, sammenfoldninger av malmen og skifrene, foldningen av mineralbånd i selve malmen. Særlig den magnetkis-rike malmtypen viser tydelig orogenesisens virkninger med sine pseudobreksierte eller «durchbewegt» strukturer.

Forholdene mellom de to hoved malmtyper diskuteres og det konkluderes med at det forelå en magnetkis-rik og en svovelkis-rik malm før metamorfosen. Den opprinnelige form, eller genesen, av sulfidene er ikke forsøkt tolket.

Bleikvassli malmen tilhører mineralogisk sett «Fløttum klassen» etter C. W. Carstens. Den skiller seg tydelig mineralogisk fra de mer vanlige norske kaledonske kisforekomster, selv om det finnes visse overgangs eksempler.

Den annen del (Part 2) behandler de mineralogisk-kjemiske forandringer som har funnet sted ved malmens utgående som et resultat av virkningen av overflate (supergene) agenser. På grunn av erosjonen under siste istid er malmens utgående som oftest skrappt ren under overdekningen, men på visse steder finnes det rester av den gamle preglasiale forvitringssone i form av en «jernhatt» («eisenerhut» eller «gossan»). Denne jernhatten er meget porøs, men gjenspeiler fremdeles malmens tekstur. Goethitt er det eneste oksyderte mineral som finnes i jernhatten, bortsett fra anglesitt (blyulfat) som er meget hyppig i dens nedre del. Under jernhatten finnes det en sone, 20–30 cm tykk, som består av sterkt forvitret malm, hvor det finnes meget gedigent svovel. Dette synes å være et mellomstadium i nedbrytningen av sulfidene, som senere fjernes i løsning som sulfat. Bortsett fra tynne hinner covellin (CuS) finnes det ingen sekundære (supergene) koppermineraler og intet som kan tolkes som en kopper-anriknings (sementasjons) sone.

Den forholdsvis svake virkning av de supergene agenser forsøkes forklart ved at klimaet stort sett har vært ugunstig for kjemisk forvitring og ved at bergartene er meget tette (impermeable). De løste metallene er derfor ført vekk med overflatevannet.

I den tredje delen (Part 3) meddeles resultatene fra en statistisk undersøkelse av metall-fordelingen i Bleikvassli malmen. Studiet er basert på Cu, Pb og Zn analyser av 150 prøver fra diamantborkjerner

eller prøver fra gruben. Den statistiske behandlingen følger den metode som er brukt ved studiet av lignende malmer i Nord-Amerika og Australia, og Bleikvassli-malmen blir sammenlignet med en del av disse.

De tre metallene undersøkes hver for seg, som par, og som en gruppe. Ingen korrelasjon er funnet mellom metall-parene, bortsett fra en meget svak sympatisk variasjon mellom bly og sink. Et trekant-diagram viser forholdene mellom de tre metallene. De fleste punkter ligger over mot sink-hjørnet ( $> 65$  atom prosent Zn) med bare noen få punkter langs Zn-Cu og Zn-Pb sidene. Dette mønster er typisk for alle de palæozoiske kisleforekomster av denne typen som hittil er undersøkt rundt om i verden.

Sammenligninger mellom de to hovedmalmtypene ved Bleikvassli viser at den magnetkis-rike typen er tydelig mer anriket på kopper enn den «pyrittiske» (svovelkis-rike) typen.

Sammenligninger av data fra Bleikvassli og fra tidligere studier av i alt 22 malmkropper synes å tyde på en fordeling i tre grupper karakterisert ved mengdeforholdet mellom metallene. Gruppene har ikke noen tydelig relasjon til geologisk inndeling basert på alder og mineralogi.