NORGES GEOLOGISKE
UNDERSØKELSE

Zinc and lead deposits in the Håfjell syncline, Ofoten, northern Norway

By

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CONTENTS

RESUMÉ

This paper is a presentation of geological studies of the mineralogically simple lead and zinc sulphide deposits (60—85 % sphalerite, 15—30 % galena, a few percent pyrrhotite, some chalcopyrite and negligible pyrite) of the Håfjell syncline, on the southern side of the Ofoten fjord, Northern Norway. It deals mainly with the stratigraphic position, the tectonic development and the major mineralogy of ores and immediate wall rocks.

Stratigraphically the ores are restricted to the uppermost units of the Caledonian metasediments of the Håfjell syncline. For the purpose of the present investigation the following four units (in ascending order) were mapped on the scale 1:5000:

Hekkelstrand limestone/dolomite, garnet-mica schist, Djupviknes quartzite, and uppermost garnet-mica schist.

The ores, centred about the Djupviknes quartzite, are mainly located in the surrounding garnet-mica schist. Their strike extent is about 7 kms and while thin sulphide layers are unevenly distributed within 20—70 ms of the stratigraphical column, their total true thickness is only of the order of 1 m.

Generally, the ores are strata-bound. They have been present within their wall rocks prior to the folding of the mountain range. Within the metasediments, the ores are thought to have been primarily concordant to the sedimentary layering.

Two fold episodes may be distinguished. The main fold axis strikes 60^{g}[1] East of North, plunging on average 10—15^{g}. A crossfolding has taken place, more or less orthogonally to the above direction. Combination of these two foldings (repeated axial flexures) has in the central part of the syncline given rise to a chequered folding pattern. Observed ore thicknesses are intimately connected with this pattern. On the outer limbs of the great Håfjell syncline the intensity of the tectonic development is relatively weak. Ore thickening here is only observable where tectonic irregularities occur.

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[1] ^{g} = new degrees, i.e. 400 degrees circle.

It is reasonable to state that the present shape and location of the ores depend directly upon the intensity of the tectonization.

A weak segregation of the main minerals has taken place during the metamorphie mobilization. The lead has been most mobile in sulphidic form. Galena has been transported further than sphalerite into zones of tectonic weakness. Zinc, the more mobile of the two elements in oxidic form, occurs in a zinc spinel, distributed symmetrically with respect to the ore plates in both the hanging and foot wall directions.

The two-phase development of the metamorphism indicated by tectonic relations, is repeated in several individual gangue minerals. Good indicators are zoned tourmalines and garnets. Stepwise and gradual development of metamorphic conditions is indicated by the sulphides, but the interpretaion of the trend of intensity variations may be different from one locality to another.

The metamorphic facies is one and the same throughout the area: the lower part of the epidote-amphibolite facies. Both wall rocks and ores generally exhibit medium grain size, but in the heaviest tectonized localities, the ore grades into coarse grained varieties.

Sphalerite and galena, the main ore constituents, may occur quantitatively in all proportions, though sphalerite dominates on the whole. Together with pyrrhotite the lead and zinc sulphides exhibit in most parts of the ores mutual inclusions of different size. None of them being of any particular "crystallization strength», vis-á-vis the others, the ore textures are mainly an interweaving of aggregates where the individuals seldom show crystal faces parallel to the grain boundaries.

There are no eruptive bodies, dikes or sills near or in the immediate vicinity of the deposit, and there is no evidence for formation by circulating ore-depositing solutions. Moreover, the distribution of sulphides through the stratigraphic column does not show any evidence of such processes. The transition from ore to wall rock is always abrupt. There is no reason to suppose that certain rocks should have poseded permeability characteristics capable of controlling the observed sulphide distribution. This is supported by the fact that the sulphides are found in mica schists both above and below the quartzite, as well as within the quartzite unit itself.

The control of the spatial ore distribution is both of tectonic and sedimentological character. That is, sedimentological criteria dictated the primary work of ore localization. The folding during Caledonian orogeny with its accompanying metamorphism and ore mobilization made tectonics the clue to the appraisal of ore volumes and their possible economic value. The sulphides, undoubtedly of pretectonic origin, are very intimately interbedded with at least two of the Håfjell-syncline metasediments. Exterior morphology of the different strata seems to indicate a similar origin and development of ores and wall rocks.

The thorough transformation these ores have undergone during the orogeny has disguised many of their original characteristics. Howewer, the internal textures of the sulphide assemblages do not seem to contradict the hypothesis that these ores may be metasediments themselves.

PRESENT WORK

The aim of this investigation has been to acquire a more detailed knowledge of the form and mineralogy of the very characteristic ore types within the upper part of the Håfjell syncline metasediments.

The possibilities of economic exploitation of the Djupvik — Skårnesdal claims have been evaluated on the basis of detailed geological mapping.

The mapping of these claims was completed during the summers of 1962 and 1963. The writer continued his work on these ore types by carrying out a survey of similar deposits on the other side of the Ofoten fjord in 1964. He intends later to publish a broader survey on the Ofoten lead-zinc province based on a comparison of structural criteria, mineralogy, and geochemistry of several of the lead-zinc ores.

The present paper is thus a finished portion of a study which is still proceeding.

The writer is grateful for permission to use material from a degree thesis at the University of Oslo.

The laboratory work was carried out at the Mineralogisk-Geologisk Museum, Oslo.

ACKNOWLEDGEMENTS

The economic expenses of the field work have been paid partly by the private consortium I/S Angelus, Oslo/Harstad, partly by Norges geologiske undersøkelse, Trondheim. I am grateful to these two organizations for their support and for the permission to publish the results.

Professor, dr. philos. Henrich Neumann, University of Oslo, was the instigator of the project. He encouraged me to undertake a deeper investigation of the area. Professor, dr. philos. Frank M. Vokes, Technical University of Norway (NTH), Trondheim, introduced me to the field problems of the region. Hereby, I want to thank these two gentlemen for their willingness to give advice and support during my work.

I am indebted to Frank M. Vokes and dr. philos. Harald Carstens (NGU) for a critical review of this paper.

PREVIOUS WORK

Published work on the lead-zinc claims in Håfjell is restricted to a short report in Bergmester[1]) Torgersen's survey of lead-zinc deposits in Northern Norway (12). In this, the locations of surface and underground workings are described, and a short account of the main mineralogy of ores and immediate wall rocks is given.

State geologist Steinar Foslie has carried out extensive geological work in the Ofoten basin. He mapped the Håfjell syncline on the scale 1:50 000, thus covering the area of the Djupvik — Skårnesdalen claims. In his publication "Håfjellsmulden i Ofoten og dens sedimentære jern-mangan-malmer" (3) he presents the sedimentary sequence of the syncline and treats in great detail the Fe/Mn ores situated lower in the stratigraphic column than the lead-zinc ores in question here.

Foslie has also made a topographic survey-map on a scale of 1:2000 containing most of the surface workings and ore zones of Skårnesdalen. Corrected by help of enlarged aerial photographs, this map served as basis for the geological mapping in this particular area.

According to the local tradition, the claims have been known since time immemorial and their rather difficult access should be due to the prehistoric legendary figure Bal.

In modern times several prospectors have taken interest in the deposits. Early in the century, extensive surface workings were made. Systems of cuts and trenches reveal the intricate folds and the varying intensity of mineralization. Attempts have been made, with little success, to follow the ores underground. Several shorter drifts exist, but no workings in depth. No regular mining operations have taken place and only few tons of ore have been extracted.

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[1]) Inspector of Mines.

INTRODUCTION TO THE INVESTIGATED AREA

The Håfjell syncline (Håfjellsmulden) is located on the southern side of the Ofoten fjord, community of Ballangen, Nordland County, Norway (Fig. No. 1). The culminating point of the area is the Mount Håfjellstuva (817 m above sea level, lat. 68°22′ N and long. 5°59′E Oslo Mer.). The administrative centre of Ballangen community is the hamlet around Bjørkåsen pyrite mine (opened 1910, closed down 1964), situated 43 kms southwest of Narvik, along the National Road No. 6 (E 6). An unpaved all-year road runs along the fjord westwards from Ballangen centre.

The folded Caledonian metasediments which constitute the syncline, contain various groups of ore deposits at different levels. Several pyritic deposits are distributed mainly in the lower parts of the series. The sedimentary iron-

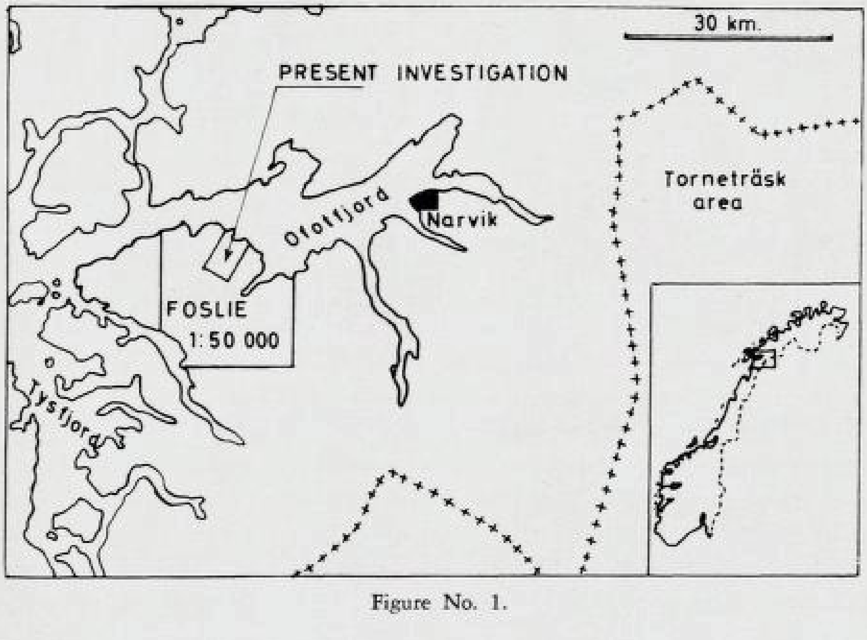
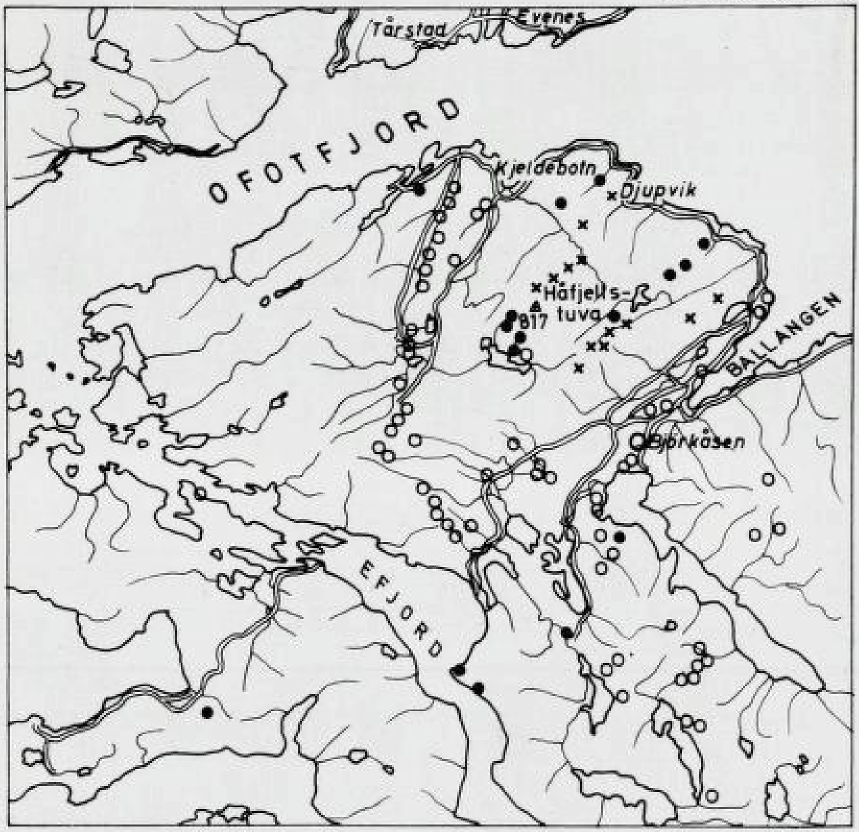


Figure No. 1.

REGISTRERED CLAIMS BALLANGEN AREA

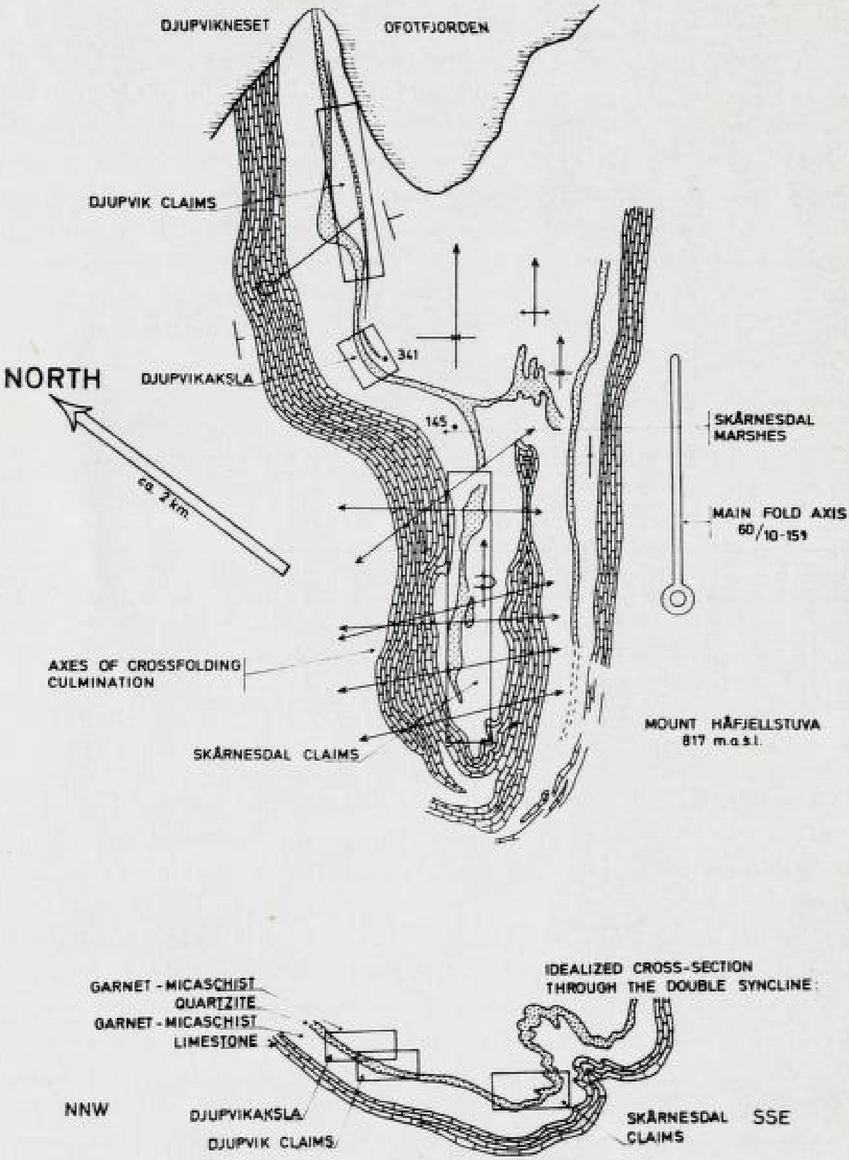
scale: ca. 1/290 000



• = Fe/Mn o = py/cpy × = Zn/Pb

manganese ores investigated by Steinar Foslie (3) are located within a wide range of the middle part of the stratigraphical column. Djupvik — Skårnesdalen zinc and lead deposits, the subject of the present investigation, are situated in the uppermost parts of the series. (See maps pp. 10 and 11.) In addition, minor occurences of the same mineralogical and geometric type are found lower down in the syncline.

The Djupvik — Skårnesdalen zinc-lead zone containing the somewhat discontinuous mineralization runs from the fjord at Djupvik to the northwestern slope of Mount Håfjellstuva (about 600 m.a.s.l.) — a distance of more than 6 kms. The access to the Djupvik claims is thus easy from the fjord side. The hilly topography complicates the accessibility to the rest of the claims. However,



GEOLOGICAL MAP OF THE CENTRAL PARTS OF THE HAFJELL SYNCLINE

a summer cart road leads from Kjeldebotn to the marshes of lower Skårnesdalen (150 m.a.s.l.).

Up to about 300 m.a.s.l. the vegetation consists mainly of dense, low birch forest. Above, there is a belt of willow (Salix) thicket, up to 1 m high and of varying width. Higher up, only grasses, lichen, mosses, and dwarf birch (Betula nana) are found. Viscaria alpina, the so-called "copper flower" is found in and around the ore zones, and seems to be restricted to that area. At some localities, the birch forest is less dense when growing on limestone ground. With this exception, the vegetation zoning seems to be a direct function of temperature (altitude). The water circulation is intense all over the area, the few geological indications given by the flora are certainly influenced by this. Below the upper birch forest limit, overburden is almost continuous, and at places very heavy.

GENERAL GEOLOGICAL FRAMEWORK OF THE DEPOSITS

The four uppermost units of the stratigraphical column of the Håfjell syncline were mapped on the scale 1:5000:

Unit. No.	Nomenclature	Approximate true thickness.
4	Upper garnet-mica schist	250 m (?)
3	Djupviknes quartzite	20 m
2	Garnet-mica schist	100 m
1	Hekkelstrand dolomite/limestone	170 m

The Håfjell syncline is a part of the Caledonian fold system in which the main stratigraphic units can be followed over long distances. On a regional scale this has provided us with relatively unambiguous knowledge of its main geological structure.

Two distinctive fold episodes may be distinguished, these being well determinable at some localities. The main fold axis strikes 60^{g} East of North, plunging on average, at 10—15^{g}. The associated axial plane is overturned and at some localities nearly flatlying. It is inclined towards the south-east with a dip between 10^{g} and 40^{g}. A weaker cross-folding has taken place, more or less orthogonally to the main folding direction.

The central part of the trough forms a more or less flatlying double syncline of considerable magnitude. Minor folds, some of them recumbent, thus form a small scale synclinorium with the Djupviknes quartzite as the most conspicuous unit. It is possible to follow this main structure from Mount Håfjellstuva down to the Ofoten fjord.

VARIATION OF THE STRATIGRAPHICAL COLUMN ALONG THE STRIKE OF THE SULPHIDES

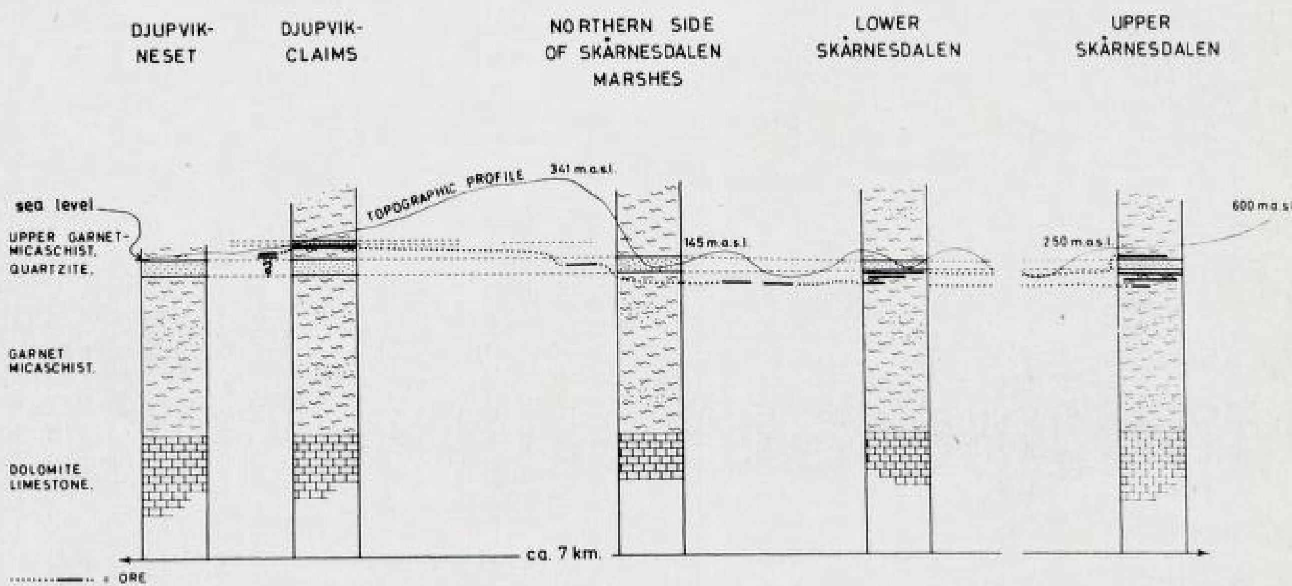


Fig. No. 2.

The small scale "synclinorium" of Skårnesdalen finds its tectonic counterpart in the anticlinal structure of the limestone masses of Mount Håfjellstuva itself. Stratigraphically lower (topographically higher), the limestone here illustrates well the dissymmetry of the whole Håfjell syncline.

The combination of the main folding and the cross folding (repeated fold axis flexures) has in these central parts given rise to a chequered folding pattern. On the regional scale, the cross folding is illustrated by the direction of lower Skårnesdalen, orthogonally to the main folding direction. The underlying limestone unit crops out in the bottom of the valley.

In upper Skårnesdalen the result of the cross folding is best observable in the quartzite unit. Its undulating course down the hillside is the best expression of the repeated fold axis flexures which characterize the area.

The zinc and lead ores, interbedded in these tectonized metasediments, reflect this folding pattern very intimately. Their form and structure are direct functions of the degree of tectonization observed in the other units of the stratigraphical column. It must be mentioned here, that their primary "mise en place" is considered to be of pretectonic age. Structual control of the sulphide distribution is thus quite directly connected to the two-phase regional folding development.

On the other hand, the sedimentological control is no less important for the understanding of the ore geometry. The sulphides, which generally are remarkably strata bound*) are always found near to the Djupviknes quartzite. Mostly, the ore zones are located in the mica schists just below the quartzite unit, but they are also found within the quartzite itself as well as above it. Thus the ores do not seem to prefer a characteristic wall rock type. There is no difference in mineralogy and morphology between ores located in mica schist and ores located in quartzite. This would imply that the primary "mise en place" of the sulphides was not especially influenced by the different wall rocks. However, phenomena such as different competence towards folding have influenced their secondary mobilization during regional metamorphism.

No eruptive massifs, sills or dykes are found in or in the immediate vicinity of the area. Metamorphic facies is generally very uniform. Plagioclase in coexistence with epidote was used as an indicator of metamorphic facies. Small grain size and lack of twin lamellae in the plagioclase sometimes hindered an accurate determination. Generally, the lower part of the epidote-amphibolite facies prevails. In particular the same facies is found also in the coarser grained varietes of the host rocks of the mineralization and in the gangue.

The ores, which are metamorphosed in intimate contact with their wall rocks, must be considered in the light of the above described features.

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*) Determined within 50—70 m vertical distribution on ca. 7000 m horizontal distribution.

EXTERIOR MORPHOLOGY OF THE ORES

The word ORE as used in this text must not be understood as an economic term. It only designates concentrations of ore minerals, mainly sphalerite and galena.

*

A corollary of the pretetonic origin of the ores is of course that the geometrically simplest types of ores are those found in the least tectonized parts of the area.

The Djupvik claims are situated in the relatively undisturbed north-western limb of the great syncline. The ores are formed as a series of parallel layers, whose individual thicknesses vary from zero to few centimeters, on an average, a few millimeters. The total mineralized zone (ca. 2 m) is confined within a very limited part of the host rocks, *grosso modo* concordant to the sedimentary layering of these.

In detail it is occasionally seen that each individual thin layer may disappear over short distances and be replaced by a new layer a few millimeters above

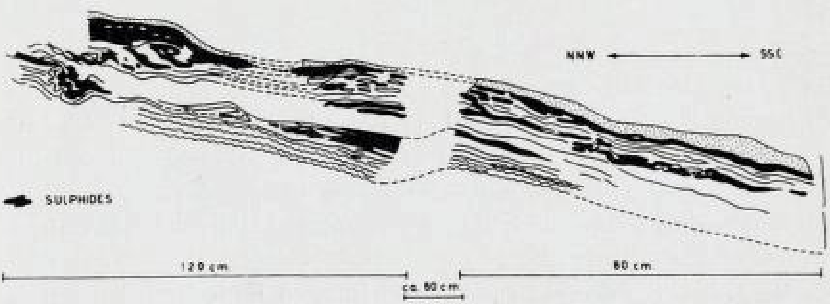

Fig. No. 3.

Profile from zinc-rich ore zone in Djupvik trench. From top to bottom:

I. Garnet (1 mm diam.) — quartz schist, quartz-garnet-biotite schist with sulphides.

II. Muscovite-garnet schist with negligible biotite.

Schistosity and sedimentary layering are parallel — sulphide layers concordant.

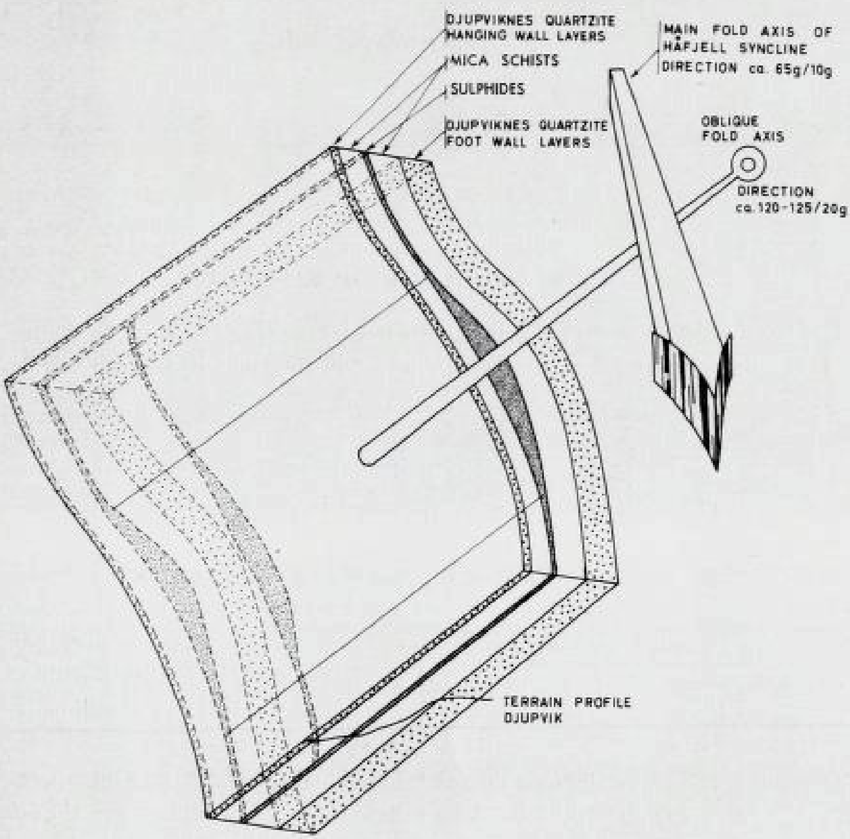

Fig. No. 4.

or below along the strike. However, such a "renaissance" along the strike mostly occurs at the same stratigraphic level. This may locally give an "en échelon" appearance, but the vertical position of the whole mineralization is fairly constant, thus giving *in toto* a strictly strata-bound impression.

The metasediments in which the ores are interbedded exhibit a uniform development along the strike as regards both their morphology and their mineralogy. Locally, however, a certain tendency to lenticular sedimentation is observed.*)

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*) Such sedimentological phenomena observed in the wall rocks seem to be reflected in some of the characteristics of the ore body morphology — thus suggesting a common physical origin of ores and wall rocks.

At a few localities in Djupvik, parts of the sulphide layers seem to have increased their thicknesses slightly. The ore texture of these parts is arranged somewhat more disorderly than in the regular layers. This textural transition is continuous along the strike. The disorder (lack of lineation, foliation — which may lead to a pseudobreccia texture) seems to be proportional to the relative increase of thickness of each individual ore layer. This special problem is related to the probable mobilization of the sulphides during the metamorphism and will be treated more detailed in another part of this paper. It is only emphasized here that an eventual mobilization within the Djupvik area, is of very local nature. However, it is possible to correlate the weak ore thickening to a special tectonic phenomenon between the Djupviknes quartzite and the mica schists.

The foot wall section of the quartzite makes an abrubt swing here (see map and Fig. no. 4) while the strike of the mica schists and of the ore zone is quite constant and only gradually adjusts to that of the quartzite when moving downwards in the strata. Competence differences between the two rock types may during the folding have given rise to a certain vertical expansion.

Thus, the actual emplacement of the sulphides is considered as being partly a direct tectonic consequence. The Djupvik ores must be considered as an expression of the very low degree of tectonization — the first step of dynamic transformation — which in the more intensively folded areas has given us quite complicated geometric forms.

Two types of ore thickening have taken place in the area. Their form is best expressed in the ore bodies of the heavily tectonized Skårnesdalen "synclinorium", but I will stress that all transition types between this and the Djupvik type are observed.

Ore thickenings of type I follow zones of tectonic weakness along the main folds. These are mostly zones of relative pressure minima, as found in drag folds, or in "saddle-reef"/"trough-reef" types around the crests of major and minor folds. The ore bodies are thus formed as long, thin rods of sicklelike cross section. (The longest axis is often tens of times longer than the width of these convex-concave cross section. Fig. no. 5.)*)

One of the causes of this type of ore thickening is that the sulphides, as some of the more mobile minerals in these rocks, have been partly mobilized during the rough tectonic treatment to which they were submitted.

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*) It is of importance that the well developed mineral lineation in the area is always parallel to the main folding direction. The crossfolding is only observable as flexures in the main fold axis.

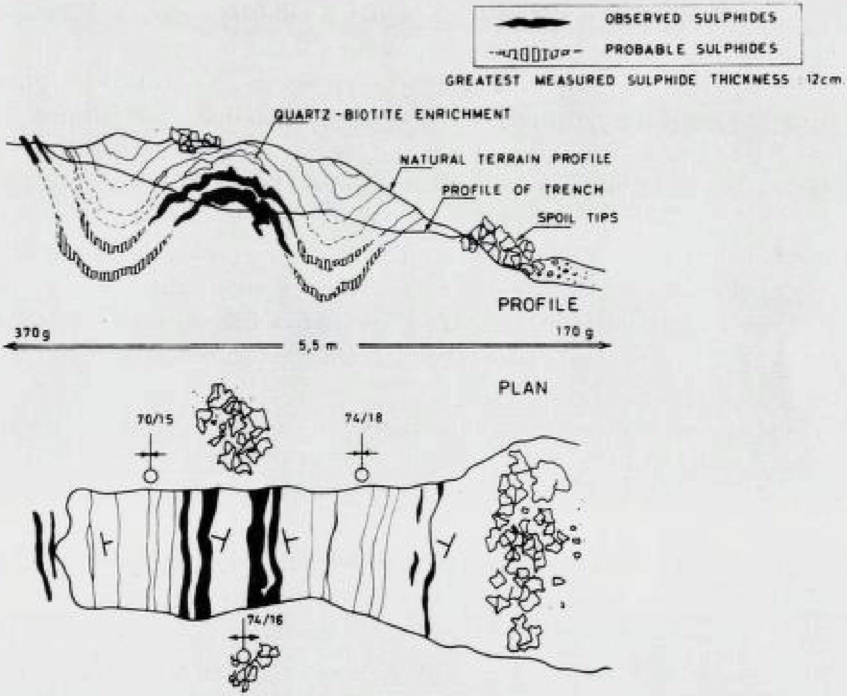

Fig. No. 5.

If most of the sulphides have recrystallized *in situ* during their metamorphism, an important part moved the short distances into the zones of tectonic weakness in order to form the particular ore body morphology of Skårnesdalen type.

The ore bodies, thickened by these processes, continue into the less disturbed schists or quartzite layers and may be followed over long distances as thin bands of equal thicknesses, perfectly conformable to their hostrocks. Thus the most tectonized ore types may be retraced back to the relatively undisturbed Djupvik type.

Ore thickenings of type II are related to the crossfolding in the following manner:

In Skårnesdalen it is observable that several parallel ore layers, of different thicknesses, have all increased their foot wall to hanging wall dimensions along certain rectilinear terrain zones. These zones are again more or less parallel to each other and nearly at right angles to the main folding direction. Erosion has left a terrain formed like a set of steps — the exterior expression of the cross folding. (Fig. 6.)

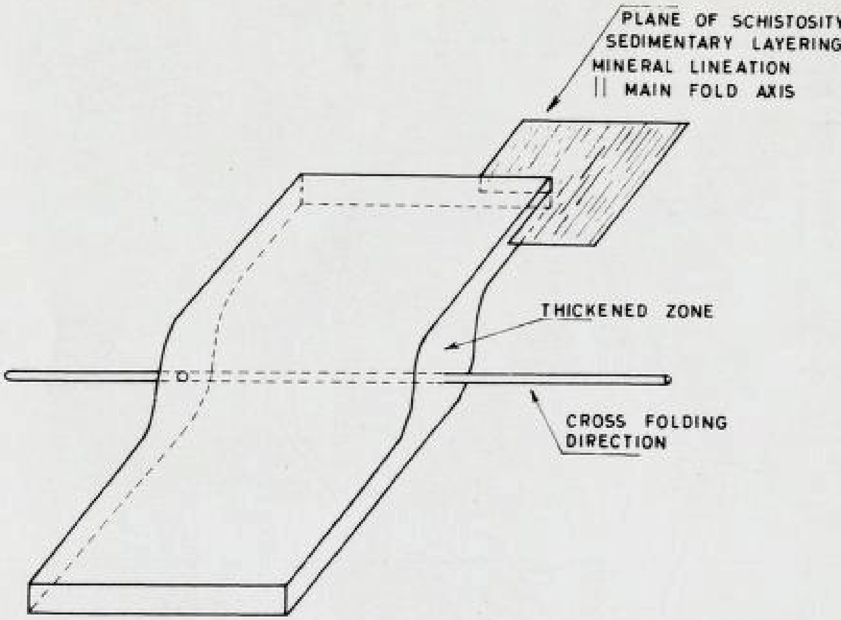

Fig. No. 6.

It was seen that these cross zones of equal (and parallel) increase in sulphide thickness always are accompanied by maximum flexure*) of the main folding axis. (Often measureable only as mineral lineation.) That the best ores are localized by a combination of the two foldings and accompanying ore thickening processes is best seen in the upper part of Skårnesdalen, where the trench systems of the old prospectors permit quite systematic observations. (See Fig. 7).

More important underground workings exist further down in the zone, but are not situated so helpfully. Heavy overburden also partly hinders complete surface observations in the lower part of the zone. However, the sum total of observations (surficial and underground) permits me to conclude that there are no reasons to believe that further prospecting (including drilling) will reveal ores of other types or of greater economic importance than those already observed.*)

*) Called "Crossfolding culminations" on the map.

*) Within the limits of the Skårnesdalen and Djupvik claims.

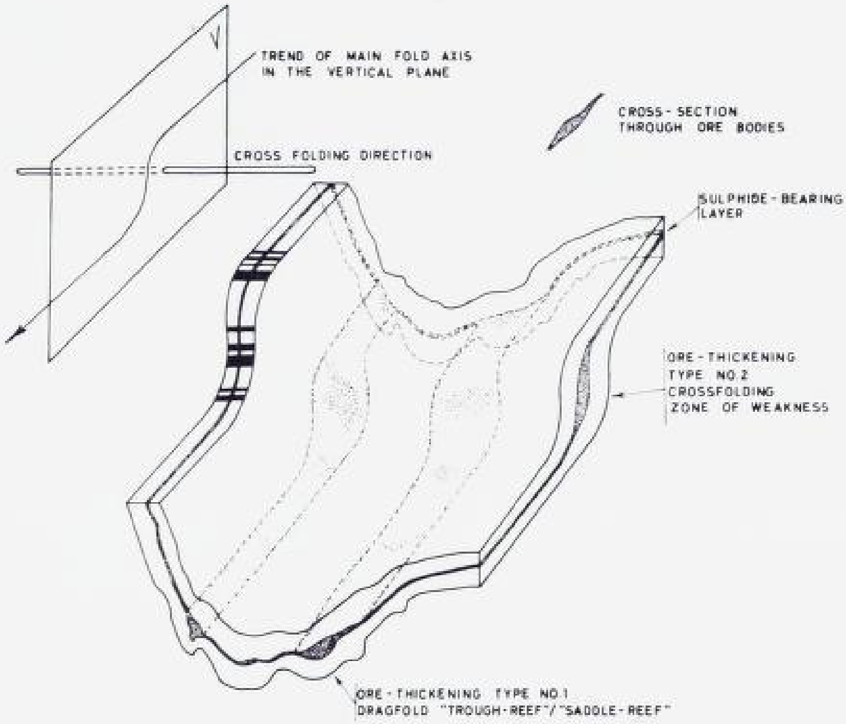
TREND OF MAIN FOLD AXIS
IN THE VERTICAL PLANE
V
CROSS FOLDING DIRECTION
CROSS-SECTION
THROUGH ORE BODIES
SULPHIDE-BEARING
LAYER
ORE-THICKENING
TYPE NO.2
CROSSFOLDING
ZONE OF WEAKNESS
ORE-THICKENING TYPE NO.1
DRAGFOLD "TROUGH-REEF"/"SADDLE-REEF"

Fig. No. 7.

MINERALOGY AND PETROLOGY OF THE ORES.

The spatial distribution of these metal concentrations, the particular composition of the ores and of their main minerals are considered in relation to the metamorphic transformation they have undergone.

The ore minerals are treated in the order of the frequency in which they occur.

OBSERVATIONS ON THE ORES

Structural features observable on the hand specimen scale are often repeated on a microscopic scale, and may frequently be retraced back to the field scale.

Two main types of ore are distinguished.

Ore type I is a stratabound, relatively massive type. In consists of thin, parallel layers, in general not at all, or negligibly, mobilized during the metamorphism.

Ore type II is a strongly mobilized ore. The inner structures are completely rearranged. It partly corresponds to the term "durchbewegt" sulphide ore. At some localities numerous inclusions of irregular or partly rounded fragments of gangue or wall rock fragments indicate that this texture is caused by a strong kneading or pseudobrecciation.*)

The "durchbewegt", brecciated ore is connected to the most tectonized parts and is typical of local zones in the Skårnesdalen claims. In slightly less tectonized ores the larger gangue inclusions often show a morphology closely parallel to that of the whole ore body, — i.e. elongated in the same directions etc. In spite of the fact that they may be included in completely disorderly sulphide assemblages, garnets especially may be formed as small scale replicas of the ore body's outer form.

In one and the same sulphide layer it is possible to observe the continuous transition from "durchbewegt" type in tectonized surroundings to type I

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*) **Type I** corresponds to the most regular of the Djupvik ores. **Type II** is mostly typical of some of the Skårnesdalen claims. These two types being extreme representatives of the development, it is stressed here that all transitions between them are found. manner:

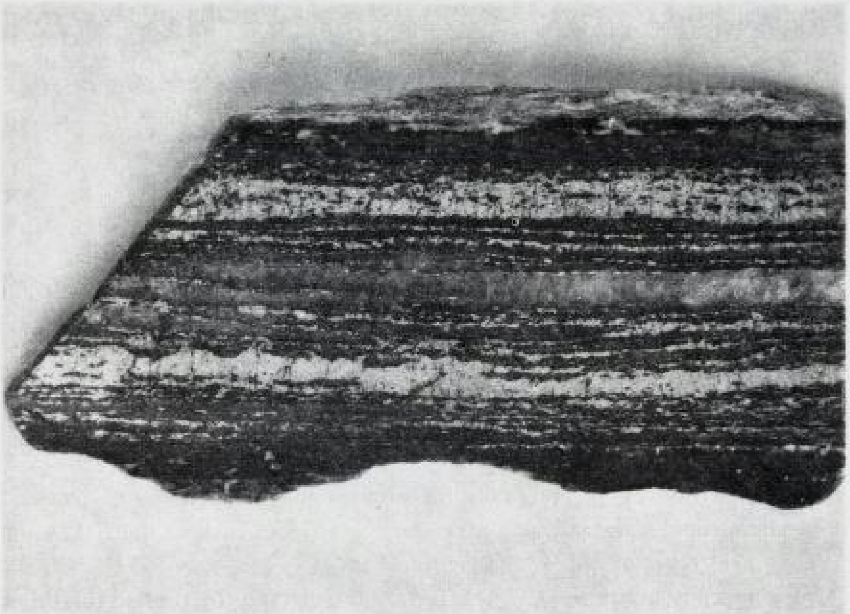

Fig. No. 8. 1,35X.

Fine-banded ore, Djupvik type. Grey with transversal cracks — ore — only sphalerite visible. 7—9 % galena finely distributed in the sphalerite. Grey, with glassy appearance — quartz. Dark grey — mica schist.

between relatively undisturbed wall rock layers. (Several localities in upper Skårnesdalen). It has been of interest to look for possible differences between ore types I and II other than the purely structural and textural. From field observations I had reasons to believe there was also a quantitative development in the relative mineral content of the different ore types. That is, galena is always more conspicuous in the brecciated ore types than in the indisturbed ones. In addition, the minor constituents such as pyrrhotite, chalcopyrite, and pyrite are also more noticeable in the former.

As no drilling has taken place, and systematic quantitative sampling has been very difficult to carry out in the thin ore bands, no absolutely conclusive answer can be given at the present regarding the relative amounts of Pb and Zn in the ores. However, the microscopical and other laboratory investigations very strongly indicate that there are no major compositional differences between the various ore types.

Grain growth and mobilization have been favoured by the dynamo-metamorphism. When galena sometimes is easily visible in certain localities, this

Fig. No. 9. Magn. 1,25X.

Ore type II. "Durchbewegt", brecciated lead-zinc ore from Shaft, Middle Skårnesdalen. Especially lead-rich type, while sphalerite only slightly prevails over galena.
White, often concave grains — galena.
Light grey — spahlerite.
Middle grey and dark — gangue, mostly quartz and garnet.
Big, rounded fragments — mostly quartz.

is certainly often due to its great relative mobility vis-à-vis sphalerite. However, sometimes it may be simply a question of greater general grain size of *all the constituents* in the ore. I will stress this last statement because some of the minor constituents which are better visible in tectonized ore types are classically considered being of low relative mobility. The main ore constituents usually show anhedral development. The curved boundaries of one single mineral area generally delimit assemblages of several individuals. Only very seldom the "grain" consists of one individual. As both sphalerite and galena are isotropic, ordinary polished section microscopy will not reveal the position of these individuals unless the specimens are etched. However, quantitative work on etched surfaces has not yet been done with these ores.

The gradual transformations undergone by the ores according to the different degrees of dynamic influence will tentatively be illustrated by a series of photographs on the following pages.

Figure No. 10 represents the zinc-rich ore from the least tectonized parts of the syncline. In unpolished hand specimen the thickest sphalerite band has a very massive look. Cracks and gangue inclusions reveal a certain porosity. The orientation of some of the silicate inclusions indicate that small translation movements may have taken place along the sulphide bands during the folding.

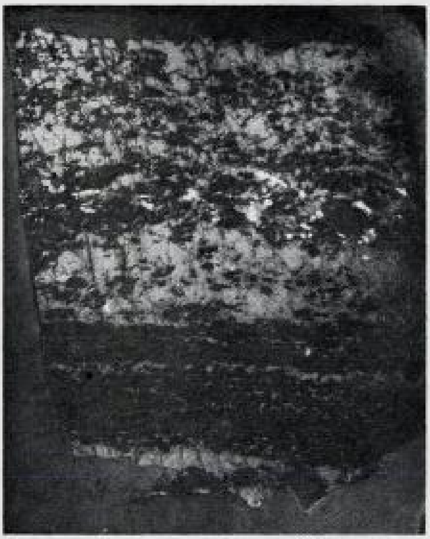

Fig. No. 10. Magn. 2X.
Polished section, layered ore, cross-shaped trench, Djupvik.
White — galena. Middle grey — sphalerite. Dark — silicates.

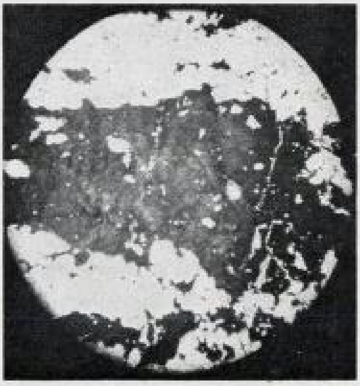

Fig. No. 11. Magn. 45X.
Thin section photo from "massive" sphalerite band, cross-shaped trench. Djupvik.

Figure No. 11 shows silicate inclusions and small cracks in the *in situ* recrystallized sphalerite, same locality as Fig. No. 10.

With increasing tectonic influence the sulphides gradually exploit the new mobilization possibilities: transverse cracks are invaded, voids behind rotated gangue fragments are filled etc. Galena forms larger areas of concentration in disturbed bands. Later the individual gangue layers in the sulphides are broken up and fragmented, while sulphides and silicates are rearranged to form an intimate mixture without distinct foliation.

Fig. No. 12, Magn. 2X.

Layered ore, weakly mobilized. White — galena. Light grey — sphalerite. Darker — silicates. Dark band ⅓ from bottom is mainly quartz. NB! Galena in larger concentrations and as fracture fillings.

In places a real segregation has taken place between sphalerite and galena. Galena is often concentrated in the weakness zones of the wall rocks and gangue layers. Deposition of mobilized quartz is accompanied by galena as vein fillings in fold fractures. Systems of such apophyses are seen fingering out directly from the solid ore bodies into the wall rocks, or criss-crossing the intercalated silicate layers within the ore bodies. The geometry of these branching-out depositions is clearly tectonically dictated — fractures generated at a late tectonic stage — often perpendicular to the foliation.

These quartz-sulphide depositions are regarded as pure lateral secretions from the primary ore bodies. They underline the relative mobility of galena vis-à-vis for instance sphalerite.*)

One of the field-scale characteristics of ore tectonics which is visible in polished section scale is the "saddle reef"/"trough reef" phenomenon.

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*) The zinc spinel gahnite is found as gangue mineral and is also distributed with decreasing density and amount several meters in the hanging wall — and foot wall directions.

This metamorphic mineral may probably be looked upon as a mobilization product, — part of the lateral secretion from the ore bodies. It is thus a question if the observed indications of higher mobility of lead versus zinc (galena/sphalerite) be restricted to the *sulphidic milieu*.

Fig. No. 13. Magn. ca. 3X.
Lead-rich quartz deposition in wall rock. Lateral secretion directly connected with brecciated zinc-rich ore.
White — galena. Light grey, strongly cracked — sphalerite. Dark — mainly quartz.

Fig. No. 14. Magn. 2,5X.
"Saddle-reef" ore thickening. Only sphalerite (light grey) and silicates visible, but the specimen also contains some finely distributed galena.

Measurements of thickenesses around the crests and on the limbs of the smaller folds indicate that much of the translation movements must have followed the sulphide layers.

Sometimes "durchbewegt" sulphide assemblages are found between neatly folded silicate bands of even thickness all along. However, in other places it seems that the sulphides had attained a high degree of solidity while the surrounding silicates were still plastic. The recrystallization history of the sulphides must have taken place over a long part of the dynamo-metamorphic development of the area.

The main tectonic style of the whole area can be retraced down to a quite detailed scale. Thus, the supposed pretectonic origin of the mineralization is well demonstrated by the spatial relationships of ores and wall rocks. Some mineralogical features also indicate the two-phased folding pattern. (A two-

Fig. No. 15. 2X.
Folded quartz-garnet-mica schist. White — galena, light grey — sphalerite. Grey — garnet. Dark grey and dark — quartz and muscovite. Sulphides and gangue fragments in ore area strongly disarranged, ore thickening in drag zones. The central band, which now is the axial plane of the fold, must have been sulphide-bearing before the folding.

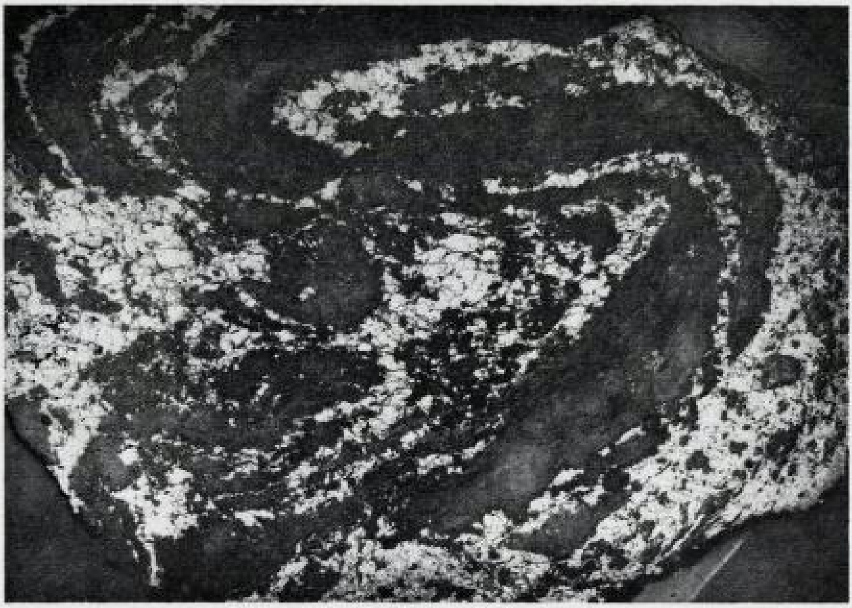

Fig. No. 16. 1,4 X.
Cross-section of strongly elongated "ore-rod", Skårnesdalen.
Illustrates how false ore thicknesses may have given the old prospectors an optimistic, but unrealistic view on the economic possibilities of these ores.

phased development is for instance indicated on a micro-scale by some gangue and wall rock minerals.)

There are many arguments indicating that the premetamorphic morphology of the ores in these sediments was of perfectly concordant character.

In spite of segregations — lateral secretions and other mobilization phenomena — it is believed that the average composition of the ores, based on foot wall to hanging wall cross-sections, is about the same throughout the whole area.

THE INDIVIDUAL MINERALS

Their mineralogical characteristics and mutual relationships.

Sphalerite is volumetrically the most important ore mineral, its variation range being from 50—95 vol. %. Macroscopically the mineral is always dark brown. The iron content is generally from 4—9 weight %. In thin sections it has partly an even red-brown colour; partly different irregular shading may be seen in the same assemblage. In polished sections, the common sphalerite-grey is seen, exceptionally with faint bluish tint. The inner reflection is strong burgundy-red, but sometimes light red and very rarely yellowish.

The mineral has not yet been found in euhedral crystals, though single faces have been observed. Mostly, aggregates with irregular, preferably convex, curved outlines occur. They consist of a great number of individuals, of very varying grain size. The results of etching a restricted number of polished sections, show that the sphalerite individuals are mainly fine - to medium-grained, although single crystals of up to 5—6 mm may be observed.

Twinning lamellae seem to be relatively common. Twins seem to be rarer in the fine-grained varieties than in the coarse-grained.

In the aggregates, the mutual sphalerite boundaries are mostly curved, irregularly zig-zagging lines, obviously independent of, for instance, the tectonic directions, or twinning.

Small blebs, nearly exclusively of pyrrhotite, but also some chalcopyrite, are found in certain aggregates. Their size is highly variable, as well within one single sphalerite grain as from one aggregate to another, and the blebs do not show any systematic orientation — neither mutually nor vis-à-vis their host mineral.

Relatively larger bodies of pyrrhotite are frequently seen as elongated areas near the boundaries of sphalerite aggregates or as rims on the grain boundaries. This may most probably be connected with exsolution processes during grain growth.

The large sphalerite aggregates contain numerous inclusions of the gangue minerals. More generally, it may be said that all the other important minerals of the occurrence may be found included in sphalerite. At places sphalerite fills up all possible voids in the silicate mineral assemblages, thus forming a continuous matrix network for the gangue.

Morphologically this can quite equally be evidence of the ubiquitous presence of sphalerite within the ore body *boundaries* during the metamorphism, and of its *mobilization*.

In addition, sphalerite is found as inclusions in the other chief mineral galena, in pyrrhotite, and in some of the silicates. Mutual inclusions of all the paragenetic members is quite common, thus indicating their possible "contemporaneity."

appears as small assemblages with irregular outlines, the mineral being always

Galena is the second main mineral of the ores. Macroscopically it mostly characterized by its cubic cleavage. Cubes up to 4—5 mm have been measured.

In the tectonically least disturbed ores (Djupvik type) galena may be visible only with difficulty. Percentages up to 5—6 may not be seen with the naked eye.

The individual granularity varies considerably, though a fine to medium size prevails. The grain size of the whole assemblages may in the most tectonized areas reach a couple of centimetres, — mostly, however, 1—2 mm grains dominate here. Euhedral crystals are seldom observed, subhedral to anhedral individuals in aggregates are the prevailing forms.

Generally, galena is relatively far more conspicuous under the microscope than at other scales. Apart from the already mentioned, lead-rich lateral secretions, galena may in places make up to one half of the sulphide volume. From polished section measurements the average lies between 15—25 %.*)

Sphalerite/galena — mutual distribution.

Generally it may be said that in intimate mixtures between these two minerals, sphalerite has a great tendency to show convex, though somewhat irregularly curved outlines. The galena assemblages usually have concave, cusplike, boundaries. Thus, galena often seems to fill interstices between more or less rounded sphalerite grains. Small galena inclusions in sphalerite may appear as a series of pointed stars, whilst the smallest galena inclusions may have a droplet-like rounded form.

The starlike, cuspy galena bodies in sphalerite are seen as a result of relative

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*) It has to be emphasized that the systematic sampling in the ore zone is mainly of qualitative value. Separately, some of the more than 150 trenches have been chip sampled, but mostly their evaluation has been carried out visually and at low magnifications.

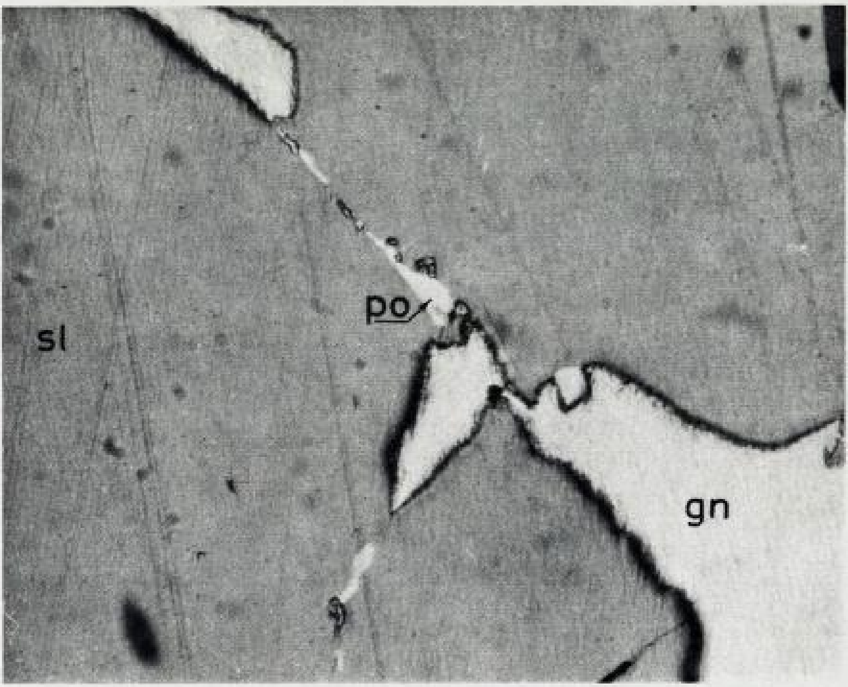

Fig. No. 17. Magn. 165 X.
Common spatial relationship between sphalerite (convex) and galena (concave). On the grain boundaries droplets and elongated bodies of pyrrhotite.

grain boundary forces during metamorphic grain growth (10). However, as regards the much smaller rounded galenas, it is possible that when their including sphalerite only consists of one single individual, all throughout the metamorphism, this form may be kept intact from beginning to end. Inversely, the sphalerite inclusions in galena aggregates have always adopted a more or less rounded form.

However, when the mineral is influenced by other factors, as for instance in filling up tectonic voids, especially in gangue-rich parts, sphalerite may have radiating satellite arms in different directions. Further, of course, embayments in the convexely curved outlines may be caused by the other ore minerals, for instance pyrrhotite or pyrite.

Two features of the sphalerite/galena segregation are of special importance.

1. The microscopy reveals that in the relatively undisturbed ore types, where

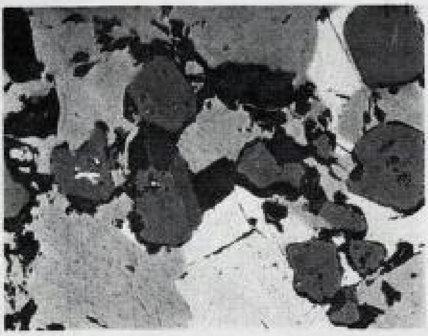

Fig. No. 18. Magn. 100 X.
Section of sphalerite/silicate aggregate. A galena branch seems to force its way into the aggregate. Galena is already included in the silicates. White — galena, light grey — sphalerite, dark-grey and black — silicates and holes.

galena may be hardly visible to the naked eye, the lead/zinc proportion may be the same as in highly tectonized ore types.

2. The lateral secretions have formed a corona of galena-rich deposition along the border zones of some parts of the ore bodies. This galena must derive from the inner parts, thus making these zones correspondingly poorer in galena. I am of the opinion that the total cross-sections of these ore bodies have not changed notably in total metal content during the metamorphic rearrangement

The relatively greater transportability and faculty to form larger concentrations, is typical for galena in this particular sulphide paragenesis.

Minor constituents.

Pyrrhotite is seldom visible to the naked eye. It has a shiny bronze-brown colour. In the more tectonized parts, pyrrhotite is seen as small irregular aggregates.*)

As in the case of galena, the microscope reveals that pyrrhotite is far more widely distributed than is apparent from field observations. Its average quantitative distribution is actually unclear, variation ranges being probably between 1 % and 6 %.

Textural appearance is partly quite similar to that of sphalerite, but pyrrhotite is, if possible, less able to develop crystal faces. Possible faces are observed at only few localities (Fig. 19). As a rule the mineral appears as small droplets or as larger, uneven assemblages with convex outline.

*) Very exceptionally it has been observed in some brecciated offshoots from the ore body to be a main constituent together with chalcopyrite and pyrite. These localities are few and small, without perseverance in any direction. The wall rock here contains some graphite.

Fig. No. 19. Magn. 100 X.
Sphalerite aggregates with cross-cutting vein of galena. The "vein" is blocked by pyrrhotite with galena inclusions. The rectilinear outline is an expression of crystal face development, a rare occurrence in these ores.
Black — silicates and holes, in galena-polishing scars, blacksquares — hardness measurements. Droplets of unidentified mineral in upper middle part — probably fahlerts.

Pyrrhotite has numerous inclusions, both of galena and sphalerite and is itself frequently included by these. It is often found as elongated biconvex bodies along sphalerite/galena boundaries. Proportionally, in equal areas of galena and sphalerite, the latter mineral is the richer in pyrrhotite inclusions. These are often concentrated near the boundaries of the actual sphalerite aggregate. As these numerous inclusions seldom show any common orientation in the host mineral, and may be of very different size, it is always difficult to know if they are simple inclusions or exsolution products. Even the smallest blebs are mostly constituted by several individuals.

Pyrrhotite in contact with sphalerite may sometimes be interpreted as a sign of formation under iron-saturated conditions of the sphalerite's contact area. This has been exploited as one of the fundamental principles in the so-called "FeS—ZnS thermometer" (5 and 9). The debate on these principles has now lasted some years. At the moment much uncertainty is connected with the application of such "thermometry", especially in the metamorphic complex sulphide ores (1). Only the bare mineralogical results concerning the present investigation are presented here.

If the chemical components had full opportunity for complete exchange in all directions and proportions throughout the whole ore body, the sole presence of one single pyrrhotite crystal would be the necessary and sufficient condition of sphalerite formation under iron excess conditions. This is certainly not the case in most of our Caledonian ore bodies, and in particular it is absolutely not the case for the lead-zinc ores of Håfjellet. Only a small percentage of the sphalerite grains of these ores are in direct contact with pyrrhotite, and the varying solid solution content of FeS in sphalerite from Djupvik — Skårnesdalen may as well be caused by lack of free FeS in the orignal admixture as by differences in temperatures (see diagram page 37).

It is often observed in some of the normal Caledonian pyrite/base metal deposits that the distribution of chalcopyrite seems to a certain degree to parallel that of the pyrrhotite. Without further comparison or comments it can be mentioned that this is also the case in the presently investigated ores.

Chalcopyrite is found as inclusions in the above mentioned sulphides, and in some of the sparse pyrite observed. As a rule, when chalcopyrite is found (totally only in trace mounts) it is always accompanied by pyrrhotite. Either, pyrrhotite is located a short distance away, or they are in contact with each other.

Elongated bodies of chalcopyrite are often found making up the border of sphalerite aggregates. When it is wholly surrounded by the latter it mostly takes on well-rounded forms, such inclusions seem to be preferably located towards the boundaries of the host grain.

In places whole multitudes of composite inclusions of pyrrhotite/chalcopyrite are found in sphalerite, (more seldom in galena and pyrite). Usually well rounded towards their host, they are of different size and there is no visible alignment between the different inclusions. Within the single included body, the boundary pyrrhotite/chalcopyrite seems to be arbitrarily zig-zagging.

The well-known tendency of chalcopyrite to "fill in" interstices and small cracks is frequently observed. Crystal faces are never seen.

Pyrite is present only locally and in negligible amount. The fraction zinc-lead sulphide/pyrite must be several hundreds to one.

The size of the pyrite ranges from sub-microscopic to crystals of 3—4 mms. It seems typical that in the ordinary development of these ores, just as it is seldom to find pyrite at all, so is perfect crystal development relatively rare.

Pyrite may be found as tiny droplets, with few distinct faces, along sphalerite or galena boundaries, and as rounded inclusions in sphalerite. It seems as if the mineral has best chances to develop crystal faces when it is situated at the meeting point of boundaries from several other minerals. The greater individuals, over 1 mm, are usually subhedral, seldom euhedral, and mostly in contact with two or three other minerals (seldom included in one single phase).

Inclusions in pyrite are commonly chalcopyrite, sometimes pyrrhotite.

The frequency of inclusions increases towards the border of the mineral, and especially towards the imperfect corners. The crystal core is often totally exempt from guest minerals.

The finely distributed bodies, the rarity of good crystal faces, and its inclusion-relationships give the pyrite a somewhat remarkable textural appearance. This seems to underline the probability of contemporaneous formation of all the mentioned minerals in the parageneses.

Magnetite and ilmenite, occur in trace amounts. The two accompany each other, and are found as inclusions, mainly in sphalerite, but also as free grains

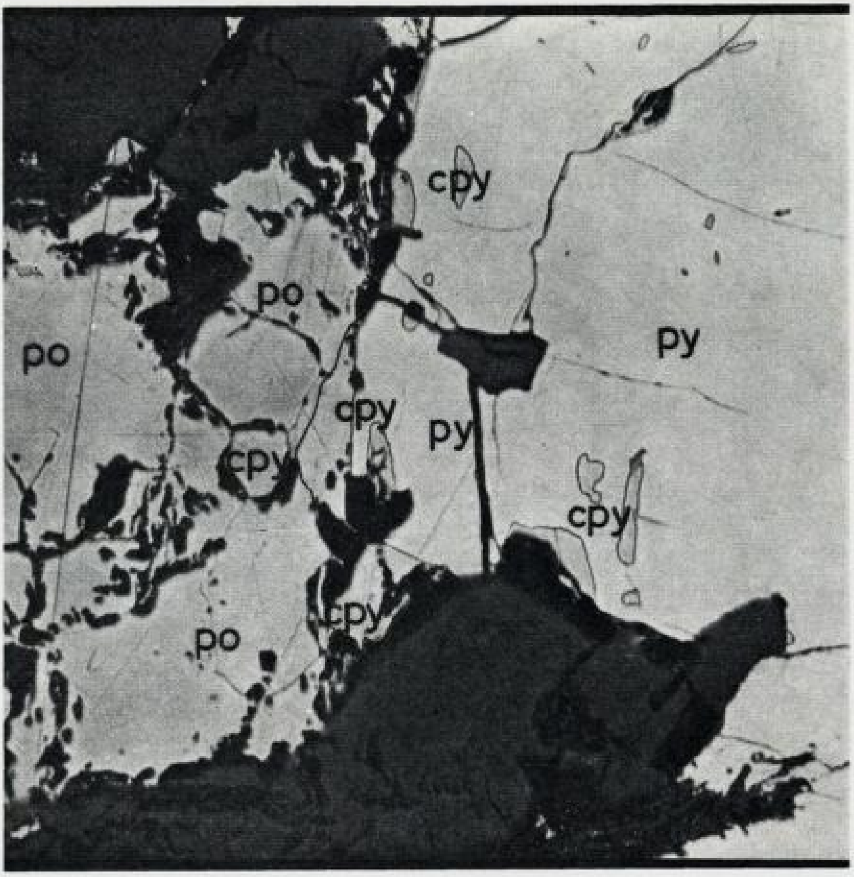

Fig. No. 20. Magn. 67 X.

Distribution of chalcopyrite in border zone between pyrite and pyrrhotite. The boundary itself is occupied by an elongated chalcopyrite body. The cracked pyrrhotite assemblage to the left, and the big pyrite crystal are elsewhere very sparsely contaminated by chalcopyrite. Black and dark grey — silicates.

in contact with sphalerite, galena, and pyrrhotite. Systematic information regarding their detailed distribution is lacking.

Hematite has been found in very few specimens only, — in contact with sphalerite and pyrrhotite.

The main constituents of these ores are thus few. In composition, the ores represent a very uncommon type of sulphide deposit in the Caledonian mountain range. Their textures exhibit a striking "contemporaneity" of formation

Fig. No. 21. Magn. 70 X.
Corner of pyrite crystal which elsewhere shows perfect cubic development. Rectilinear cubic faces do not complete the right angle in the corner zone.

of all minerals. No consistent depositional sequences are observed. The mineral interfaces give evidence of general metamorphic grain growth.

In the course of the whole metamorphic transformation local variations of temperature and pressure may have favoured certain minerals or reactions, but such differences seem to have been adjusted over short distances within the ore bodies.

The compositional homogeneity of the ores, throughout the area, more or less independent of dynamic transformation also indicates that the sulphide distribution is a premetamorphic feature.

Together with the earlier mentioned morphological arguments, it does not seem unreasonable to suggest that this distribution be really of syngenetic origin.

(Two isotropic minerals of high reflectivity have remained unidentified. Quantitatively their distribution seems to be insignificant. Marcasite is found at a few localities of supergene alterations of special pyrite pockets. The supergene alterations of the ores will be the subject of a separate note. (See also 4).)

SPECIAL MINERALOGICAL CHARACTERISTICS OF SPHALERITE AND GALENA

Determination of iron content and unit cell edge of sphalerites.*)

Twelve sphalerites from different parts of the area and from different ore types were analysed. They were chosen as representatives of ores which possibly could have been formed under different conditions.

Specimen number	Analyzed weight % Fe	Calculated weight- % FeS	Calculated mole-cular- % FeS in specimen sup-posed consisting only of ZnS and FeS	Calculated mole-cular- % FeS in specimen with 0.5 % trace elements	Cell-edge length in Ångstrøm units
6222 A	3.925	6.179	6.803	6.814	5.4135
6222 B[II]	3.93	6.187	6.81	6.823	5.4155
6224	4.303	6.77	7.45	5.465	5.4220
6229 A	4.54	7.15	7.86	7.873	5.4197
6206	4.76	7.49	8.24	8.251	5.4190
6262	6.305	9.925	10.884	10.901	5.4175
6253 A	6.425	10.11	11.09	11.106	5.4175
6253 B	6.64	10.45	11.46	11.475	5.4180
6201	6.84	10.77	11.797	11.815	5.4194
6257 B	7.88	12.40	13.57	13.588	5.4205
6259	9.215	14.51	15.83	15.855	not determined.
6264	11.864	18.68	20.29	20.3225	5.4225

*) As mentioned earlier these determinations have been carried out partly for the purpose of trying out some of the principles of the so-called "FeS/ZnS-geothermometer". The discussion is omitted in this paper, only results and statements relevant to these ores are given.

The iron content was determined by a wet chemical method. Limits of precision — relative percentage ± 0.2.

The cell dimensions were calculated from Debye-Scherrer diagrams (cameras of Geological Museum — 9 cm diam.). Graphical extrapolation was used; theoretical precision — 0.002Å.

Surplus of FeS is a condition for maximum admixture at a given temperature. As pyrrhotite is not present throughout the ores and particularly in contact with every sphalerite grain present, it is maintained that the FeS content is not always representative of the highest temperature met with by the actual sphalerite individual. Thus if extreme tectonization has been accompanied by locally higher PT conditions, it may in this way not be expressed by higher iron content in the sphalerite.

The present determinations do not express consequent differences between sphalerites from more or less tectonized ore types. Further there does not seem to be any consequent differences between the same ore types taken from separate ore bodies. Thus, the varying composition of the investigated sphalerites, is, I think, more attributable to different FeS concentrations available in the local depositional milieu.

Actually the results are only interpreted as being expressions of sphalerite recrystallization in a partly undersatured iron milieu under the temperature and pressure conditions of the epidote-amphibolite facies.

Trace element contents of three sphalerites.

Professor Ivar Oftedal, Oslo, has kindly interpreted optical spectrograms of three sphalerites, two from Djupvik ore zone, and one from a brecciated ore zone, Upper Skårnesdal.

The three proved to be very equal in composition:

"Cd: 2000 — 3000 ppm.
Fe: probably > 1 %*).
Co: relatively much for sphalerite.
Cu: some.
Mn: probably some".

The low contents of Cd and Mn are thought not to influence the unit cell dimensions. That means they are also too low to influence the solubility of FeS in ZnS.

The values are not given with accuracy, but should give a correct impression of the conditions.

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*)Determined chemically for the three: 4.3 — 6.305 % Fe.

Trace elements in galenas.

a) From optical spectrograms interpreted by professor Ivar Oftedal.
Values in p.p.m.

	Sb	Zn	Bi	Ag
6253 PbS*)				
Moderately mobilized ore	500	20	100	200
6262 Pbs				
Brecciated ore	500	10	20	100

b) Silver content determined by help of atomic absorption spectrograph (analyst: Brenda Jensen, B. Sc., Geologisk Museum.)

No.	Provenance/type	% Ag
6253 A	Adit No. 3 Sk.dal,	0.013_1
6253 B	moderately mobilized ore	0.013_4
6203	Trench C. Djupvik, least mobilized ore	0.016_2
6259	Adit No. 1 Sk.dal, moderately mobilized ore (impurities).	0.019_9
6262 A	Adit No. 3 Sk.dal,	0.030_1
6262 B	strongly mobilized ore	0.029_0

Margins of theoretical precision: ± 2 % relatively.

*) Sphalerites from the same two specimens had 6.425 % and 6.305 % Fe.

THE SURROUNDING ROCKS — WALL ROCKS — GANGUE

The rocks in which the zinc-lead ores are interbedded are:

a) quartzite, the Djupviknes unit.

b) garnet-mica schists.

General description.

a) The Djupviknes quartzite is a very pure sedimentary quartzite. Other minerals than quartz are only found in very small amounts, — the minor constituent is mainly muscovite. Feldspar especially seems to be quite absent from the unit. Its bedding planes/schistosity are defined by thin muscovite layers. A weak lenticular sedimentation may be observed.

b) Garnet-mica schists are situated below and above the Djupvik unit. As the main bulk of the sulphides lies immediately under and partly above the quartzite, their wall rocks are chiefly made up by these schists.

   Main constituents of the schists are: quartz, mica and garnet. Their composition is somewhat variable. Vertically, radical changes may occur from layer to layer, and minor horizontal variations (original sedimentary lateral variations) are locally found.

   Layers consisting chiefly of only one of the main constituents occur.

   Identified constituents are: quartz, muscovite, biotite, garnet, zoisite/clinozoisite (epidote), plagioclase, hornblende, chlorite, sphene, rutile, (zinc spinel), tourmaline, apatite, zircon.

   The quantitative role played by the minor constituents varies within wide ranges. The individual minerals may be found concentrated in certain layers, — elongated lenses or "pockets".

   For the whole mapped unit each individual constituent may usually be found, however, in small amounts, within all limited areas. By a certain degree of extrapolation it is thus possible to determine the mineral facies throughout the distribution area of the unit.

As mentioned earlier, there are no eruptive massifs, no sills or dikes in or in the immediate vicinity of the area.

Abrupt mineralogical changes from strata to strata — for instance of garnet and mica contents — are due to primary differences in the chemical composition of the sediments.

Generally, the mineral facies is extremely uniform. The lower part of the epidote-amphibolite facies prevails all over the area. In his comprehensive study of the stratigraphical column, Steinar Foslie came to the same conclusions on the basis of sampling along the coast line. The present investigation based on detailed work in and around the ore zones can only confirm Foslie's views. In particular, the gangue and the immediate wall rocks of the ores, exhibit the same mineral facies as the country rocks. Minor changes in mineral facies are strictly local and may probably in every case be connected with small tectonic irregularities — stress or shear zones. Exceptionally, the higher part of the epidote-amphibolite facies has been reached. In addition, thin (few cms) chlorite zones are observed at several localities — not only in the most tectonized areas. They are supposed to be representative of tectonic shear zones and their mineral content to be the result of a retrograde metamorphic development. A very marked schistosity is in general parallel to the sedimentary layering. The foliation planes are mostly well defined by silvery, shiny, slightly wavy muscovite layers.

In the more tectonized parts an oblique schistosity is locally well developed. When strong oblique schistosity crosses the concordant sulphide layers, ore

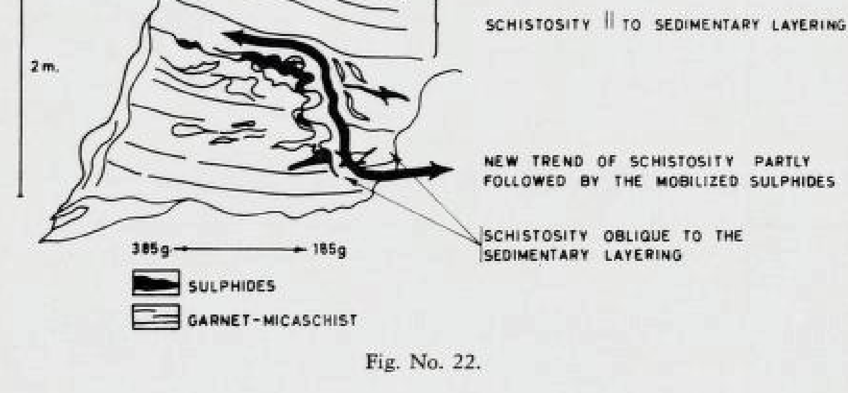

Fig. No. 22.

may in some places be seen to have been mobilized and redeposited more or less conformably to these new directions. (See fig. No. 22.)

On the whole, the sedimentary sequence of the unit consists of quite persistent layers, however, by analogy with observations in the quartzite, a weak tendency to lenticular development is observed.[1])

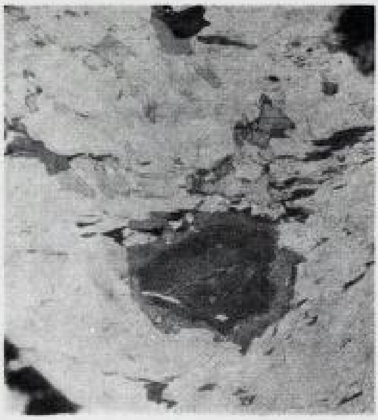

Fig. No. 23. Magn. 160 X.
Zoned tourmaline in quartz-garnet schist. Skårnesdalen.

Particular development of garnets.

Some of the schist constituents exhibit a well developed zoning, mostly two phases are seen. This may probably be interpreted as a reflection of the two phases of tectonic development in the area. Tourmaline seems to be made up of two main zones. The garnets are in places highly influenced by the tectonic development and also show remarkable zoning features which may be correlated with the two phases observed elsewhere:

1. Elongated rods, with longest axis up to ten times as long as the cross section diameter.
2. Zoning, mostly two-phased.
3. Helicitic development and different orientation of inclusions in the inner and outer zones.
4. Garnets within the ore bodies may exhibit different kinds of inclusions. Sulphides preferably occur only in the outer zone.

Differences in colour shading between inner and outer zone are occasionally visible under the microscope. By the use of super-panner, magnetic separator and hand picking it was possible to separate two different garnet fractions from a big specimen with zoned garnets.

Three properties were used in order to determine the two zones (dark garnet, light garnet):

1. Cell-edge dimension calculated from Debye-Scherrer diagram.
2. Refractive index.
3. Principal chemical constituents determined by optical spectrography.

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[1]) It is stressed that these extremely elongated flat "lenses" are caused, not by tectonics, but by sedimentation itself.

Fig. No. 24. Magn. 90 X.
Elongated garnet from sulphide-bearing schist. Skärnesdalen. Black — sulphides.

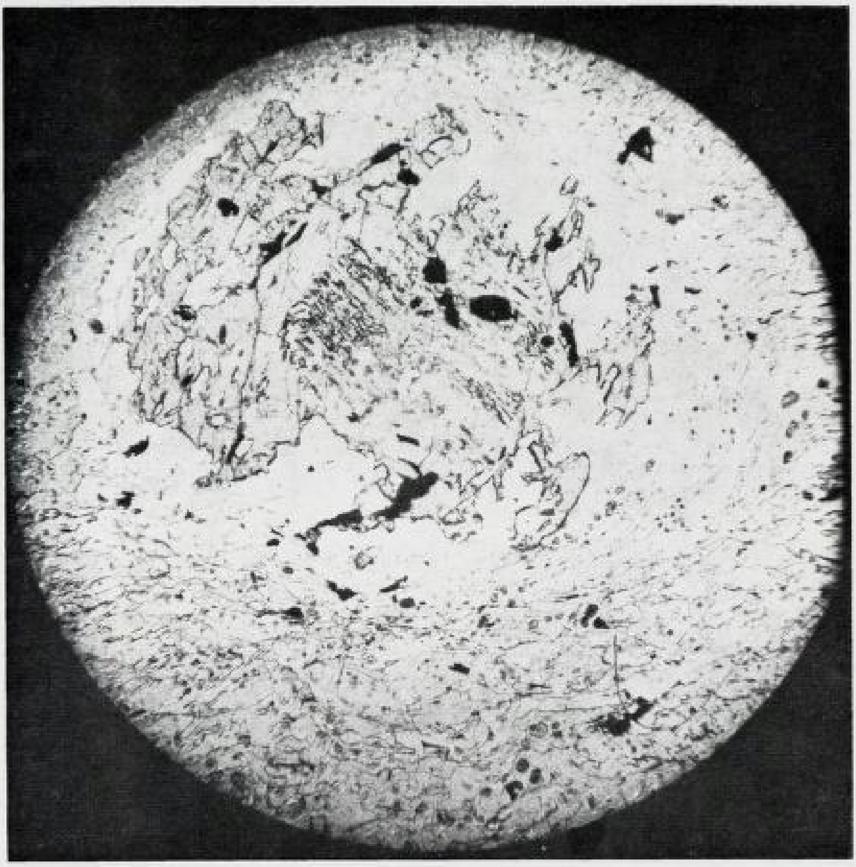

Fig. No. 25. Magn. 90 X.
Helicitic, zoned garnet from sulphide-bearing schists, Skårnesdalen.
Parallel oriented inclusions in the core. Helicoidal structure and sulphides in outer zone.
Schistosity plane of surrounding silicates is here "horizontally" oriented.

Characteristics:

	a_0	R.I.	Chemistry
Dark garnet	11.5795 ± 0.002	1.8210 ± 0.003	Fe-Al-Mn-Mg Ca ⩾ 1 %
Light garnet	11.5815 ± 0.002	1.8225 ± 0.003	Fe-Al-Mn-Mg Ca = 0,1 %.

The main elements are given in decreasing order of abundance. Only Ca is well quantitatively determined. There is a marked difference in the Ca-contents.

According to the diagrams of Sriramadas (8) and Winchell (14), a semi-quantitative three-component determination of the two garnets would give the following percentages:

	Almandite	Spessartite	Andradite
Dark garnet	59	37	4
Light garnet	60	35	5

The sum of each is 100 %; the small pyrope constituent is omitted. However. the qualitative differences are well illustrated.

These systematic zonings provide evidence of physico-chemical variations during the growth of the minerals. They may possibly be related to the clear two-phased development of the dynamo-metamorphism.

Sturt has used the compositional variations of garnets to express differences in regional metamorphic conditions (11). The fact that the Ca-content of the outer zone decreases to only 1/10 of what is found in the core, would, accordin to Sturt, lead to the presumption that the outer zone was formed under slightly higher PT-conditions than the core.

Nothing conclusive is, of course, drawn from this single observation. The interesting fact is mainly that a more or less distinct two-phased development also is observable in some of the minerals.

THE GANGUE OF THE ORES — SPECIAL FEATURES

The constituents of the surrounding rocks also form the gangue of the ores. However, the gangue and the immediate wall rocks exhibit some particular features:

1. Quartz is more conspicuous and occurs in more coarsely crystalline aggregates than elsewhere in the schists.
2. A very dark biotite occurs in large concentrations of differently oriented

individuals. These are only exceptionally seen outside the actual ore zones.
3. The garnets occasionally contain sulphide inclusions in the outer zone.
4. The metamorphic zinc spinel, gahnite, is part of the gangue of the ores and also shows a specific distribution in the immediate foot wall and hanging wall rocks.

Glassy and milky-looking quartz bodies are formed on the same scale and according to the same pattern as some of the ore bodies. The elongated rod-form may, as for the garnets, be followed down to the microscopic scale. (Mineral lineation parallel to the main fold axis of the region.)

Quartz enrichments have taken place within the tectonized sulphide concentrations.

The biotite concentrations are notable because of both the high iron content of the mineral and its particular spatial relationships. The absence of foliation planes in the mica bodies places their formation at a late stage of the dynamometamorphism. Their very dark colour (also compared to other biotites in the country-rocks) probably relates them to the iron equilibrium between ores and wall rocks. Occasionally, the border zone of certain biotite individuals may be somewhat bleached.

Gahnite, the zinc spinel, is uniquely met with in the ore zones and in the immediate wall rocks of the sulphides. Grain size and frequency decrease from the central ore plane symmetrically in the hanging wall and foot wall directions.

Beautiful, deep green gahnite octahedrons of up to 5—6 mms are locally found in glassy quartz enrichments. Surrounded only by quartz, it may thus develop subhedral to euhedral individuals. In intergrowth with for instance garnet, crystal faces may be totally absent and the mineral recognizable only with difficulty. Useful diagnostic features under the microscope are its weak greenish shading, best seen by help of additional incident light, and when developed, its cubic parting pattern — parallel the (001) planes.

This spinel is here regarded as a metamorphic product (6 and 13). Zinc has been mobilized into the surrounding rocks in oxidic form. It is typical that the distance from sulphide concentrations at which gahnite may be found, seems to be proportional to the tectonic intensity of the actual locality.

While lead was the more mobile of the two main elements in sulphidic form, zinc has been the more mobile of the two, however, in oxidic form.

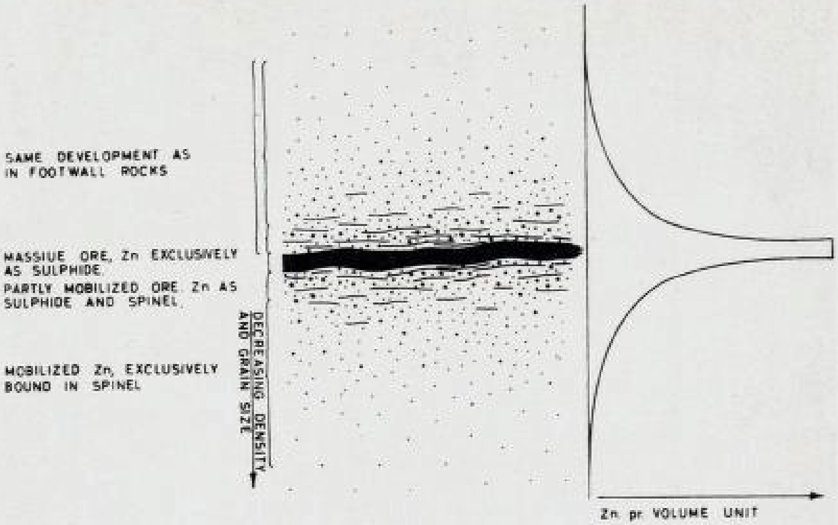

Fig. No. 26.
Symmetrical distribution of gahnite.

Fig. No. 27. Natural size.
Gahnite in tectonically conditioned quartz enrichment.

Fig. No. 28. Magn. 160 X.
Gahnite showing octahedral outline and cubic parting.

Mineralogical data on gahnite from the zinc-lead ores.

1. Refractive index determined in gahnite from four different localities:

   R.I. $= 1.797 \pm 0.005$.

2. Lengt of unit cell edge was calculated from Debye-Scherrer diagram of one specimen:

   $a_0 = 8.1038 \pm 0.002$.

3. Optical spectrographical analyses were kindly interpreted by professor Ivar Oftedal:

   Main components: Zn, Fe, Al, Mg.
   Some Si is considered as impurity.

Fig. No. 29. Magn. 160 X.
Gahnite partly intergrown with garnet. Black — sphalerite, matrix — quarts and light mica. sp — spinel, ga — garnet.

Trace elements: Ni, Pb.

Pb probably derived from admixed galena. The presence of Ni is enigmatic.

4. Analysis carried out on X-ray fluorescence spectrograph, Geological Museum, Oslo.

An artificial mixture of oxides was used as standard. Because of similarity of refractive index and cell edge dimension with the values of the gahnite F. M. Vokes has found in the Bleikvassli ore, his analysis proportions were chosen for the mixture.

Results: Gahnite, Skårnesdalen, Ofoten. No. 6202.

Al_2O_3	56.25 %	
Fe_2O_3	6.20 %	
MnO	0.04 %	Analyst: Sv. Bergstøl.
ZnO	36.90 %	
MgO	1.00 %	
	100.39 %	

Determination of the lighter oxides is subject to some uncertainty. For Al_2O_3 the limits of error are ± 5 %, relatively.

Determination of MgO was made partly by direct comparison with standard, partly by difference.

The other oxides are considered to have been determined with great accuracy.

This zinc spinel must mainly be a solid solution of the three molecules gahnite $ZnAl_2O_4$, hercynite $FeAl_2O_4$, and pleonaste $MgAl_2O_4$.

POINTS OF VIEW ON THE GENETIC PROBLEM OF THE ORES

The zinc-lead ores of the Håfjell syncline are considered as a strata-bound mineralization. Their horizontal distribution may be followed several kilometers while their restricted vertical position is within a few decameters of the stratigraphical column. The layering of the sulphides is characterized by the same formal features as those found in their wall rocks.

It is concluded that the ores were present within their host rocks before the folding epochs of the Caledonian orogeny, and they are supposed to have been interbedded in the sediments in a perfectly concordant manner.

The folding has remodeled the orebodies; ore thickening patterns are, even on a very detailed scale, in good accordance with the regional tectonic development.

The metamorphism has transformed the inner textures of the sulphide assemblages, but their chemistry is supposed to have undergone only very local changes — for instance in the form of lateral secretions; lead in the original sulphidic form, zinc partly as sulphide, partly as oxide.

Metamorphic recrystallization has mostly taken place *in situ*, but mobilized material has also for a larger part been redeposited at some distance from the original site.

Very locally redeposition has taken place along secondary discordant schistosity planes, but these exceptional "apophyses" may generally be traced back to an original concordant position.

As regards the question of the temperatures of ore-formation, it is at present not possible to use the existing geothermometers well enough to give absolute temperatures. Of course, the metamorphic recrystallization took place within a wide temperature range and over a long period of time. It is maintained that the ore formation temperatures were within the range of the epidote — amphibolite facies — a regional mineral facies well determinable in the gangue and in the wall rocks.

The ore textures do not reveal any "age" differences between the individual constituents. All the ore minerals have probably been assembled within the depositional volume at the same time. Thus many arguments indicate that the primary "mise en place" of the sulphides took place at a very early stage of diagenesis of their host rocks. But as the metamorphism has masked and transformed many of the supposed primary characteristics, it is in fact quite speculative to try to affirm an absolute syngenesis of ores and wall rocks.

However, the theory that the zinc-lead ores may be metasediments themselves, and thus of syngenetic origin, seems very fruitful from several points of view.

The supposed metamorphic mobilization (lateral secretion) has created a distribution of ore-forming elements in the hanging wall and foot wall directions which seems to be symmetrical with respect to the central plane of ore bodies. It is doubtful if an epigenetic process would be able to generate such a distribution without traces of feeding channels on either side.

The intimate relationship between the ores and the Djupviknes quartzite does not seem to have had any primary genetic influence on the metal distribution. However, the mechanical qualities of the quartzite created special mobilization possibilities during the folding.

No eruptive massifs, no sills or dikes are found in the area or its immediate vicinity. Further, the sulphide layers do not seem to claim any special host rocks, they are homogeneous — in form and composition — throughout the area, interbedded in mica schist or in quartzite.

According to field and laboratory evidence, a sedimentary process seems the most reasonable cause of the primary emplacement of the ores.

Sedimentary processes which accumulate zinc and lead are of different kinds. With our present knowledge of these ores and more generally of the complex metal province of Ofoten,[1]) an evaluation of these processes would give an ambiguous answer to the problem today. However, two different ways of sedimentary accumulation of the present metals may be considered with some profit:

1. The exhalative-sedimentary ore forming process.
2. Sedimentary enrichment originating in the chemical weathering of basement deposits of zinc and lead.

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[1]) We will have to consider the problem of what Émile Raguin (7) calls "metamorphic convergence": Ore deposits of different primary origin may be transformed during a metamorphism to become formally and compositionally so equal that their individual characteristics are difficult to tell apart. Several groups of Ofoten deposits may be connected in this manner.

On 1.

There is no field evidence supporting this theory directly. None of the country rocks have characteristics usually connected with deposits of the exhalative-sedimentary type. It is, for instance of special interest, that the Djupviknes unit is a very pure sedimentary quartzite, practically without feldspar.

However, it is not possible to exclude that a process of that type may have been active from a very distant source of zinc and lead.

One possible source may have been contemporaneous hydrothermal acvtivity which deposited Pb-Zn in the Precambrian basement below and to the east of the Håfjell basin of sedimentation. The mechanism envisaged is one similar to that proposed by Dunham (2) for the Kupferschiefer — Marl Slate mineralization.

On 2.

It is not possible with our limited detailed knowledge of the whole Ofoten province to exclude the possibility that a sedimentary enrichment originating in the chemical weathering of old basement deposits may have caused the primary mineralizations of zinc and lead in the Håfjell syncline. Several zinc-lead occurrences of the sub-Caledonian basement near-by will have to be taken into consideration with regard to such an origin.

A stable Caledonian basin has been the site of transport and sedimentation of cyclic character. Chemical and clastic sediments have given rise to a variegated stratigraphical column — mica schists, quartzites and limestones in which several groups and types of ores are interbedded.

With allusion to the sedimentology of the wall rocks, as well geometrically as mineralogically, it does not seem impossible that the sedimentary conditions could have given rise to the accumulation of zinc and lead ores of the here described type.

From the highly metamorphic ore textures themselves it has been difficult to provide solid arguments for any one of the above-mentioned assumptions. In spite of the so-called metamorphic convergence, I hope that a more thorough knowledge of the detail geo- chemistry of the whole district will throw more light upon these problems.

For the time being it seems logical to suggest the following classification term for these deposits of the Håfjell syncline:

"Metamorphic sedimentary sphalerite-galena occurrences".

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