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Løkken pyrite mine, Norway

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Sammendrag

Lökken Pyrite Mine

Norway

G. M. Kershaw,

Royal School of Mines. 196

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ABSTRACT

Rock types

The Løkken orebody is the largest of the many occurrences of cupriferous pyrite in the Trondheim region. The rocks of the Løkken belong to the Lower Ordovician Støren group and are predominantly volcanics which have been metamorphosed in the greenschist facies of regional metamorphism to produce rocks of spilitic mineralogy, and are known locally as greenstones. They are partly schistose and partly massive, and in the latter case are often developed as pillow lavas, indicating the submarine origin of many of the flows.

The spilites have in places, especially near the ore, been exposed to alteration, and the most common alteration is that of carbonitization, which is ascribed to the action of CO_2 bearing solutions associated with the ore.

Many of the rocks are impregnated to a greater or lesser extent with sulphides, mainly pyrite, but also pyrrhotite.

Ores and Orebodies

The Løkken ores are situated as concordant bodies in metavolcanics containing layers of sedimentary pyrite. (vasskis) The metavolcanics enclosing the ores dip to the north and form the limb of a syncline, the axis of which pitches to the west-northwest at about 15^{o}.

The orebodies are situated close beneath a thrust plane which dips at about 20° to the west-northwest. In the eastern parts of the mine the orebodies are some distance below the thrust plane, while in the western parts, the ore was thought to have been cut off by the thrust until recent exploration proved a further extension of the ore.

The massive orebodies are characteristically in the form of elongated lenses or plates, the longest axis of which is parallel to the lineation and fold axis direction of the enclosing rocks. Three orebodies have been mined. Their relative sizes are approximately 30 : 3 : 1 respectively.

The Løkken ore is fine grained (0.005 - 0.1mm.) and of simple mineralogy: 70-75% pyrite, 6% chalcopyrite and 2.5% sphalerite with some magnetite. The main gangue mineral is quartz, 12-14%, with smaller quantities of calcite and chlorite. Sulphur averages 42%, copper 2.3% and zinc 1.8%.

The second type of sulphide mineralization at Løkken is the vasskis. This is of syngenetic origin and formed contemporaneously with the submarine metavolcanics.

The sulphide layers in the vasskis are mainly pyrite with 20-40% sulphur. The copper and zinc content is low to absent so the vasskis is not mined as an ore. The texture is very fine grained and the sulphide layers vary in thickness from a few centimetres to about a metre, very seldom more.

ACKNOWLEDGEMENTS

I should like to acknowledge the help of the staff of the Orkla Grube - Aktiebolag, particularly the manager Mr. P. Sandvik and the mining engineers Mr. O. Nordstein and Mr. K. Brandbou, for their help during my stay at Løkken.

Also I wish to gratefully acknowledge the assistance of Dr. W. Skiba of Imperial College, who supervised the petrological aspects of this report, both in the field and in the laboratory.

Part I.

INTRODUCTION

INTRODUCTION and HISTORY

During the summer of 1966, three undergraduate students from the Royal School of Mines, under the supervision of Dr. W. Skiba, were invited to map the area around Løkken mine and the newly discovered extension to the orebody. Mr. J. May was to specialise in petrology and geochemistry, Mr. E. Rutter in structures and myself in the local geology around the mine and also the geology of the orebody extension.

Location

Løkken mine is just outside the small town of Løkken Verk in the county of Sør-Trøndelag, about 70 km. southwest of Trondheim. At present it is the largest producer, in Norway, of cupriferous pyrite, with a run-of-mine capacity approaching half a million tons per year. The mine is connected to the shipping harbour of Thamshavn on Trondheimsfjord by a 25 km. long privately owned electric railway. Thamshavn is also the site of the company's smelter.

(See figure 1.)

History

The first ore at Løkken was discovered in 1654, and for the first two hundred years the mine was worked for its copper content only. A smelter was erected at Svorkmo, about 7 km. north of the mine, and eight years later another at Grustsaeter, 15 km. southwest of Løkken.

By 1770, the mine had reached a depth of 166 metres, at which depth a water filled fracture plane was met with. The influx of water proved too great for the pumps and the mine filled to a depth of 14 metres. Nevertheless a limited production was possible from the upper parts of the mine until 1845, when working stopped and the mine allowed to fill with water.

During this early period of 190 years, 11,300 tons of copper were produced. At first the ore held 4.7% copper but later it diminished to about 2.5%.

In 1855 the mine started again to export a relatively small quantity of pyrite to England for sulphuric acid manufacture. Due to gradually worsening prices for the ore, work became unprofitable so that in 1891 the mine was once again forced to close.

Shortly before 1900 the task of dewatering the mine was commenced and this work lasted four years. Prospecting work was carried on at the same time.

In 1904 the present company was formed and undertook the sinking of a new shaft, building of a concentrating plant and construction of the electric railway to Thamshavn. This work was completed in 1910, when production once more started.

In 1912 the known reserves at Løkken were about two million tons, but in late 1913 a faulted extension was found, and following an extensive diamond drilling programme, these reserves were increased to 17 million tons by 1920.

In 1931, the smelter at Thamshavn was blown in, and the well known Orkla method was used to produce copper matte and elemental sulphur.

The highest annual output of the mine was attained in 1937, when production reached 562,000 tons containing 41.08% sulphur and 2.14% copper. Since then, with dwindling reserves, the annual production has fallen off somewhat and in 1959 totalled 342,300 tons.

In recent years a further continuation of the orebody was located, and after exploratory underground drilling, an underground shaft was sunk and preparations for mining the ore by 1968 are at present being made. The present ore reserves have not been disclosed.

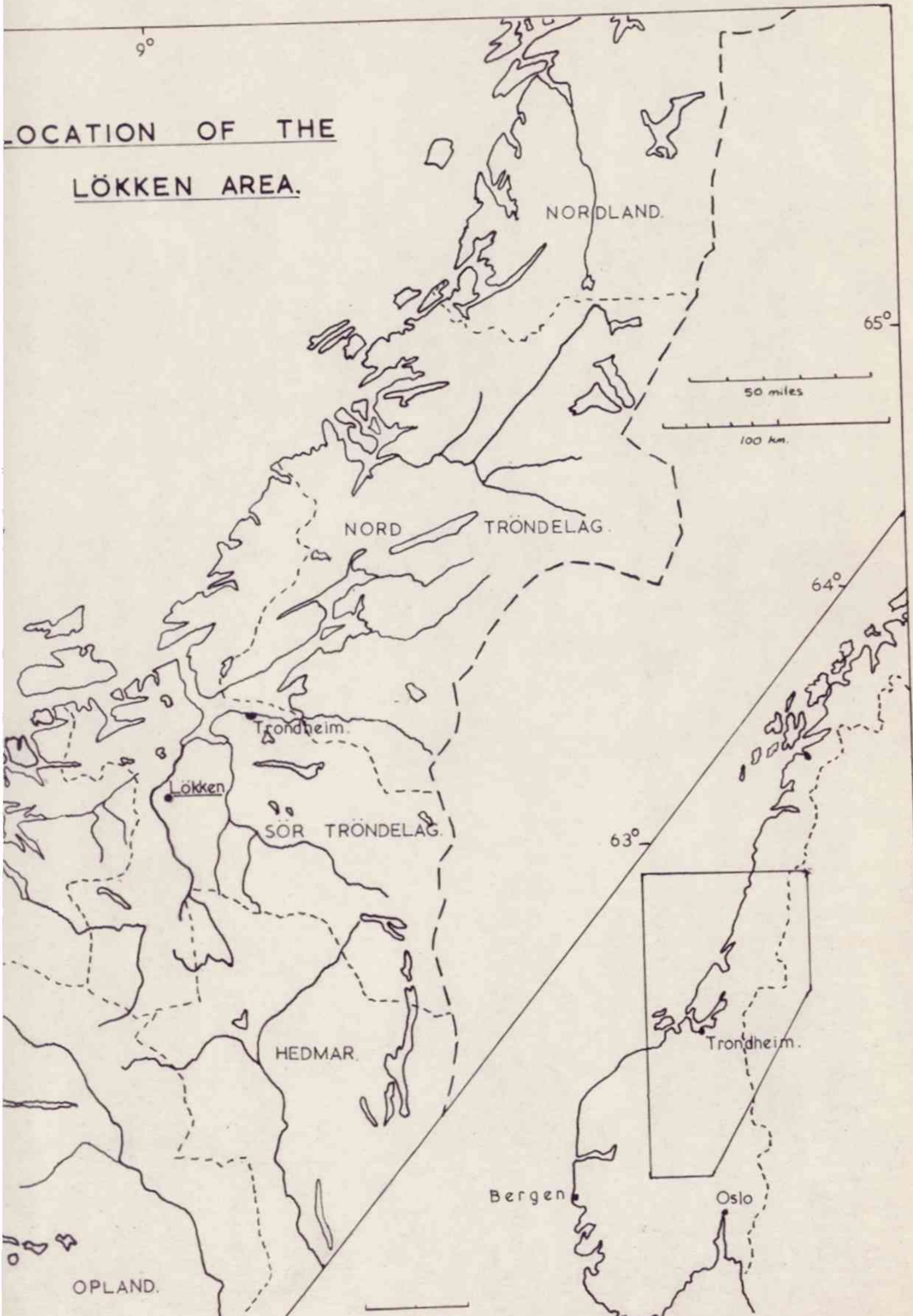

LOCATION OF THE
LÖKKEN AREA.
9°
NORDLAND.
65°
50 miles
100 km.
NORD TRÖNDELAG.
64°
Trondheim.
Lökken
SÖR TRÖNDELAG.
63°
HEDMAR.
Trondheim.
Bergen
Oslo
OPLAND.
200 km.
9°
Fig. 1

Plate I.

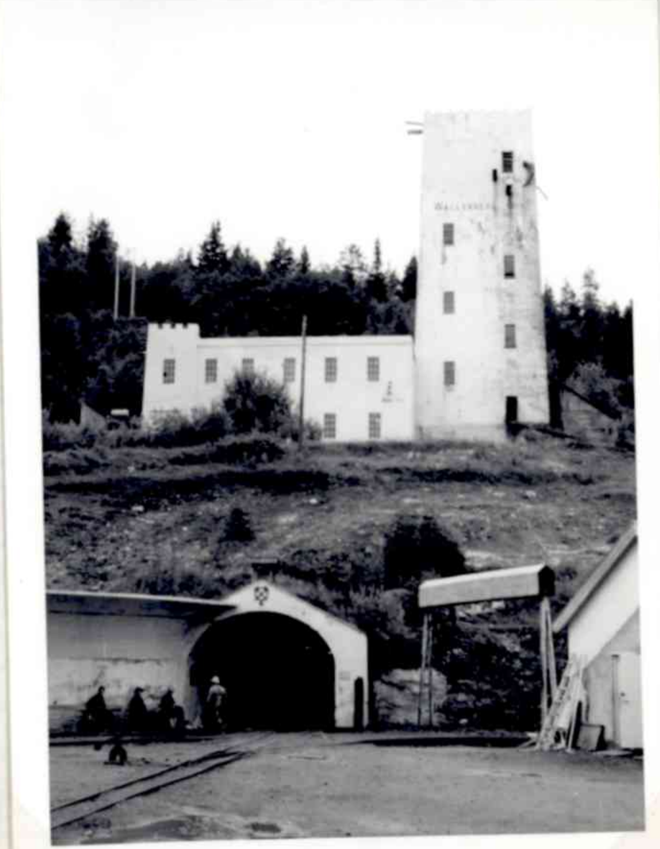


Plate 2.

Plate I. New underground shaft from level 430m. to a depth of 1000 m, to serve the extension to the orebody.

Plate 2. Wallenberg shaft, the main entrance and exit to the mine.

SUMMARY OF THE GEOLOGY OF CENTRAL NORWAY

The geology of central Norway can be divided into three broad groups of rocks; the Caledonian or basal gneiss, the Eocambrian sparagmite succession and the Hovin, Støren and Røros groups. Løkken lies in the Støren group of rocks and is surrounded by the Hovin and Roros rocks, with basal gneiss and Eocambrian to the north - east and south - east. (see Fig. 2).

1). The Caledonian Gneiss

The caledonian or basal gneiss, as the name indicates, is the lowest group of rocks in the structural sequence, and probably also the oldest group in the stratigraphical column. The gneiss is overlain by Eocambrian rocks and the Hovin, Støren, and Røros groups of rocks.

In essence, the Caledonian gneiss of Central Norway is very similar to the Archaean gneiss found in south - east Norway. It is thought that the gneiss consists of Pre-Cambrian rocks which have been highly metamorphosed and tectonically intercalated with Eocambrian and Cambro - Silurian rocks. Such has been the tectonic transformation of the gneiss that any possible angular unconformity, which may have been present between the gneiss and Cambro - Silurian rocks of the Trondheim region has been completely obliterated.

2). The Eocambrian Sparagmites

The Eocambrian rocks compose what is known as the Sparagmite succession, originally a term used to describe a metamorphosed feldspathic sandstone, but now includes a wide range of rock types; sandstone, shale, limestone and conglomerate. (The sparagmite conglomerates have been interpreted as formally being a glacial tillite.) The sparagmite formation is generally unfossiliferous, but stromatolites have been found.

The sparagmites are essentially a sedimentary succession, and is stratigraphically older than the fossiliferous Cambro - Silurian rocks. Eocambrian is used to indicate the close association between the true sparagmites and the fossil bearing Cambrian rocks although it is most probable that the formation extends into the Pre-Cambrian.

The upper part of the Eocambrian is the equivalent of the Scottish Dalradian rocks.

The sparagmite succession is fairly extensive and extends to the east into Sweden where it is found to be mineralized, although no mineral deposits have been found in the Norwegian sparagmites.

In the north the Eocambrian is tectonically overlain by Cambro - Silurian rocks and itself overlies the basal gneiss.

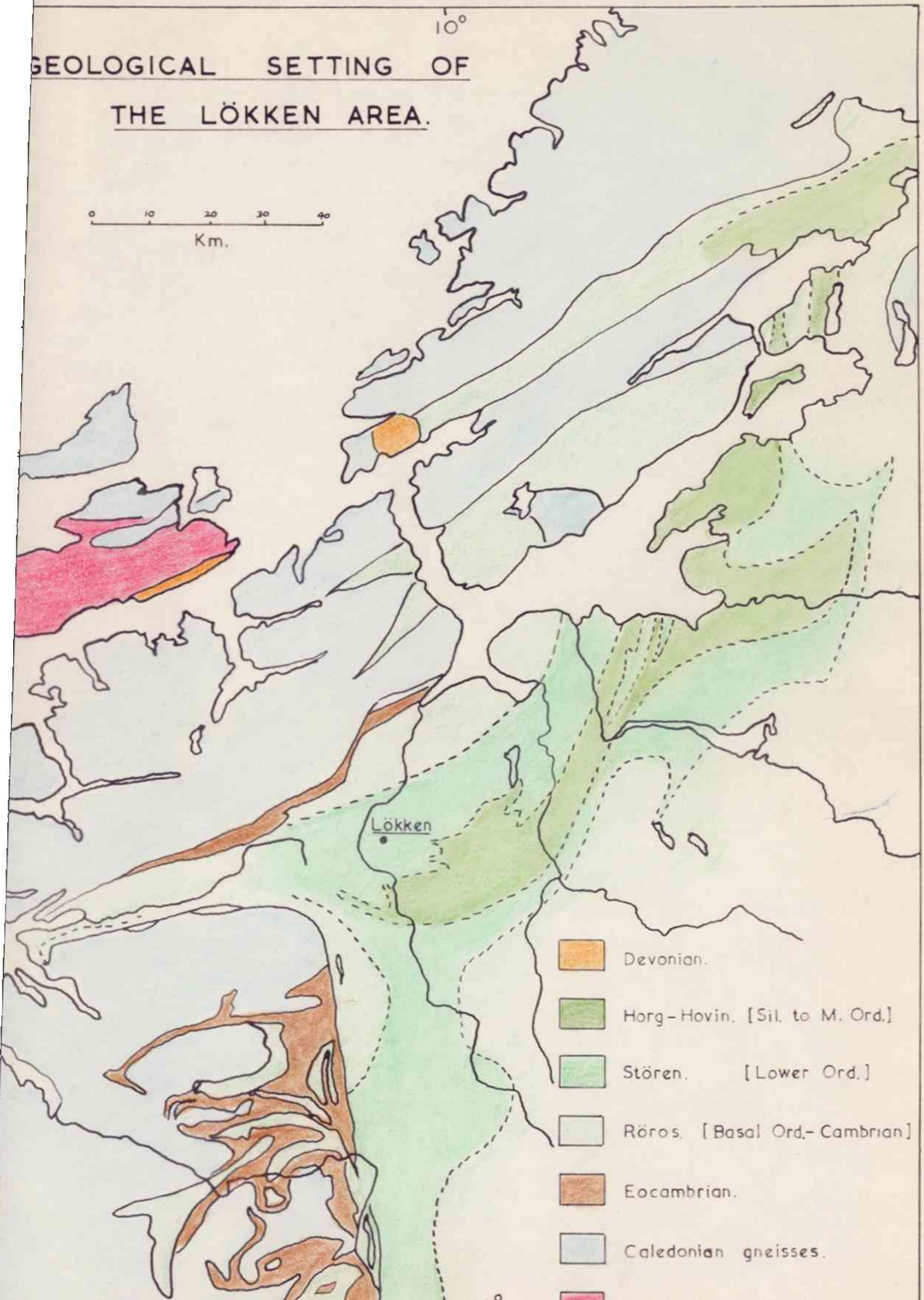
Intrusives are not common in the sparagmite succession.

3). <u>The Hovin, Støren and Røros Rocks</u>

Running south - east through Trondheim and Løkken is a broad depression in which metamorphosed Cambro-Silurian rocks have escaped erosion. The three groups of rocks, the Hovin, Støren and Røros groups have been dated as Silurian to Middle Ordovician, Lower Ordovician and Basal Ordovician to Cambrian, respectively. It has been found that the higher the rocks are in the structural succession, the lower is the grade of metamorphism. Thus the rocks in the centre of the synclinorium are hardly metamorphosed, whilst at the base of the succession, just above the Caledonian gneiss, garnet grade rocks are present.

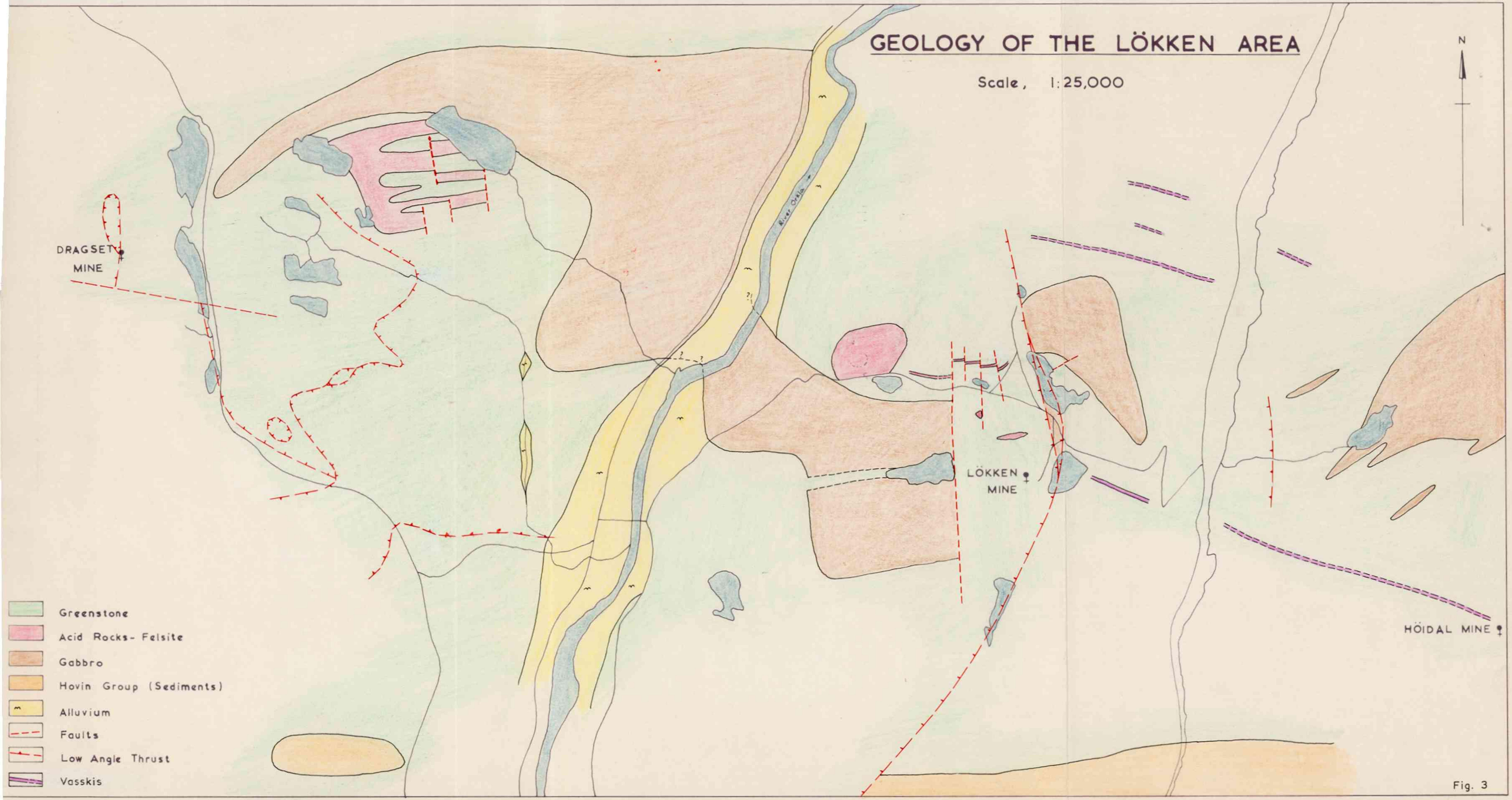
The rocks of the Hovin, Støren and Røros groups are mainly meta - argillites, although meta-volcanics are predominant in the Støren group where they are represented as 'greenstones' after being metamorphosed in the Greenschist facies of Regional Metamorphism. Intruded into the Støren greenstones are masses of gabbro, whilst locally there are large intrusive bodies of trondhjemite. (a type of granodiorite).

Closely associated with the metavolcanics are several bodies of massive pyrite, many of economic importance, and often containing a few percent of copper. The reason for such a marked association between massive pyrite and the meta-volcanics is dealt with in the following chapters.



GEOLOGICAL SETTING OF THE LÖKKEN AREA.
10°
0 10 20 30 40
Km.
Lökken
10°
Devonian.
Horg-Hovin. [Sil. to M. Ord.]
Stören. [Lower Ord.]
Röros. [Basal Ord.- Cambrian]
Eocambrian.
Caledonian gneisses.
Caledonian intrusives.

Fig 2



GEOLOGY OF THE LÖKKEN AREA

Scale, 1:25,000

Fig. 3

Part II.

LØKKEN MINE AREA

LOKKEN MINE AREA

SUCCESSION

Despite the fact that there are relatively few rock types at Løkken, the stratigraphy of the area is somewhat complex and can only be divided into broad lithological units. Lack of recognisable marker horizons, and poor exposure over the majority of the area make detailed mapping of the meta-volcanics difficult. It is for these reasons that for the last three hundred years, whilst the mine has been operating, no reliable detailed maps of the area have been produced, and the rocks were known collectively as greenstones.

Mapping, during the summer of 1966, enabled some subdivision of the area into major rock types, (dealt with in the following sections) and gave a rough idea of their succession and history.

The rocks of the Løkken area have been subdivided into three broad stratigraphical units; the Hovin, Støren and Røros groups.

Hovin group (M. Ord. Silurian)	Nyplassen beds - originally shales and sandstones. Fjeldheim beds - shales, sandstones & limestones. Fjeldheim conglomerate
Støren group (L. Ordovician)	Støren rocks - mainly basic lava with some pyroclastics and sediments. Gabbro and acid intrusives.
	? ?
Røros group (Cambrian - basal Ord.)	Chlorite schists Garben schists

The Hovin and Støren groups have both been subjected to metamorphism in the Greenschist facies of Regional Metamorphism, destroying much of the original nature of the rocks.

The Fjeldheim conglomerate is found at the base of the Hovin group and contains pebbles of rocks from the Støren group, (jasper and greenstone), and hence the Hovin group is younger than the Støren group, although there is little or no angular discordance between them. The Røros group is thought to be the oldest of the three groups because of the higher grade of metamorphism found in these rocks.

Graptolites of Arenigian age are reported to have been found in the shale in the Fjeldheim rocks by Blake and Chadwick in the area to the east of the Løkken valley. The Støren group has therefore been dated as Lower Ordovician.

The volcanics of the Støren group were deposited as massive and pillow lavas, with occasional pyroclastic bands of tuff and agglomerate. It is probable that many of the massive flows were formed on land, whilst the pillow lavas formed by submarine eruptions. (However, the viscosity of magma plays an important part in whether a lava will form pillows when extruded onto the sea bed, therefore many of the massive flows may be submarine). The peak of volcanic activity has been dated as upper Cambrian to Lower Ordovician.

At the time of the Caledonian Mountain Building period, these rocks were subjected to folding and metamorphism in the greenschist facies. This metamorphism has altered the original composition of the volcanic rocks, to a greater or lesser degree, so that the predominant minerals now present are albite, chlorite, and epidote, the latter two giving the rocks their characteristic colour, and hence the term 'greenstone'. Towards the end of the period of metamorphism the greenstones or metavolcanics were intruded by several masses of gabbro. This too has suffered from the effects of metamorphism. From the geological map of Løkken, (Fig. 6), it can be seen how the boundary of the gabbro intrusions cut across the trend of the earlier fold structures indicating its later origin.

GEOMORPHOLOGY

Much of the physical geology of the central part of Norway is a result of glacial action, and the Løkken area exhibits several features of glaciation. The present day land surface is about 300 metres above sea level and is cut by north-south valleys with steep sides, in some cases almost vertical, running perpendicular to the predominant east-west strike direction of the rocks. The topography is fairly flat away from the river valleys, and surprisingly it is the meta-volcanics rather than the gabbro masses, which makes up the highest hills. The Løkken and Orkla River valleys are both good examples of glacial valleys, having steep sides and flat floors of alluvium. Hanging valleys are common in both valleys.

The Orkla River valley is particularly interesting because of the river terraces, which make very good agricultural land. The river has cut through the terraces indicating the rapid uplift of the land surface since the end of the Ice Ages.

Glacial debris is mainly restricted to the valleys, where it is worked for sand and gravel, and little is present on the higher land surfaces.

Vegetation is predominantly pine forest with a deciduous undergrowth of small bushes.

Plate 3. View looking south down the Orkla River valley. Note the steep sides of the valley and the well formed river terraces, indicating the rapid elevation of the land surface.

Plate 4. View looking south down the Løkken valley. Note the very steep sides and flat bottom of the valley floor. Mine surfaces plant can also be seen.

STRUCTURAL SETTING

The structural setting of the rocks in the Løkken area is difficult to ascertain due to the massive nature of the metavolcanics, which are devoid of any schistosity throughout the majority of the area. Dip and strike determinations are, for the most part, doubtful because pillow lava formations offer the only readable structures, and dip and strike readings from only two-dimensional outcrops of pillow lava can only be approximate. Joints are not well developed due to the massive nature of the rocks.

However, even from the limited information available, it is clear that the rocks have undergone several recognisable phases of deformation connected with the Caledonian Orogeny, and these are summarised below.

1) First periods of folding before and during the introduction of the pyrite ore, and at the same time as the metamorphism in the greenschist facies.
2) Second period of folding to produce the Løkken syncline and the minor folds on the sides of the large syncline.
3) Thrusting, towards the end of the second period of folding.
4) Third and last period of folding, producing a gentle flexure about an appeoximately north-south trending axis.

5) Faulting and jointing, cutting across other structures resulting from, and not deformed by deformations 1 to 4.

Features resulting from the above periods of deformation

It is clear that the rocks to the north of Løkken must have been strongly folded to have developed a schistosity, and as there is no sharp boundary with the rocks at Løkken, which have only a little schistosity developed, it follows that the rocks have been isoclinally folded, as schistosity is characteristic of isoclinally folded rocks. The isoclinal folding has produced linear structures in the more strongly deformed rocks to the north such as elongated vesicles and stretched pillows, but such features are not easily seen around Løkken. The ore must have been present at this time as the ore is pre-metamorphism and the metamorphism accompanied the first period of folding. At this stage the orebodies would have been a single, long narrow flattish body, the folding and splitting into the three sections taking place with the second period of folding.

The second period of folding was co-axial with the first period, and formed the large Løkken syncline, the axis of which pitches to the west-northwest at about 15°. Smaller minor folds were also produced on the limbs of the large syncline, and the ore is found in such folds. The orebody plunges to the west down the southern limb of the Løkken syncline, beneath an extensive thrust plane which dips at 20°, also to the west-northwest. The thrust was formed at, or near the end of the second period of folding, and is slightly warped by this folding as well as the last period of folding.

The thrust is easily seen in the mine as a clay gouge, several centimetres thick. (see Plate 5). In places the thrust occurs close to the ore and is sometimes in contact with the ore. (see Plate 15). This is clear evidence for the thrust being of later origin than the ore, and it is possible that the thrust was localised by the presence of the very hard ore.

The relative direction of movement of the rocks at either side of the thrust plane is difficult to prove as there are no marker horizons that can be traced across the surface outcrop of the thrust. It would appear to be most probable that the movement was in a north-south direction which would correspond to the direction of movement of other thrusts in the Norwegian Caledonides.

N.

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However, direct evidence for the direction of movement is somewhat contradictory, Examination of small drag folds in, and close to the thrust suggests that the sense of movement was definitely north - south, but that in one case the rocks above the thrust were displaced to the north, and in the other the movement was to the south.

Should the latter case prove to be the overall predominant movement, i.e. rocks above the thrust were displaced to the south, then it is possible that the thrust is not a true thrust but in fact a low angle sinistral strike - slip fault. Nevertheless, this seems to be unlikely as other definite thrusts have been detected to the west of the Orkla River.

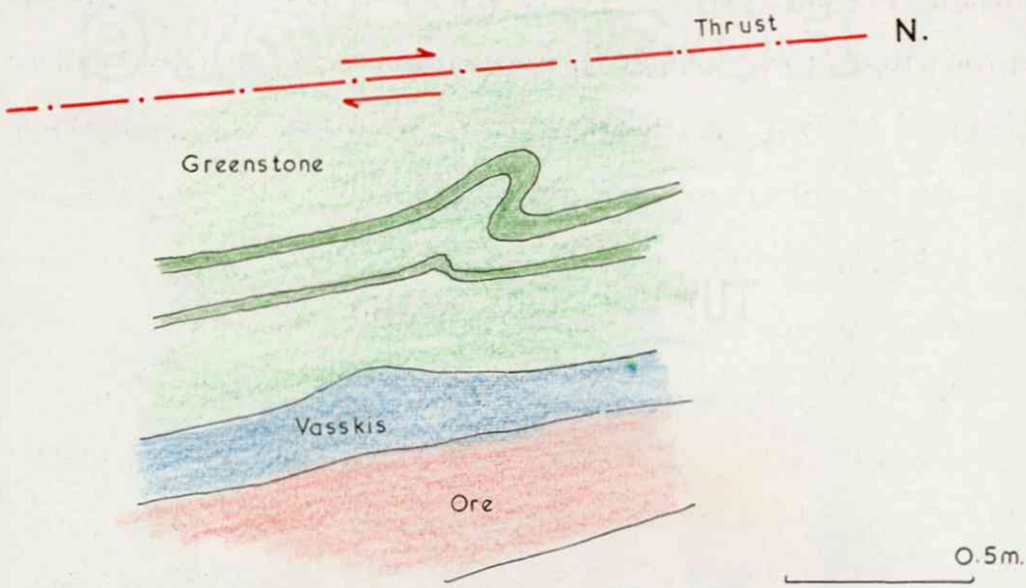


Figure 4. Drag fold developed in greenstone, below the thrust on level 481.

Plate 5. Thrust with sheared greenstone above and massive greenstone below. Level 481m.

Plate 6. Small quartz drag fold along the thrust plane. Level 430m.

The amount of movement on the thrust plane is probably not very much, only a matter of a few kilometres, although this again is doubtful and is based mainly on the lack of strong cataclastic deformation, which one would expect to be associated with a thrust of large displacement.

The third and last period of folding was only a gentle flexure about an approximately north-south axis. This has had the effect of deforming the Løkken syncline into a gently undulating syncline, with the change in plunge of its axis being a matter of only a few degrees. The thrust has also been given a gentle undulation about the north-south axis.

Faulting has cut across the earlier structures and there are undoubtedly many faults cutting the area, but the majority of these will remain undetected due to the lack of outcrop and the uniform nature of the rock type. Several faults have been detected where they displace the more easily distinguishable acid felsite sills. Many faults and shear zones can be seen in the gabbro in the mine although faults cannot be seen in the surface outcrops of the gabbro. Many of the faults seen in the gabbro underground (level 481) have been intruded by dykes. Faults in the meta-volcanics appear to be less common than in the gabbro.

Both the surface and underground faults that have been mapped appear to have a prefered strike orientation of approximately north-south and dipping to the west, with others having an east-west orientation and dipping to the south, with dips averaging 60 - 70°.

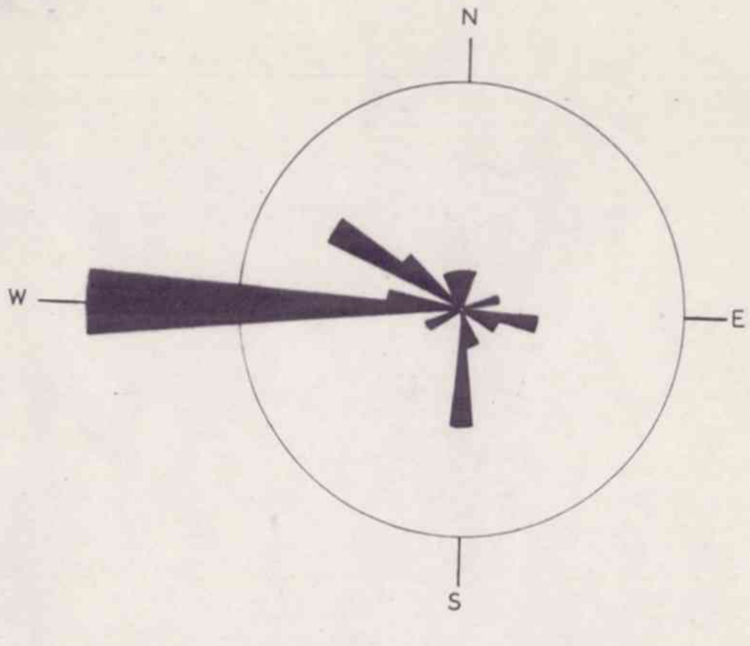
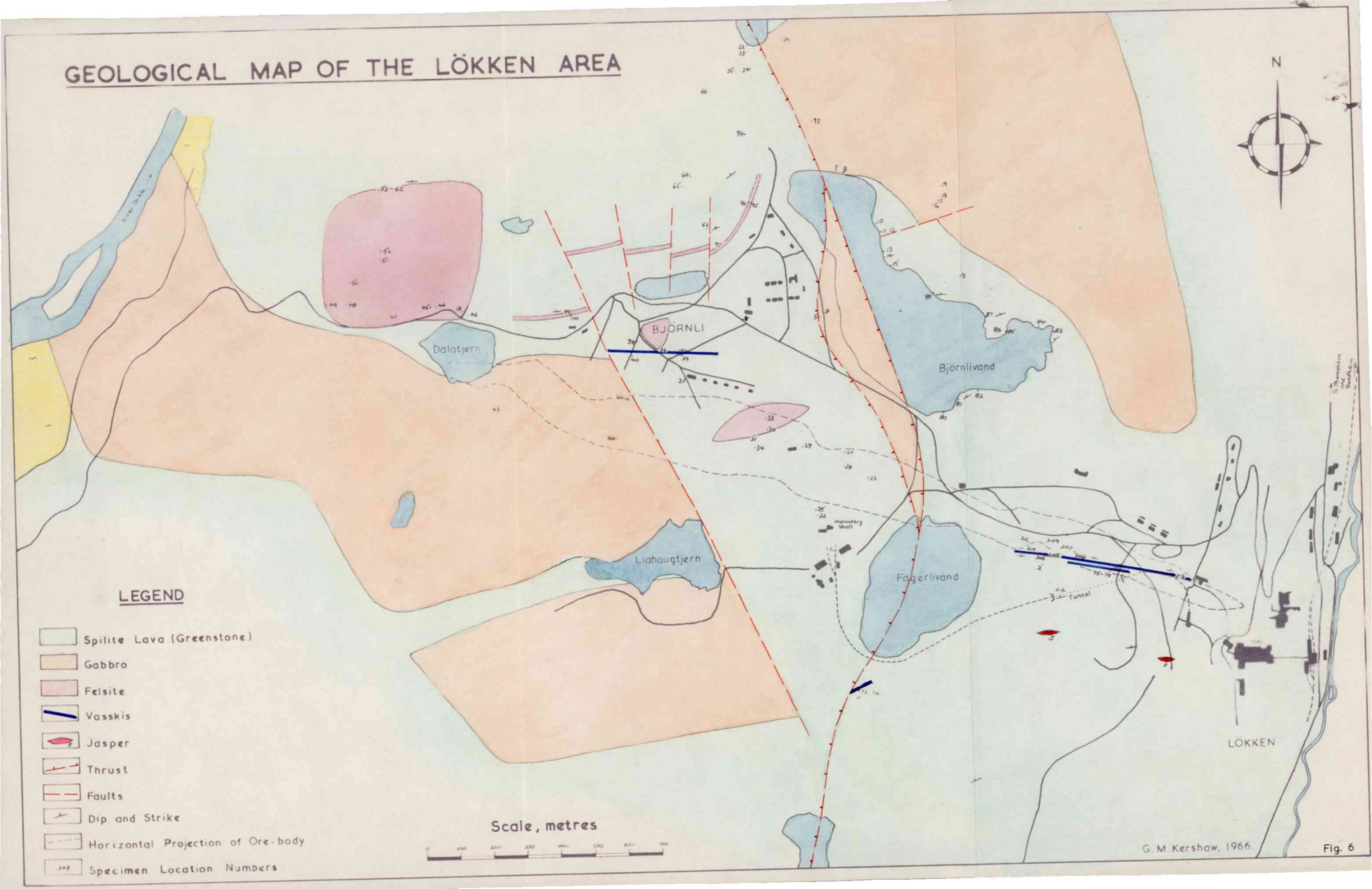


Fig. 5 Frequency-diagram for the dip directions of 32 faults and dykes seen underground. Bearing interval 10°.


GEOLOGICAL MAP OF THE LÖKKEN AREA
N
BJÖRNLI
Dalatjern
Björnlivand
Liahaugtjern
Fagerlivand
Tunnel
LÖKKEN
LEGEND
Spilite Lava (Greenstone)
Gabbro
Felsite
Vasskis
Jasper
Thrust
Faults
Dip and Strike
Horizontal Projection of Ore-body
Specimen Location Numbers
Scale, metres
G. M. Kershaw, 1966.
Fig. 6

Part III.

PETROLOGY

PETROLOGY

The rock types of the Løkken area have, for some time, been divided into five clear divisions :

i. Gabbro

ii. Greenstone

iii. Felsite

iv. Vasskis

v. Pyrite ore

Of the five, only the first two are of major occurrence, the felsite, vasskis and pyrite being of significant interest, however. The above subdivision is based on clear field differences of the rock types, but no scientific subdivision has been made. Attempts to subdivide the greenstones, on the basis of colour differences, have been made with little or no success. It was therefore decided to adopt a more scientific nomenclature when describing the rocks, and because of the effect of metamorphism on the mineralogy of the rocks a terminology was adopted, based on the spilitic suite of rocks :

i. Metagabbro

ii. Spilites (basic metavolcanics)

iii. Quartz keratophyres (acid metavolcanics)

iv. Vasskis

v. Pyrite ore

METAMORPHISM

Before considering the present day petrology and mineralogy of the rocks in the Løkken area, the effect of metamorphism must be mentioned.

As previously stated the rocks at Løkken have been metamorphosed in the greenschist facies of regional metamorphism, giving the rocks their characteristic mineralogy of albite, epidote, chlorite and calcite. It is however, more difficult to place the rocks into the appropriate sub-facies, as defined by Winkler, due to the fact that the rocks are basic volcanics of a fairly uniform composition which might, or might not, produce the required index minerals. Winkler defined the three sub-facies of the greenschist facies as possessing the following mineral assemblages :

B.1.1. Quartz - Albite - Muscovite - Chlorite

B.1.2. Quartz - Albite - Epidote - Biotite

B.1.3. Quartz - Albite - Epidote - Almandine

or for basic rocks :

B.1.1. Albite - Epidote - Chlorite - Actinolite - Sphene ± Stipnomelane ± Quartz

B.1.2. Albite - Epidote - Chlorite - Actinolite - Sphene ± Biotite ± Quartz

B.1.3. Albite - Epidote - Hornblende ± Almandine ± Biotite ± Quartz

Hence the index minerals for the three sub-facies are stipnomelane, biotite and hornblende or almandine (and not chlorite, which is found in two of the sub-facies). Stipnomelane, although not common in the basic meta-volcanics, is found in abundance in the more acid rocks; biotite has been reported in meta-sediments, of a more variable composition than the meta-volcanics, by Mr. Rutter from the area to the north of Løkken, and hornblende, an easy mineral to identify, has been seen in only a few thin sections. Thus it would appear that sub-facies B.1.1. and B.1.2. are frequently developed, whilst B.1.3. is only locally developed. However, due to the constant composition of the meta-volcanics throughout the area, it is not possible to delineate the exact boundaries of the sub-facies, in fact it is only possible to state that the metamorphic grade increases from B.1.1. in the south to B.1.2. in the north of the Løkken area, where biotite is more common.

In general, despite the period of metamorphism, igneous textures are well preserved. In many of the coarser basic meta-volcanics, the textural arrangement of the feldspar laths suggests igneous origin, whilst in the gabbro original bent feldspars can still be seen. Spherulites are well preserved in the acid meta-volcanics.

On the sedimentary side, primary banding of pyrite, although recrystallised, is still clearly visible in the vasskis.

Contact Metamorphism

Several gabbro masses have been intruded into the basic meta-volcanics, (or true volcanics as they would have been at the time), but have failed to produce any marked contact metamorphic effect. This may be due either to the very basic nature of the volcanic rocks, or any effect produced has subsequently been removed or obscured by the regional metamorphism. Even in xenolithic inclusions of meta-volcanics in the gabbro, no contact effect can be seen.

Intrusion of acid (felsite) sills into the basic meta-volcanics has also failed to alter the mineralogy of the country rocks, although some cleavage has developed, especially in the foot-wall rocks.

METAVOLCANICS.

Problems of nomenclature

The effect that metamorphism has had on the volcanics, of the Løkken area, leads to problems in giving the rocks a scientific name which implies something of their most important characters. It soon becomes apparent that no single term can cover all aspects of origin, geochemistry and past and present mineralogy. This problem can be tackled from two different standpoints :

a) The rocks could be given a name which implies their origin and mineralogy before metamorphism.

b) The rocks could be classified using the terminology indicating their present mineralogy, if not their chemistry.

If the former of the two possibilities is applied, then the rocks, on the basis of geochemistry, (May, 1967) fall into the group of basalts, tholeiites and spilites. This classification has the most serious drawback that the above terms except spilite imply the mineralogy of pyroxene and plagioclase (labradorite to bytownite in composition). Clearly this is not the case at Løkken. The composition of the plagioclase is now albite, and pyroxene is rare, being unstable under greenschist metamorphism and having altered to colourless amphibole when present.

The second classification, based on the present day mineralogy, although to a great extent metamorphic in origin, would seem to be preferable. The spilitic suite of rocks covers the range of mineralogy as seen in thin section, but the rocks have a low soda content ranging from 2.5 to 5.1%, and as true spilites have greater than 5% Na_2O, it would appear that the rocks did not all form from a true spilitic magma but from a basaltic magma differentiated to produce a range in composition from basaltic to true spilitic lavas.

It was decided to adopt the terminology of the spilite suite, and it is as well, before proceeding further, that the term spilite should be defined to avoid the use of the same name to cover differing rock types. The terminology of the spilite suite is drawn basically from Turner and Verhoogan, page 202.

Spilites are basic lavas consisting principally of highly sodic plagioclase, (albite or oligoclase) and augite or its altered equivalent, (actinolite, chlorite, epidote etc.,) Olivine is absent or sparingly represented by serpentine pseudomorphs. Evidence of hydrothermal activity (e.g. alteration of pyroxene, infilling of vesicles with epidote and calcite) is usually conspicuous and rarely absent, while persistant relict patches of labradorite or andesine within the crystals of albite shows conclusively that, in some cases at least, the present condition of the feldspars is a result of albitization of initially more calcic plagioclase. Many spilites are pillow lavas, this however is not essential; nor are all pillow lavas spilitic.

The association of keratophyres and quartz keratophyres with spilites, with all three highly sodic, indicates that a common parentage is highly probable in the majority of cases. Thus arises the problem of whether or not there exists a primary magma of spilitic composition which could differentiate to keratophyre and quartz keratophyre magmas, itself having been formed by the differentiation of a basaltic magma. However it is beyond the scope of this report to enter into the discussion of the many and varied theories proposed to obtain a rock of spilitic composition and the problem will not be dealt with here. Sufficient to say that the majority of spilite occurrences are in greenschist metamorphic provinces, and their present mineralogy may not always reflect the original chemistry of the magma.

Keratophyres and quartz keratophyres are the silica rich equivalents of spilites, and it may be noted that as soon as free quartz shows in the melt, the ability to form amygdaloidal textures diminishes or disappears (i.e. the viscosity of the magma is much increased).

Description of the rock type known as 'felsite' at Løkken will indicate its close relationship to the above mentioned quartz keratophyres. Rocks corresponding to keratophyres have not been found at Løkken, possibly because they cannot easily be distinguished from the spilites.

SUBDIVISION OF THE SPILITES

Until recently the meta-volcanics at Løkken have been known collectively as greenstones. This is quite satisfactory when wishing to class the rocks together as being of a similar origin and appearance, but is not adequate when wanting to map the area into component flows. Further subdivision, on the basis of colour, has not proved adequate and a closer examination of the rocks must be made to find other parameters of subdivision.

The only possible characters that can be used in the field for mapping purposes are colour, grain size and the nature of the flow. (whether massive or pillows). In some respects, the colour of a rock is dictated by the mineralogy and grain size, and it is thus possible to pick out those rocks which are rich or defficient in chlorite; i.e. the green from the grey. Without considering grain size, the colour on its own is of little value. For example, a rock might contain much chlorite mixed with larger white minerals which will give the rock a grey colour, and conversely a very fine grained rock with a little chlorite might appear dark green. The nature of a flow is again somewhat deceptive as it would appear that pillow horizons merge gradually into massive flows, and in many cases it is difficult to say, for a limited exposure, if pillows are present or absent.

However, despite the problems of each individual parameter, the study of thin sections and a comparison of hand specimens has enabled the spilite group to be subdivided into three groups on the basis of composition and grain size as reflected in the hand specimen. The characteristic features of the three subdivisions, based on thin section examination are indicated below.

Type i. Large feldspar crystals, chlorite and fibrous amphibole present.

ii. Absence of large feldspars, much fibrous amphibole and chlorite present.

iii. Abundant epidote, little chlorite and feldspar.

Hand specimen differences are less obvious and depend on the grain size and colour.

i. Colour variable, usually medium to light green. Grain size is relatively coarse.*

ii. Colour again variable but usually fairly dark green. Grain size medium to fine.

iii. Colour light green to grey, grain size variable.

A typical member of each of the above groups is illustrated by the following descriptions and drawings.

* Note The grain size refers to the relative grain size of the spilites, which are all fine grained.

Type (i) (Specimen 174)

Specimen 174 comes from level 930 metres, below several vasskis horizons in the foot-wall of the ore. It is a fairly coarse grained, medium to light green spilite with several veins of calcite cutting the rock, up to four or five millimetres wide. These calcite veins must be ignored when considering the rock as typical of type (i), as they are a result of carbonatization which has affected the rocks close to the ore.

In thin section the rock is found to be composed of feldspar, a fibrous amphibole, epidote and chlorite as well as calcite from the carbonatization.

The texture of the rock is fairly uniform, there being no outstanding porphyritic minerals. It is conspicuous that the amphibole occurs in fibrous aggregates, apparently of later formation than the other minerals as it cuts through them in places.

The mineralogical composition of the rock can be obtained approximately by point counting the mineral grains, and gives the following results.

feldspar	40%
amphibole	25%
chlorite	11%
epidote	10%
calcite	14%

As the calcite is present as a result of carbonatization, a rough estimate of the composition before carbonatization can be estimated if the calcite is left out of the calculation, when the following results are obtained :

feldspar	47%
amphibole	30%
chlorite	12%
epidote	11%

The latter percentages can only be approximate as it is quite possible that other constituents were introduced along with the calcite.

Feldspar

The feldspar occurs in two generations, the first being in the form of well formed, euhedral to subhedral crystals. The second generation forms anhedral grains, interstitial between the first generation feldspar. There is little difficulty in distinguishing between the two types as the former type is nearly always twinned on the albite law, whilst the second type is most often untwinned.

The second generation anhedral grains often contain fragments of other minerals, and occasionally fragments of twinned feldspar probably from the first generation of feldspar.

Probably the simplest way to account for the two generations of feldspar is to assume that the twinned, first generation is the original feldspar of the rock and the second generation has been formed as a result of metamorphism, or possibly was added along with the calcite during the process of carbonatization.

The composition of both types of feldspar is in the range of An_{5-10}, indicating that the first generation of feldspar has possibly been altered in composition by the metamorphism.

It is the presence of these relatively large, twinned albite crystals which is characteristic of the first subdivision of the spilites.

Amphibole

Fibrous amphibole is of late crystallization as it occurs cutting through other minerals. In composition it lies in the range tremolite - actinolite family, a typical metamorphic product in the greenschist facies resulting from the alteration of primary pyroxenes. In ordinary light the amphibole is pale green indicating that it must be towards the iron rich actinolite end of the series.

No evidence of the presence, or former presence of pyroxene can be seen, all the amphibole occurring as fibrous aggregates.

Epidote and Chlorite

Epidote and chlorite occur in about the same proportions and are found as apparently late stage infilling between the earlier feldspars.

Epidote occurs as discrete grains in close association with the chlorite, which occurs as almost isotropic patches which are pale green in ordinary light. Grains of epidote are also common within the larger feldspar crystals and anhedral grains.

Calcite

It is clear that the calcite present in the rock is not of primary crystallization and most probably not a direct result of the metamorphism, and is not important when placing the spilites into their subdivisions. It is however interesting to speculate as to its origin, and the most likely theory is that of carbonatization associated with the formation of the ore, and this is dealt with further under the heading of wall rock alteration.

In the example chosen, the calcite is present as individual grains and groups of grains. Also it can be seen intersecting the larger feldspar crystals, a clear indication of its later origin.

To summarise, the characteristic features of the first type of spilite are :

a. large feldspars and fibrous amphibole.

b. medium to light green, coarse grained.

Spilite Type (i)

a. 1st generation of albite

b. 2nd " " "

c. Epidote

d. Chlorite

e. Calcite

f. Fibrous amphibole

Fig. 7

Type (ii, (specimen 208)

The second type of spilite to be recognised in the Løkken area is characterised by the absence of large feldspars, such as are found in type (i), and the presence of much amphibole and chlorite. In hand specimen, the rock is usually dark green and fine grained. Vesicles are common, although not characteristic of type (ii), and not restricted to this type.

Specimen 208 was chosen to represent this group because although possessing the characteristic features required to be placed in group two, it also has several other interesting features. Specimen 208 is from a surface exposure to the east of the mine shaft and is a fairly dark green fine grained vesicular lava flow which can be traced several hundred metres along the stiike.

The amygdaloidal texture is well developed, the individual vesicules being about 0.5 to 1 millimetres in diameter, and filled with what appears, from hand specimen, to be calcite and a dark mineral, probably chlorite.

Thin section study reveals the mineralogical composition to be amphibole, feldspar, chlorite and epidote with calcite, chlorite and epidote present in the amygdales. The texture is fine grained and marked by the lack of any well formed crystals, and the abundance of the fibrous amphibole. Also striking is the very well defined zoning of the minerals filling the vesicules.

The approximate percentage mineral composition of the rock is as follows.

Amphibole	41%
Feldspar	30%
Epidote	16%
Chlorite	13%

The above figures do not include the minerals in the vesicules as it is most likely that these are of a later introduced formation.

Amphibole

In essence, the amphibole is the same as that present in the first spilite subdivision, but occurs in larger quantities. It is of a fibrous nature and is found covering the early and much altered feldspar. In composition it must lie towards the actinolite end of the tremolite - actinolite series, but is probably not as rich in iron as the amphibole found in type (i).

It is clearly of a much later formation than the feldspars as it is cutting through the groundmass of feldspar. There is no evidence as to whether it has altered from a primary pyroxene or was introduced by a redistribution of elements from other pyroxene rich rocks close by during the metamorphism.

This type of amphibole is common to all the three types of spilite found at Løkken but is found to a greater extent in type (ii).

Feldspar

The feldspar present in the second spilite subdivision differs markedly from the first subdivision in that well formed crystals are absent, all the feldspar being highly altered and intergrown with amphibole, chlorite and epidote. Relicts of large twinned crystals can be seen, but are also altered and their boundaries merge into the groundmass of small feldspars and chlorite with a few epidote grains. The majority of the 30% of feldspar is found as interstitial, anhedral grains which are only rarely twinned, and usually enclose small fragments of the other minerals.

The composition of both the larger relict feldspars and the feldspar in the groundmass is highly sodic, falling into the albite range.

It seems evident that the present day feldspars have altered from a more calcic plagioclase to albite, releasing calcium which was used to form epidote and calcite, and leaving the outline of the old feldspar still visible through the network of amphibole.

Epidote and Chlorite

Epidote occurs as small subhedral grains in the groundmass of albite and chlorite and tends to be concentrated in and around the larger patches of albite.

Chlorite is found in abundance in the groundmass, both as fibrous aggregates and also as small patches. Once again the chlorite is very nearly isotropic, but has a very deep purple birefringence, and is pale green in ordinary light.

Zonal distribution within the amygdales

It is a well known feature of amygdaloidal lavas that the vesicle-infilling minerals are often zoned. In the case of specimen 208 the infilling sequence is chlorite-epidote-calcite from walls to centre.

Chlorite most frequently rims the walls of the vesicle with large epidote crystals in, and projecting through this rim of chlorite. The centre portion of the vesicle is nearly always filled with calcite.

It is thought that amygdale minerals aré precipitated from circulating groundwater, during or after the period of volcanic activity. It is possible that, in the case of the Løkken area, the metamorphism and associated remobilization of elements may have resulted in the infilling of the amygdales by the minerals which are most stable under greenschist metamorphism.

To summarise, the characteristic features of the second type of spilite are :

a. Lack of large feldspars, much amphibole and chlorite

b. Dark green, medium to fine grainsize.

Spilite Type (ii)

a. Chlorite.

b. Epidote.

c. Calcite.

d. Relicts of large albite crystals.

e. Amphibole.

f. Groundmass of albite and chlorite.

Fig. 8

Type (iii), (Specimen 79)

The third type of spilite differs from the previous two types in that there are no large feldspars, which are characteristic of type one, and there is much more epidote present in type three than in either of the other types.

In hand specimen, members of the third subdivision are usually pale green with a variable grain size and commonly occur as pillow lavas with well developed pillows. (see Plates 7 and 8). Although frequently found as pillows, not all pillow lavas are of type three, and type three does not always form pillows.

Specimen 79, chosen to represent type three, is from a surface outcrop, not far from the locality of specimen 208, and rests conformably on a thick horizon of vasskis. (see Plate 24). Pillows are well developed and can be seen in the photograph. The total thickness of the flow is only one metre and hence the specimen is fine grained; the grain size varies considerably throughout type three, although the finer grained varieties are the most common.

Specimen 79 is fine grained and medium to light green with some tiny scattered flakes of a mineral with an almost metallic lustre. Small patches are very pale yellowish green indicating the presence of epidote. The specimen from the pillow lava shown in Plate 8, contains a lot of epidote, much of it concentrated in vesicles, which are aligned parallel to the edge of the pillows. The light centre of the pillows is also due to a high concentration of epidote, and this can also be seen in Plate 8.

In thin section, the rock is found to be very fine grained indeed, so much so that the minerals forming the groundmass, in which small epidote crystals are found, can only just be identified, but cannot be point counted so that only the percentage of epidote to groundmass can be calculated :

Epidote	54%
Groundmass	46%

The epidote occurs as very small, often less than 0.025 millimetres, anhedral to subhedral grains, both as isolated and intergrown grains. The concentration of the epidote grains varies from one part of the slide to another, in places occupying up to 80 or 90% of the area of the slide, but in general the ratio remains about one to one.

The groundmass is very dark, due to the very fine grained nature of the individual minerals present in the groundmass, which are mainly feldspar (probably albite), amphibole and chlorite.

Small cross-cutting veins of quartz are also present, and it is interesting to note that extinction is quite normal and not undulose which would suggest that the quartz is of a late stage origin, after the periods of deformation.

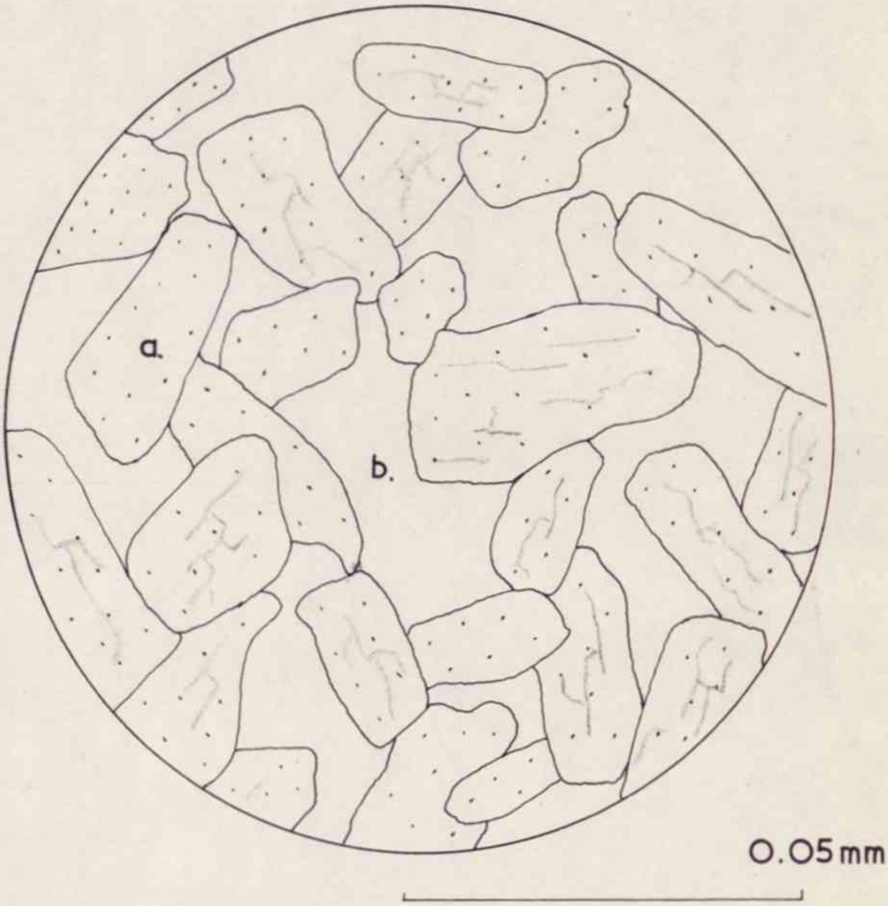
It is quite clear that the present mineralogy is entirely of a secondary nature and a result of the metamorphic processes which have affected the whole of the Løkken area.

To summarise, the characteristic features of the third type of spilite are :

a. Lack of large feldspar and the presence of much epidote.

b. Colour light green to grey, grain size variable although usually fairly fine.

Spilite Type (iii)



a. Very small subhedral epidote.

b. Fine grained groundmass composed of secondary albite, amphibole and chlorite.

Plate 7. Exceptional exposure of well formed pillows.

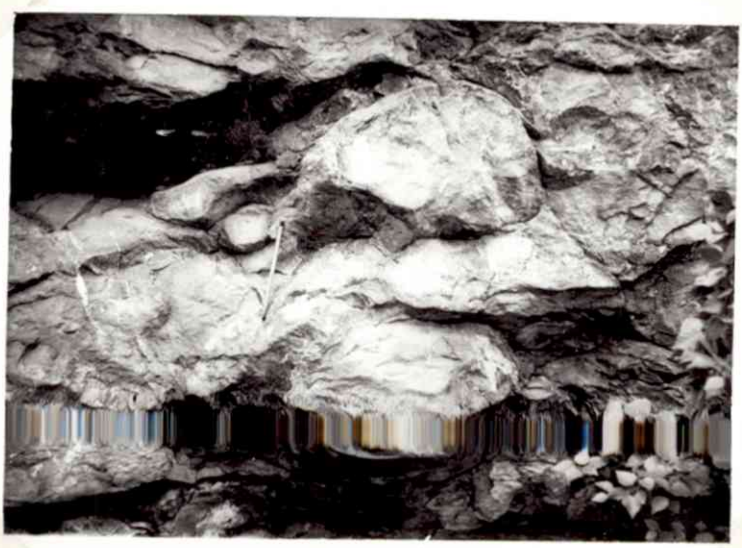


Plate 8. Close view of Plate 7, showing well formed

pillows with a possible 'way-up' structure.

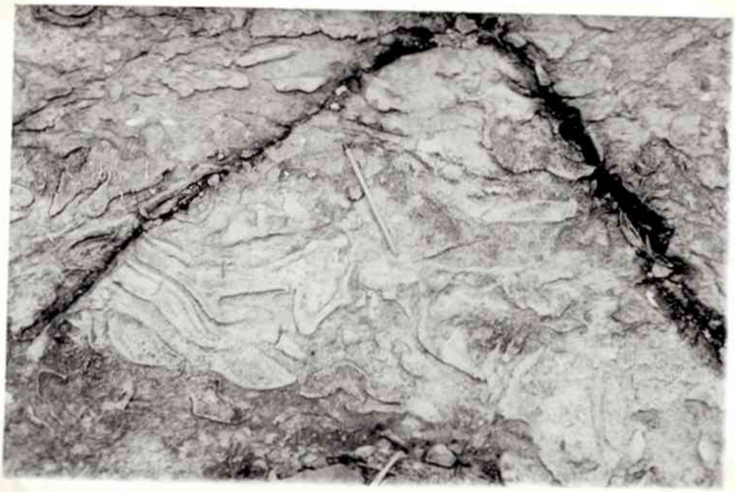


Plate 9. Broken pillow lava on the southern shore of Bjørnlivann.

Plate 10. Close-up view of infilling between pillows only a few feet from Plate 9.

KERATOPHYRES and QUARTZ KERATOPHYRES

The intermediate lavas, or keratophyres, have not been recognised at Løkken, either because they are absent, or more probably because they cannot easily be distinguished from the basic spilites.

Acid rocks (quartz keratophyres), however have been recognised for some time and are known locally as felsite, a general term indicating a quartz rich rock. In contrast to the basic volcanics, the felsites are hard, brittle and light to dark grey in colour, and are easily identified in the field. The felsites, as can be seen from the map, outcrop as lenses and thin horizons which have been faulted. The shape and position of the outcrops suggested to earlier workers that the felsites had been intruded as lenses of lava, which were not continuous. Detailed mapping how, however, indicates that although the felsites are undoubtedly intrusive, they are of a much more continuous nature than had been previously supposed. What before had been mapped as a series of discontinuous lenses is in fact a long, three to four metre thick sill of felsite which had a marked effect on the basic meta-volcanics close to it. Cleavage has developed, most markedly in the foot-wall rocks, and also to a lesser extent in the hanging wall. The sill has been displaced by several faults, the western-most of which has played an important part in bounding the gabbro mass to the south. It is probably this faulting which misled earlier workers into thinking that there were a number of isolated masses of felsite.

The sill dips to the north at about 20°, and is slightly folded, resulting in the small outcrops of felsite being present in, and just to the south of Bjørnli. The southernmost of these outcrops is on a hill, 50 metres above the faulted outcrop of the sill, and is a result of the same sill just outcroping on the top of the hill due to folding.

The largest of the felsite outcrops occurs just to the north of Dalotjern, and is somewhat thicker than the other outcrops. It seems most likely that the thinner sill is an offshoot from this mass. Folding and the local topography have conspired to make the outcrop appear to be thicker than it really is, about twenty metres.

Although thicker than the other outcrops, the felsite is almost identical in hand specimen to the thinner sill, and apart from a minor variation in the iron oxide content, indicated by a limonite stain, the mass is of uniform composition throughout.

Once again, the intrusive nature of the mass is indicated by the development of columnar jointing in some parts of the mass, as illustrated by the photograph as over :

Plate II. Columnar jointing in quartz keratophyre near Dalotjern

The felsite from all the different outcrops is essentially the same. There is a small colour variation, from light grey to dark grey. The grain size is constant in all the outcrops and little knowledge of their composition can be gained from hand specimen due to the very fine grained texture.

In thin section, the rock is fine grained with a few porphyritic feldspar crystals, Quartz and feldspar make up the bulk of the rock with very small grains of epidote scattered through the matrix.

The feldspar has a low refractive index, which puts it in the range of An_{0-10}. Twinning is not common in the smaller crystals, although the larger, porphyritic feldspars are often twinned on the albite law. Patches of the feldspar have crystallized into a sperulitic texture, and such spherulites are common to all the felsite outcrops. The individual spherulites are very small, only one or two millimetres in diameter.

Quartz is abundant as small individual anhedral grains and clusters of intergrown grains. Veins of quartz with albite are also present in most sections. As far as can be seen, quartz does not form spherulites, although it is difficult to be sure that there is no quartz mixed in with the feldspar spherulites.

Iron oxide (possible oxidised from pyrite), epidote and stipnomelane are present in accessory amounts, the former frequently colouring the rock pale brown. Stipnomelane occurs as scattered, lath shaped crystals, indicating, with epidote, that the rock is pre-metamorphism is age. Stipnomelane also indicates that the grade of metamorphism was in the B.1.1. subfacies of the greenschist facies of regional metamorphism.

The presence of spherulites, and the absence of relict perlitic structures is a further point of evidence for the intrusive, rather than extrusive, origin of the felsites.

The above desciiption c orresponds to the more scientific terminology of quartz keratophyre, rather than the somewhat vague term of felsite, and is defined in 'Petrology of the Igneous Rocks' by Hatch, Wells and Wells, where it is stated that :

> "Quartz keratophyre has been used in several senses, but the practice in this country is to apply it to the sodic rhyolites which are characterized by the presence of albite or albite rich feldspar, associated with little coloured silicates, the original nature of which has become obscure through alteration. Quartz keratophyre is a type of soda-rhyolite and a member of the spilite suite."

Clearly the above definition corresponds closely to the rocks which at Løkken are known as felsite.

Quartz Keratophyre

a. Quartz

b. Feldspar

c. Spherulitic feldspar

d. Porphyritic "

e. Epidote

f. Stipnomelane

g. Groundmass of quartz, albite and epidote

Fig. 10

METAGABBRO

At Løkken there are several gabbro masses. In hand specimen, the gabbro appears to be fresh and unaltered with the felsic to ferromagnesian ratio of about 1 : 1. The grain size varies from 5mm. to pegmatitic, with crystals up to 4cm.

The exact outcrop of the gabbro masses is difficult to ascertain, due to the nature of the vegetation and lack of outcrop. Contacts between the meta-volcanics and gabbro have been observed in only a few places, and in general, the contacts have been inferred. It is, however, evident that faulting and thrusting has played an important part in defining the extent of these masses, and the mass on the west side of Bjørnlivann is most probably a thrust slice off the larger mass to the west. Whether or not the mass to the north east of the lake is the thrusted, displaced continuation of the masses to the west, is open to question.

It is most probable that the gabbros have been extensively faulted because, although no faults have been detected on the surface, many small faults and shear planes, often intruded by dykes, can be seen in the mine.

To the west of the Orkla River, it has been suggested that the gabbro is differentiated and layered, with some granophyre developed. There is, however, no suggestion of differentiation or layering in any of the masses near the mine, but the similarity of all three masses, in hand specimen and thin section, indicates that they might have a common parentage.

The similarity of the geochemistry of the gabbro masses, and the strontium content of the feldspars in particular, also tends to indicate the same parent magma of the masses examined.

The mode of displacement of the gabbros is somewhat doubtful because there is no local distortion or thermal metamorphism of the country rocks close to the contact. The lack of these phenomenon may be explained by assuming that the gabbro was intruded into a pile of semi-molten, highly viscous, basic lavas which were able to accommodate the stress by easy movement. If the lavas were still at a considerably high temperature, when the gabbro was intruded, it is doubtful whether a thermal aureole would have been produced and survived the superimposed regional metamorphism.

In hand specimen, the rocks which have been mapped as gabbro, appear to be fresh, coarse grained and composed of large plagioclase and ferromagnesian minerals. The grain size varies considerably, from 0.5cm. to 4cm., the change in grain size taking place over the space of a few centimetres. This is especially well developed in the thrust slice mass to the west of Bjørnlivann. It must be noted that the pegmatitic patches appear to be scattered randomly, and are not restricted to later crystallization features such as dykes.

In thin section, however, what at first might appear to be large feldspar crystals in hand specimen, are in fact an aggregate of fine grained secondary feldspar and other alteration products which are pseudomorphing the original plagioclase. The large ferromagnesian mineral is a pyroxene which is also being replaced, this time by a colourless amphibole.

Plagioclase

Much of the original plagioclase has been altered leaving pseudomorphs of the lath shaped crystals. The altered plagioclase makes up 50 - 60% of the rock, the rest being pyroxene with a little iron oxide; no olivine, or olivine pseudomorphs have been recognised in the thin sections examined. On close examination of the fine grained aggregate, which has replaced the original feldspar, grains of chlorite (penninite), epidote and zoisite can be seen in a network of secondary albite. (Refractive index less than Canada balsam). Where little of the original structure of the plagioclase can be recognised, the alteration products are uniformly distributed in place of the plagioclase, but in places the epidote appears to be concentrated in veins and around the former crystal boundaries.

Even although alteration is complete, pseudomorph twinning is still clearly recognisable. The degree of destruction of the plagioclase varies from section to section, and indeed from one part of the slide to another. In some cases, good euhedral, lath shaped crystals with albite twinning can be seen, with the only evidence of replacement being the patches of epidote and chlorite found within the crystals.

Evidence of the primary nature of the original crystals of plagioclase can be seen where the crystal laths have been bent and distorted during emplacement.

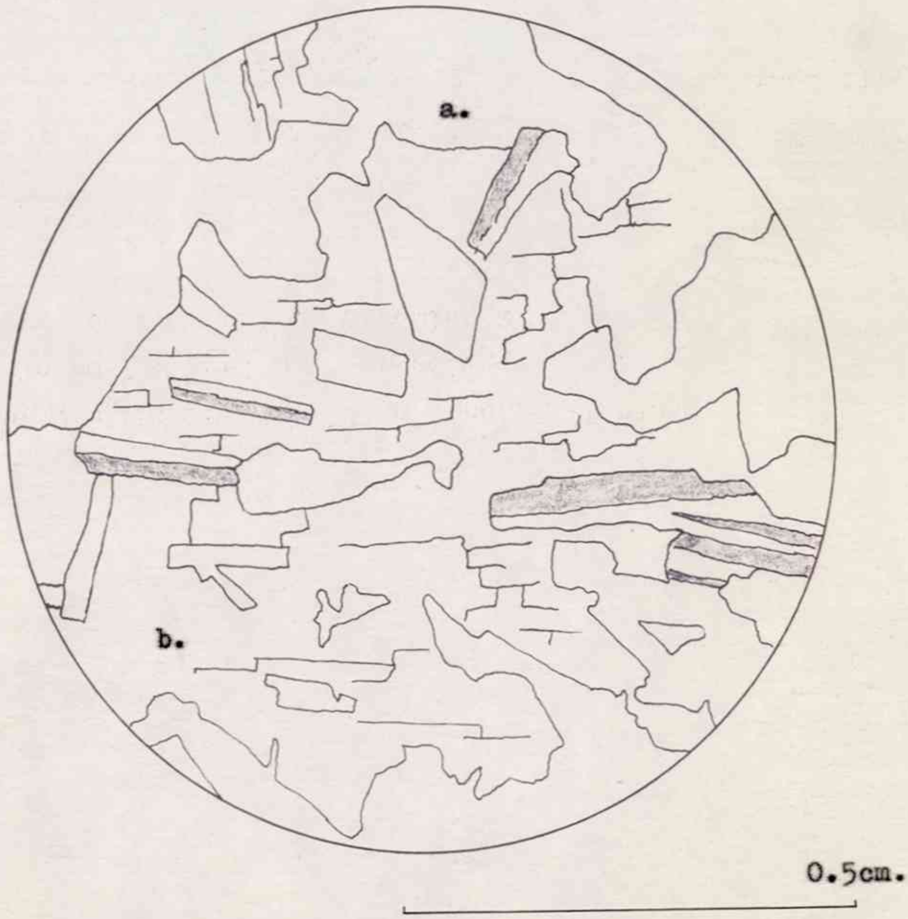
Plate 12. Distorted feldspar and pyroxene in metagabbro

<u>Ferromagnesian minerals</u>

The primary ferromagnesian in normal gabbroic rocks is clino-pyroxene, often with some ortho-pyroxene. The pyroxene in the Løkken gabbros is augite, or possibly titan-augite as it is slightly pleochroic, and it encloses the plagioclase pseudomorphs in an ophitic relationship. The augite is altering to a colourless amphibole with strong birefringence and is probably cummingtonite, a common alteration product of clino-pyroxene under incipient metamorphism.

No ortho-pyroxene was seen in any of the sections.

The alteration of the plagioclase and pyroxene is a clear indication that the gabbro masses were intruded and solidified either before the period of metamorphism had ended or started, and hence the gabbro has been metamorphosed in the greenschist facies and is therefore more properly termed metagabbro.



a. Altered plagioclase - chlorite, epidote and albite. Pseudomorph twinning can still be seen.

b. Augite altering along the cleavage to amphibole.

Fig. 11

JASPER

Jasper occurs throughout the area as as irregular patches in the basic volcanics. Commonly the jaspers are found in lenses up to several metres in size. Their colour varies from deep purplish red to pale pink and occasionally bluish white and are completely massive fine grained quartz with iron oxide stain.

The occurrence of jasper is typical of submarine volcanic activity, and is thought to have resulted from radiolarian cherts. However, no evidence of radiolarians have been found in the jaspers at Løkken. In thin section they are composed of an aggregate of quartz with a highly developed undulose extinction, indicating the effect of the strain during the deformation of the area.

Jasper is also closely associated with the impregnation type of ore found close to the massive pyrite orebodies, but it is questionable whether or not this occurrence of jasper has the same origin as that which is found in the metavolcanics. Most probably, the jaspers found in the impregnation ore have resulted from the deposition of iron rich quartz associated with the formation of the orebodies. Evidence for the abundance of quartz can be seen from the many quartz bands in the impregnation ore. (see Plate 16).

Part IV

MINERALIZATION

MINERALIZATION

Two types of mineralization at Løkken have been recognised: epigenetic ("gangkis") massive pyrite ore, and syngenetic ("vasskis") thin horizons of banded pyrite.

The orebodies at Løkken are situated as concordent bodies in basic metavolcanics containing horizons of sedimentary pyrite or vasskis. The metavolcanics dip north and form the limb of a syncline, the axis of which pitches to the west-northwest at about 15°. A culmination occurs just to the east of Løkken, so that in the eastern part of the field the plunge is gentle to the east.

The orebodies are situated just below a thrust plane which dips at about 20° to the west-northwest. The thrust was originally discovered in the mine as a clay gouge several centimetres thick. In the eastern parts of the mine the orebodies are situated some distance below the thrust plane, while in the western parts the ore "tails" ahd becomes quite thin and is, in places, in contact with the thrust (see Plate 15). It seems clear that the relationship and position of the ore and thrust are closely related to each other, and this problem is dealt with later with the problem of origin.

The orebodies are characteristically in the form of elongated lenses or are cigar shaped, the longest axis of which is always parallel to the lineation and fold axis direction of the enclosing rock. At Løkken all three orebodies; the Hovedgruben (main), Indien (India) and Bakindien (Back India), have been worked and strike east-west and dip to the north. The plunge of their long axis is around 9° to the west-northwest. The wall-rocks dip generally about 45° to the north.

Hovedgruben is the largest of the orebodies and the Indian and Bakindien lie in its hanging wall and are much shorter and not as thick. The size relation is about 30 : 3 : 1 respectively.

In the east, towards the original outcrop, the three ore-bodies lie practically parallel to each other, but they converge west-wards. Hovedgruben had, until the newly discovered extention was found, a known length along its plunge of about 2,500 metres. Indien and Bakindien gradually approach each other towards the west and have almost converged at the point where Bakindien peters out at about 1,150 metres from the outcrop (now covered by mine dumps). Still further westwards, Indien and Hovedgruben come closer together before Indien disappears some 1,700 metres from outcrop.

The Løkken ore has a fine to very fine grained texture, with a grain size of between 0.5 and 0.005 mm. The mineralogical composition is very simple: pyrite forms 70-75% of the ore, while there is about 6% chalcopyrite and 2.5% sphalerite with occasional magnetite. Gangue minerals are 12-14% quartz, with small quantities of calcite and chlorite. The fine grained texture and abundant quartz makes the ore exceptionally hard. The mineralogical composition of the ore varies slightly in the three orebodies and also within the Hovedgruben itself. No regularity has been observed in these variations but it is most usual to find the parts which are richest in copper and sulphur nearest the centre of the orebody as seen in vertical transverse section. Towards the foot wall the ore is often especially hard and holds more quartz and less copper and sulphur than normally. The same is also the case with the upper and lower edges of the ore lens. Towards the hanging wall, the main orebody has, as a rule, lower copper and quartz contents than usual. In crushed parts near the faults, the copper content is at times especially low on account of leaching, whilst there is usually a copper rich ore in the vicinity. In one or two limited areas near the foot wall of the orebody, exceptionally rich copper ore, carrying bornite as well as chalcopyrite, has been found.

Magnetite occurs on the hanging wall or Hovedgruben, east and west of Wallenberg shaft. The magnetite-bearing zones are impregnated with pyrite (see cross-sections of orebodies).

In the eastern part of the deposit, in the hanging wall of the main ore, there is a body of breccia ore which has a strike length of over 200 metres and a thickness of up to 100 metres. This breccia ore consists largely of fractured country rock which is cemented together with veins of cupreferous pyrite. Further west there occurs a zone of pyrite impregnation in the hanging wall of the orebody. The orebody's foot wall contact is in general sharp, which is also the case as regards the hanging wall of the compact ore.

There normally occurs a bed of the sedimentary pyrite (vasskis) along the foot wall of the main ore, and in places along its hanging wall. Other beds of sedimentary pyrite lie in the metavolcanics, some distance below the foot wall of the ore. Normally only the epigenetic type of ore is mined with 42% sulphur, 2.3% copper, and 1.8% zinc. (see Appendix I).

The second type of sulphide deposits in the Løkken area is vasskis, and is thought to be of syngenetic origin, being formed contemporaneously with the metavolcanics. (In 1922, Carstens assigned an exhalative - biochemical origin to this type of deposit, which he named Leksdal type, from a locality east of Trondheim).

The sulphide layers contain mainly pyrite, with pyrrhotite, iron oxides and quartz. Their sulphur content is most often between 20 and 40%, and only occasionally rising over 40-45%. The copper and zinc content of the vassiks is lower than the massive ore and is sometimes absent. It is significant that the trace element content of the vasskis is markedly different from that of the massive ore (see Appendix I).

The texture is extremely fine grained, much more so than in the epigenetic ore. The sulphide occurs in layers varying in thickness from a few centimetres to about 1 metre, and are interbedded with thicknesses of jasper and magnetite chlorite rock. The sulphide bearing layers normally have very considerable areal extent and can be traced geophysically for several kilometres.

Vertical, longitudinal and transverse sections through the Lökken ore-bodies.

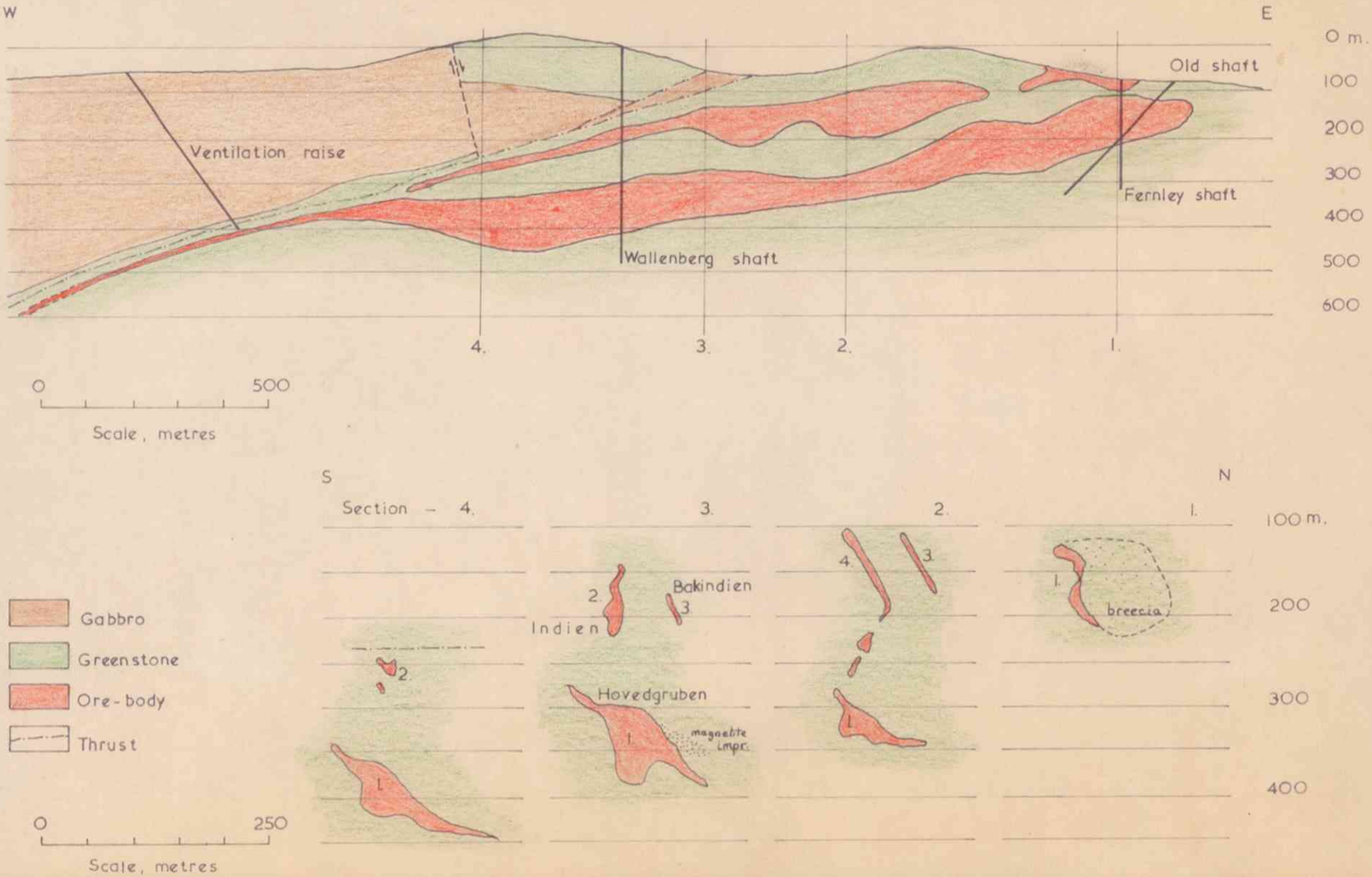


Plate 13. Hanging-wall contact between massive pyrite ore and greenstone. Level 430m.

Plate 14. Foot-wall contact of massive ore, vasskis and greenstone with jasper and quartz. Level 930m.

Plate 15. Intersection of ore and thrust plane with bands of vasskis and greenstone. Level 430m.

Plate 16. Impregnation ore: bands of pyrite, greenstone and quartz. Level 930m.

<u>The newly discovered extension to the main or Hovedgruben orebody</u>

From the vertical longitudinal section of the orebodies at Løkken it can be seen that all three narrow towards the west and the Indien and Bakindien die out completely. The Hovedgruben orebody continues but slowly thins as it comes closer towards the thrust plane until it is only a few metres thick at a depth of 480 metres below the surface. It was thought that the Hovedgruben too would soon die out but an exploratory drive was made into barren gabbro and many holes drilled to intersect any possible extension. Fortunately the ore was found to thicken and ore reserves were sufficiently increased to enable the sinking of an underground shaft and preparations made for mining operations to begin early in 1968.

It was at this early stage in preparation for mining that the author was invited to map the underground geology encountered and geological plans of levels 430, 463, 481, 720 and 930 metres are enclosed. The extention of the ore had in the summer of 1966 only been exposed on level 930 and in a raise on level 720, but extensive drilling has proved that the orebody is a continuation of the Hovedgruben orebody as shown on the geological plan of level 481.

The ore on level 930 is fine grained massive sulphide with a body of impregnation ore above its hanging wall. Several vasskis horizons below, and in contact with the foot wall of the ore were encountered, and provided a useful indication to the attitude of the orebody. The structure of the new orebody is still uncertain but is probably a flat, lenticular deposit, which, on evidence from boreholes, pinches and swells and may be faulted in places. (Unfortunately detailed core logs were not available to the wuthor as this information is still considered confidential by the mining company).

The descriptions of massive pyrite ore and vasskis from different parts of the mine and from the surface are given below to illustrate the nature of these rocks and their general conformity over wide areas.

(1) MASSIVE PYRITE ORE

The massive pyrite ore present at the western end of the Hovedgruben orebody can be subdivided into four main types.

a. relatively coarse grained massive pyrite with euhedral cubic crystals of 0.5-1mm. visible.

b. medium grained massive pyrite, no visible crystal grains.

c. fine grained; very fine with a marked angular fracture habit.

d. Impregnation ore; band of quartz, greenstone, and coarse pyrite grains (see Plate 16).

This subdivision is purely abritrary, and apart from the impregnation ore there does not appear to be any relationship to each other. The impregnation ore is only present on the hanging wall side of the massive pyrite ore. Even in the coarsest pyrite ore, the grain size is still fine. The chalcopyrite content varies with the grain size to some extent, as does the sphalerite, although to a lesser degree than the chalcopyrite. The gangue content, and hence the pyrite content, is greatly dependent upon grain size: the finest grained pyrite ore contains up to 85% pyrite and 10% gangue, whilst the coarser varieties, with only 50 - 60% pyrite, contain much more gangue, up to 30%, the remainder being chalcopyrite and sphalerite.

Point counting indicates the association of grain size with pyrite content.

	Fine	Medium	Coarse	
	0.005mm.	0.05mm.	0.1mm.	0.25mm.
Sample No.	139	125	191	187
Pyrite	82%	61%	60%	46%
Chalcopyrite	3.5%	23%	6.5%	25%
Sphalerite	3.5%	1%	-	1%
Gangue	11%	15%	33.5%	28%

Although it is clear that there is a wide variation in the chalcopyrite content, it is also evident that the finer the grain size, the smaller is the gangue content. Measurement of grain size in the finer grained specimens can only be satisfactorily done after first etching with chromic acid for a few seconds.

a) Fine grained variety - specimen 139

Specimen 139 is from level 463m., and is very fine grained in hand specimen. Fresh surfaces are a pale yellowish silver colour, with a very distinct angular fracture habit resulting from the compact massive nature of the rock. In hand specimen, only pyrite can be identified, and there is little indication of the presence of gangue. Chalcopyrite and sphalerite cannot be detected, even with the aid of a hand lens.

On a flat surface, the massive fine grained pyrite can be seen to be fractured by very thin dark lines suggesting a concentration of gangue in these areas.

On examination of a polished section of the ore, little further information can be obtained without first etching the surface of the section. The pyrite is so fine grained and intergrown that individual grains cannot be distinguished and only small patches of chalcopyrite and sphalerite and larger patches of gangue can be recognised. The majority of the 7% chalcopyrite and sphalerite occurs in a fracture zone traversing the section. The fracture zone is only a millimetre across but is quite extensive, passing from one side of the section to the other, a distance of two centimetres. Although only one mineralized fracture was seen in this section it would appear that it is this later infilling of fractures that is responsible for the copper and zinc content of the fine grained ore. Such fractures were not seen in any of the other coarser grained sections and this would tend to suggest that their development is only local. (Plate 18).

The chalcopyrite is also found away from the fracture zone and occurs as tiny aggregates of crystals infilling the gaps left between the pyrite crystals. Because of the very small size of these patches, it is not clear if there has been any replacement of the pyrite by the chalcopyrite, although the size of the patches makes this a somewhat unimportant feature. Larger patches of chalcopyrite are present in the fracture zone and from these it is possible to say that very little, if any, replacement of the pyrite has occurred.

The sphalerite is almost confined to the fracture zone, except for a few small patches in the pyrite. Such is the quantity of the sphalerite in the fracture zone that it is clear that it must have been introduced, with some of the chalcopyrite, along the fracture after the formation of the pyrite. The sphalerite has considerably attacked and replaced the pyrite and small corroded pyrite crystals are present in the larger patches of sphalerite.

In some areas, chalcopyrite has been exsolved from the sphalerite producing an emulsion texture. It seems unlikely that this phenomenon can be used to indicate, with any certainty, the temperature of formation, as recent work on exsolution textures has shown that pressure plays such an important part in the formation of such textures that unless the pressure at the time of formation can be established, the temperature of formation of exsolution bodies cannot be determined. It is interesting to note however that the exsolution bodies do not occur close to existing chalcopyrite masses, suggesting that a degree of un-mixing has already taken place.

The pyrite is, for the most part, very fine grained, with crystals less than 0.005mm. common. Larger crystals do occur and may measure up to 0.25mm., although these are not common and can only be detected after etching. Etching also reveals that the larger pyrite crystals are chemically zoned, the zones being parallel to some of the present crystal faces. Many of the smaller crystals are also zoned and a most interesting feature is the way the zones are often terminated by irregular grain boundaries, indicating that the very fine nature of this part of the ore is a result of deformation, in which the larger pyrite crystals have been broken into fragments. Further evidence of such deformation is the presence of matching walls of two or more fragments of a single crystal. This is also compatible with the formation of small fracture zones and the introduction of the more mobile elements into these zones of weakness.

The main gangue minerals are quartz and calcite.

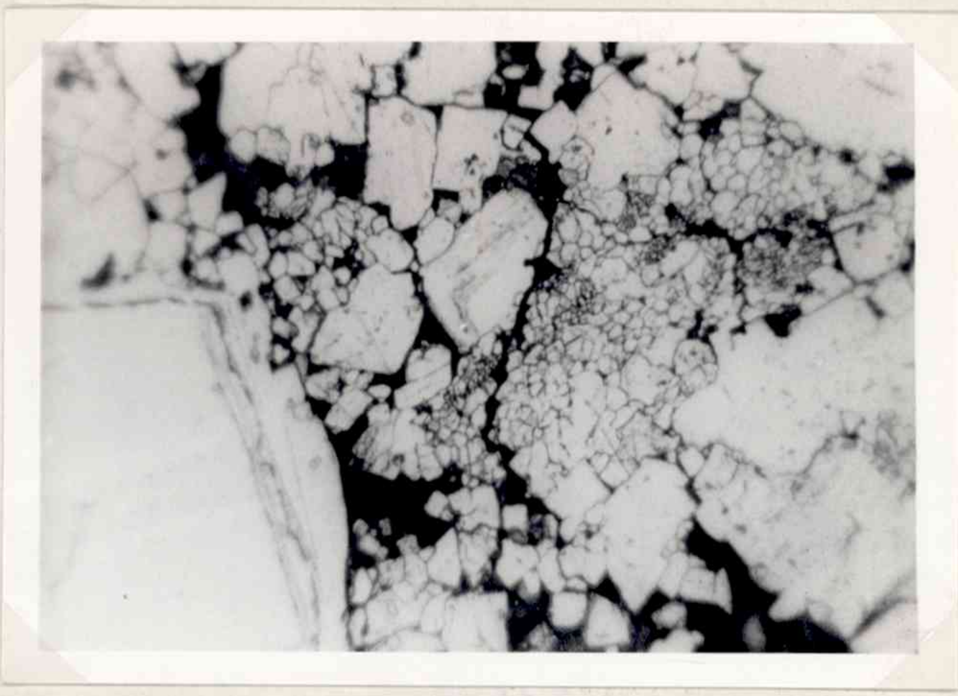


Plate 17. Zoned pyrite after etching. Note the very fine grained pyrite and the zones terminated by fracture boundaries. Specimen 139, level 463m. x 420.

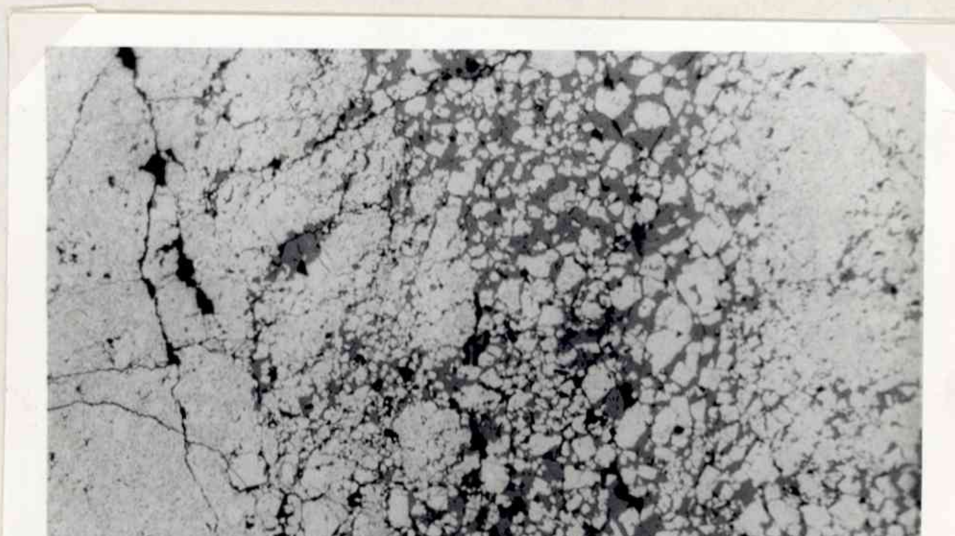


Plate 18. Fracture zone in fine grained ore filled with sphalerite and some gangue. Specimen 139, level 463m. x 70.

b) Medium grained variety - specimen 125

Specimen 125 is from the new orebody exposed in level 930, and is a very uniform fine grained (0.05mm.) massive sulphide. Its pyrite content is lower than the very fine grained ore, 61%, but the chalcopyrite content is abnormally high at 23%, and this is reflected in the colour which is a yellowish gold, even though chalcopyrite cannot be distinguished from the pyrite in hand specimen using a hand lens. The angular fracture that developed in the very fine grained ore is lacking and although the fracture is hacky, the faces of the fractures are not as smooth as specimen 139.

Polished section examination of the medium grained variety of ore reveals that its texture is completely different from that of the fine grained ore. The pyrite crystals are much larger, and unlike specimen 139, are not so intergrown as to make their boundaries difficult to distinguish and resulting in the presence of many well formed euhedral crystals. The large quantity of chalcopyrite is also significant as it would seem that because the pyrite crystals are larger, there is a larger void between them capable of being filled by chalcopyrite and gangue. The chalcopyrite has attached and destroyed many of the original boundaries of the pyrite crystals, producing some excelent replacement textures which are illustrated in Plate 20.

There is very little sphalerite present and the reason for this is obscure. A possible explanation for the defficiency in the coarser grained specimens is that much of the sphalerite is of later formation and, not being capable of replacing any of the minerals already present, it was forced to migrate into the late stage fracture zones.

The individual pyrite crystals range in size from small crystals, (rather than grains) about 0.005mm., to large 0.1mm. crystals, but the majority are about 0.05mm. Most of the crystals are subhedral, but good euhedral crystals are also common. Many of the larger crystals are fractured and have been attacked along these planes of weakness by the chalcopyrite, and occasionally sphalerite, resulting in small veins of chalcopyrite and sphalerite traversing the grains.

Etching reveals that the pyrite crystals are strongly zoned, and it is interesting to note that, unlike specimen 139, most of the crystals appear to be whole and not broken fragments of larger crystals. Plate 19 shows some typical well developed zonal structures in the pyrite.

23% chalcopyrite is far above average for the orebody as a whole, but it is known that local enrichment in copper due to leaching from a neighbouring area does occur although it has not yet been established exactly why there should be this variation. The chalcopyrite forms anhedral grains about 0.01mm. in size, and this grain size of the chalcopyrite stays fairly constant in all the different grain size types. As previously mentioned, the chalcopyrite has attacked the pyrite producing atoll structures and discontinuous replacement veins. Clear evidence for replacement is indicated by the textures shown in Plate 20.

Very little sphalerite is present and is clearly associated with patches of chalcopyrite, although tending to attach itself to the pyrite crystals. Evidence that the sphalerite is also, to a limited extent, replacing the pyrite is shown by veining of the pyrite. Whilst there is no evidence that the sphalerite has attacked the chalcopyrite, or has been attacked by it, it seems most probable that the chalcopyrite and sphalerite were formed at, or nearly at the same time, and both after the formation of the pyrite.

No exsolution textures were found in the sphalerite in this section, probably because the grains are small and un-mixing has proceded to completion.

The gangue is composed mainly of quartz and calcite, and a certain amount of leaching has enabled the gangue to penetrate cracks and grain boundaries, although it would appear that the ammount of leaching is small. It is however, clear that fracturing is not very important as the veins of gangue do not pass right through the pyrite crystals indicating leaching and not fractureing as a fracture would bisect the crystal.

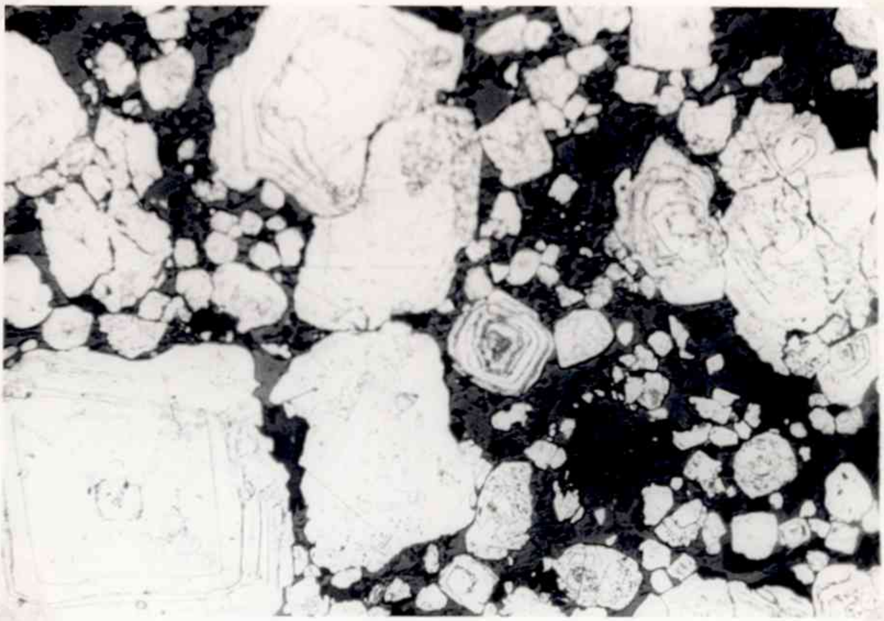


Plate 19. Well developed zonal structures in pyrite. (after etching) Specimen 125, level 930m. x 150.

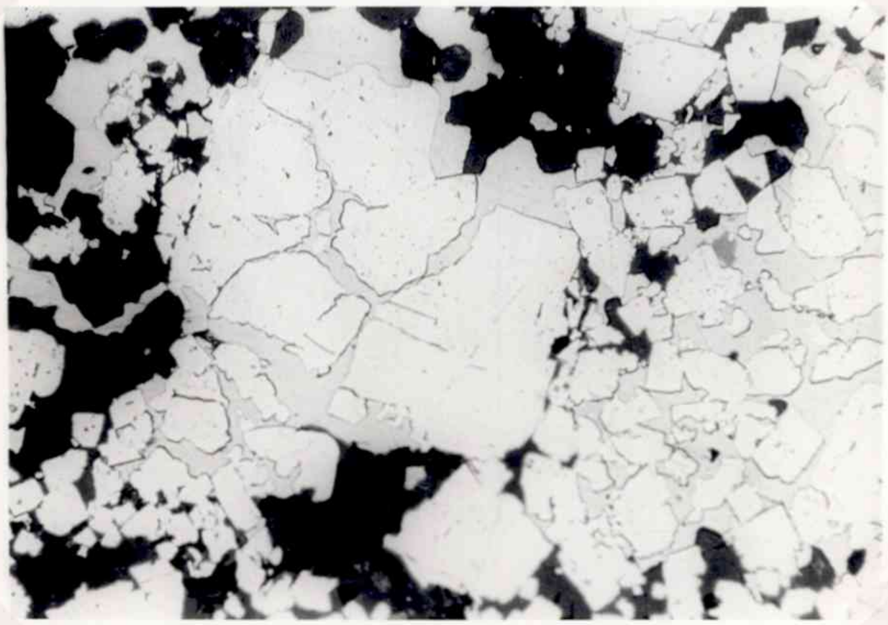


Plate 20. Replacement of pyrite by chalcopyrite. Specimen 125, level 930m. x 150.

c) Coarse grained variety - Specimen ~~167~~ 187

Specimen 187 is the coarsest type of ore and in hand specimen individual crystal grains can be identified with the naked eye. Thetexture is still very uniform except for some large patches of white quartz, but these are not typical of the coarse grained ore as a whole. The colour is again yellowish gold, reflecting the high proportion of chalcopyrite present; 25%. Apart from the quartz, there is little sign of the 28% gangue other than a suggestion of a dark rim to the larger pyrite crystals.

The coarse type of ore is found in abundance in the new ore-body exposed in level 930m., and it is from the new ore that specimen 187 was collected.

In contrast to the finer grained specimens already described, specimen 187, on examination in polished section, is coarse grained with much less pyrite and more chalcopyrite and gangue. The sphalerite content remains low at about 1%. It is immediately obvious that the pyrite has been replaced by both chalcopyrite and gangue, whilst many of the larger pyrite crystals have been split into smaller fragments by replacement veins of chalcopyrite and gangue. It is for this reason that euhedral and subhedral crystals are not common, the original boundaries of most of the crystals having been destroyed by replacement.

The grain size of the pyrite is quite variable, but averages about 0.25mm., although larger crystals of up to one millimetre are also plentiful. Smaller fragments result from the splitting up of larger crystals. In general the leaching and replacement by gangue has not proceded as quickly as the replacement by chalcopyrite and this has led to the gangue protecting the pyrite from the chalcopyrite, and some interesting textural relationships have developed.

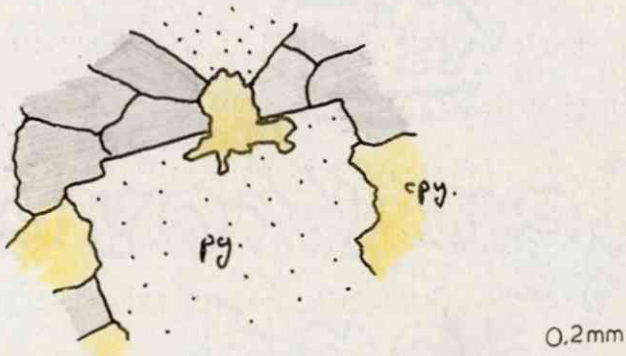


Fig.13

Etching proves undoubtedly that replacement of pyrite by chalcopyrite has resulted in the splitting up of large crystals into smaller anhedral grains.

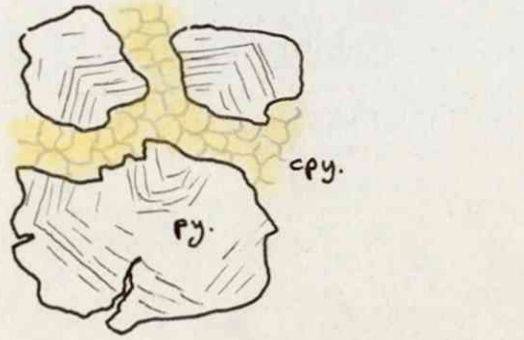


Fig.14.

Essentially the chalcopyrite is similar to that which is found in specimen 125, as also is the sphalerite, and there is little need to dwell further on their particular features. The gangue is also the same, quartz and calcite, although there is much more present; 28%; this no doubt being due to the increase in the size of the pyrite crystals and the voids between them. It is perhaps worth mentioning that gangue filled fractures pass through all the minerals present, without displacing them, and are therefore post mineralization in age and probably result from the deformation suffered during the metamorphism and folding.

Polished section LN-2

Polished section LN-2 was not collected by the author and unfortunately there is no record of its locality, other than it was collected "west of the shaft". Nevertheless, it is of interest and worth mentioning as it contains pyrrhotite, which was not seen in any of the other sections examined.

It is a very fine grained specimen, finer than 139, and contains pyrite, pyrrhotite, chalcopyrite, sphalerite and gangue. Pyrite and sphalerite are present in greater quantities than in the other sections, whilst the gangue content is lower, and is again mainly quartz and calcite.

The pyrrhotite occurs surrounding and veining the pyrite crystals. (see Plate 21) and does not appear to be replacing the pyrite, but is rather infilling interstices between the pyrite crystals. It is difficult to suggest an explanation for the presence of the pyrrhotite without knowing more about its location in relation to the shape of the orebody, but it seems possible that during the formation of the orebody, the sulphur deficient parts crystallized as pyrrhotite, rather than pyrite, after as much pyrite had crystallized as the sulphut content would allow.

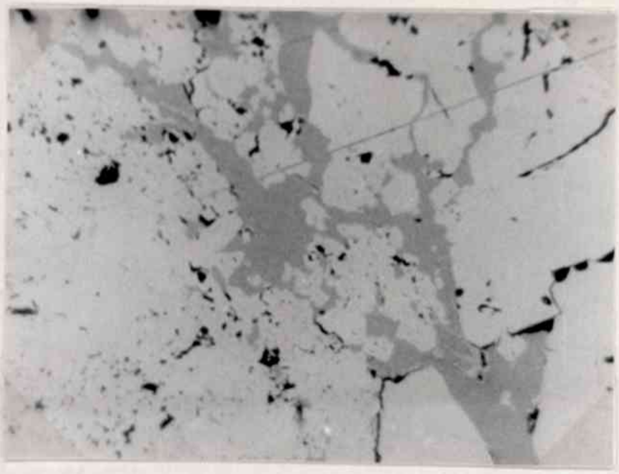


Plate 21. Pyrrhotite surrounding and veining fine grained pyrite.
Section LN-2. x 300.

WALL ROCK ALTERATION

Examination of hand specimen and thin sections shows that the rocks close to the ore are exceptionally rich in calcite. Not only does the calcite vein the rocks but thin sections reveal that calcite is intimately mixed with the rock forming minerals of both the hanging and footwall rocks, of the ore. Such is the quantity of the calcite that it cannot be disputed that the process of carbonatization has taken place, notably pre-dating the ore, as little calcite is found actually in the ore itself.

The effect of carbonatization, combined with the metamorphism, on what must originally have been a normal volcanic flow, is illustrated by the following description of a rock sample, and thin section, collected from just below the massive ore.

Specimen 194 is from level 930 metres, close to the base of a vasskis horizon, which is in contact with the foot-wall of the newly discovered extension to the orebody.. It is one of the coarser grained, grey-green spilites, with several small veins and pockets of calcite visible. No pillow structures were seen, and the texture is compact and massive.

On examination of a thin section, the rock is found to be composed of feldspar, calcite and chlorite with accessory epidote. The most characteristic features of this rock are the well formed feldspar crystals, which put it in the spilite subdivision (i), and the large amount of calcite. A modal analysis, obtained by point counting, gives 53% feldspar, 29% calcite and 18% chlorite.

Corroded feldspar crystals are surrounded by calcite and chlorite, the calcite appearing to be attacking the feldspar. Calcite also veins the rock. Epidote is only present as a few scattered anhedral grains, richest in the chlorite patches.

The feldspar is albite and is frequently twinned on the albite law, and also less commonly on the bavino law. The twinning is quite sharp, which suggests that the crystals grew after, or because of the metamorphism, and are undoubtedly formed from a more calcic rich plagioclase. Some of the larger crystals are cut by veins of calcite indicating the late incoming of solutions rich in CO_2. Most of the crystals are being corroded by the calcite and have ragged edges. The chlorite, almost isotropic, is also attacking the albite, and occurs interstitial between the albite.

According to C. W. Carstens, the rocks nearest to the ore contain large amounts of added quartz, but none was seen in the above thin section, although sections cut from samples taken from other parts of the mine, close to the ore, did contain small amounts of quartz. Also, Carstens suggests that as well as quartz, much chlorite, with or without sericite, has been added. Further away, sericite becomes the chief added mineral. Quartz is present in minor quantities in most of these types. Carstens concluded that the local metasomatism associated with the ore had involved the addition of silica, potash and water.

T. Strand has also described rocks rich in albite which he ascribes to the addition of sodium. (or the local enrichment of sodium).

(2) THE VASSKIS

The second type of sulphide mineralization, in the Løkken area, is the vasskis, usually thin bands of iron sulphide separated by a dark grey to black, fine grained rock. The vasskis is found in association with the massive pyrite orebodies, just below the footwall, and occasionally above the hanging wall, although this is more uncommon than footwall occurrences. Several horizons of vasskis may be present below the ore, (see geological plans of level 930m.), and up to a considerable distance away from the ore. It is also found to the north of Løkken where no massive pyrite has yet been found.

The sulphide layers, mainly pyrite with hematite and magnetite and small amounts of chalcopyrite and sphalerite, occur usually in parallel bands, a few millimetres to a metre thick, in dark vasskis 'shale'. Several sulphide bands may occur within the same shale horizon, and many shale horizons may be close together and parallel to each other. The vasskis occurs interbedded with jasper, magnetite-chlorite rock and the basic metavolcanics.

It is the parallel nature of the vasskis horizons, and their conformable relationship with the lava flows, as shown by pillows lying in contact with the vasskis, that led to Carsten's in 1922, who was convinced of a syngenetic origin for the vasskis, to assign an exhalative biochemical mode of formation. It has long been thought that the vasskis was formed by sedimentary deposition, and in fact vasskis means 'water pyrite' in Norwegian.

Plate 22. One metre thick vasskis horizon, resting on massive metavolcanics and overlain by pillow lava. Note the chlorite rich rims to the pillows and also their conformable relationship with the vasskis shale, on which they lie. (The white patch is quartz.) Level 720m.

Although the vasskis occurs in such close association with the massive pyrite ore, there is no difficulty in distinguishing between the two different types of pyrite mineralization.

Only the massive pyrite is mined as the vasskis has a sulphur content too low to repay working, never exceeding 40% and usually only about 30%. The copper and zinc content is also much lower in the vasskis than in the massive ore and is occasionally absent.

Although the vasskis is not mined as an ore, it is a useful indication of possible massive sulphide mineralization. The connection between the vasskis and the massive ore is open to question, but it is clear that their methods of formation are completely different, and this is reflected in the trace element of the ore and vasskis, which differ considerably. (see Appendix I).

Because of the close association between vaskiss and pyrite ore, not only at Løkken, but also at other massive sulphide deposits in Norway, such as at Hjerkin and Foldal, the location of the vasskis has been determined with some care using geophysical methods. Resistivity and electro-magnetic surveys have detected several vasskis horizons of considerable areal extent which have been traced and drilled to explore for any massive sulphides which might be present.

Plate 23. Footwall contact between massive ore and a thick vasskis horizon.
150m. west of Wallenberg shaft, Level 430m.

Plate 24. Outcrop of vasskis with pillow lava resting conformably above it and possibly a dyke below.

From the study of thin sections, the dark 'shale' found in such close association with the pyrite bands appears originally to have been a sediment. This conclusion is reached from the texture of the rock, rather than the mineral composition, which has been much altered and probably completely destroyed by the subsequent metamorphism in the greenschist facies.

Although called shale, the rock has no cleavage and is completely massive and very fine grained. In hand specimen the shale is dark grey to black in colour, and apart from veins of quartz and calcite, and of course the pyrite bands, no individual minerals can be identified with the naked eye.

Examination of the rock in thin section reveals a criss-cross pattern of fibrous chlorite, with larger subhedral epidote in a groundmass of feldspar. From comparison of the refractive index of the feldspar with that of Canada balsam, it was found that the feldspar was less than An_{10}. Unfortunately, the rock was too fine grained for refractive index liquid determinations: but it seems most probable that the feldspar is albite in composition.

The chlorite occurs as small needle shaped crystals which are most probably twinned, but are too small for positive determination to be made. These small needles intersect and cross one-another without any apparent orientation with the pyrite bands, which are parallel to the bedding of the shale horizon. Cutting through the chlorite needles, are larger, subhedral epidote grains.

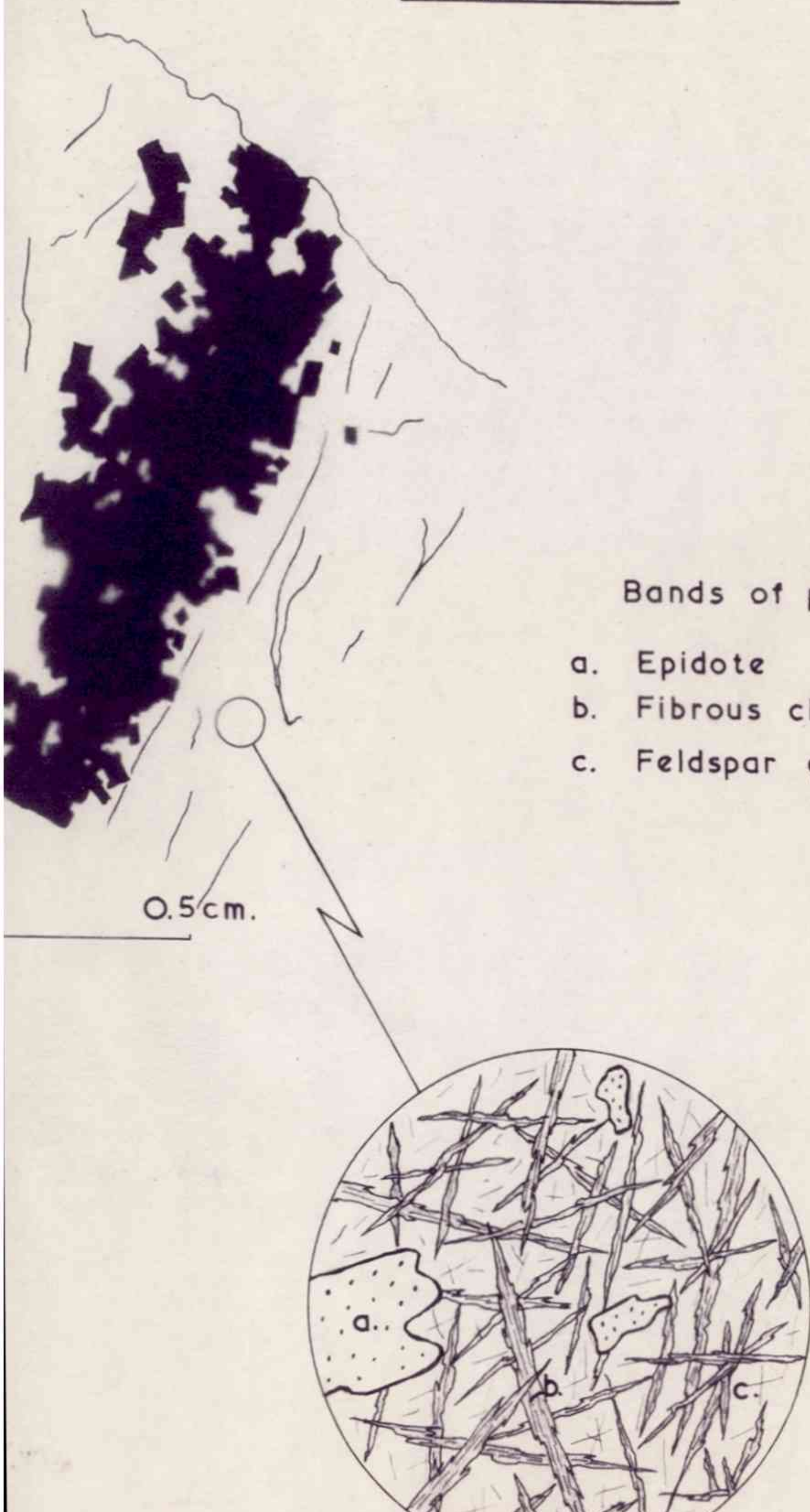
These too occur scattered throughout the rock. Between the network of chlorite needles and the spidote can be seen small patches of albite. From the textural relationships it would appear that the albite formed before the chlorite and epidote, which have then grown so as to almost hide the albite.

Veins of later quartz and calcite are abundant, especially close to the massive pyrite ore. The quartz is badly strained and has an undulose extinction and is also often found in shadow zones alongside some of the pyrite indicating that it must have been deposited during a time of great strain. (During the formation of the ore ?).

Pyrite is plentiful and occurs as euhedral crystals, dust like grains and bands of interpenetrating crystals. The very fine grained texture of some of the pyrite may be taken as evidence for deposition as a sediment, most probably with the help of bacteria producing hydrogen sulphide. (Polished section examination confirms this theory). The coarse crystals would be formed by the re-mobilization and recrystallization of the fine grained pyrite during compaction and metamorphism.

In polished section it soon becomes apparent that the opaque mineralogy of the vasskis is much more variable than that of the massive pyrite ore. Pyrite is still the most abundant mineral but occurs ih two different habits. The most common occurrence is that of euhedral crystals which form layers parallel

Vasskis 'Shale'



Bands of pyrite with

a. Epidote
b. Fibrous chlorite
c. Feldspar groundmass

Fig. 15

to the bedding of the vasskis horizon as a whole. Between the pyrite rich layers occurs the second type of pyrite and is found as very small spheres. Other minerals present, although to a lesser degree than the pyrite are hematite, chalcopyrite, sphalerite, magnetite, pyrrhotite and arsenopyrite.

The following description of the opaque minerals in three polished sections indicates the varied appearance and mineralogy of the vasskis. The first polished section is typical of the banded vasskis, whilst the other two illustrate the varied nature of the mineralogy and vasskis in general.

Specimen 184

Specimen 184 comes from level 810 metres and is composed of thin bands of pyrite only a centimetre or two thick and separated by very massive dark greenish black vasskis shale. At first glance the pyrite layers appear to be one single band but closer examination reveals that they are in fact composed of many very thin layers very close together, giving the appearance of a single band.

Microscopic examination of the pyrite rich bands reveals the presence of euhedral pyrite crystals and smaller spherical bodies of pyrite concentrated into the layers and, especially the spherical bodies, scattered through the rest of the gangue between the layers.

The individual pyrite bands vary in thickness from a few millimetres down to fractions of a millimetre, and are composed of small euhedral pyrite crystals, often intergrown with each other, and very small spheroidal aggregates of pyrite. The photograph below illustrates the parallel nature of the banding.

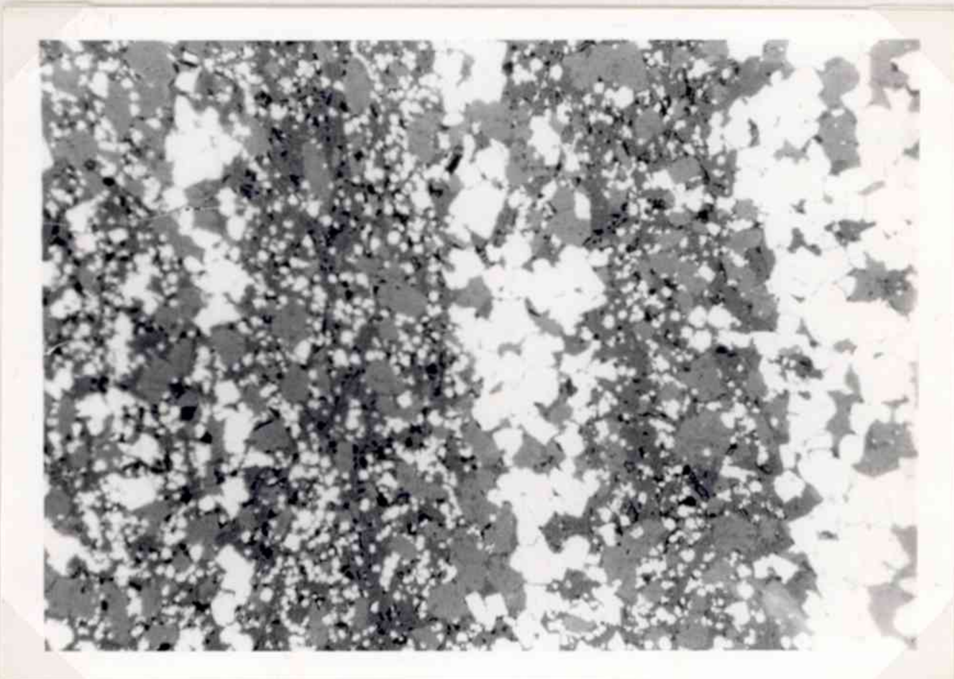


Plate 25. Bands of pyrite crystals in vasskis shale.
Note the smaller round framboids between the pyrite bands.
Specimen 184, level 810m. x 150.

The most interesting feature of this section however, is the fine spheroidal pyrite, because, on close examination, they are found to be framboids which are composed of orientated crystallites of pyrite. (see Plate 26).

The origin of framboids is not fully understood but their formation from colloidal precipitation is known. From the abundance of framboids in marine sediments and the presence of organic matter, it is thought that they were precipitated by the action of hydrogen sulphide, produced by bacteria, on iron hydroxides in the sea. (Framboids have also been reported from high temperature veins, (Cornwall) although the framboids reported did not contain oriented crystallites. It has also been suggested that sulphides would be precipitated as colloids and framboids on the sudden release of pressure in veins, and this theory has been used to account for the presence of framboids at Rio Tinto, Spain, although once again the crystallites are not orientated).

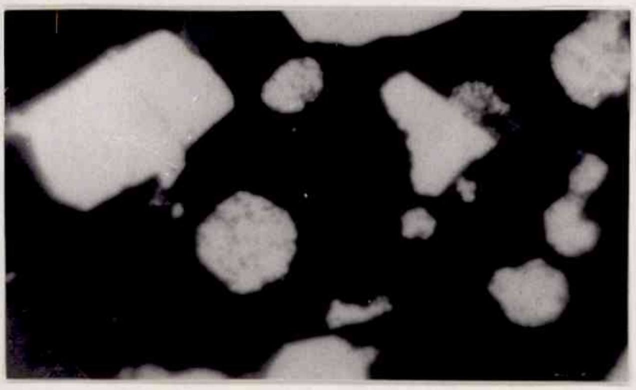


Plate 26.

Framboidal and subhedral pyrite in vasskis shale. Specimen 184, level 810m. x 1900, oil immersion.

The second example of vasskis is one containing a large quantity of magnetite and smaller quantities of pyrite, sphalerite, chalcopyrite and pyrrhotite. In hand specimen the rock is dark grey with lighter grey bands which are richer in pyrite, and is strongly magnetic due to the high content of magnetite.

The locality of specimen 216 is in Løkken, just to the north of the mine surface plant and is not far from the outcrop of the ore. (now covered by dumps).

Polished section examination reveals the bands of mainly pyrite and magnetite. The banding is not as well defined as that described in specimen 184, but is still well developed.

The pyrite is found as subhedral and anhedral grains confined mainly to the magnetite rich bands. Framboids are not common but much of the pyrite is poorly crystallized and may well be the result of recrystallization of the framboids. Small grains of pyrite are also found enclosed within some of the larger magnetite grains.

The magnetite is an anomalous blueish grey colour and forms anhedral grains in both the bands and the rest of the rock matrix. The presence of so much magnetite would indicate that the conditions during deposition did not favour the formation of sulphides, either because there was a lack of bacteria to produce hydrogen sulphide or sea currents brought sufficient oxygen to the sea bed as to oxydize most of the pyrite produced. This latter suggestion would account for the magnetite being found away from the bands, and the general absence of framboids.

Sphalerite, chalcopyrite and pyrrhotite are not common, but their presence indicates the varied mineralogy of the vasskis. Sphalerite occurs often as large patches, usually away from the sulphide layers, and in some of the larger patches, exsolution chalcopyrite can be seen. This suggests a higher temperature of formation than is compatible with a sedimentary origin of the vasskis. However the presence of such exsolution textures is explained if we can except that in this locality the vasskis is close to the ore and it is possible that, being a mobile mineral, sphalerite might well migrate away from the ore, and into the surrounding rocks.

Chalcopyrite also occurs as individual patches, frequently associated with pyrrhotite. Pyrrhotite is also found close to, or in the pyrite and Plate 27 illustrates such a pyrite crystal with a zone of pyrrhotite parallel to the crystal faces of the pyrite. This would indicate a period of time during the formation of the pyrite crystal in which there was insufficient sulphur to permit the formation of pyrite and as a result pyrrhotite was produced. When the sulphur availability increased again, pyrite crystallized over the pyrrhotite.

The main gangue minerals are chlorite, calcite and quartz. Chlorite forms interpenetrating lath shaped crystals, whilst the calcite and quartz are restricted to the gaps left between the chlorite laths.

Plate 27. Magnetite rich band in the vasskis.

Specimen 216, x 150.

a. Magnetite

b. Pyrite

c. Chalcopyrite and pyrrhotite

d. Pyrrhotite enclosed within a pyrite crystal

e. Gangue minerals, chlorite dark grey, quartz black.

Specimen 182 was collected on level 750 metres and is an unusual type of vasskis, differing in appearance and mineralogy from the more usual vasskis horizons.

The most striking feature of specimen 182 is the absence of well defined bands or layers of pyrite, but instead the opaque minerals form flattened, branching loops which enclose lenses of the dark shale. These lenses are only small, the largest being only two centimetres long and one centimetre thick. The opaque minerals surrounding the lenses are only fractions of a millimetre thick, slightly thicker where two branches meet.

The flattening of the loops and lenses is parallel to the strike of the vasskis horizon as a whole.

The mineralogy of the loops also differs from the pyrite rich bands already described, the most predominant mineral being hematite with pyrite and small quantities of sphalerite, chalcopyrite and arsenopyrite. The hematite forms the matrix of the loops in which are found euhedral pyrite crystals. The sphalerite, chalcopyrite and arsenopyrite are also found as irregular patches in the hematite but are present in accessory amounts only.

The pyrite, as well as forming euhedral crystals in the hematite is also present in the form of framboids, suggesting that, despite the absence of parallel layering, this variety of vasskis is also of sedimentary origin. The framboids are scattered evenly through the lenses but are not visible in the hematite bands.

The euhedral crystals of pyrite frequently cut right through the hematite bands and must have crystallized after the hematite. Smaller euhedral and subhedral crystals are also found mixed in with the framboidal pyrite.

The other three opaque minerals are of minor occurrence and are found mainly in the hematite bands. Sphalerite and chalcopyrite form only small patches but the arsenopyrite occurs as large irregular patches, sometimes as large as the largest pyrite crystals, about 0.25mm. However only four such patches of arsenopyrite were seen in the polished section examined. One of the larger patches of arsenopyrite is shown in the photograph below.

Plate 28. Section of a hematite band in specimen 182.
Level 750m, x 150. a. Hematite b. Pyrite
c. Arsenopyrite d. Sphalerite

Note also the framboidal pyrite in the dark gangue.

The unusual texture and the presence of hematite must be explained before any theory of origin can be accepted. The presence of the hematite offers little trouble to the sedimentary theory, simply that there was insufficient sulphur in the form of hydrogen sulphide being produced by bacteria to keep up with the precipitation of iron oxides and hydroxides. Therefore not all the oxide could be converted to sulphide and hence after compaction and metamorphism hematite was produced along with as much pyrite as could be formed from the available sulphur.

The presence of iron oxides in the form of hematite or magnetite is not uncommon in the vasskis and were seen in several of the sections examined. Arsenopyrite is unusual and can only be attributed to the local concentration of arsenic on the sea bed. This must combine with any iron and sulphur to produce arsenopyrite.

The texture of the hematite bands enclosing lenses of vasskis shale is more difficult to explain, but the only possible explanation must involve remobilization and recrystallization associated with the metamorphism.

ORIGIN OF THE LØKKEN OREBODIES AND VASSKIS

Several theories have been proposed to account for the formation of the Løkken orebodies as we see them today. The earliest of these was J. H. L. Vogt's theory of formation as injections of magmatic sulphides derived from the gabbro magma of the area, C. W. Carstens' proposed that the ores were formed as hydrothermal replacements of the greenstones. In 1944 he described a pillow-structure from the Løkken ore which he claimed was a relict structure from the original pillow of the lava flow.

T. Strand has reported seeing similar structures in the ore without being convinced that they really represented relict pillows. In view of the position of the ore above the sedimentary vasskis with the greatest thickness of ore coinciding with the maximum curvature of the folds, he thinks that the possibility cannot be excluded that the ore, for the greater part, is intrusive, in the sense that the sulphides were deposited in spaces opening between the vasskis and the massive greenstone. The primary origin of the massive pyrite is still in doubt.

However, before any theory can be accepted it must satisfy several points of geological evidence,

i) The association of massive pyrite deposits, throughout Norway, with the volcanics which have been metamorphosed to a greater or lesser extent.

ii) The conformable attitude of the orebodies to the surrounding country rocks.

iii) The lack of any informative primary structures preserved within the orebodies.

iv) The syngenetic nature of the vasskis and its connection with the orebodies.

v) The presence of the thrust plane at Løkken.

If we can imagine a basalt magma differentiating to produce the assemblage of rock types that is found at Løkken - basalts, tholeiite basalts, spilites etc., then it is well known that the late hydrothermal and pegmatitic stages lead readily to monomineralic crystallization products. In many cases hydromagmatic differentiation of basaltic magma has led to the concentration of major constituents of rocks, such as iron, manganese, titanium and calcium and silica. All of these elements would form oxides and some of them sulphides, provided that sulphur was available. Also the rarer metallic elements such as copper, silver, and gold may be concentrated. Such deposits have been subdivided into oxy, sulpho, and native metal deposits (e.g. Kiruna - Fe, Telness - Ti, Michigan native copper and Canadian gold deposits).

During this process of differentiation a portion of the volatile fraction may escape and form replacement deposits, or is shed into the ocean as submarine exhalations and leads to exhalative sedimentary deposits such as the Kupferschiefer and Copperbelt. In this way it is most probable that the vasskis would have been produced. Iron and minor elements such as copper were exhaled into the sea where, due to bacterial action in producing hydrogen sulphide, pyrite was precipitated on the sea bed as a sediment. During the same process, whilst conditions were calmer, the shale associated with the vasskis would also be deposited. The pyrite would be precipitated as a fine dust but metamorphism and compaction would lead to the re-crystallization of the pyrite into the banding seen at the present time.

After several vasskis horizons and a considerable thickness of volcanic flows, many submarine as indicated by pillows, were formed, the differentiated pyrite hydromagma was intruded at depth, more or less, in the form of a sill into the pile of volcanic lava flows, conformable or nearly so with the vasskis horizons. The exact conform-a ble nature cannot readily be determined as the only definable strati-graphic horizons are the vasskis, which are not always close to the ore and cannot be followed underground, for any distance. The pyrite hydromagma although at a high temperature produced little metamorphic affect on the surrounding rocks as they are predominantly basic and stable at high temperatures, much in the same way as the gabbro also failed to produce a metamorphic aureole. The impregnation ore was formed simply by the more volatile constituents and later products invading the country rocks close to the ore. This would account for the quartz bands and pyrite rich in chalcopyrite. Much of the quartz is stained red with iron producing jasper. Carbon dioxide associated with the intrusion has resulted in carbonatization of the surrounding meta-volcanics. After the formation of the orebody the area was subjected to folding, during which the orebody was folded to produce the small folds, seen in the sections in Figure 12, on the limb of the large syncline.

Towards the end of the folding the gabbro was intruded near the ore. The ore and gabbro being more competent than the volcanics focused the stresses so that planes of weakness were developed at their contact with the volcanics, and hence the thrust formed along their contacts bringing the ore and gabbro closer together.

Prolonged metamorphism in the greenschist facies of regional metamorphism has destroyed the original mineralogy of the volcanics producing the 'greenstones' but has had little effect on the ore. This is clear from the primary textures, (i.e. banding) still displayed in the vasskis.

A late flexure of the existing folds has resulted in the present attitude of the orebodies as seen at Dragset, Løkken, and Høidal, and although the orebodies may not be connected by thick ore horizons they are most probably of the same origin. It is significant that the Løkken and Høidal orebodies are connected by a vasskis horizon. No connection has been established between Løkken orebodies and the Dragset orebody.

Evidence for and against other possible modes of formation.

1) Sedimentary

The most favourable piece of evidence for a sedimentary formation is the conformable nature of the orebodies with the vasskis and surrounding spilite flows. However, the methods of deposition of such a quantity of almost pure pyrite cannot be immagined. Bacterial action required to produce sufficient H_2S to precipitate so much pyrite is out of the question as the carbon content of the ore would be considerable. Also one would expect sedimentary structures such as layering to be present and to have survived the metamorphism as has the vasskis. It is not possible for molten pyrite, in any state, to be extruded onto the sea bed, due to the high temperatures and the presence of oxygen at the earth's surface.

Therefore it would seem that a sedimentary formation was not possible.

2) Replacement of the metavolcanics

Carstens claimed to have seen relict pillow structures of lava replaced by pyrite. Strand reported similar structures but was not convinced that they were relict pillows. Unfortunately, such structures have now been mined and further examination is not possible.

The main objections to a replacement origin are the conformable nature of the ores, (It has been suggested that replacement might take place along a horizon of lava chemically favourable for replacement, but there is no evidence for this being the case and, in general the lava flows at Løkken are chemically very similar). The absence of relict patches of country rock and gradational contacts is also significant, although the impregnation ore might be taken as evidence for replacement on a local scale. No evidence of a replacement origin was seen in the polished sections examined.

Evidence for a replacement origin is largely lacking, but this in itself cannot exclude the possibility of such an origin.

Plate 29. Pyrite veining country rock at Høidal Mine. Remobilization, due to intense shearing and metamorphism, has resulted in the country rocks, in the immediate vicinity of the massive pyrite orebody, (now worked out) to be veined by pyrite. Silicification and carbonatization have greatly altered the country rocks.

APPENDIX I

Although the mineralogical composition of the massive pyrite ore, at Løkken, is very simple, the chemical composition is complex. The following may be taken as a typical analysis :

Sulphur	42.0%	
Iron	38.0%	
Insolubles	14.3%	(mainly quartz)
Copper	2.3%	
Zinc	1.8%	
Manganese	0.08%	
Cobalt	0.07%	
Arsenic	0.05%	
Lead	0.02%	
Cadmium	0.01%	
Selenium	0.007%	
Nickel	0.001%	kommafeil ?
Silver	16gr/ton	
Gold	0.2gr/ton	

The vasskis is of variable chemical composition, the sulphur content being most often between 20 and 40%, and only occasionally rising over 40-45%. As already mentioned, the copper and zinc content of the vasskis is normally extremely low to absent and the trace element content varies markedly from that of the massive ore, notably selenium has not been found in the vasskis. A comparison of the most contrasting trace elements in the vasskis and massive ore is given below.

Four samples, two from the ore and two from different vasskis, horizons were analysed spectrographically and four trace elements were found to contrast most markedly between the ore and vasskis. These were nickel, chromium, silver and titanium.

	Massive ore		Vasskis	
Specimen	139	125	72	184
	ppm.	ppm.	ppm.	ppm.
Nickel	Trace	absent	750	700
Chromium	-	-	150	300
Silver	300	250	-	100
Titanium	50	100	1000	1000

Note The samples consisted of crushed ore, including gangue and samples from the pyrite rich layers in the vasskis shale, but must have included some of the shale.

APPENDIX II

List of thin and polished sections referred to in the text

a). Thin Sections

Specimen No.	Section No.	Location	Description
1	30382	Entrance to Wallenberg shaft.	Pillow lava
6	28303	Road cutting in Bjørnly	" "
24	28304	North of Bjørnlivann	Spilite
33	28306	South of Bjørnli	Quartz keratophyre
43	28307	"? " Dalatjern	Metagabbro
45	28308	North of "	Quartz keratophyre
75	28310	Vasskis outcrop,Løkken	Spilite or dyke
76	28311	7m.above vasskis o/c.	Spilite
77	28312	5m. " " "	"
78	28313	1.5m. " " "	"
79	28314	0.5m. " " "	Pillow lava
98ii	28315	West shore of Bjørnlivann	Metagabbro
101	28316	Level 481	"
117	28317	Level 720	Vasskis shale with diseminated py.
128	28318	Level 430 above thrust	Spilite or Sheared gabbro
137	28319	Level 463 above ore	Spilite
145	28320	Level 481	Dyke in metagabbro
149	28321	" "	" " "
154	28322	Level 930	Vasskis
172	28323	" "	Spilite
174	28324	" "	"
185	28325	Level 810	Vasskis
190	28326	Level 930 foot-wall contact with ore	"

Specimen No.	Section No.	Location	Description
194	28327	Level 930 foot-wall contact with ore	Spilite
196	28329	Level 720 above vasskis	Pillow lava
197	28330	" " below "	Massive spilite
198	28331	Level 481	Metagabbro
202	28332		Pillow lava
208	28333	Vasskis outcrop Løkken	Vesicular lava
209	28334	" " "	Porphyritic spilite
211	28335	" " "	Spilite
212	28336	Entrance to mine tunnel, Løkken	Pillow lava
215	28339	S.E. of Bjørnlivann	Broken pillow lava

b). Polished Sections

Specimen No.	Location	Description
72	Vasskis outcrop,Løkken	Massive pyrite in vasskis
72	" " "	Banded pyrite from vasskis
125	Level 930, new orebody	Ore
135	Level 430	"
139	Level 463	"
153	Level 930	Banded pyrite from vasskis
182	Level 750	Network of pyrite from vasskis
184	Level 810	Fine pyrite bands
187	Level 930,new orebody	Ore
191	" " " "	"
216	Below viaduct in Løkken	Magnetite rich vasskis
LN-1	Not recorded	Ore
LN-2	" "	"

APPENDIX III

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GEOLOGICAL PLAN OF LEVELS 930, 720, 481, 463 & 430 METRES.