NORDRE GJETTRYGGEN GRUVE, FOLLDAL, NORWAY — A DETAILED STUDY

by

Norman J Page

ABSTRACT

Nordre Gruve in the Folldal district, is located at approximately 62°9'N. latitude and 10°E. longitude in the Hedmark Fylke. The mining of copper, zinc, and sulfur from pyritic ores began 205 years ago in the area and alone from Nordre Gruve has yeilded up until 1957, 1.1 metric tons of raw ore. Since then it has produced about 65 thousand tons of raw ore per year. The mine has been developed for about 420 meters along a strike N.42°E. and to a depth of 510 meters. The ore body dips 38°N. in the western part and between 45-50°N. in the eastern part; the zone plunges 45°N.E. The average thickness of the o re is 1.66 meters.

The district, geologically, is located in the southwestern part of the Trondheim region near the Sparagmite boundary while Nordre Gruve can be considered to rest in the southwest limb of a northeasterly plunging syncline composed of schists metamorphosed to quartz-albite-epidote-almandine subfacies fo the greenschist facies which have been tentatively assigned to a stratigraphy similar to that of the Hølonda-Horg District. The rock units which were mapped are; undifferentiated schists (composed of an assemblage of six dominant minerals; quartz, chlorite, calcite, biotite, epidote, and hornblende), quartzitic schists, hornblende-quartz schists, trondhjemite (albite-quartz-garnet gneiss), and debris covering outcrops. The trend of the rocks is N.50E. dipping 40-80°N.W. containing two trends of minor folding.

The gangue consists of individual mineral grains and aggregates of quartz, feldspar, and chlorite lenses; disturbed and folded undifferentiated and quartzitic schist partings; and angular fragments of calcite. The gangue minerals have exactly the same characteristics as they do in the country rocks.

The ore minerals are pyrite, pyrrhotite, sphalerite, chalcopyrite, galena, cubanite, molybdenite, arsenopyrite, and fahlerts.

There are three types of banding present in the ore (1) magnetite banding, (2) one caused by a change in pyrite grain size, and (3) banding due to a change in ore to gangue ratio. Pyrite in some cases contains "inclusions" of other ore and gangue minerals and also exhibits a cataclastic series of textures ranging from fractured crystals to those with pieces of crystals "floating" in matrix sulfides. It is also elongated, probably parallel to the foliation. At some localities a very fine-grained, non-recrystallized pyrite was observed.

Trends in ore mineral variation across the thickness of ore were observed. Pyrite in percentage decreases from hanging wall to foot wall while pyrrhotite is concentrated on the foot wall and chalcopyrite on the hanging wall. Both sphalerite and galena are more concentrated toward the walls. Contoured vertical profiles of assay data show trends in high areas of Cu, Zn, and S which correspond to the directions of minor folding.

The original origin of the ore deposit is uncertain, but if it is epigenetic related to the trondhjemite or if it is sedimentary, the structural and textural characteristics of the ore must have been inherited from processes of regional metamorphism. Various sulfide geothermometers give temperatures of crystallization which are consistent with the highest possible temperature of metamorphism.

INTRODUCTION

The Folldal district, about 20 kilometers in length and 5 kilometers in width, is located in the Hedmark Fylke along the Folla River Valley at approximately 62°9'N. latitude and 10°E. longitude (50'W. of Oslo). Its general position with respect to Oslo and Trondheim is indicated on Figure 1. The Nordre Gjettryggen Gruve (Mine), operated by Folldalsverk A/S, which is now considered their main mine, lies 11 kilometers by road or about 5 kilometers airline northeast of the village of Folldal. Access to the mine is by the road between Hjerkin and Alvdal to the mine road turnoff, 3.8 kilometers east of Folldal.

In general, the topography of the region is representative of a mountainous area once covered by Pleistocene glaciation. The mine itself is 961 meters above sea level on a moraine and glacial lake debris-covered shelf or plateau a little above timber line. Most habitation is limited to the river valley, except for the scattered summer seters and the few buildings provided at Nordre Gruve for the housing of employees. The highest point in the immediate region of the mine is Haanesklekken which is 1220 meters above sea level. Other topographic high points include Gjettryggen, 1035 meters above sea level, and Storhovdet, 994 meters above sea level. Svenasbekk flows southward, originating mear Storhovdet, into the Folla River. Water for this stream probably comes from the seepage into the moraine. The geomorphology of the area is discussed in Marlow (1935) by I. K. Streithen.

In the Folldal region there are five mines; the old mine or Folldal Hovedgruve, Nordre Gjettryggen, Søndregruve, Nygruve, and Grimsdalsgruve. Nygruve and Grimsdalsgruve are on the west side of the village of Folldal, while the others are to the east. This mining region has been in operation for 205 years. The mining which began in 1748 at Folldal Hovedgruve for copper lasted until 1878. The total production in this period was 250,000 metric tons of ore, yielding 3500 metric tons of copper. In 1907, the mining of pyrite for sulfur recovery was begun after the English company, The Folldal Copper and Sulphur Co. Ltd, who had become owners in 1904, had established a cable car to the Alvdal railroad station. In 1938, Folldalsverk A/S took over the concession and in 1959 joined with A/S Borregård. More detailed history of the old mine can be found in "Folldal Verk gjennom 200 år."

Nordre Gruve was discovered in 1917 and was put into production by 1935. In the same period, a flotation plant was built in Folldal. From this plant come three concentrates; pyrite, copper, and zinc. Up until 1957, Nordre Gruve had produced 1.1 million metric tons of raw ore yielding approximately 11,000 metric tons of copper, 33,000 metric tons of zinc, and 330,000 metric tons of sulfur. Since then, the mine has been producing 65 thousand metric tons of raw ore per year. All of the ore has been mined by shrinkage stoping. Levels 1-13 are serviced by the main haulage shaft and the opening shaft or 250 Shaft. Levels 1-3 were served in the past by the old shaft which is now part of the ventilation system. Levels 6-13 are accessible by the Marie Louise Shaft as well as the 250 Shaft (See Plates 1 and 2).

The ore is crushed on Level 6 by a jaw crusher before being hoisted to the surface and taken by cable cars to the flotation plant in Folldal. More information on the mining engineering can be found in Hjelseth (1957).

REGIONAL GEOLOGY

The Folldal ore deposits are located in the southwestern part of the Trondheim region (Trondheimsfelt), very near the Sparagmite boundary and within the garnet zone of metamorphism as delineated by Goldschmidt (1915). The stratigraphy and structure of this region are very poorly known. Some of the earliest work done in the area is that of K.O. Bjørlykke (1905) who, in a series of maps including the Folldal area, indicates the contacts of granulite, mica schists, and phyllite trending northeast in alternating bands ("granulit, glimmerskifer," and "graalig-fyllit"). Carstens (1919) who mapped the area to the north and northeast of the Folldal quadrangle, showed what he called eruptive rocks, probably similar to Bjørlykke's "granulit", passing through the Folldal area. G.Holmsen (1918), in mapping the ore belt in the Trondheimsfelt, included the Folldal area on his map. He shows (1918, p.171) an anticline with a core made up of the Røros Group and limbs of Støren-Hovin and Gula Groups plunging northeastward as the main structure of the Folldal Quadrangle, but neglected the existence of the "granulit" that was mapped previously (See Fig.2). No structural interpretation was made by Marlow (1935) when he mapped the Folldal Quadrangle, since he only indicated areas of outcrop, differentiated between different rock types, and recorded attitudes measured in the field.

Other quadrangles of importance besides that of Folldal in interpreting the regional structure are those of Oppdal, Kvikne, Røros, Dovrefjell, Tynset, Øvre Rendal, Sølnkletten, Randvasshed, and Sel. Only the Tynset (Holmsen, 1943,1950), part of the Sel (Strand, 1951), Oppdal (P.Holmsen, 1955) and the northern part of the Dovrefjell quadrangles (P.Holmsen, 1955) have been mapped. Geiss(1958) has mapped a small region near Hjerkin in the Dovrefjell Quadrangle. A few broad brushed structures are indicated on the Geologic Map of Norway (Holtedahl, 1960), while Vogt (1953,1954) in attempting to link structures of the Caledonian in Scotland with those in Norway has drawn his Syncline II through the region. This is a northeast trending syncline which, south of the vicinity of Hjerkin, has a bend in it to a northwest-southeast trend and then returns to the normal northeast trend. Strand in Geology of Norway, (Holtedahl, 1960) implies that the area under discussion is a broad synclinorium which has been thrust out over the Sparagmites from the northwest.

The only area of the Trondheim district in which any detailed stratigraphy is known is in the Hølonda-Horg District near Trondheim (Vogt, 1945). Holmsen (1960) and Marlow (1935, p.14) both suggest that the mica schists and phyllites lying upon the Sparagmites in the Folldal area belong to the Røros Group, the oldest unit recognised in the Hølonda-Horg District.

Although it is dangerous to link stratigraphy over such a great distance, taking the above information of Vogt and Marlow into account, plus that gathered in the field around the village of Folldal, one can make a tentative structural and questionable stratigraphical interpretation of Marlow's (1935) geological mapping. This has been done in a cross-section passing through Nordre Gruve trending approximately northwest to southeast (See Fig. 3). Certain rock units as indicated are taken directly from Marlow's work, while those in the vicinity of Nordre Gruve are from the author's surface mapping. Marlow's phyllite which he tentatively (Marlow, 1935, p.14) assigned to the Røros Group appears to be the same unit as Holmsen (1950) mapped as the Røros Group in the Tynset Quadrangle. According to the stratigraphical section in the Hølonda-Horg District, (Vogt, 1945,p.459) the Støren Group of meta-basalts interlayed with sedimentary beds is about 2500 meters thick. The series of undifferentiated schists include chlorite-epidote schists with quartz-rich layers, while the other rocks indicated on the cross-section are quartzitic schists, hornblende-quartz schists, and trondhjemite. This group is approximately 2500-3000 meters thick excluding the trondhjemite. This suggests that this series could be assigned to the Støren Group, while Marlow's large area of quartz-mica schists might possibly represent part of the Hovin Group in this area of the Trondheimsfelt. The structure of anticlines and synclines is taken from Marlow's map as interpreted by the author from attitudes indicated, except for dip values near Nordre Gruve which come from the author's work. This locates Nordre Gruve on the southwest limb of a syncline, probably plunging to the northeast, as part of a broad synclinorium. The extension of the trondhjemite to the northeast is not entirely necessary.

Other interpretations are possible for this structural arrangement. One could interpret the trondhjemite as having discordant contacts, an uncommon phenomena for this particular type of rock in the Caledonides, which might add another anticline to the picture (See Fig. 4). The author prefers the first interpretation.

PETROLOGY AND SURFACE GEOLOGY OF NORDRE GRUVE

An area of approximately 4 kilometers by 3 kilometers around Nordre Gruve was mapped on a topographical base map, prepared by the mine, having an original scale of 1;10,000. At the time no aerial photographs were available but have since been obtained. The map (Fig.5) is basically the one mapped on the topographic base with slight adjustments for location made from the photographs. Aerial photographic coverage (scale: 1:20,000) of the region from slightly west of Folldalsverk to the eastern end of Gjettryggen between the Folla River and Grønko was also studied for major structural trends. Five different rock units were differentiated in the field. From south to north they are: undifferentiated schists, quartzitic schists, hornblende-quartz schists, trondhjemite, and Pleistocene and Recent cover.

In general, megascopically, the undifferentiated schists are dark greenish-gray to black, fine-grained, foliated schists, often characterized by a phyllitic appearance. In the southern portion of the map area, the phyllitic type is especially prevalant, while in the middle to northern part of the map area, one finds the same schist type with carbonate or hornblende-rich layers, areas with glassy quartz lenses, and sometimes thin beds of dirty quartzite. Also there are certain horizons which contain abundant garnets, with or without much hornblende. Nowhere were pillow structures or anything ressembling filled vesicles observed. The major minerals composing the schist are quartz, members of the epidote group, chlorite, and hornblende. Albite, orthoclase, biotite, sphene, moscovite, and disseminated pyrite are the minor constituents. One modal analysis of the undifferentiated schists is presented in Table 1 to show the variation in composition of the rock. For more analyses, the reader is refered to Table 8, p.29.

Table 1: Modal Analysis of Undifferentiated Schists.

	1
Quartz	35.5
Albite	4.6
Chlorite	14.3
Biotite	3.4
Hornblende	15.5
Epidote	25.9
Apatite	0.1
Sphene	0.3
Ore minerals	0.0

1) Quartz-epidote-hornblende schist, Svenasbekk, Nordre Gruve.

Microscopically, the schist is composed of larger subhedral to anhedral crystals of quartz; sometimes feldspar, full of small dusty inclusions; and chloritized hornblende set in a ground mass of micas, quartz, and members of the epidote family. In many specimens, there are closely spaced shear planes as evidenced by trains of chlorite, biotite, and probably clinozoisite stretched out concordant with the foliation, and by broken or sheared and stretched feldspar crystals with quartz tails surrounded by micas. These look like clots and bumps on a hand specimen. In other thin sections, one notices a banding of quartz-rich layers alternating with more mafic layers.

The rock unit, designated as quartzitic schist, is a foliated white to light gray rock composed mainly of subhedral quartz grains with minor muscovite, chlorite, epidote, calcite, albite, and ore minerals. A modal analysis is presented in Table 2 along with the estimated range of mineral variation.

Table 2: Modal Analysis of the Quartzitic Schists

	1	Range of Composition (vol.%)
Quartz	79.1	60 - 97
Albite	0.4	0 - 5
Muscovite	2.2	0 - 20
Chlorite	tr.	0 - 30
Calcite	14.9	1 - 20
Epidote	1.4	0.5 - 10
Ore minerals	2.0	0 - 3
Accessories		0 - 0.5

1) Quartz-calcite-muscovite schist, Svenasbekk, Nordre Gruve.

In some localities, the quartzitic schist is entirely given over to glassy quartz bands or lenses, occasionally containing disseminated magnetite in bands concordant with the foliation. The rock marked Ts on the map is a good example of this (See Fig.5). Microscopically, the rock, in some sections, has a banded appearance due to the alternation of layers of quartz grains of different sizes. Quartz grains in most sections show some strained or wavy extinction.

The hornblende schists are an easily mapped unit in the field because of the contrast of dark hornblende needles attaining, in some cases, 1 centimeter in length, against the light gray groundmass of quartz, chlorite, epidote, and occasionally garnet of the almandine-pyrope solid solution series. Other minor minerals in the rock are muscovite, orthoclase, albite, sphene, and in one case probably a spinel. The refractive index of the garnet was 1.802±.002, which probably puts it into the almandine pyrope series. The hornblende has the following optical properties: n_z=1.695±.002, n_y=1.684±.002, n_x=1.675±.002, positive, 2V less than 70°, and $Z \wedge c$=18°. The pleochroism is Z dark green, Y greenish, and X brownish green. Hornblende and garnet are both porphyroblastic and have a sieve structure enclosing numerous quartz and mica inclusions. Quartz grains have a granulated texture in some instances. Some of the hornblendes have rims of chloritic micas suggesting retrogressive metamorphism. Table 3 shows a modal analysis of this rock.

Table 3: Modal Analysis of the Quartz-Hornblende-Epidote Schists.

	1
Quartz	52.6
Albite	tr.
Chlorite	6.2
Hornblende	29.9
Garnet	2.3
Epidote	7.7
Ore minerals	1.3

1) Quartz-hornblende-epidote schist, Svenasbekk, Nordre Gruve.

The rock called trondhjemite by Marlow is a pinkish-white to light gray, holocrystalline, foliated rock containing abundant porphyroblasts of garnets which attain the size of 0.5 centimeter in cross-section. The author would prefer to call it an albite-quartz-garnet gneiss because of the genetic implications of the word trondhjemite, but since it already carries the name trondhjemite, both terms will be used here. At some localities, it contains scattered hornblende porphyroblasts, while in others, not on the map area, near the Hovedgruve, it is cross-cut by many veins of glassy quartz ranging in thickness from microscopic to 0.5 meter or more.

The major minerals in the rock are quartz, albite (An_{5-9}), hornblende, chlorite, biotite, garnet, and sphene. The refractive index of this garnet is 1.796±.002, which also puts it into the pyrope-almandine solid solution series. Each subhedral to euhedral plagioclase is full of mica, quartz, and epidote inclusions giving it a sieve texture. The inclusions are subhedral and unlike most feldspar alteration phenomena have clear, sharp edges under a high power objective lens. A few quartz grains also have similar types of inclusions. None of the inclusions are on the edges of the crystals. One postulated explanation is that the inclusions represent material from an earlier period of seritization which has recrystallized. Some plagioclases seem to be composed of patch perthites and normal perthites. The quartz shows a granulated texture which has been recrystallized in part as evidenced by the lack of wavy extinction in the quartz grains. The members of the epidote family are crushed and broken; possibly slightly alterated to sericite. According to Johannssen's classification the rock is a sodaclase tonalite (218P) or a sodaclase dacite (218E). This terminology implies an igneous origin which at this time is impossible to prove or disprove. Table 4 presents some mineral modal analyses of the rock (See p.12).

There are a few references (Marlow, 1935, p.16; Geophysical Malmleting, 1941; Hjelseth, 1961, personal communication) to graphitic schists in the Folldal area but none were observed by the author.

Table 4: Modal Analyses of Plagioclase-Quartz-Garnet Gneiss.

	1	2
Quartz	33.9	51.4
Albite	46.2	27.9
Muscovite	3.6	4.5
Chlorite	0.7	0.0
Hornblende	0.2	1.1
Epidote	2.9	1.6
Garnet	6.2	3.5
Zircon	0.1	0.2
Sphene	0.0	0.1
Ore minerals	0.1	0.1

1) Albite-quartz-garnet gneiss, Haanesklekken, Nordre Gruve.
2) Quartz-albite-muscovite gneiss, near Hovedgruve, Folldal.

Quarternary cover includes glacial moraine, talus, landslide, and glacial lake debris washed out from the lake that was dammed up behind Haanesklekken probably by ice. The amount of cover makes detailed geological mapping difficult, although at most locations it is not very thick. For example at the mine, the cover is about meters.

From the petrographic study of the schists in the Folldal area, the rocks have mineral assemblages characteristic of the quartz-albite-epidote-almandine subfacies of the greenschist facies (Turner and Verhoogen, 1960, p.539-541), the highest of the greenschist facies. This was formally the albite-epidote-amphibolite facies, chloritoid-almandine subfacies. Typical mineral assemblages are hornblende-albite-epidote-almandine-biotite-quartz and hornblende-chlorite-almandine. The latter represents magnesian-rich schists and the former basic schists. Since the lowest temperature at which the almandine-amphibolite facies is probably stable (Turner and Verhoogen, 1960, p.553) is 500°C., this region probably never reached a temperature higher than 600°C. The maximum pressure was probably well below 4000 bars. In the rims of chlorite on hornblende crystals there is also a suggestion of retrogressive metamorphism which is also implied in the amount of chlorite in the various modal analyses. Metamorphism and shearing movement during folding have destroyed most of the structures, textures, and probably minerals of the original rocks which makes it difficult to postulate on the premetamorphic stratigraphy. Still it is possible to compare average mineral modal analyses with those of some from well-known areas of the Trondhjemsfelt and with various rock types from other localities.

In Table 5, the average modal mineral analysis of the undifferentiated schist and the hornblende schist is compared with one given by Vogt for a basaltic Støren greenstone from Lake Benna and with average modal analyses of graywackes calculated from mineral percentages given by Pettijohn.

Table 5: Comparison of Various Modal Analyses of Greenstones and Graywackes with Folldal Undifferentiated Schists.

	1	2	3	4	5	6
Quartz	10.90	52.6	35.5	33.1	46.7*	tr.
Albite	11.99	tr.	4.6	5.4	16.7"	29.9"
Hornblende	37.20	29.9	15.5	8.6	0.0	10.5
Epidote	22.43	7.7	25.9	8.1	0.0	0.0
Chlorite	14.82	6.2	14.3	25.6	25.0#	46.2#
Biotite	0.00	tr.	3.4	8.5	0.0	0.0
Muscovite	0.00	0.0	0.0	1.0	0.0	0.0
Garnet	0.00	2.3	0.0	0.2	0.0	0.0
Titanite	2.25	0.0	0.0	0.0	0.0	0.0
Pyrite	0.04	1.3	0.3	0.8	0.0	0.0
Apatite	0.26	0.0	0.o	tr.	0.0	0.0
Calcite	0.48	0.0	0.0	9.2	4.6	0.0
Rock fragments	0.00	0.0	0.0	0.0	6.7	13.4

1) Basaltic Storen Greenstone, (Vogt, 1945, p.446).
2) Quartz-hornblende-chlorite schist, Svenasbekk, Folldal.
3) Quartz-epidote-hornblende schist, Svenasbekk, Folldal.
4) Average mode of undifferentiated schists, 17 analyses, Folldal.
5) Average of 6 mineral analyses of graywackes, (Pettijohn, 1957, p.304, Table 50, No.A).
6) Average of 2 graywackes, (Pettijhhn, 1957, p.304, Table 50, No.E.)

*Quartz includes chert." Feldspar. #Includes sericite.

It is evident that the schists around Nordre Gruve do not contain a very large amount of albite as do normal greenstones and graywackes. Their mineralogical composition is more like that expected from calcareous clays metamorphosed to this degree. Table 6 compares the modal mineral analyses of the quartzitic schist with Vogt's analysis of a Støren quartz-keratophyre from Sagelva and a silicified quartz-keratophyre from Lake Gørtvatn and an average modal analysis of quartzite. It is evident that the composition of the quartzitic schists in no way approach

Table 6: Comparison of Modal Analyses of Quartz-keratophyres and Quartzitic Schists.

	1	2	3	4	5
Quartz	31.55	67.92	79.1	77.3	86.8
Albite	48.75	15.21	0.4	2.6	3.0
Muscovite	15.76	10.99	2.2	8.5	2.3
Biotite	0.45	0.00	tr.	1.9	5.3
Chlorite	1.97	4.63	tr.	0.2	2.3
Epidote	0.49	0.00	7.4	3.5	
Calcite	0.30	0.41	14.9	4.0	
Magnetite	0.51	0.74	0.0	0.0	
Titanite	0.45	0.21	0.0	0.0	
Pyrite	0.04	0.04	2.0	0.7	tr.
Rutile	0.00	0.04	0.0		
Zircon	0.00	0.06	0.0	0.2	
Apatite	0.07	0.03	0.0		
Hornblende	0.00	0.00	0.0	1.1	

1) Quartz-keratophyre, (Vogt, 1945, p.469).
2) Silicified quartz-keratophyre, (Vogt, 1945, p.469).
3) Quartzitic schist, Folldal.
4) Average mode of 6 quartzitic schists, Folldal.
5) Average mode of 4 quartzites from various areas as determined by associates at Mineralogisk-Geologisk Museum.

that of the quartz-keratophyre or an acid pyroclastic as has been postulated, but the plagioclase-quartz-garnet gneiss (trondhjemite) more closely approaches this composition (See Table 4, p.12).

All of the foliation of the rocks in the area mapped strikes about N.50°E. and dips between 40° and 85° northwest making fairly constant trending bands of schist as indicated by Bjorlykke (1905) (See Fig.5). There are also two trends of minor folding, one plunging northwestward and the other northeastward. The northeastward trend is probably related directly to the thrusting movements from the northwest toward the southeast (See Ore Description and Structure, p.16), while the northwestward trend is related to a compression at right angles to the thrusting due to the shape of the blocks involved in the tectonic movements. The aerial photographs indicate a northwest trending warp of the general synclinal strike, as does the bend in the thick quartzite bed mapped 800 meters south of Nordre Gruve. The plagioclase-quartz-garnet gneiss (trondhjemite) body, on aerial photographs shows the same effect in the northwestern corner of the map area. This is not a major structure which could offer a "structure control" to the ore body, nor is the ore body located in its crest or trough. From the study of aerial photographs, no major "structural controls" of either Nordre Gruve, Søndre Gruve, or Hovedgruve are apparent.

The contacts between the various rock units are sharp where observable, except for the different mineral assemblages of the undifferentiated schists which appear in some places to be gradual transitions. This suggests that the variation in lithology is actual bedding and not an effect of the regional metamorphism. Since the trondhjemite contact was never observed, it is impossible to say definitely whether the body is conformable or not or whether it is an igneous rock or a metamorphic one. Rocks of similar composition have been mapped in northern Norway with conformable contacts, therefore, it is assumed to be similar for this particular trondhjemite.

There are five prospects besides Nordre Gruve within the region mapped, all located on the western side of Storhovdet. These are usually shows of pyrite disseminated in schists, sometimes with magnetite, and occasionally some chalcopyrite. They lie on the electromagnetic indications of the geophysical survey (1941) and all are nothing more than pits in the ground. From the surface showings one would believe that they are small local concentrations of sulfides.

The overall picture presented by the series of schists seems to indicate that one has an interfingering facies of sedimentary rocks, both water-laid tuffs and non volcanic debris mixed in with effusive basic volcanics. The quartzites represent periods of relative stability, while the undifferentiated schists are manifestations of more rapid sedimentation and igneous activity. This mass was deposited in a broad synclinal down-warp, which was later thrust southwest out over the Sparagmites, at the same time being isoclinally folded with the main fold axes trending northeast-southwest. At the same time the compressive forces, resulting from differential thrusting on different blocks, caused the second axes of minor folding to be at approximately right angles to the main ore During this time the mass was regionally metamorphosed. The time of emplacement or deposition of the trondhjemite is not known.

ORE BODY DESCRIPTION AND STRUCTURE

Although Nordre Gruve is composed of several different ore lenses, the generalized ore zone has a strike length of 420 meters and has been developed to a depth of 510 meters below the surface. The average thickness of the ore is 1.66

meters. The zone strikes N.42°E. and dips 38°N. in the western part and closer to 45-50°N. in the eastern part. The generalized ore zone plunges about 45° to the northeast. The ore body, as thus far explored by Folldalsverk, is in agreement with the electromagnetic anomaly found in 1941 (Geophysical Malmleting, 1941), except that the geophysical survey indicates more ore to the east of where it appears to pinch out underground. This extention of the anomaly could be caused by zones of pyritic impregnations.

The 30° projection of Nordre Gruve (See Fig.6) better illustrates this information in three dimensions. The projection is a simplified representation of a series of vertical cross-sections every 20 meters along the x-coordinate which were prepared by the mine. This has removed many of the complexities of branching and detailed folding from the diagram. Also, any structures behind the plane of the foremost ore lenses are obscured. The geologic map presents a detailed picture (See Plates 1 and 2). But neither the geologic map nor the projection shows the zones of disseminated pyrite and chalcopyrite in the chloritic schists which have been proven in places by diamond drilling. The schematic drawing shows that the ore body is not one continuous manto or lens (See Fig. 6) but is instead composed of five separate ore lenses or possibly only four, if one considers lenses 1 and 7 to be interconnected (the numbers of lenses used here appear in the figure). To the main and largest lens, in the eastern part of the mine, number 1, are attached as vertical upward branching lenses, numbers 2,3, and 5, and possibly lens 7. Lens 4 appears to be unconnected to lens 1 and lies in front of the main plane of the ore zone or to the north of lens 1. Lens 6 is connected to lens 7 by a similar type of branching, and to lens 8 is attached the smaller one, number 9. The most westerly and first mined lens, number 10 appears to be separate from the other lenses and is pierced by a hole which is a parting or an area of quartz-mica schists.

Plates 1 and 2 present the geology of the mine of all the presently explored Levels (1961) except the eastern part of Level 3 and Levels 4 and 5. This map is compiled from the work of Sandvik (1937) who indicated ore, wall rocks, and faults, when mapping the western parts of Levels 1, 2, and 3; from the work of Geis (1958,1961) who mapped Levels 7,8,9,10, and the eastern part of Level 11; from the up-to-date record of located ore by Folldalsverk; and from the author's mapping of Levels 13,12,6, and the western part of Level 11 and his observations in the rest of the mine over a three month period. The previous workers did not map the attitudes of foliation, lineation, and minor folding and are not responsible for the interpretations of structures indicated by the form lines of the map. In the field to simplify the problem of the compiliation, the same three main rock units were used in mapping as were used by the previous two workers.

Preliminary to a consideration of folding, a discussion of ore thicknesses would be useful. The thickness of the massive sulfide ore varies, as measured in the mine 664 times, and has a range of 0.1 to 10.4 meters. These values were plotted on a frequency diagram and gave a mode of 1.0 meter. The calculated average thickness is 1.66 meters. On account of the irregular distribution of measured thicknesses, they were put into 19 different classes and the percentage of thicknesses within each 0.5 meter class was calculated (See Table 7, p.19).

Table 7: Thicknesses of Ore

Class	Range of Thickness Class (meters)	Percentage of Measured Thicknesses	Cumulative Percentage
1	0.1- 0.5	23.9	23.9
2	0.6- 1.0	20.5	44.4
3	1.1- 1.5	14.8	59.2
4	1.6- 2.0	13.4	72.6
5	2.1- 2.5	7.8	80.4
6	2.6- 3.0	7.2	87.6
7	3.1- 3.5	2.6	90.2
8	3.6- 4.0	4.1	94.3
9	4.1- 4.5	1.7	96.0
10	4.6- 5.0	1.1	97.1
11	5.1- 5.5	0.8	97.9
12	5.6- 6.0	0.5	98.4
13	6.1- 6.6	0.1	98.5
14	6.6- 7.0	0.6	99.1
15	7.1- 7.5	0.1	99.2
16	7.6- 8.0	0.3	99.5
17	8.1- 8.5	0.1	99.6
18	8.6- 9.0	0.3	99.9
19	9.1-10.5	0.1	100.0

Note that 44.4 percent of values measured fall below 1.0 meter, while 87.6 percent of the values measured fall below 3.0 meters. Since all of the thickness data were located on mine maps, it was possible to prepare a profile (See Fig.7) of Nordre Gruve on which the thickness of ore, irrespective of the lens in which the ore is located, was contoured with an interval of 1.0 meter. From this profile there appear to be two lineations, one trending northeast and the other northwest. The northeast trend is marked by the plunge of the ore body, while the northwest trend is delineated by the individual high areas of thickness. In the following discussion, thickness of ore is demonstrated to be controled partially by intensity of folding.

The largest structures which can be observed on the projection, map, and cross-sections (See Fig.8) are flexures down the dip of the ore body and warps along the strike of the ore as emphasized by the curving drifts on the map. As can be seen in the cross-sections 1,2, and 3 (See Fig.8), these are not tight folds, nor are they structures one would expect to offer structure control. The present location of thick and thin ore, appears though to be controlled by this gentle warping and a tighter type of folding which is responsible for the branching and lensing shown on the map and cross-section. This is not in accordance with Geis' (1958) suggestion that the branching is entirely due to original sedimentary interfingering of ore beds and rock beds. Nowhere underground were any interfingering type of relations observed between ore and rock.

Underground and on the surface where there are exposures, there are many minor folds. These, both in the undifferentiated schists and the quartzitic schists, plunge in one of three directions, either approximately N.15-20°W., N.80°E., and N.45-55°E. at angles between 10° and 90°. The direction N.80°E. has a minor number of folds, while the other two trends are about equal in frequency. Where it is possible to measure the attitude of a mineral alignment, mainly in the hornblende schists, the same is found to be true. Although not evidence in itself, this suggests two periods of folding if the N.20°W. and N.50°E. trends are assumed to belong to the same period, since they are almost perpendicular to each other. Since the Folldal area is supposed to be a sheet thrust out over the Sparagmites to the south, it is plausible to connect one set of lineations with the thrusting and the other to an earlier period of folding. Others studying the Scandinavian Caledonides have postulated more than one period of folding (Kvale,1953). Lindstrøm (1955, 1957, 1958a, 1958b) is an ardent proponent of more than one axes of a tectonic transport and therefore many periods of folding.

On the geologic map can be seen branches or prongs of ore going out from the main massive sulfide ore lenses. On the footwall the majority of these point eastwardly, while on the hanging wall the larger number of branches or prongs point westwardly. In about 75 to 80 percent of the cases observed on the horizontal section, this relation holds. From the underground examination, there were many cases of folding in the hanging wall rocks which is manifest in the ore zone by the thickening and thinning of the ore. In some cases, the prongs or branches of ore seem to be direct results of folding, for example on Level 6, (coordinates 350x and 310y). Here in the broader less intense fold, plunging 55°N.W., the ore is thickest, while in the more intense fold the massive sulfide pinches out into a prong-like form (See Plate 1).

The consistency of branching seems to be best explained by a shear couple parallel to the ore zone during the formation of the syncline. This would form drag folds with the appropriate plunges. Such a shear couple appears to have been in operation over the entire period of folding and metamorphism and to have continued until a much later time. Earlier parallel shear couple shows its effects on the ore minerals, expecially pyrite which has been brecciated and fractured (See the Ore, p.46). Evidence of movement parallel to the ore zone is found in the foot wall cross-cuts. There are zones in the schists where loose chloritic schists are accompanied by carbonates. Near the Marie Louise Shaft on Level 11, such a zone was studied in some detail and was found to contain prochlorite, pyrite, and a carbonate forming a loose schist hazardous to mining. This appears to be a shear zone. There are other examples underground of the same relationship. This could be early or late tectonic movement. The latest tectonic movements parallel to the ore body are evidenced from slickensides on the ore and immediate wall rock, in places, and by the loose chloritic schist envelope generally found on both sides of the ore.

From Levels 5 to 8 near the x-coodinates 250-350 east, there are generally two branches of ore forming and eye-like area. This is believed to have been formed by an area of relatively intense folding in a zone plunging about 60-70° northwest. Within this zone, many minor folds controlling the thickness of the ore have been observed plunging to the northwest. The broader more gentle fords contain the greatest thickness of ore, while in the narrower more intense folds, the massive sulfide ore pinches out. On Level 3 (about 250x) there is a similar suggestion of a zone of folding. On other levels in the wall rocks, there are many examples of minor folds, sometimes affecting the ore, but more often not.

The present location of the ore, besides being partially controlled by folding, has been affected by much later tectonic movements transverse to the ore zone. There are two fairly distinct groups of transverse faults; one striking northeast and the other northwest. Those of either set may dip east or west, although the majority of the northwest trending faults dip westward. On Level 1 there are a large number of faults, as mapped by Sandvik (1937), many of which die out before reaching Level 2. Possibly some of these could have been joints or other surface phenomena, especially those which show no horizontal or vertical displacement. At a depth below Level 6,post-ore faults are much more persistent and can generally be traced from level to level. The maximum apparent strike-slip displacement on any one fault is about 18 meters.

The post-ore faults are sometimes without a breccia or crush zone, and at other times they have one. For example, the fault zone on Level 11, (coordinates 500x and 640y) was studied in detail. The fault strikes N60°W. and dips 77°W. It has a breccia zone of about 0.3 meters composed of crushed and fractured fragments of massive pyrite ore in a carbonate matrix containing ground up chloritic schists. The massive sulfide fragments were fractured and later filled with crystalline calcite. The ore fragment-free part of the fault zone contains small quartz lenses and fragments. A specimen of the brecciated ore shows that there were no strong metallic mineralization solutions at this time (See Plate 3, Fig.2) in this location, as the ore is still composed of primary pyrite and sphalerite. All of the mineral constituents are the same and in the same association as samples of ore taken away from the fault zone. A fault zone on Level 5 (coordinates 180x and 280y) contains calcite, limonite, and geothite (?) plus massive ore fragments. The secondary iron minerals may be much later than the faulting and associated with secondary descending oxidizing solutions.

Another reason for localization of ore appears at first glance from the map to be the thickness of the quartzitic schist, but upon further study, the thickness of ore is not necessarily related to the thickness of the quartzitic schist in the foot wall nor is the location of the ore related to it. For example on Level 10, there is a bed of quartzitic schist approximately 0.75 meter thick which has been affected by post-ore faulting. On either side of the fault where one would expect to find ore, as it is normally associated with the schist, one does not. In another case on Level 2 west, where the ore is 5 meters thick for a strike distance of about 75 meters one does not find any quartzitic schist intimately adjacent to the ore. On the lower levels, sometimes it is noticed that ore pinches out as the drift approaches more quartz-rich rocks. The occurrence of quartzite or quartz-mica schists of the foot walls of massive sulfide bodies in the Norwegian Caledonides is quite common, but just because the relationship exists does not necessarily imply that the ore and the quartz-rich rocks were formed at the same time. It must be remembered that a quartzite is a competent rock, while chlorite-hornblende-epidote schists are incompetent and that at the contact of competent and incompetent rocks during folding, a shear zone can develop. This could later be a locus of deposition for hydrothermal fluids.

The irregular lenses or plates of ore are essentially concordant with the enclosing wall rocks, at the first observation. On the map (See Plates 1 and 2) one can observe many places where the attitude of foliation appears to be discordant with the ore zone, for example Levels 12 and 13. This is usually due to both the ore and wall rocks having a concordant roll or flexure at this place. Typical of this apparent discordancy is the minor anticline on Level 6 (coordinates 300x and 325y). Here the ore is flexed over the anticline in the chloritic schists without any discordant or cross-cutting relations. The gentle folding of the wall rocks and the snake-like form of the ore and the apparent cross-cutting relations along strike are clearly illustrated on the map.

The non-cross-cutting relations shown in a first approximation are not upheld by a detailed scrutiny of the ore to wall rock contacts. Underground there are many examples of small minor folds where the ore has been folded into the wall rocks or has replaced a fold in them. There are also cases of the reverse where the wall rocks appear to have been folded into the ore. At the crests and troughs of these folds, or in areas of lower pressure, the wall rocks are most often corroded or replaced by massive sulfide ore.

Several examples of this cross-cutting relation are presented in Fig. 9. All are of varying sizes. Notice that the minor fold on Level 7 (See Fig. 9(a)) contains glassy quartz at its crest where the ore forms an intrusion into the quartzitic schists. Also, note the undistrubed remnants of the chloritic schists in the ore. If one constructs a theoretical picture of the fold without the intrusion of the ore, it could ressemble (b) of Fig. 9. In the gentle fold one has, going from the foot wall to the hanging wall, quartzitic schists, massive sulfide ore with chloritic schist partings, and chloritic schists. Upon more intense folding, the ore, being more mobile than the quartzitic schists, would be injected or forced into the area of least pressure in the crest of the fold, carrying with it the partings of chloritic schists. This would give the result seen in Fig. 9(a). On the otherhand, it is difficult to picture the chloritic schists during intense folding, before the emplacement of the ore, forming an apophysis into the quartzitic schists where massive sulfide could replace all of the schist except for the oriented folded partings. One could explain the partings of chloritic schists as an alteration product accompanying epigenetic ore deposition, but then one would have to hydrothermally alter all of the chloritic schists for 40 meters in the hanging wall, plus the rest of the chloritic rocks of the area. The mass of glassy quartz in the crest of the fold, also suggests that this was an area of tension or low pressure where quartz could recrystallize from the quartzitic schists. An example of schists folded into the rocks is Fig.9(c). At this location, the massive sulfides appear to have corroded the wall rock and pulled pieces of it out into a sulfide matrix. Fig.9(d),(e),(f) are further examples of the cross-cutting effects shown underground on different scales. At one location underground a definite and impressive cutting relation of the ore was observed. On Level (See Fig.9(e) a series of folds plunging N.40°E. at 15-25o had a well preserved foliation which could be traced to the contact of the quartzitic schists and the ore and was found to make an angle of slightly less than 90° with the ore. In the majority of cases, the concordancy of the contact is observed.

The study of discordancy can be approached at a smaller scale and in more detail through hand specimens and polished sections. On this scale there is no true concordancy of the wall rocks with the massive ore lens. At every contact, there are sulfides and silicate minerals transgressing the imaginary contact boundary. In some specimens, the ore is folded into the schists but exhibits cross-cutting relations to the foliation of the schists (See Plate 5,Fig.1). In other cases, the schists are folded into the ore, generally chloritic schists

(See Plate 5,Fig.2). At other contacts of ore and schists, there is an apparent sharp contact, but moving less than a centimeter away from it into the schists, there are impregnations of pyrite, chalcopyrite, and pyrrhotite (See Plate 6,Fig.1). In some places especially where an actinolite-rich chloritic schist is in contact with the ore, there is a zone of transition between schists and ore. Actinolite being the the main remnant of the schists in the gangue of the ore (See Plate 6,Fig.2) and pyrrhotite and chalcopyrite most frequent in the schists. In general at the contact there is a transgression of either silicate minerals or sulfides by zones of impregnation, folding, or remnants.

The structures at the ends of the massive pyrite body along strike vary from a gradual transition between the ore lens and pyrite-impregnated wall rock to an abrupt contact between massive ore and quartz-rich wall rocks. On Level 12, at the west end, the ore zone within a strike distance of 20 meters narrows from a thickness of 1.0 meter to a zone of disseminated pyrite cubes (maximum size is 1 centimeter) and chalcopyrite veinlets in loose chloritic schists of about 0.25 meter thick. This narrowing of ore is accompanied, in some places (for example Level 5 west), by the main ore splitting up into branches and fingers from a half a meter thick down to microscopical size. On Level 13 at the western end, the massive ore has a tail-like form which looks as if it had been stretched and boudinaged off in quartz-rich schists. Immediately adjacent to the pinched off lenses are loose chloritic schists. An effect such as this probably originated during the movements at some period parallel to the strike length of the ore body. Contrary to what one would expect, had the Folldal deposit been formed by the injection of a fairly homogeneous pyritic magma as suggested by Vogt (1935, 1948), the wall rocks at the ends of the ore body are not bent nor moulded around the ends of the ore lenses. This would have been expected had the "magma" been injected and forced the wall rocks apart to make room for itself to crystallize.

PETROLOGY OF THE WALL ROCKS

The wall rocks are similar to those found in the area mapped around Nordre Gruve, but because of their importance in theoretical considerations concerning the origin of the ore, they were studied in more detail. In general, the hanging wall rocks are of the undifferentiated schist series, except upon occasion when there are lenses of quartzitic schists. The immediate foot wall of the ore is generally composed of quartzitic schists which as one goes south from the ore, change to the undifferentiated schists. Unfortunately, there is only one locality where a large section of the hanging wall rocks is exposed. It is in the drilling cross-cut on Level 10 at coordinates 450x and 580y. Foot wall rocks are well exposed by the cross-cuts from both shafts below Level 6; above that level they are exposed only in one cross-cut and in footwall drifts. At some localities, a quartz-albite gneiss-to-schist is also exposed underground.

The undifferentiated schists both in the hanging and foot walls consist of various assemblages of six minerals; quartz, chlorite, calcite, epidote, biotite, and hornblende. The accessory minerals are muscovite, garnet, albite, rutile, apatite, sphene, zircon, allanite, and ore minerals. Table 8 contains modal analyses of the various mineral assemblages (See p.29). A very thin layer of loose chlorite-calcite schist appears on the immediate hanging and foot walls of the ore body in most cases.

The texture of the rocks of the undifferentiated schist series varies from fine-grained and foliated with a homogeneous assemblage of minerals to schistone, with distinct interlayering of the quartz-rich bands with those rich in mafic minerals. Sometimes intense folding and shearing has disrupted the layering

Table 8: Modal Analyses of Undifferentiated Schists.

	1	2	3	4	5
Quartz	40.7	29.0	29.4	18.3	50.6
Albite	0.0	0.0	0.0	tr.	0.0
Hornblende	0.9	tr.	53.7	1.5	1.6
Chlorite	16.5	29.2	11.8	67.5	13.6
Biotite	9.4	0.0	0.0	0.0	19.4
Muscovite	0.0	0.0	0.0	1.9	0.0
Epidote	11.3	35.8	3.5	5.3	4.5
Calcite	19.5	1.3	0.3	0.0	9.5
Garnet	tr.	0.0	0.0	0.0	0.0
Rutile	0.7	0.5	1.0	1.2	0.0
Apatite	tr.	tr.	tr.	tr.	0.0
Sphene	0.0	0.0	0.0	0.0	0.3
Zircon	0.0	0.0	0.0	0.0	0.1
Ore minerals	1.0	0.6	0.5	3.6	0.5

1) Quartz-calcite-chlorite schist, foot wall, Level 10 Nordre Gruve.
2) Epidote-chlorite-quartz schist, foot wall, Level 10 Nordre Gruve.
3) Hornblende quartz-epidote schist, foot wall, Level 10 Nordre Gruve.
4) Chlorite-quartz-epidote schist, hanging wall, Level 11 Nordre Gruve.
5) Quartz-biotite-chlorite schist, hanging wall, Level 11 Nordre Gruve.

and lensing. At various localities, quartz and calcite are in lenses ranging from microscopic to 0.3 meters or larger in thickness. Quartz often appears as the only constituent of a lens as does calcite. Figures 10 and 11 exhibit typical examples of zones enriched in calcite and quartz in the foot and hanging walls. Zones of carbonate and quartz enriched schists were noted on the original map but because of their size could not be reproduced on the map in this paper.

Microscopically, the minerals are generally subhedral to anhedral, exhibiting granulated and crushed grains as well as recrystallized areas. Quartz has strained extinction under crossed nicols and is usually finely granulated in the groundmass. When occurring as blastocrysts and lenses, it is recrystallized into larger grains. Hornblende is often in euhedral crystals forming a matted mass without any alignment of grains. Frequently the edges of hornblende grains are altered to chlorite. The biotite is a light brown pleochroic mica, possibly a phlogopite, which can be found altering to chlorite. It occurs as aggregates of grains and as individual bent and sheared books and folia. Calcite has a sieve texture with inclusions of quartz, muscovite, and epidote and in many instances appears to be in the process of porphryoblastic growth. In some specimens, two generations of calcite in a porphryoblast could be recognized because the centers of grains showed extinction under crossed nicols in one position and the edges showed extinction at another. In some cases, calcite is a secondary mineral filling in around grain boundaries and in fracture zones and in other cases it does not seem to be of this origin. Chlorite is the ubiquitous mineral of undifferentiated schists, occurring as an alteration product typical of retrogressive metamorphism. The chlorite folia show the effects of shearing and folding in their warped and torn grains. A member of the epidote family occurs in twinned on the (100) plane subhedral crystals, isolated anhedral grains, and aggregated masses of granulated grains. In one case, the optics of the mineral were determined. The mineral has a n_y=1.725±.002, n_z=1.732±.002, n_x=1.719±.002, $X \wedge c$=0°, positive, and large 2V. It occurred in green elongated tabular prisms with a maximum length of 0.5 milimeter and a width of 0.1 milimeter. According to Tröger (1959), it is a pistacite containing about 15 mol percent of the molecule $HCa_2Fe_3Si_3O_{13}$. At other places, tabular prisms of a greenish gray mineral were found associated with glassy quartz lenses. By x-ray methods, the mineral was determined to be zoisite. It is evident that composition of the epidote minerals in the schists varies depending paetly upon the original chemical composition of the schists. In some thin sections, especially rich in ore minerals, the epidote contained centers or inclusions of a pleochroic brown, very high positive relief, high birefringent mineral which is tentatively identified as allanite. Garnet, where it occurs as an accessory mineral, is euhedral with numerous inclusions of quartz. The ore minerals are usually aligned along foliation planes in the schists.

In the foot wall cross-cuts are exposed zones of loose chloritic schists, included in the undifferentiated schists, which range in thickness from 0.3 meter to 2 meters or more. These zones have the appearance of having been highly sheared and perhaps a locus for the flow of solutions, either hydrothermal ascending or secondary descending ones. The dominant mineral in the zone is chlorite, usually in amounts of more than 85 percent by volume. It has a n_y=1.615±.002, is optically positive and shows green pleochroic colors. According to Winchell (1951), it would be a prochlorite or ripidolite. Pyrite cubes, having an elongated axis parallel to the foliation, are sometimes present. They attain a size of 1 to 2 centimeters. In other zones, discrete crystals of a carbonate mineral with a n_o=1.695 to 1.706 is found. It was determined by a x-ray powder pattern to be in the group dolomite-ankerite. From its refractive index using a chart in Kennedy (1947,p.569) it must be a dolomite containing about 25 percent ankerite. Other minerals found in the chloritic schists in small amounts are actinolite, quartz, sphene, chalcopyrite, biotite, and apatite.

On Level 6 at coordinates 250x to 260x and 330y a distinct layer or bed of chlorite-epidote-garnet schist containing large amphibole blades up to 5 centimeters long was mapped. No where else was this distinct layer observed, except in the Marie Louise Shaft on Levels 9 and 10, although the undifferentiated schists in the foot wall of the western end of the lower part of the mine are very rich in amphiboles, usually actinolite. This schist contained 88 percent of chlorite in a felted mass of anhedral crystals, 5.1 percent of epidote, 4.1 percent of garnet porphyroblasts (a maximum size of 0.5 centimeter) containing epidote inclusions, 1.4 percent of amphibole, more or less occurring in rosettes of euhedral crystals, and minor amounts of quartz, calcite, and ore minerals. The garnet has a refractive index of 1.800±.002 and probably belongs to the almandine-pyrope family. The optical data of the amphibole are; n_y=1.676±.002, n_z=1.684±.002, $X \wedge c$ 12.5°, X is yellowish brown, Y is greenish yellow, Z is dark green, positive, and 2V=75°. This according to Tröger (1959,p.72), makes it an actinolite with 70 to 80 mol percent of the imaginary molecule Ca_2Fe_5 or an iron-rich actinolite. The chlorite is optically positive and has a n_y=1.623±.002 and according to Winchell is probably ripidolite, and occurs as the main mineral in the schist.

Normally, the quartzitic schists compose the immediate foot wall of the ore wherever the thin selvages of chloritic schists are not present. The quartzitic schists are also present as lenses and boudins "floating" within the undifferentiated schists. They range in composition from mica-(muscovite and sericite) quartz schists to recrystallized, sometimes glassy, quartzite containing less than 5 percent accessory minerals. The majority of the schists contain 60 to 90 percent quartz, up to 10 percent muscovite and sericite, up to 20 percent calcite and other minor minerals such as hornblende, epidote, chlorite, albite, sphene, and ore minerals. In crests of folds the schist contains a higher percentage of albite than elsewhere. The rock is foliated by the alignment of the phyllosilicates and trains of ore minerals at some localities. The main ore mineral is fine-grained crystals of cubic pyrite, with minor amounts of of chalcopyrite and pyrrhotite. The quartz generally shows strained extinction in the larger grains. These large grains can be surrounded by many finer grains which make it appear as if the quartz has been granulated and later recrystallized. A normal microscopic texture is a lens of large recrystallized quartz grains, sometimes glassy quartz, stretched out parallel to the foliation. The average grain size of the quartz is 0.5 millimeter, while the larger grains have an average size of 0.8 millimeters. Table 9 presents several modal analyses of the quartzitic schists, while in the diagram representing rocks with more than 60 percent quartz plus feldspar, their compositions are compared with those of the quartz-plagioclase gneisses (See Fig. 12).

Table 9: Modal Analyses of Quartzitic Schists.

	1	2	3	4	5
Quartz	79.1	85.5	75.9	76.2	66.3
Albite	0.4	3.1	8.2	0.9	1.8
Muscovite	2.2	11.1	0.0	12.7	7.3
Biotite	0.0	tr.	6.6	tr.	4.6
Chlorite	tr.	tr.	0.0	0.1	0.0
Calcite	14.9	1.1	0.0	7.4	0.1
Hornblende	0.0	0.0	0.5	0.0	6.4
Epidote	1.4	0.4	2.8	2.2	13.5
Sphene	0.0	0.0	tr.	0.0	6.4
Zircon	0.0	tr.	0.0	tr.	tr.
Ore minerals	2.0	0.9	0.0	0.4	0.0

1) Quartz-calcite schist, Level 10, foot wall, Nordre Gruve.
2) Quartz-muscovite schist, Level 12, foot wall, Nordre Gruve.
3) Quartz-albite schist, Level 11, near 250 Shaft, Nordre Gruve.
4) Quartz-muscovite schist, Level 13, foot wall, Nordre Gruve.
5) Quartz-epidote-muscovite schist, Level 10, foot wall, Nordre Gruve.

Since the quartzitic schists show marked lack of feldspars, the author believes that they represent metamorphosed equivalents of dirty sandstones, deposited during a period of relative stability and not the equivalents of metamorphosed quartz-keratophyres or acid tuff accumulations, although no relic sedimentary textures were observed. The strained extinction, granulated textures, and foliation are evidence of tectonic movement after deposition.

Underground the quartz-albite gneiss (occasionally with a schistose texture) was mapped as undifferentiated schists unless it exhibited clear contacts with the other rocks. Where it did show a definite contact and not a gradiation into schistose rocks, it was separated, mapped, and indicated on the map(See Plates 1 and 2) expecially on Level 6. The gneiss occurs as distinct bands which continue for short distances along strike as lenses and boudins and as an indistinguishable gradational rock. As can be seen on the diagram (See Fig. 12), it closely approaches the composition of trondhjemite mapped on the surface and not that of the quartzitic schists. To explain its occurrence underground in the distorted and folded lenses within undifferentiated schists is difficult. One suggestion, though a poor one, is that it formed more continuous beds or lenses than it does at the present and that due to the competency of the gneiss relative to the undifferentiated schists, under folding and thrusting of the region, the gneiss was boudined and broken up, while the other schists flowed in around it. Only one problem with this is that the foliation is generally parallel to that of the surrounding schists, and not different as would be expected if the gneiss went through such an intense tectonic movement. Since they do not occur in any one definite stratigraphic zone, they do not seem to represent lava or tuffs that were once in a molten state, but are more likely reworked material or water laid tuffs which could have a more irregular type of distribution.

The quartz-plagioclase gneiss has an inequigranular, allotriomorphic texture. Microscopically, it is composed mainly of quartz, albite, and epidote. Minor minerals are calcite, muscovite, chlorite, biotite, orthoclase, garnet, rutile, sphene, and ore minerals. Table 10 presents some modal analyses (See p.36). The quartz tends to ahve a wavy extinction under crossed nicols. Albite (An_5-An_9) occurs as crystoblasts as well as in the groundmass. The crystoblasts sometimes show

Table 10: Modal Analyses of Quartz-albite Gneisees.

	1	2
Quartz	47.2	57.7
Albite	40.0	26.2
Orthoclase	0.4	tr.
Muscovite	0.0	tr.
Biotite	0.0	1.7
Chlorite	2.1	3.6
Calcite	9.3	0.4
Epidote	0.4	8.1
Garnet	0.1	0.1
Rutile	0.0	tr.
Sphene	0.1	1.8

1) Quartz-albite gneiss, occurs as a lens, Level 10, Nordre Gruve.
2) Quartz-albite schist, occurs as a continuous band, Level 6, Nordre Gruve.

a perthitic texture and always have a sieve texture caused by numerous subhedral inclusions of quartz, muscovite, and epidote. Albite in the rock is frequently twinned. Infrequently the albite is sericitized or kaolinized giving it a dusty appearance. Garnets, when they occur, are of the pyrope-almandine group and are occasionally rimmed with biotite, and contain many inclusions of epidote. Calcite seems to be a secondary mineral in most cases, filling in around grains along cleavage planes and expanding in aggregates from that type of original position. It generally has a dusty texture to it, except when it forms clear veins in fractures.

On Level 5 west at about coordinates 200x and 280y, an odd occurrence for Nordre Gruve and the surrounding area was observed. A large carbonate mass, 2.5 meters thick, was found exposed at various localities along 100 meters strike distance in the foot wall. The exposures are limited by the areas which have been stoped out probably removing part of the body and by unstoped areas where the rock disappears into the walls. In thin section, it consists of 95 percent carbonate with traces of quartz, micas, and ore minerals. Magnetite is occasionally found aligned in planes in the carbonate. The contact of the carbonate with the ore is of a gradational type. Several samples of the carbonate was separated and identified by an x-ray powder pattern as belonging to the dolomite-ankerite group. The n_o refractive index was determined for these samples and found to range from 1.692 to 1.711. According to Tröger's chart (1959, p.26), this makes it a dolomite with about 25 percent $CaFe(CO_3)_2$ in it. No dolomites or limestones have been reported in the Folldal district previously, but this could be due to the limited amount of geology done in the area. The author believes that this dolomitic mass represents a thin bed of carbonate deposited in the original synclinorium. Besides its occurrence, other evidence for its sedimentary origin, is the large amount of calcium in the other schists as shown by calcite in the modal analyses. Thin bands of limestone in a similar series of rocks, although less metamorphosed, are common in the geologic column.

In Fig. 13 are plotted the recalculated modal analyses of all schists containing less than 60 percent quartz plus feldspar. The apices of this compositional diagram were chosen to be calcite; the micas, chlorite plus biotite plus muscovite; and epidote plus hornblende. Each analysis is distinguished as a hanging wall, foot wall, or surface rock depending upon its occurrence. Those schists and gneisses with more than 60 percent quartz plus feldspar are represented in Fig. 12 in a triangular diagram with quartz, feldspar, and mafic minerals at the apices. Fig. 13 represents the more basic and magnesium rich schists, while Fig. 12 illustrates the compositional variance in the more acid rocks. The acid rocks are clustered into two groups, one around the analysis of trondhjemite and the other along the quartz-mafic minerals' composition line near 70 to 80 percent quartz.

The trinagular diagram of the more basic rocks combined with the general geology of the region considered in this study suggests interesting, but so far unproven, clues concerning the depositional environment of the original rocks forming the schists around Nordre Gruve. Assuming that the schist series is not overturned, there was a change from argillaceous sedimentation, as illustrated by the modal analyses of the foot wall which are near the mica apex to a more calcareous type of deposition as shown by the modal analyses of hanging wall schists. Following the argillaceous sedimentation, a dolomitic limestone was deposited, succeeded by a quartz-rich sandstone before the hanging wall calcareous sediments. This sequence is suggestive of conditions similar to a border facies of a basin. Geis (1961) states that some massive sulfide deposits in the Folldal district occur on the flanks of a trough. The problem of sedimentary envoronment of the schists has only been opened up by the work so far done and has by no means been solved.

An attempt was made to distinguish whether an alteration halo or zone existed around the ore body. This was done by making a detailed mineralogical study of a hanging wall and foot wall section of the undifferentiated schists. The results of this detailed study were then compared with wall rock samples collected in various other locations near the ore zone. Figures 10 and 11 summarize the results of the detailed study. In each diagram, a graph of the modal analyses versus location with respect to the ore body is exhibited and remarks on the various other samples are made. One can see that immediately there is no simple trend or variation in mineral percentages with respect to distance from the ore zone. In part, this again reflects the original heterogeneity of the undifferentiated schists, and in part, reflects probable results of varying metamorphic processes, but it does not give evidence for an alteration halo around the ore body. As shown in pages 8 through 12 chlorite as a secondary alteration product is present all over the area mapped, and therefore, can not be used as evidence of hydrothermal alteration accompanying the ore. Other rock samples studied throughout the mine give no evidence for an alteration halo.

THE ORE

There are really two different types of ore. One is the massive sulfide ore consisting mainly of pyrite, pyrrhotite, magnetite, sphalerite, chalcopyrite, and gangue. The other is dissemanated ore which occurs in the wall rocks and along the continuation of the strike of the massive ore in some localities, which is composed of euhedral crystals of pyrite and veins and aggregates of pyrrhotite, chalcopyrite, and occasionally sphalerite. The abundance of the disseminated type in relative volume percentage is exceedingly small nor is it generally mined or exposed in many localities. It seems to occur mostly in sheared zones either related to the main ore or separate from it. This type ranges from very sparse disseminations of single crystals of pyrite to the more concentrated occurrences approaching in their concentration of sulfides to that of the massive sulfide.

In the massive ore three types of ore can be distinguished; magnetite banded ore, a banded ore causde by changes in the gangue to ore minerals' ratio, and a banded ore due to changes in pyrite grain size. Only the first type of banding can be followed for more than a meter underground because of the difficulties in recognizing the characteristics of the other types of banding. The massive sulfide type of ore has in the past been assumed to be a very homogeneous type of mineralization and by rough approximation appears as such. The following discussion should demonstrate that this is by no means true. Before continuing on this, one needs to know the detailed ore mineralogy.

The silicates and gnague minerals have been either derived mechanically or chemically from the wall rocks, although it is possible that some are of hydrothermal origin and are therefore discussed under Gangue Minerals (See p. 62).

The only primary oxide mineral observed is magnetite, Fe_3O_4, which is a relatively abundant constituent of the massive ore. In distinguishing different sub-types of massive ore, one variety is the magnetite banded ore where the magnetite occurs among the sulfides as euhedral to subhedral crystals of an average grain size of 0.5 millimeters and as aggregates in lens-like forms or beds concordant to the foliation of the wall rocks (See Plate 3,Fig.1). This could be described as a type of discontinuous banding, each lens or band of solid magnetite extends along strike for a few centimeters, but the zone of lenses extends along strike for great distances. There are several examples of a conformable re-

relation where the wall rocks have been folded controlling the thickness of the ore. In these cases the magnetite bands are also folded in a similar fashion. Also in some localities, the magnetite bands were found to bend around glassy quartz lenses. This sub-type is mixed with the banded massive type caused by a variation in the ore to gangue ratio. A suggested possibility for the origin of the magnetite banding is that the ore could have been folded after deposition if one considers the magnetite to be of the same depositional phase as the sulfides. If one assumes magnetite to be of any earlier mineralizing phase on textural relations, then it and the wall rocks could have been folded with a favorable horizon which was later replaced by sulfide minerals. Magnetite also occurs as subhedral and euhedral grains, sometimes fractured and crushed, concentrated around carbonate fragments in the massive sulfide ore. In either mode of occurrence, the sulfide minerals are moulded around and occasionally replace the magnetite grains therefore suggesting that the magnetite is of an earlier age of crystallization than the sulfides. Small blebs of pyrrhotite are found within the magnetite in some cases. An example of magnetite banded ore is illustrated in Plate 7,Fig.1. The lenses or bands of magnetite banded ore can attain a thickness of 2 centimeters. In a couple of cases, magnetite was replaced along its crystallographic growth boundaries by a carbonate mineral (See Plate4,Fig.2). This is an uncommon phenomena in Nordre Gruve.

The sulfide and sulfosalt minerals identified in the massive sulfide ore of Nordre Gruve are the following(See p.42):

Main minerals	Accessory minerals
Pyrite, FeS_2	Galena, PbS
Pyrrhotite, $Fe_{1-x}S$	Cubanite, $CuFeS_3$
Chalcopyrite, $CuFeS_2$	Molybdenite, MoS_2
Sphalerite, ZnS	Arsenopyrite, FeAsS
	Fahlerts

The accessory minerals amount to less than one percent of a modal analysis of 1000 points in any one specimen. Cubanite never appears in a modal analysis of the ore because of its scarcity.

Pyrite is an ubiquitous mineral and also by far the most abundant mineral of the ore. For this reason, a detailed study of pyrite grain size was done. Grain size, in this case, is the size in length and width of rectangular sections of pyrite with a cubic habit as shown in a polished section. Some 200 rectangular sections were measured and plotted on a graph of length versus width. The mode of the maximum dimensions that the pyrite cubes have is 0.67 millimeters squared and that of minimum dimensions of the cubes is 0.58 millimeters squared based on 200 measurements (See Figure 14). The range is from smallest measurable size to about 3 millimeters squared, (this includes macroscopic measurements), although there are examples of euhedral pyrite in the disseminated type of a maximum size of 2.5 centimeters and places in the massive ore where the pyrite attains a much larger size.

If one takes a large number of randomly oriented cubes and passes a randomly oriented plane through the cubes, in practice a polished section of ore minerals with cubic habit, it is possible to calculate the longest theoretical edge of a rectangle made by the random cut. Of course such a plane will give other sections besides rectangles, i.e., triangles, rhombs, and five sided polygons, but one is interested in only those sections that are definitely rectangles. The longest side of a rectangle made by a random cut in a cube is, simply, the diagonal of a square. A line representing the diagonal as an edge of a rectangle and a line representing a perfect cube can be plotted on a graph of length versus width as is done in Figure 14. Any measurement of rectangles which fall in the region below the line representing the diagonal as an edge line on the figure, indicates a theoretical impossibility if one assumes the habit is cubic. Such points as these in Figure 14 can be explained in several ways; (1) a subjective error exists in choosing only rectangles to measure, (2) the actual habit of pyrite departs from a cubic formand tends toward an octahedral habit, or (3) the pyrite cubes have been elongated in one direction due to stresses either during or after deposition of the minerals. About 20 percent of the rectangles measured fall into the region of elongation, which suggests case (1) not to be entirely adequate. There are no visual reasons for believing in case (2) from macroscopic specimens. Therefore, to the author the elongation of the pyrite cubes offers the best explanation.

The variation in grain size of pyrite gives rise to a third major sub-type of massive sulfide ore which is characterized by a textural banding and lensing due to more or less abrupt changes in grain size, which is generally conformable to the foliation of the immediate wall rocks. This type of banding is impossible to follow underground for large distances and so it is difficult to determine its extent. This sub-type is complicated by occurring not only by itself, but in the same specimen with magnetite banded and/or gangue to ore banded types. Pyrite also forms a massive ore without conspicuous banding.

An example of pyrite texture banding is presented in Plate 7,Fig.2. On the right side of the specimen, there is a band 6 millimeters wide of euhedral to subhedral pyrite crystals 0.25 millimeters in size. There is about 10 percent gangue in this band. Following this, comes a zone of 5 to 6 millimeters wide of pyrite crystals 1 to 2 millimeters in size with about 30 percent gangue. Newt is a band 8 to 10 millimeters thick of pyrite crystals with a maximum size of 0.5 millimeter but containing more than 25 percent gangue minerals. The next zone is similar to the first band of 0.25 millimeter crystals but is 5 millimeters thick. The following zone ressembles the fourth band of 0.5 millimeter crystals with 25 percent gangue. The first band type is again repeated for a thickness of 25 millimeters or more. In this speciment the pyrite grain size banding is evident as is also the relation of the gangue to ore mineral ratio banding. Although the grain sizes and zones above are typical of this type of banding, they are not of any use in determining a succession of grain size bands throughout the mine because of the great variation from one location to the next which is illustrated by Plate 8,Fig.1 and 2. In Plate 8,Fig.1 the specimen has one band of coarse crystals while the specimens in Plate 9,Fig.2 and Plate 10,Fig.1 show a more lensing and irregular arrangement of different grain sizes set off more or less by concentrations of gangue minerals. The subhedral and euhedral crystals of pyrite in polished section sit in a matrix of chalcopyrite, pyrrhotite, and sphalerite. Often the edges of the pyrite crystals have been corroded by chalcopyrite and pyrrhotite and exhibit irregular boundaries against these two matrix minerals.

Generally, pyrite shows distinct crystal edges when against sphalerite, In many cases, what appear to be inclusions of sphalerite, chalcopyrite, galena and silicates are seen in the middle of euhedral pyrite crystals. Interestingly, pyrrhotite is scarce as "inclusion" material. If these represent true inclusions in three dimensions and not embayments in the pyrite, they could therefore be explained by the pyrite crystal growing around the other minerals during metamorphic processes. A three dimensional investigation was carried out in the following manner. Specimens which showed "inclusions" in polished specimen similar to those seen in Nordre Gruve sections were chosen from friable ore material from Bleikvassli and were leached in nitric acid to remove all other sulfides which may have made caries in the pyrite and therefore appear as "inclusions" in two dimensions. After this,polished specimens were prepared of the leached pyrite grains and observed under the microscope. In Plate 4,Fig.1, the result is shown by the gray areas of plastic, used as a mounting medium, where the inclusions would have been in a polished section such as Plate 10,Fig.1. One or two inclusions were observed after this process, but the majority of "inclusions" did not exist. From this, it can be assumed that most of the "inclusions" really represent a three dimensional continuation of the carie structure. It is still possible for some of such textures to be inclusions. Plate 10,Fig.1 shows a pyrite crystal penetrated by a silicate grain, probably an amphibole, which could be interpreted as pyrite growing around a silicate or as a silicate replacing pyrite. The author prefers the sulfide growth theory.

In many places, the pyrite crystals have been fractured along cleavage plane, crushed, or granulated and therefore exhibit a cataclastic texture. The intensity of this texture varies from pyrite crystals which show only slight traces of fracturing to crystals where the fracture parts of the pyrite grains have "floated" away from the crystal and have later been filled around by the matrix minerals. Each fragment could be joined back together to form the original crystals because of the slight amount of corrosion of the pieces (See Plate 11,Fig.2). At stages in between the extremes, one finds the pyrite crystal still as an entity but with cleavage fractures not filled with ore minerals as in Plate 11,Fig.1. There is a continuous series of textures from those crystals which are euhedral and unfractured to those which are broken into pieces "floating" in matrix minerals. From the given examples it can not be assumed that there has not also been some replacement along the fractures and at the edges of pyrite crystals by the matrix minerals. Plate 14, Fig.1 shows a late stage of this type of replacement of pyrite by sphalerite.

The greatest concentration of euhedral, non-cataclastic pyrite crystals, entirely free from "inclusions" appear in the crests of folds which have gone off from the main ore into the wall rocks. Plate 13, Fig 2 illustrates this texture and also shows each of the matrix minerals at such locations. Also, under reflected light, pyrite grains near glassy quartz and quartz-carbonate inclusions seem to be relatively free from "inclusions"

Besides the above normal types of pyrite textures for the massive ore of Nordre Gruve, there is at certain localities quite a different appearing pyrite (See Plate 13, Fig. 1).

This type is very fine-grained, less than 0.015 millimeter in diameter and dusty because of the abundance of fine flecks of silicates in the pyrite. It is similar in grain size for Løkken pyrite deposit which varies in grain size from 0.01 millimeter to 0.10 millimeter (Vokes, 1960). The main matrix mineral is sphalerite while pyrrhotite and chalcopyrite are rare in this type of ore. The pyrite of fine grain size, in some cases, seems to be a result of intense shearing and granulation. In other cases, it could be remnants of originally deposited pyrite which has not recrystallized to the same degree as the rest of the ore body. This explanation only holds if one accepts the theory that the ore body was deposited earlier and then later involved in the regional metamorphism. Where this fine-grained pyrite occurs as a breccia in a post ore fault, as illustrated in Plate 3, Fig.2, it is reasonable to postulate that it originated from shearing movements. This is also true of its occurrence within a couple of centimeters of the wall of the ore body, as associated with slickensides caused by the parallel shear couples. When it occurs at locations where there are no visible evidences of post-ore movement, the origin of the fine-grained pyrite may be explained by local areas of unmetamorphosed ore. An example of this occurs on Level 10 at coordinates 540x and 690y. The hanging wall and foot wall areas are medium-grained massive pyrite ore with normal amounts of matrix minerals. The pyrite crystals are well developed, generally euhedral, with few inclusions, while the middle ore is composed of the fine-grained, dusty type of pyrite with sphalerite as the main matrix mineral. This zone does not appear to continue along strike more than a few meters, nor does it at any point become hanging or foot wall ore.

Sphalerite occurs as one of the matrix minerals for the pyrite crystals. In some cases where there is ore relatively rich in magnetite, sphalerite is sparce or lacking, otherwise it is an almost ever present mineral of the ore. It occurs as irregular masses or aggragates moulding around and replacing pyrite, as caries in pyrite, replacing chalcopyrite, and alone associated with silicate and carbonate minerals. It is extremely rare to find sphalerite associated with pyrrhotite. Sphalerite is some cases, segregates into large masses which appear as bands or zones in pyrite ore without other matrix minerals. Embayed and acalloped contacts of sphalerite with chalcopyrite are frequently observed, while the opposite effect also has been noted. This makes the determination of a general crystallization series impossible between sphalerite and chalcopyrite, but the overall evidence can be interpreted that both minerals probably have crystallized simultaneously.

Occasionally, sphalerite contains blebs and dots of chalcopyrite oriented along parallel planes. This seems to be an exsolution texture although in many cases, it has been completely destroyed. Bueger (1934) gives as a temperature range of chalcopyrite unmixing from sphalerite as 350 to 400°C. Sometimes the chalcopyrite in the sphalerite appears in no definite orientation but is more like an emulsion testure.

The sphalerite in thin section has a dark red-brown color caused by its iron content. Vokes (1962, personal communication) has analyzed clean sphalerite from the zinc concentrates of Nordre Gruve and obtained the following results for iron content:

	FeS in Sphalerite Wt. %	Mol. %	Temperature (uncorrected)	Temperature at 1500±1000 atms.
Analysis 1	11.81	12.93	425°C	462±25°C
Analysis 2	11.56	12.66	420°C	457±25°C

The temperatures given are based on the refined investigations of Barton and Kullerud (1958) for the Fe-Zn-S system. According to Barton (1962, personal communication) the Fe-Zn-S system for the sphalerite-pyrite-pyrrhogite curve is still not completely established below temperatures of 600°C, but must be near to Kullerud's solvus. This means that the amount of error expressed in Vokes' corrected temperatures must be greater than is shown.

Chalcopyrite is found as a matrix sulfide in association with both sphalerite and pyrrhotite as well as pyrite. There is a tendency for it to be concentrated on the foot wall of the ore, around inclusions of carbonate, and in chlorite schist partings. Chalcopyrite generally has mutual boundaries with both other matrix minerals, but it is seen to replace pyrite and upon occasions to form veinlets seemingly cutting across pyrrhotite. Sometimes it contains minute blebs of sphalerite which may be remnants of a former exsolution texture, but now can not be definitely so classified. The association of chalcopyrite with pyrrhotite is typical of veinlets and disseminations in chloritic hanging wall schists. Pyrite infrequently gets into the immediate rock of this hanging wall zone. The chalcopyrite occurs as irregular mouldings or groups throughout the ore but in far lesser amount than does sphalerite. It often appears to be replacing silicate minerals, especially amphiboles, along cross-fractures and cleavage planes. As can be seen, it is difficult to interpret this as anything other than a replacement phenomenon.

Pyrrhotite is perhaps the third most abundant ore mineral. It has the tehdency to be concentrated along wall zones, in the immediate chlorite schists of the hanging wall, in chloritic schist partings in the ore, and around inclusions of glassy quartz and carbonate (See Plate 10. Fig.2). Rarely does it occur as inclusions in the pyrite as do the other matrix minerals. The texture of pyrrhotite is allotriomorphic and never shows crystal boundaries under crossed nicols in reflected light, occurring as anhedral and rounded grains in aggregates associated with chalcopyrite but rarely with sphalerite. Sometimes it shows strained extinction and is further evidence of tectonic movement in the ore zone. Examples of pyrrhotite cross-cutting and embaying the other matrix minerals has been observed as well as the reverse relationship.

Galena occurs in amounts of less than 0.5 percent by volume in the ore as small masses in the other matrix minerals and in pyrite as inclusions. In one specimen one euhedral crystal was observed. It is not abundant enough to be able to define any textural or time of crystallization relationships.

Cubanite is a rare mineral in the massive ore (observed in only two polished sections) and occurs only in copper rich areas where there are high concentrations of magnetite and pyrrhotite. The magnetite in these cases is usually partly replaced by chalcopyrite and pyrrhotite. It is found only in chalcopyrite where it forms single lamellae or groups of lamellae having variable dimensions probably oriented along (111) planes in chalcopyrite. Under crossed nicols it shows a strong anisotropism while in plain light it exhibits slight pleochroism. Schwartz (1927) showed by experiments that cubanite was exsolved out of chalcopyrite solid-solution at temperatures ranging from 400 to 450°C. Ramdohr (1962) says that this exsolution takes place at lower temperatures (about 250°C) without giving evidence for the statement. Any chalcopyrite containing cubanite lamellae must have been above the temperature of 250°C at least.

Arsenopyrite was observed in a few cases to occur in euhedral grains in pyrite rich ore from samples only near the hanging wall of the ore body. In most cases, it was not corroded by other sulfide minerals, but in a few cases the arsenopyrite grains were rounded anhedral fragments which had the appearance of having been rolled, breaking off the crystal corners. The Fe-As-S system has been worked out in some detail by Clark (1960). He states that the maximum temperature of pyrite-arsenopyrite association in nature must be 491±12° C (Clark, 1960, p.1642) and that this applies whether pyrrhotite is present or not. Therefore one of the two minerals, pyrite or arsenopyrite, probably crystallized below 491±12°C in Nordre Gruve. This only applies to those specific localities in the mine where the association is found.

Molybdenite was observed in a couple of polished sections. It always occurs as small blades either in sphalerite or more normally in pyrite. None of the blades seen was bent or twisted.

A mineral occurring in small amounts in a few specimens was observed. It is isotropic, has a white to bluish-white color, is harder than chalcopyrite and is softer than pyrrhotite. It was only observed in areas of the ore relatively rich in galena. Its properties seem to indicate that it is a member of the fahlerts group (tetrahedrite-tennatite) comprising sulfosalts containing As, Sb, Cu, Zn, Fe, Ag, and Bi.

Nowhere was it present in large enough grains to assign more than a tentative identification.

Earlier it was mentioned that massive sulfide ore deposits similar to Folldal have been considered to be fairly homogeneous bodies in mineralogical and chemical composition. In light of this, a study of the compositional variation of the ore minerals with respect to the location of the sample in the ore body was carried out. Polished sections of well located ore samples were point counted to obtain modal analyses. These were then tabulated and plotted on triangular diagrams in all possible combinations in an attemtp to find trends in mineralogical variation.

The mineralogical composition of the ore in volume percent as summarized in Table 12. The gangue free composition of a

Table 12: Mineralogical Composition of Ore.

Mineral	Average (%)	Range (minimum % - maximum %)
Pyrite	55.6	1.5-81.3
Sphalerite	7.5	0.0-44.9
Chalcopyrite	5.5	0.0-62.0
Pyrrhotite	5.3	0.0-29.5
Magnetite	1.8	0.0-12.9
Galena	} 0.5	0.0- 0.5
Arsenopyrite		0.0- 0.2
Fahlerts		0.0- 0.3
Gangue	23.8	1.2-72.7

limited number of sections can be observed in Table 13 while Figures 15,16, and 17 are triangular diagrams of gangue free massive sulfide ore. In Figure 15 the three components plotted are pyrite volume percent, pyrrhotite volume percent, and the volume percent of matrix sulfide minerals (chalcopyrite, sphalerite, galena, arsenopyrite, and fahlerts). This shows that the Folldal massive ore is mainly a pyritic ore and that it is unlike certain others of the massive Caledonian ore bodies, for example Bleikvassli, which shows both a pyrrhotitic and pyritic ore type (Vokes, 1961, personal communication). In Figure 16, the components of the ore are split up in a different fashion. Since pyrite is an ubiquitous mineral and its occurrence is generally unrelated directly to the occurrence of other ore minerals, it was chosen as one apex. In polished sections and hand specimens, pyrrhotite and chalcopyrite are usually intimately associated and therefore form the second apex of the diagram, while sphalerite and galena form a common assemblage in the ore and are the third apex. The diagram illustrates that the pyrrhotite-chalcopyrite assemblage is a more dominant one in volume percentage of the ore than is the sphalerite-galena assemblage. The third triangular diagram (See Fig. 17) is plotted with the components being pyrite, sphalerite, and chalcopyrite. Analyses of Folldal ore are represented by the black points. These indicate that the ore is not one of dominant pyrite-chalcopyrite composition but tends to have a larger amount of the zinc bearing constituent, sphalerite. Du Rietz (1951) gave 63 modal analyses of four types of ore; wet, dry, zinc, and pyrite, from the Kristineberg deposit in Sweden. These analyses were recalculated to pyrite plus sphalerite plus chalcopyrite totaling 100 percent and plotted on Figure 17 as black crosses. Except for the zinc ore of Kristineberg, which contains 10 percent galena enclosed in a dashed line on the diagram, there is a very close similarity of Kristineberg bulk composition to that of Nordre Gruve.

Table 13 (See p.54) presents the results of 49 modal analyses of samples collected at 13 different locations as sections across the width of the ore body. Since thickness

Table 13: Analyses of Ore Located with Respect to Wall Rocks by Percentage of Thickness. (Pyrite pyrrhotite-sphalerite-chalcopyrite-galena 100%).

Pyrite, gangue free (volume %)

Loc.	2B	3A	4B	6C	6G	8A	9D	11F	11H	12G	12H	13A	13E
HW.	87.6	88.4	85.6	85.6	68.3	92.8	79.0	83.2	84.0	62.4	79.0	47.5	53.2
0.25						88.7	49.9	71.7	83.2	75.3	82.8	68.1	86.8
0.50	77.8		59.5	84.9	54.7	87.5	76.5			75.3	83.8	16.5	96.7
0.75	82.3					75.2	85.6	72.6	73.2		77.5	62.6	70.5
FW.	75.7	86.5	63.8	82.8	69.4	70.0	54.4	86.1	70.0	64.2	75.5	87.1	52.4

Pyrrhotite, gangue free (volume %)

Loc.	2B	3A	4B	6C	6G	8A	9D	11F	11H	12G	12H	13A	13E
HW.	0.5	0.1	0.1	3.8	19.5	2.4	9.2	2.9	4.2	3.7	1.5	24.9	13.4
0.25						2.7	14.4	2.8	5.4	3.7	1.2	14.5	1.5
0.50	2.5		12.6	4.8	18.9	1.9	6.5			12.4	0.8	7.6	0.4
0.75	4.9					7.5	0.1	22.1	5.0		0.9	12.1	29.4
FW.	5.8	0.9	0.8	2.4	6.4	10.6	37.4	0.5	5.2	0.0	10.3	8.8	46.4

Matrix sulfide minerals, gangue free (volume %)

Loc.	2B	3A	4B	6C	6G	8A	9D	11F	11H	12G	12H	13A	13E
HW.	11.9	11.5	14.3	10.6	12.2	4.8	11.8	13.0	11.8	33.9	19.5	27.6	34.4
0.25						8.6	5.7	25.0	11.4	21.0	16.0	17.4	11.7
0.50	19.7		27.9	10.3	26.2	10.6	17.0			12.3	16.1	6.5	2.9
0.75	18.4					17.3	21.0	22.1	22.7		21.6	25.3	20.9
FW.	18.5	12.6	35.4	14.8	24.2	19.4	8.2	13.4	24.8	35.8	14.2	4.1	1.2

Pyrrhotite plus chalcopyrite, gangue free (volume %)

Loc.	2B	3A	4B	6C	6G	8A	9D	11F	11H	12G	12H	13A	13E
HW.	5.8	1.2	1.5	9.1	23.4	3.7	10.0	8.1	7.3	30.1	7.6	48.2	45.6
0.25						3.8	18.4	9.5	8.1	24.2	3.4	24.0	13.2
0.50	8.0		21.9	9.2	35.2	7.7	16.1			16.0	1.1	12.0	3.1
0.75	5.4					18.0	1.5	23.6	14.9		3.1	20.9	30.7
FW.	9.6	4.3	5.0	8.2	11.4	16.3	42.0	3.4	13.0	0.2	12.9	10.1	47.4

Sphalerite plus galena, gangue free (volume %)

Loc.	2B	3A	4B	6C	6G	8A	9D	11F	11H	12G	12H	13A	13E
HW.	6.6	10.4	12.9	5.5	8.3	3.6	11.0	8.7	8.6	7.5	13.9	4.4	1.1
0.25						7.4	1.7	18.8	8.7	0.5	18.8	7.9	0.0
0.50	14.2		18.7	5.9	10.0	4.8	7.4			0.1	15.8	1.5	0.2
0.75	12.5					6.5	12.9	3.8	12.8		19.4	16.5	19.6
FW.	14.7	9.2	31.2	9.0	18.3	14.5	3.4	10.4	17.0	35.6	11.6	2.8	0.2

Locality 2B: 240x, 150y; thickness, 0.76 meter, Level 2.
Locality 3A: 180x, 200y; thickness, 0.80 meter, Level 3.
Locality 4B: 330x, 250y; thickness, 0.70 meter, Level 4.
Locality 6C: 470x, 420y; thickness, 0.61 meter, Level 6.
Locality 6G: 310x, 350y; thickness, 1.22 meters, Level 6.
Locality 8A: 260x, 440y; thickness, 0.72 meter, Level 8.
Locality 9D: 300x, 490y; thickness, 1.52 meters, Level 9.
Locality 11F: 490x, 640y; thickness, 0.91 meter, Level 11.
Locality 11H: 460x, 640y; thickness, 1.22 meters, Level 11.
Locality 12G: 500x, 680y; thickness, 2.50 meters, Level 12.
Locality 12H; 540x, 690y; thickness, 0.61 meter, Level 12.
Locality 13A: 500x, 720y; thickness, 2.00 meters, Level 13.
Locality 13E: 470x, 680y; thickness, 0.20 meter, Level 13.

varies from location to location, the analyses are located with respect to the hanging wall and foot wall by percent of thickness. The thickness of the sections analyzed range from 0.20 meter (Locality 13E) to 2.50 meters at Locality 12G. The table presents data for the variation in pyrite, pyrrhotite, matrix sulfide minerals, pyrrhotite,plus chalcopyrite, and sphalerite plus galena, all calculated on a gangue free bases. The average volume percent of pyrite for 49 analyses is 75.8: pyrrhotite, 7.6; matrix sulfides, 17.2; pyrrhotite plus chalcopyrite, 14.0; and sphalerite plus galena, 9.9. Histograms of each one of the five components tabulated showed that from 49 analyses, the matrix sulfides were normally distributed with a mode around 12 percent and that pyrite gave a normal distribution skewed toward the higher percentages with a mode about 80 percent, while the other three components gave distributions that skewed toward lower percentages. In thirteen sections, eight can be considered to have pyrite percent decreasing from hanging wall to foot wall, two have pyrrhotite decreasing and three have matrix sulfides decreasing. In six sections, matrix sulfides increase from hanging wall to foot wall, while in four, these percentages tend to fluctuate. In seven sections, pyrrhotite fluctuates while in six sections pyrrhotite plus chalcopyrite fluctuate. Seven sections have sphalerite plus galena tending to increase. Each observed variation is for only the locality stated and the specimen used.

Although it is possible by using such a method to trace variations in mineral composition across the ore body for specific locations, it does not tend to give an overall generalized picture. In order to summarize the data of the thirteen sections, the analyses for each component at all of the five thickness positions in the ore were averaged together to give one value for each of the five positions in the ore for each component. The author may not be justified in doing this because of lack of many more analyses and not knowing whether the samples, except those on the hanging and foot walls, correspond to each other in location, but such a summation as presented in Figure 18 is useful and also the frequency diagrams of each component seem to represent fairly well distributed samples in each population. In Figure 18, the average percentage of each component at five positions across the ore is plotted. Pyrite shows a decrease from hanging wall to foot wall with a slight increase in the middle of the ore. Matrix minerals, as a group, are about equal in bulk percentage at the walls, but tend to fluctuate in the middle of the ore body, being more concentrated in the foot wall half of the ore thickness. Pyrrhotite is more concentrated on the foot wall than on the hanging wall and is at a minimum in the middle of the ore body. This can be seen both in polished hand specimens and polished sections (See Plate 10, Fig.2). There generally seems to be a concentration of pyrrhotite near the contact of the ore with the wall rocks. In Figure 15, there are analyses which fall closer to the pyrrhotite apex than the majority of analyses and are accounted for by this variation in pyrrhotite composition across the ore body. Sphalerite and galena are concentrated more toward the walls as is pyrrhotite with a minimum concentration in the middle of the ore. Thus, sphalerite (this is the main component of sphalerite plus galena wihce the galena percentage never rises above 0.5 volume percent) is more concentrated on the foot wall. Chalcopyrite seems to be concentrated mostly on the hanging wall, but has a large amount near the center of the ore body.

Du Rietz's (1951) study of the pyritic ore of Kristenberg, Sweden, showed a decrease in Fe percent and pyrite across the orebody from the hanging wall to the foot wall. This is exactly analogous with Nordre Gruve. The Cu decreased as did the chalcopyrite from hanging wall to foot wall which is also similar to Nordre Gruve massive ore. Below is an abstract of his data for pyritic ore (See Table 14).

Table 14: Analyses of Pyritic Ore, Kristineberg, Sweden, from Du Rietz (1951, p.51).

	Foot wall	Middle	Hanging wall
(wt.%)			
SiO_2	17.50	9.30	3.77
TiO_2	0.13	0.07	0.02
Al_2O_3	7.62	3.41	0.94
Mn	0.07	0.10	0.01
MgO	6.71	5.13	1.13
Fe	30.99	36.08	42.10
Cu	2.44	3.40	3.53
S	29.07	38.14	46.61
Zn	0.0	tr.	tr.
Pb	0.0	0.0	0.0
(vol.%)			
Pyrite	49.0	64.9	81.0
Chalcopyrite	7.0	9.8	10.2
Chlorite	36.0	15.0	4.5

Vokes (1957) has found that, within the Birtavarre district, Troms, Northern Norway, chalcopyrite tends to be concentrated around rock fragments in the ore and on the walls. He suggests that the chalcopyrite was influenced by the physical presence of the wall rocks and their chemical composition. Vokes (1962, personal communication) has found for Bleikvassli that there are fairly definite variations in modal mineral composition from foot wall to hanging wall for the massive pyrite ore, besides there is a pyrrhotitic ore on the foot wall at some locations. He studied twelve cross-sections of various types of ore and found that in eight out of nine sections there was a moderate to marked increase in pyrite percentages from foot wall to hanging wall, and that there was a decrease in matrix sulfides from foot wall to hanging wall for seven out of twelve sections. In general the individual matrix sulfides showed a decrease from foot wall to hanging wall. This is exactly analogous to Nordre Gruve except in Nordre Gruve the trend is not as pronounced. This may be due to the fact that Bleikvassli ore was probably subjected to a higher degree of regional matamorphism than Nordre Gruve or it may be due to differences in the original conditions of depositions o f the sulfides at the two different locations.

There have been relatively few studies of this type done on massive sulfide ore bodies and as can be seen from the probable trends found above, similar studies would be very helpful to contribute facts which may aid in the solution of the problems of origin. From this, it can be seen that massive sulfide deposits are probably not homogeneous, but do indeed contain mineralogical variations possibly unique to them that can only be recognized by a detailed study.

CHEMISTRY OF THE ORE

Unfortunately, Folldalsverk has no located assay data above Level 4, below this there are 201 usable assays all located with respect to the mine coordinates. Copper, zinc, sulfur, and occasionally iron were analyzed in samples across the thickness of the ore body. Although in polished sections, one finds traces of galena, giving the ore a lead component. Folldalsverk has not analyzed for this metal. Table 15 presents a summary of modes, averages, and ranges for copper, zinc, and sulfur.

Table 15: Statistical Parameters of the Assays.

Metal	Mode (%)	Average (%)	Range (%)
Copper	1.25	1.25	0.32- 4.2
Zinc	3.25	5.25	0.75- 8.0
Sulfur	33 and 43	35.64	21.50-48.2

Frequency-distribution curves were drawn from the data (See Fig.19). All of the curves are unimodal except the one of sulfur which tends to be bimodal. The copper frequency curve is skewed toward the lower percentages of copper.

An attempt was made of correlating copper versus zinc by using the product moment correlation coefficient (Moroney, 1960) which in this case is defined as

$$r \quad \frac{1/N \sum (Cu - \overline{Cu})(Zn - \overline{Zn}}{S_{Cu} \times S_{Zn}} ,$$

where r is the correlation coefficient; N, the number of analyses; $\overline{Cu}$ and $\overline{Zn}$, the average percentage of copper and of zinc; and S_{Cu} andS_{Zn}, the standard deviation of copper and zinc. With the values N equals 201, S_{Cu} equals 55.2, S_{Zn} equals 219.6, $\overline{Cu}$ equals 1.25, and $\overline{Zn}$ equals 5.25,upon substitution r equals -0.32. A perfect straight line correlation would have a r equal to 1.0 and no correlation is represented by r equals 0.0. The minus sign on -0.32 means that as the copper percentage increases, the zinc percentage decreases. The number 0.32 represents a fairly poor correlation at a high level of significance. From this, one would say that the distribution of zinc is probably not related to that of copper.

Values of the ratio Cu/Cu Zn were calculated and plotted in a frequency distribution (See Figure 19) which gave a normal distribution skewed toward the lower ratios. This curve has a similar shape to one published by Wilson and Anderson (1959) for the Geco massive sulfide ore in Canada which contains more zinc than copper as does the Folldal ore deposit.

In an attempt to better understand the distribution of copper, zinc, and sulfur in Nordre Gruve or to spot any zonal relationships, the located assay data were plotted on a vertical profiles and contoured. Figure 20 presents the sulfur distribution with a contour interval of 4 percent. There are no readily apparent trends here, except that the sulfur percentage seems higher in the eastern part of the mine. Figure 21 is a similar diagram of the zinc percentages, interval 1.0 percent. One trend is readily apparent, plunging northeasterly due to the trend of the ore. Another trend is discernible in the individual contour lines which seem to plunge northwesterly. In Figure 22 of the copper distribution, one sees the same two trends, but they are more apparant. The areas of high zinc percentage fall on a zone plunging about 45°E. in the plane of the profile, while the individual contoured highs plunge 40°W. in the plane of the profile. Projecting such a profile into the true plane of the ore body gives the two trends of the plunging lineations, one northeast and the other northwest. These two trends are in accordance with the directions of minor folding and the broader structural features of the Nordre Gruve massive ore. In order to check on representing assay data on vertical profiles, an average value of each metal was calculated for an individual level. Where the level passed through the largest number of high contours relative to the adjacent levels, the average value for the level was high relative to the other levels, thus supporting the method used. The distribution of copper and zinc is by no means as regular in Nordre Gruve as Gjelsvik (1960) found for the Skorovass ore body in the Grong area, Norway, although they both seem to have other similar characteristics such as the banding due to changes in grain size of pyrite.

The ratio of copper to zinc was also contoured in a vertical profile (See Fig.23). All values of the ratio greater than 0.6, lie within the heavy black contour. This has a flame-like shape upwards along the western edge of the ore body. Again, one notices two different trends in the contours. Interestingly, the very lowest values of the ratio are associated with the extreme high values (at coordinates 240x and 675y). The lowest value is 0.20 and the highest, 54.1.

There are other elements in the Folldal ore as shown by a few scattered analyses. Folldalsverk recieves a reward from the smelter for gold and silver recovered in their zinc concentrate. Carstens (1941) presents an analysis for Folldal pyrite concentrate which gives in weight percent; Cu, 0.32; S, 48; and Se, 43 grams per metric ton. One must remember that Folldal's pyrite concentrate does not all originate from the same mine, although the majority of the ore comes from Nordre Gruve. Also Oftedal (1940) gives an analysis of the zinc concentrate (See Table 16). The Bi reported in the analysis may be associated with the traces of fahlerts found in the ore. Arsenic has been reported in analysis of Hovedgruve ore (Marlow, 1935) and, if analyzed for, would probably occur in Nordre Gruve. Any arsenic found in

Table 16: Oftedal's Analysis of Zinc Concentrate.

Element	Weight (%)	Element	Weight (%)
Cd	0.3	Mn	0.3
In	0.001	Co	0.005
Ga	0.001	Pb	0.1
Sn	0.001	Ag	0.003
Hg	0.001 (?)	Bi	0.005
Fe	10.		

Nordre Gruve can probably be atttributed to the minor anounts of arsenopyrite found in the ore from polished section study. This is the extent of the data on the minor elements in the Folldal ore.

THE GANGUE

The abundance of gangue in the massive sulfide ore varies from 1.2 to 72.7 volume percent as found from the polished and thin sections studied. It averages about 23.8 volume percent. The variation of percent gangue with percent thickness of the ore does not seem to showa a trend for the whole mine. Some localities have more gangue in the foot wall ore and hanging wall ore than in the middle, but others show the reverse relationship. In the cross-sections of volume percent gangue plotted versus thickness percentage of ore, no consistent trends were found.

Gangue, in this discussion, includes individual mineral grains and aggregates; quartz, feldspar, and chloritic lenses; disturbed and folded undifferentiated and quartzitic schist partings; and angular fragments of carbonate. All are composed of the same dominant minerals, quartz, calcite, and amphibole. Minor minerals are plagioclase (albite in some cases, where determined by optics), epidote, garnet, biotite, chlorite, muscovite, and the common accessories found in the wall rocks.

In some cases the amphibole was determined by optical methods to be an actinolite. It had the following optical data; n_x= 1.628-1.633, n_y=1.643-1.646, n_z=1.654-1.658; $Z \wedge c$=13-15°, negative, 2V about 80°, X is very pale yellow, Z is pale green, and Y is yellow green. Quartz grains generally show strained extinction and occasionally granulated and recrystalized textures. This is exactly analygous to the quartz observed in thin section from schists within the entire region of study. The amphibole occurs as euhedral to subhedral crystals and aggregates which are fractured perpendicular to their c crystallographic axes. These fractures are filled with sulfide matrix minerals. Calcite exhibits two generation porphyroblasts, occurs as late secondary fillings in cracks and shear planes, and also is moulded around other silicate minerals. Plagioclase, which occurs in greater abundance as a gangue mineral than as a constituent of the wall rocks, is broken along cleavage directions. In polished sections and thin sections, the micas were observed as blades which are bent around other gangue minerals and in some cases around the ore minerals. Very seldom do mica foliae project into a crystal or aggregate of an ore mineral. The other gangue minerals have exactly the same characteristics as they did in the country rocks.

Schist partings either of the undifferentiated schists or the quartzitic schists are found in all sizes ranging from a microscopic thickness to greater than 0.75 meter in thickness. They extend aling strike for distances from microscopic to more than 5.0 meters. Generally, attitudes of foliation measured in such partings are similar to those measured in the adjacent wall rocks. In many cases such partings consist of discontinuous, highly distorted and folded bands in the ore. In all cases, they appear to be remnants of the original wall rocks.

Glassy quartz lenses or masses, sometimes surrounded by rims of chlorite, but more generally not, are very common in the massive ore. They do not seem to occur along any particular horizon or position within the ore body except that in some cases near the foot wall, there were trains of glassy quartz lenses encased in chlorite in a horizon parallel with the quartzitic schists in the foot wall. Sometimes there are disseminations of chalcopyrite and pyrrhotite within the quartz lenses.

Another type of gangue accumulation in the massive ore is angular, and some round, carbonate fragments composed of aggregates of coarse crystals. These fragments are spread throughout the massive ore within the entire ore zone. The greatest concentration of their occurrence seems to be on the lower six levels west of the Marie Louise Shaft. They are especially abundant on Levels 4 and 5. A number of the fragments from localities covering the extent of the ore zone were x-rayed and shown to be calcite. Also the n_o refractive indexes were determined and fell with the range 1.653 to 1.664$\pm$.002. The calcite fragments usually at their edges have a rich concentration of magnetite or minerals of the pyrrhotite-chalcopyrite assemblage. Infrequently they are cut by veins of matrix minerals, usually along fractures and cracks within the fragments. The general appearance of the fragments in the ore is that of limestone breccia which contains some fragments that have had their corners and edges rounded due to tectonic movements. In postulating possible origins of the calcite fragments, it should be remembered that on Level 5 there is a large carbonate mass which is ankeritic dolomite and that various carbonate porphyroblasts in the loose chloritic schists were ankeritic dolomite. One possible origin is that the fragments represent hydrothermally introduced carbonates. Either theory makes it possible for later metamorphism to have redistributed the carbonate. There is no definite evidence for the last statement, but it remains as a possibliiy.

The ore contains lenses and fragments which consist of mixtures of glassy quartz and calcite distributed rather randomly in the ore zone.

At one or two locations were noted rounded lenses of quartz and feldspar, where well-crystallized albitic feldspar was the dominant mineral. The groundmass or matrix of these lenses consisted almost entirely of ore minerals, mainly chalcOpyrite and pyrrhotite. Besides these very localized concentrations of plagioclase, there are thin bands in the ore which consist dominantly of albite with minor quartz. These bands, about 0.5 centimeters thick, do not appear to be very common in the ore, nor do they have great aerial extent. All of the gangue, except the schist partings which show characteristics due to tectonic movements of folding, exhibit evidences of tectonic activity in the ore zone either due to movements during folding and metamorphism or much later tectonic activity parallel to the ore zone. Evidence for later tectonic movement as the cause of rounded fragments seems to be poor because of the way in which sulfide minerals, particularly the matrix sulfides, are moulded around the gangue fragments. This is very striking in a number of cases where ore containing a large number of the various gangue fragments which were rounded and apparently rolled were found. This is similar to the "Durchbewgung" structures described in German and other literature.

The author believes that the majority of the gangue minerals, if not all, have been derived mechanically from the surrounding schists and dolomitic beds and that all of the structures found in the gangue canbe related to tectonic activity during metamorphism and the folding of the ore horizon.

CONCLUDING REMARKS CONCERNING ORIGIN

The origin of ore deposits of the massive sulfide type is a much debated question and highly confusing, since theory not based on experiments, is liberally mixed with the interpretations and presentations of facts. The schools of thought may be basically divided into those who favor sedimentary processes as being responsible for the original deposition of the sulfides and those who prefer deposition of the ore minerals by methods related to the fluids emanating from a magma. Before entering the realm of origin, one must be able to unravel the history of the deposit from the present time back to its birth. This includes, in this case, the effects of the metamorphic and tectonic history, if there have been any.

Starting with two possibilities, sedimentary and epigenetic, one may arrive at the conclusion that Nordre Gruve, though not every other deposit of this type, has been metamorphosed. First suppose that the original origin of the deposit is epigenetic, then one must have an igneous source at depth for the mineralizing fluids. The only rock which could be of magmatic origin within the area is the trondhjemite, whose contact with the schists at the surface is less than a kilometer away from the ore deposit. The relation of trondhjemites to nearby ore deposits is not a new idea but has existed in Norwegian as well as foreign literature for many years. As has been shown, the rock contains metamorphic minerals, such as garnet, and has been strongly foliated; both of which point to the fact that it has been metamorphosed. If one does not accept the trondhjemite as being of magmatic origin and as the source of ore fluids and postulates some mysterious, unknown source, the epigenetic therefore metamorphosed argument is invalidated. The conclusions arrived at if the original origin is sedimentary are obvious. This argument is naturally limited to one deposit within the Folldal district because of the nature of this study, but from the nature of their occurrence, probably could be applied equally well at least to Søndre Gruve and Hovedgruve if not also to the other three deposits in the district. On the overall picture of similar deposits in the Norwegian Caledonides, the argument is generally not valid. This necessitates another approach to the problem which uses observable facts to build a theoretical model.

Observed facts which must be explained by such a model are: (1) the different types of banding, especially the magnetite banding, which are conformable with the folded wall rocks; (2) the non-esistence of an alteration halo; (3) the gangue minerals not having characteristics of introduced minerals but ones similar to the same minerals found in the wall rocks; (4) the existence of gangue lenses which have the appearance of having been moved or rolled; (5) the existence of breccia-like structures formed by gangue and ore minerals ("Durchbewegung" structures); (6) the wall rock to ore relations which are non-conformable and the crests of folds in the wall rocks broken by the massive sulfide ore; (7) the texture evidence of the pyrite cataclastic series which shows that there was continuous tectonic movement during or post deposition and continuing to a much later time; (8) the "inclusions" in the pyrite; (9) the concentration of matrix minerals, i.e. chalcopyrite, sphalerite, and pyrrhotite near the walls of the ore body; (10) the occurrence of assay high areas of Cu and Zn corresponding with the directions of folding found in the wall rocks; (11) the elongation of the pyrite crystals; and (12) the local unrecrystallized areas of pyrite. All of these facts can and have been explained for individual cases in various ways, but to use these past explanations requires the construction of a highly comples series of events to explain simultaneously all of the observed facts for Nordre Gruve.

The author's theoretic model of origin to explain the known facts about Nordre Gruve emphasizes the effects of regional metamorphism within the conditions of the high greenschist facies. The original origin of the main part of the ore minerals could be either sedimentary, hydrothermal, or a contribution from both processes. Evidence presented by Shaw (1954) and Kuroda (1961) on trace elements in metamorphic assemblages suggests that the amount of ore material needed to form an ore deposit the size of Nordre Gruve could not come from scattered amounts of metals in the original rocks which were later concentrated by metamorphic processes. If originally of hydrothermal origin, the ore was probably emplaced before or at the same time as metamorphism and folding. During regional metamorphism and continuing to a later date, there were tectonic movements parallel to the ore zone and in the latest stage transverse to it. The clastic texture of pyrite is accounted for, as are the rolled gangue lenses, the wall rock to ore relationships, and the variations in the compositions in the ore body by the conditions of temperature and tectonics imposed upon the area. Any hydrothermal alteration halo would have been destroyed by metamorphism. The "inclusions" in pyrite and local areas of fine-grained pyrite could be the results of differences in local recrystallization rates. Admittedly, little is known about such a complex system experimentally, but this model seems to best explain the evidence from Nordre Gruve.

On a larger scale, samples of ore from other Norwegian Caledonian massive sulfide ore deposits, show a definite increase in grain size of pyrite as there is a corresponding increase in the metamorphic grade of the rocks in which the deposits occur. This can be seen in any representative set of examples of Caledonian ores from the various regional metamorphic grades. Other evidence to support a metamorphism of the ore is the close similarity between the assumed temperatures for quartz-albite-epidote-almandine subfacies of the greenschist facies and the possible indications of the various geothermometers as to the final temperatures of formation or recrystallization of the ore. These are summarized in Table 17.

Table 17: Summary of Temperature Data

Metamorphic temperature maxumum	550°C
Sphalerite geothermometer, average	459 ± 25°C
Arsenopyrte geothermometer maxumum	491 ± 12°C
Sphalerite-chalcopyrite exsolution	300- 400°C
Cubanite-chalcopyrite exsolution	400- 450°C

All of these temperatures fall within the same range.

Other geologists are at the present time advocating the theory of metamorphosed ore deposits no matter what their original origin was. Also in the past literature, there are references and discussions of similar cases to Nordre Gruve. Emmons (1910) discussed deposits of the massive sulfide type located in Hancock County, Maine, and the Milan Mine in New Hampshire which he thought had suffered the effects of regional metamorphism. He stresses, in the case of the Milan Mine, that the ore is folded exactly as are the wall rocks and that this fold as well as the ore has been broken and off set by a shear fault in the fold's crest. He, of course, emphasized the effects of dynamic metamorphism. Newhouse and Flaherty (1930) did experiments to explain the origin of textures of some banded sulfide ores by applying deforming pressures to various sulfide minerals. Pyrite was sheared into thin plates and arranged "en echelon" producing elongated masses, chalcopyrite flowed with the crystals becoming elongated 2 to 3 times their width and sphalerite was fractured. Zavaritsky (1950) discussed effects of metasomatism and metamorphism of pyrite deposits in the Urals, briefly. Marmo and Mikkola (1951) studied sulfides in black schists and their local concentration in the crests of folds and explained their origin was due to migration of sulfides under metamorphism to areas of least pressure. Their evidence consisted mainly of textural interpretations and was backed by no experimental evidence. Williams (1960) also describes and theorizes on the cataclastic effects pyrite suffered and the migration of softer sulfides to crests of drag folds from their limbs in Rammelsberg, Germany, during folding. All of which took place at temperatures of about 225°C. Schadlun (1958,

1960) strongly supports the theories emphasizing the dynamic metamorphism of ore deposits. The photographs of massive sulfide ore from Russia which Schadlun has studied, are almost identical with similar texture found in polished sections of the ore of Nordre Gruve. Banno and Kanehira (1961) attempted to build up a sulfide and oxide mineral facies andstability fields to correspond with those worked out for metamorphic silicate assemblages. Their results were only schematic but represent a notable approach to the problem. From this list of work done in the past it can be noted that the metamorphism of an ore deposit has been suggested, but the effects of such conditions in the ore is little known experimentally or in detail from the field. Textural evidence and criteria for mineral replacements, such as Bastin, Graton, et.al. (1931) suggest, can not be used as evidence alone for a past metamorphic history because of the great ambiguity involved in distinguishing an epigenetic replacement and a metamorphic growth process. Probably the original origin of such a deposit can never be understood until much more is known about the distribution of minor elements in ore minerals under sedimentary and hydrothermal conditions, since any structures or textures due to original deposition are probably destroyed partially or completely by metamorphism.

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PLATES

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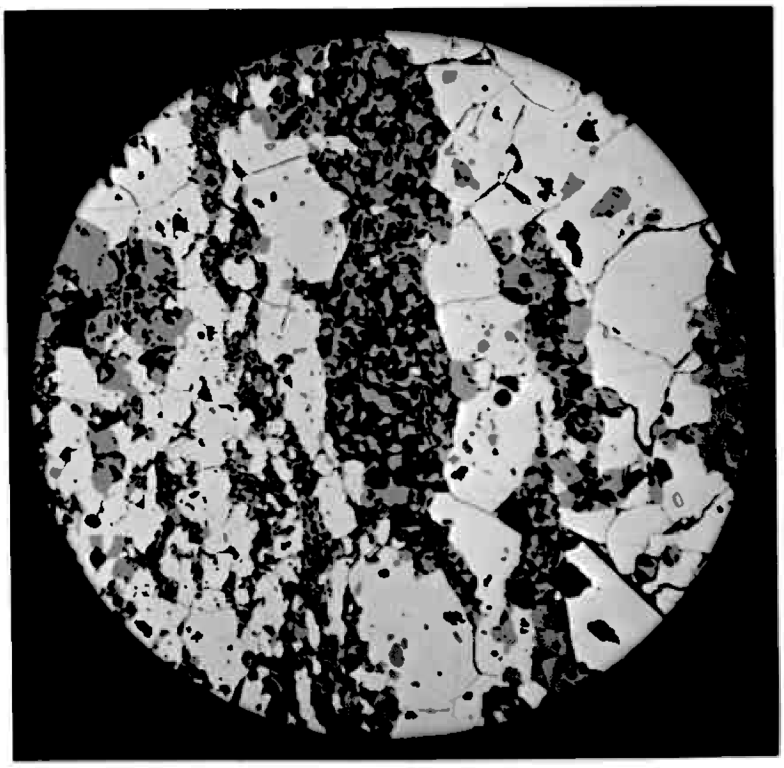
Plate 3, Fig. 2. Brecciated pyrite (white) with sphalerite (gray) in gangue (black) from a post-ore fault. Reflected light. X 200.



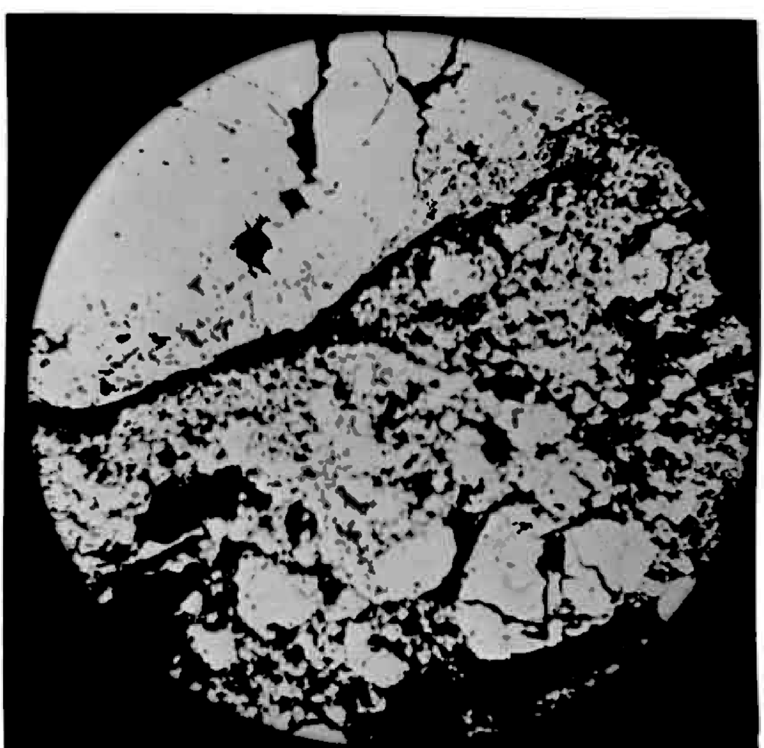
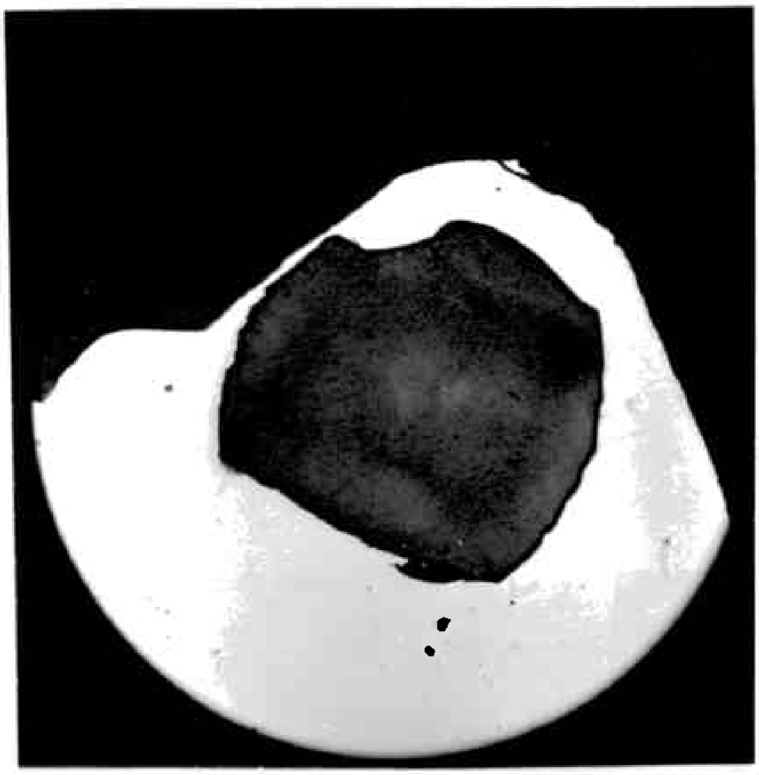


Plate 4, Fig. 1. Etched pyrite crystal (white) mounted in plastic (gray) showing an embayment which in polished section appears to be an inclusion. Reflected light. X 200.

Plate 4, Fig. 2. Magnetite crystal (gray) being replaced by carbonate (black) along octahedral partings. Pyrite crystal (white). Oil immersion, reflected light. X 310.



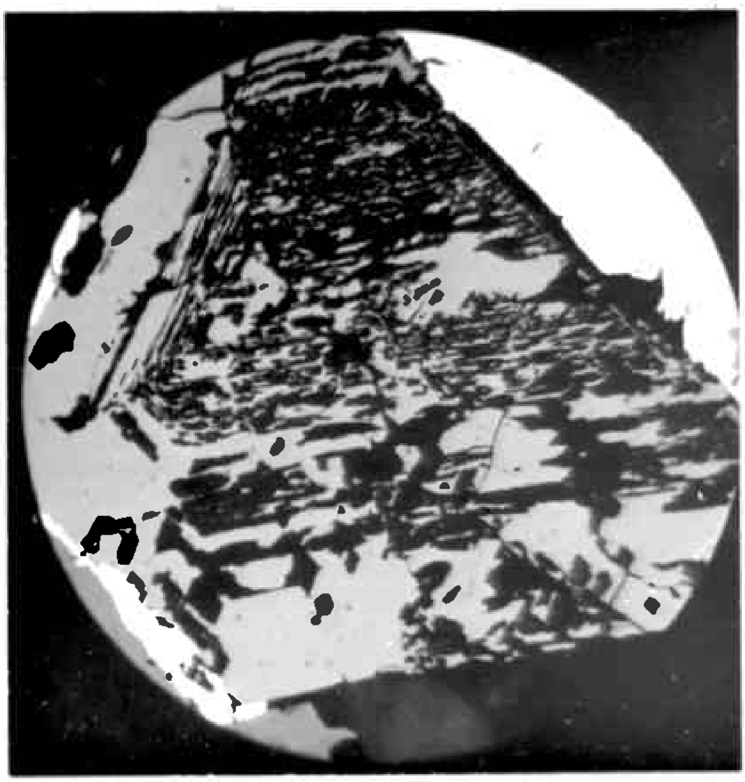
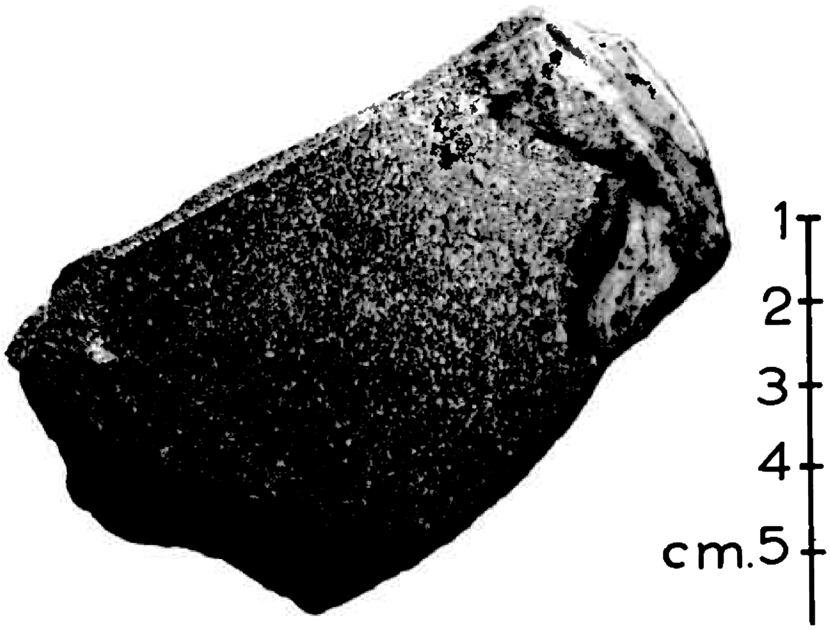


Plate 5, Fig. 1. Massive pyrite ore folded into quartzitic schists of the foot wall. Daylight.

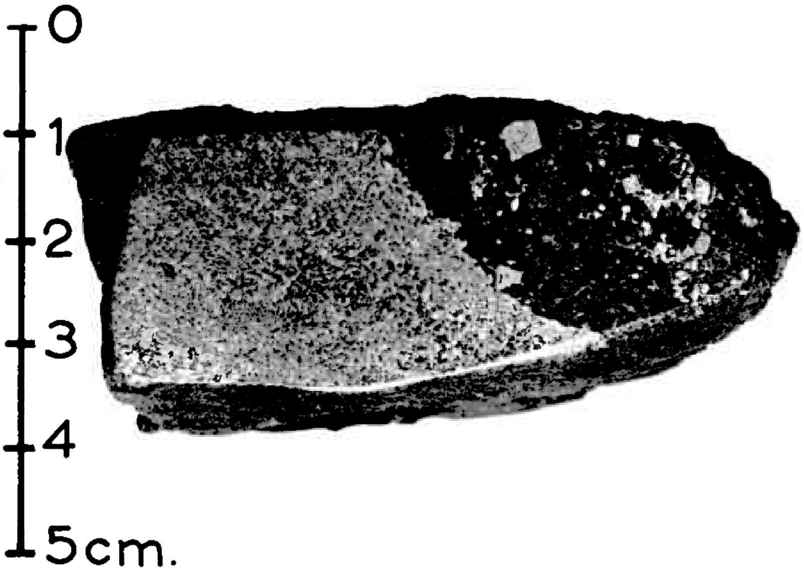
Plate 5, Fig. 2. Massive pyrite ore with undifferentiated schists folded into the ore. Note pyrrhotite in schists and along the contact. Daylight.


1
2
3
4
cm.5


1
2
3
4
5
6cm.

Plate 6, Fig. 1. Typical contact relations between massive pyrite ore and quartzitic schists. Daylight.

Plate 6, Fig. 2. Contact of amphibole rich undifferentiated schists with massive pyrite ore which is enriched in chalcopyrite and pyrrhotite. Daylight.


0
1
2
3
4
5cm.

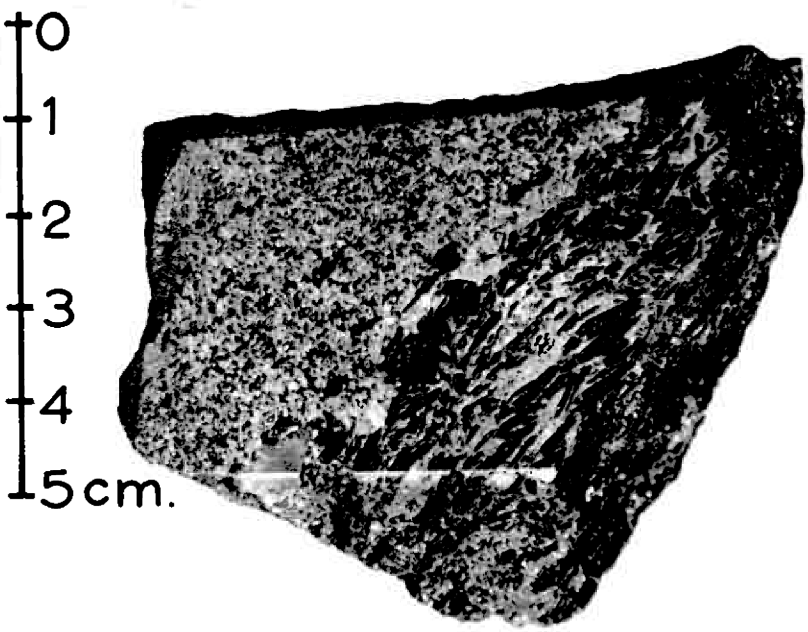
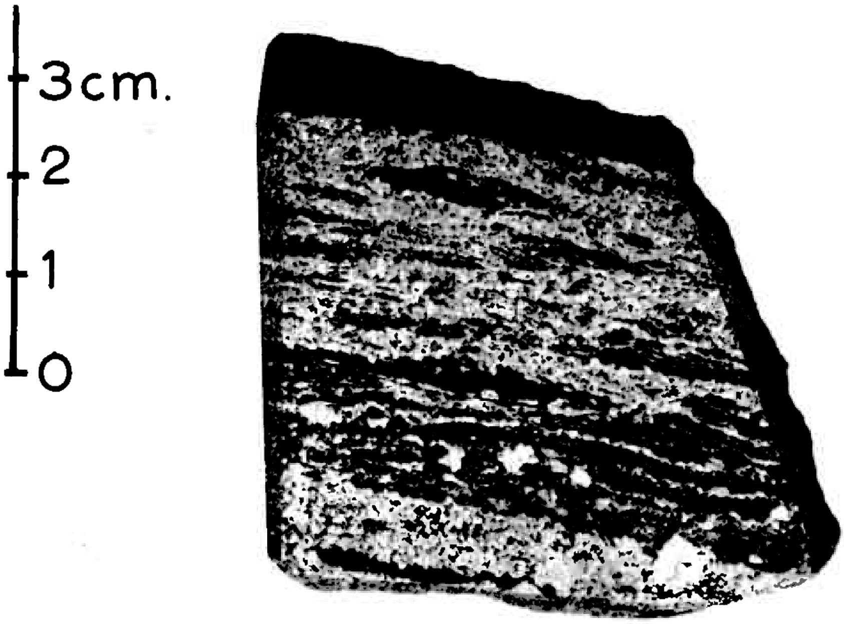

0
1
2
3
4
5cm.

Plate 7, Fig. 1. Magnetite (black) banded pyrite ore (white) showing typical lensing of the magnetite. Daylight.

Plate 7, Fig. 2. Massive pyrite ore banded by a change in pyrite grain size.


3cm.
2
1
0

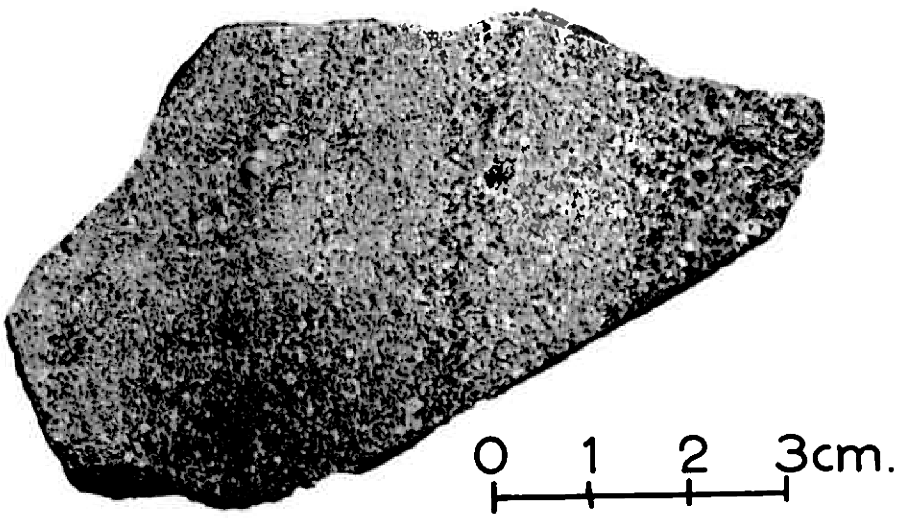

0 1 2 3cm.

Plate 8, Fig. 1. Massive pyrite ore banded by change in grain size in contact with undifferentiated schists. Daylight.

Plate 8, Fig. 2. Massive pyrite ore banded by change in grain size and the ore mineral to gangue ratio. Daylight.


0
1
2
3
cm.4

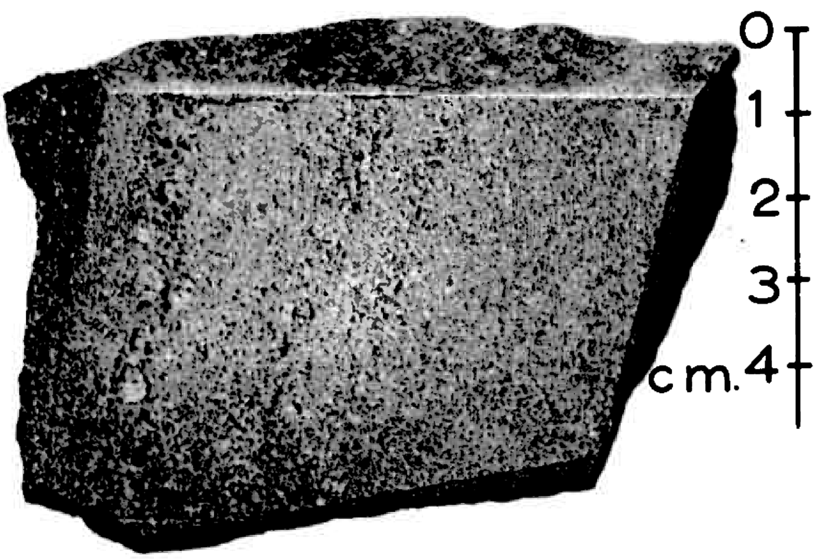

0
1
2
3
cm.4

Plate 9, Fig. 1. Massive pyrite ore with band of coarse pyrite crystals. Daylight.

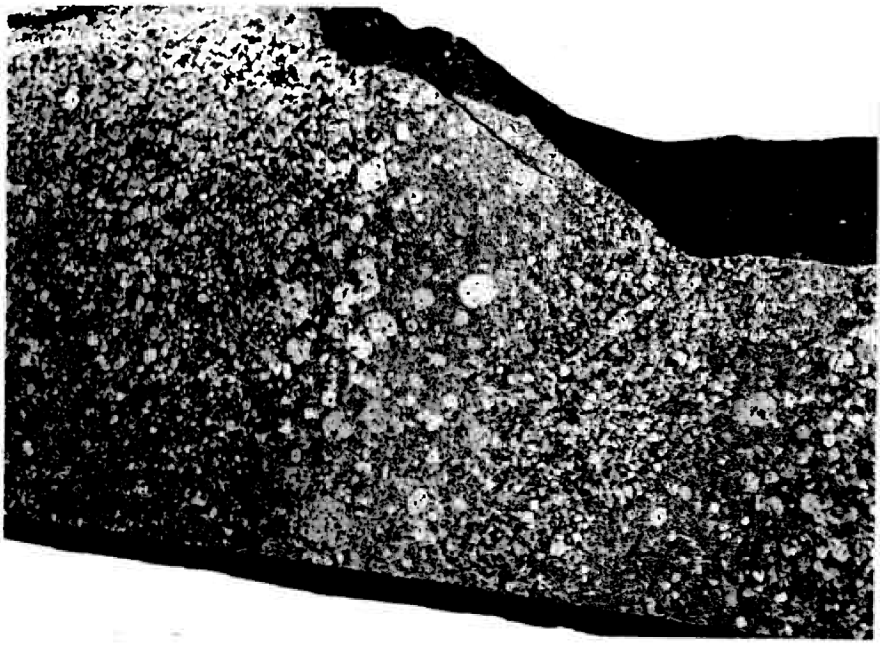
Plate 9, Fig. 2. Massive pyrite ore banded by change in grain size. Daylight.


0
1
2
3
4
5cm.


0
1
2
3
4
5cm.

Plate 10, Fig. 1. Enlargement of Plate 8, Fig. 2 showing detail of banded pyrite ore. Daylight.

Plate 10, Fig. 2. Massive pyrite ore showing pyrrhotite and chalcopyrite concentrated at contact of undifferentiated schists. Daylight.



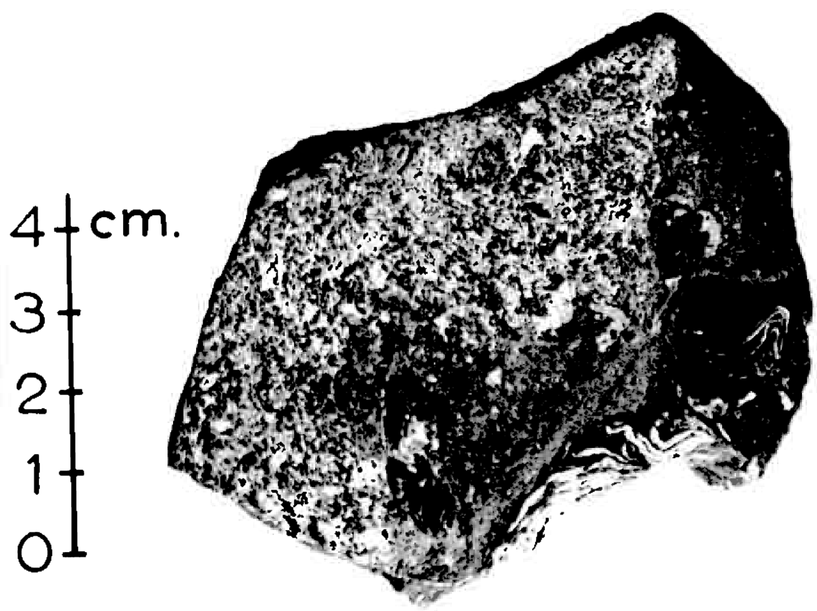
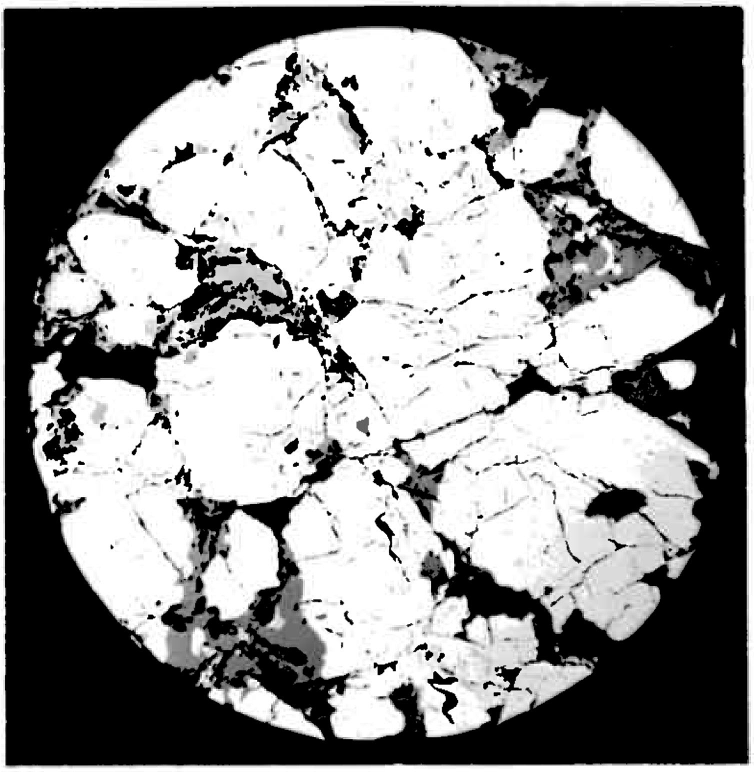

4 cm.
3
2
1
0

Plate 11, Fig. 1. Cataclastic pyrite (white) fractured but not filled with matrix minerals such as sphalerite (dark gray) and chalcopyrite (light gray). Gangue (black). Reflected light. X 200.

Plate 11, Fig. 2. Cataclastic pyrite (white) with fractures filled with chalcopyrite (light gray) and sphalerite (dark gray). Reflected light. X 200.



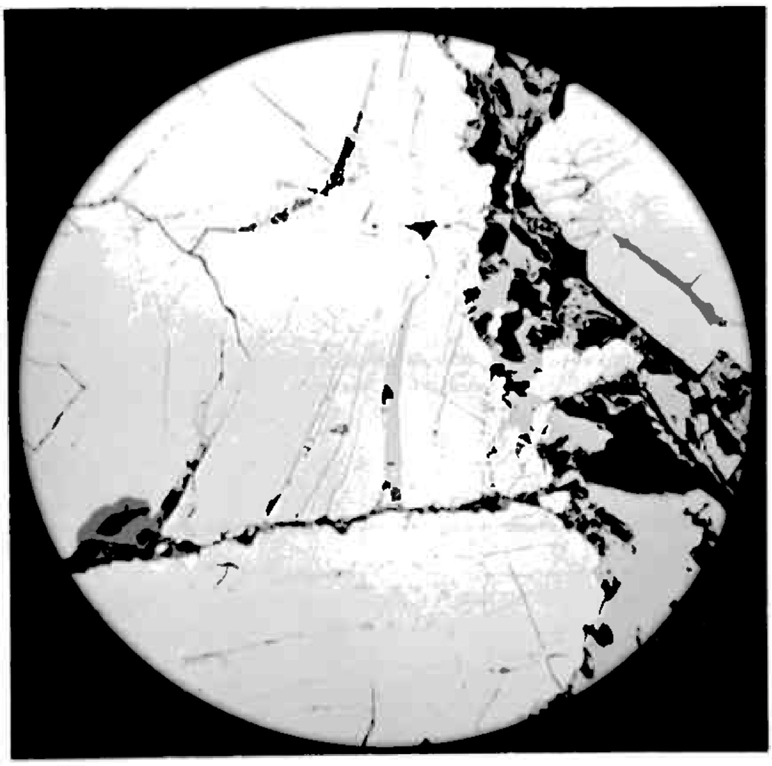


Plate 12, Fig.1. Pyrite cube (white) penetrated by a silicate gangue mineral (black). Reflected light. X 200.

Plate 12, Fig.2. Sphalerite (dark gray) and chalcopyrite (light gray) "inclusions" in pyrite (white). Reflected light. X 65.

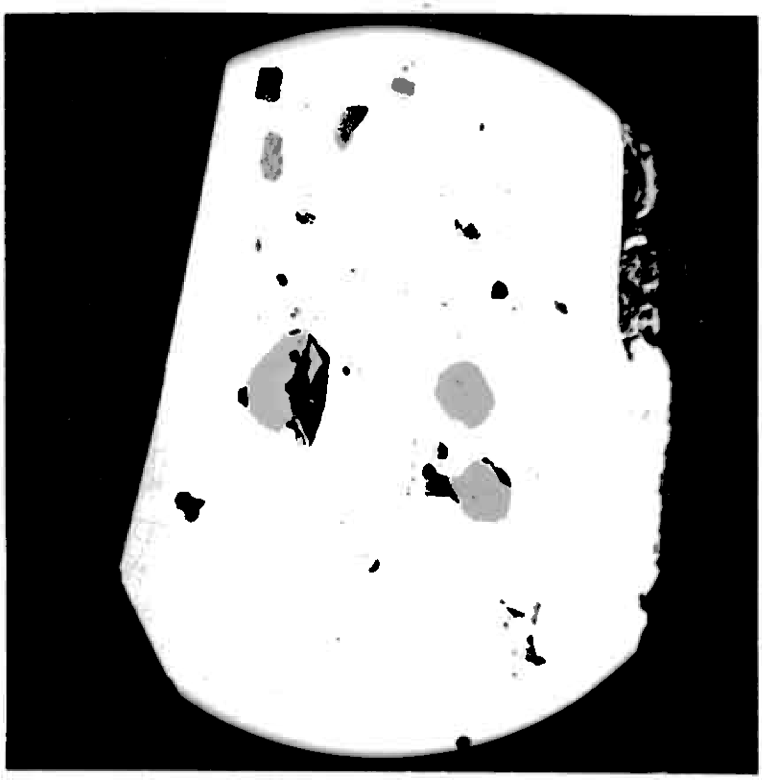
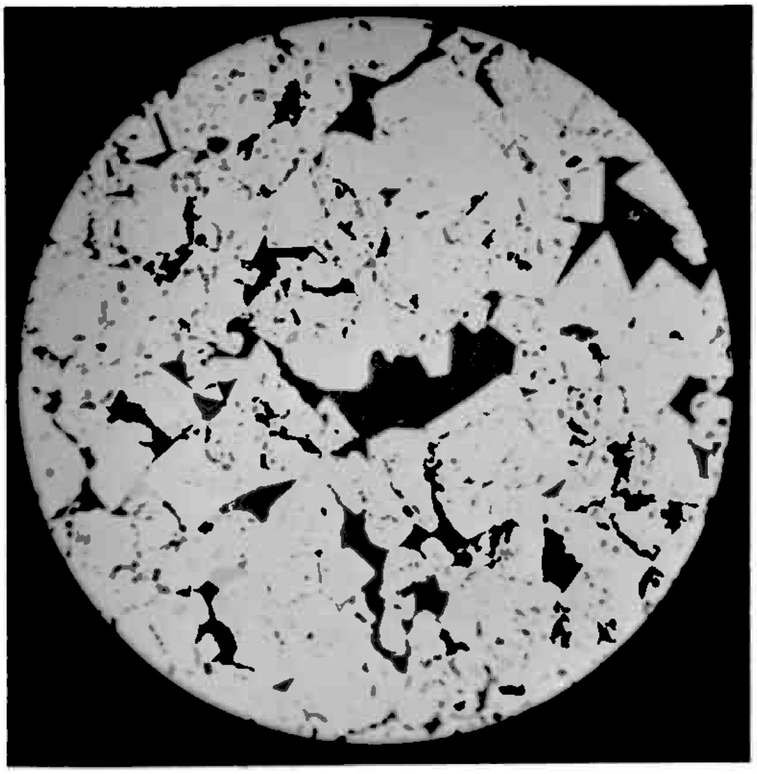


Plate 12, Fig. 1. Fine-grained dusty pyrite (white) with sphalerite (gray). Reflected light. X 200.

Plate 12, Fig. 2. Typical non-cataclastic pyrite (white) with chalcopyrite (light gray) and sphalerite (dark gray). Reflected light. X 65.



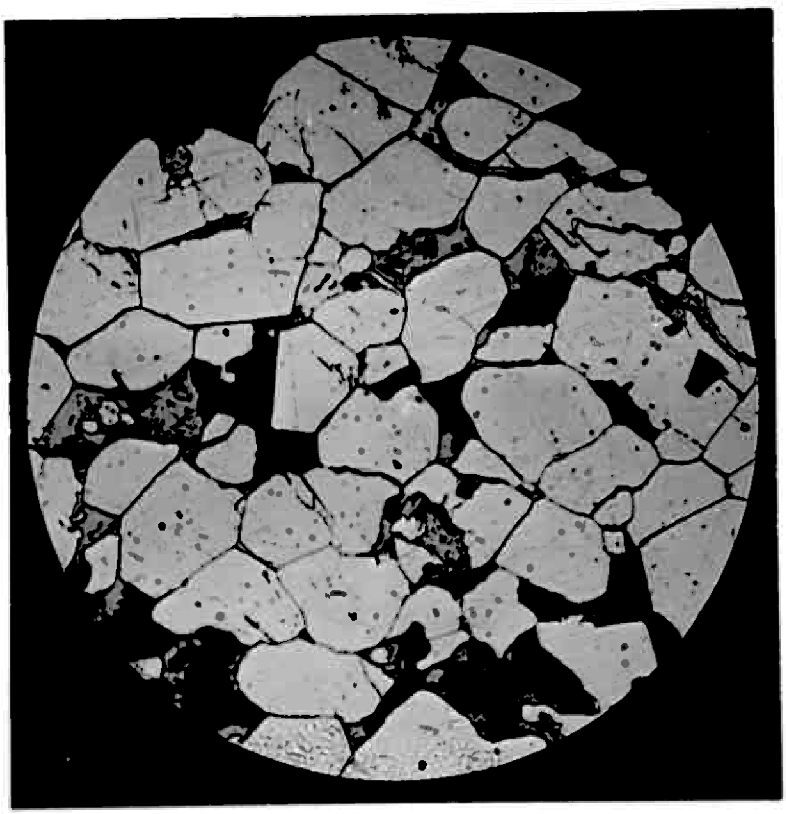
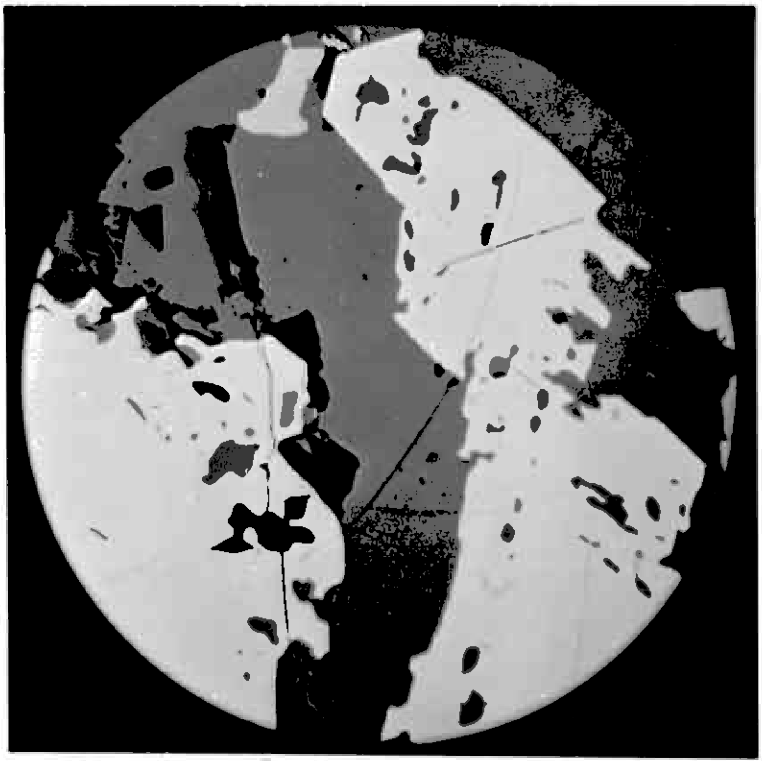


Plate 14, Fig. 1. Pyrite (white) being replaced by sphalerite (gray). Reflected light. X 200.



Seterveien 9,
Nordstrandhøgda
October 20, 1961

Messers. Hjelseth and Klunderud
Folldal Verk A/S,
Folldal Verk, Folldal

Dear Messers. Hjelseth and Klunderud:

Enclosed are copies of the assay Cu/Zn ratio, contour maps, as well as a geologic map of the part of the mine that I mapped this summer. Remarks on the probable value of the items follow. There is still much more work to be done before any real interpretations of the assembled data can be made.

Remarks of the Cu/Zn ratio Profile.
The Cu/Zn ratio was arrived at, by using the precent values of Cu and Zn given on the mine analysis. A high ratio indicates higher Cu percent, while a low ratio indicates a lower percent of Cu. It also indicates the total metal content of the ore. ?

The highest ratios attained are 25.0 and 54.0, both at coordinates x=240, z=675, while the lowest ratio 0.03 obtained, is at coordinates x=270, z=660. The association of the low ratio with that of the high ratio suggests the possibility that the metals originally at the location of the low ratio migrated up and westward to form the rich concentration.

Notice also that all of the ratios above .60 are in the western part of the mine, as far as it has been explored and assayed, except for two small local areas of Cu concentration on the esrt part of level 11 and 12.

The exact contour pattern on the profile may be an illusion due to number and locations of the assays and the judgement of the one who contoured the ratios, or it may be real. In either case it definitely shows the tendency of the highest metal values to be located in the western part of the mine.

Remarks on the Geologic Map.
The map sent to you includes only those parts of the mine that I mapped in detail. The units mapped are similar to those of Dr.Geis, as are the symbols used, except for those indicating strike and dip of foliation which is probably similar to bedding. Notice that where the rock is highly folded, so is the ore. (See especially, level 6 coordinates x=350, y=310). Later, a more interpretive geologic map will be made including Geis' work and my own.

I will be interested to know the results from the exploration west of the 250 shaft and also any at depth.

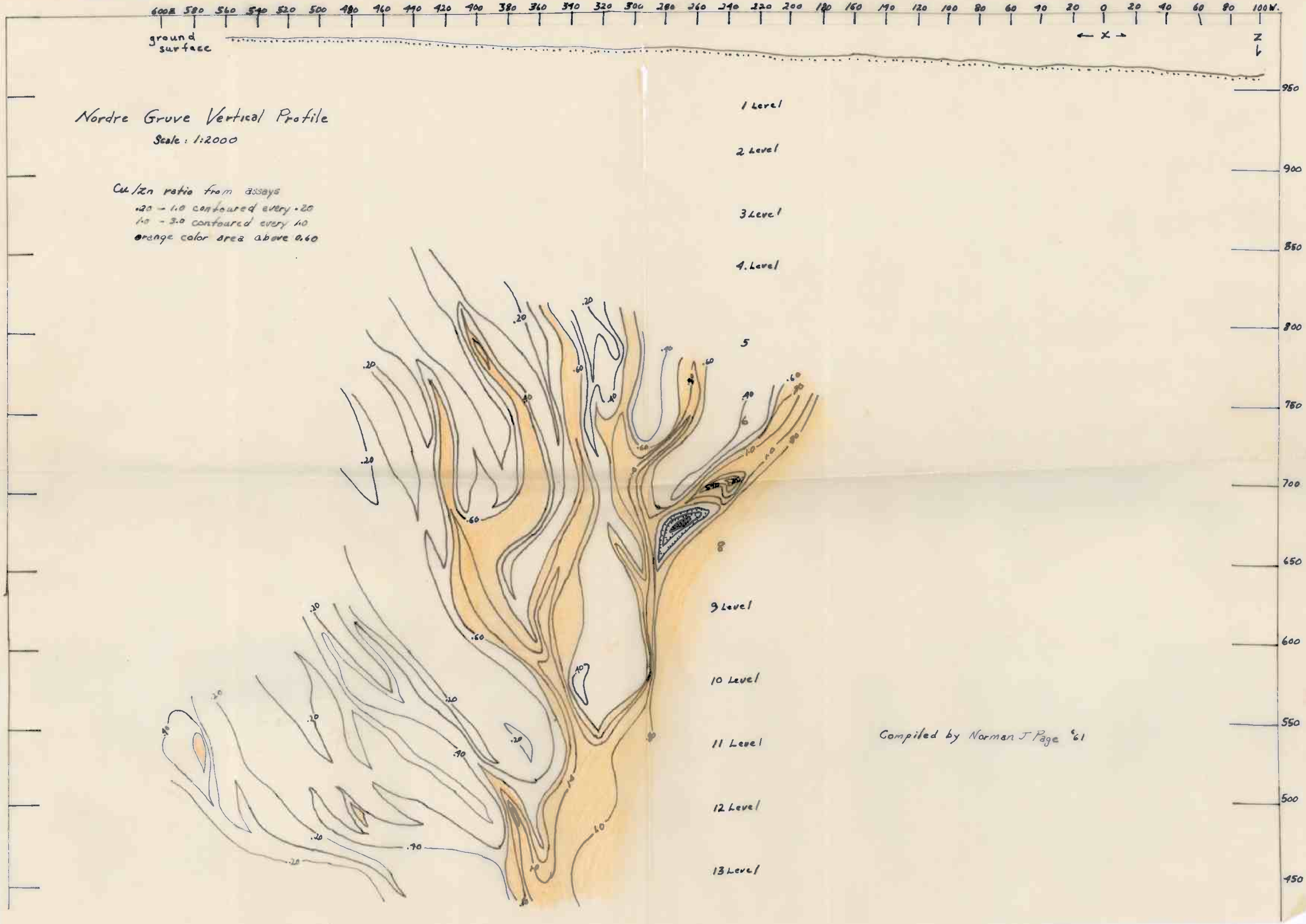
Thank you for an enjoyable summer.

Sincerely,

Norman J Page

Norman J Page

Nordre Gruve Geologic Map
parts maped by Norman J Page, '61
Scale: 1:500
Legend
Massive pyrite ore
Quartz - sericite schist ("granulit")
Biotite - chlorite schist ("green stone")
Amphibolite - garnet schist
Trondhjemite looking rock
Strike and dip of foliation
Plunge and strike of minor folds
Minor anticline
Fault with dip
Mag. N.
Coordinates for Etasje 6
x+380
x+360
x+340
x+320
x+300
x+380
x+360
x+340
x+320
y+300
y+320
y+340
y+360
Etasje 6
Coordinates for Levels 11, 12, 13
x+600
x+580
x+560
x+540
x+520
x+500
x+480
x+460
y+600
y+620
y+640
y+660
y+680
Etasje 11
Etasje 12
Etasje 13


Nordre Gruve Vertical Profile
Scale: 1:2000
Cu/Zn ratio from assays
.20 - 1.0 contoured every .20
1.0 - 3.0 contoured every 1.0
orange color area above 0.60
ground surface
600E 580 560 540 520 500 480 460 440 420 400 380 360 340 320 300 280 260 240 220 200 180 160 140 120 100 80 60 40 20 0 20 40 60 80 100W.
← X →
Z
950
900
850
800
750
700
650
600
550
500
450
1 Level
2 Level
3 Level
4. Level
5
6
8
9 Level
10 Level
11 Level
12 Level
13 Level
Compiled by Norman J Page '61