The sulfide deposit of Nordre Gjetryggen Gruve, Folldal, Norway.

By
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Abstract.

Nordre Gjetryggen Gruve in the Folldal district, southern Norway, is at approximately 62° 9′ N. latitude and 10° E. longitude. The mining of copper from pyritic ores began in the area in 1748, while the recovery of zinc and sulfur became important in the 19th century. Nordre Gruve alone yielded 1.1 million metric tons of raw ore before 1957. From then until 1962 it produced about 65 thousand tons of raw ore per year. The mine has been developed for about 420 meters along the strike of N. 42° E. and to a depth of 510 meters. The ore body dips 38° NW. in the western part and between 45–50° NW. in the eastern part; the ore zone plunges 45° NE. The average thickness of the ore is 1.66 meters.

Geologically, the district is in the southwestern part of the Trondheim region near the Sparagmite boundary and Nordre Gruve can be considered to be on the southwest limb of a northeasterly plunging syncline composed of schists in the quartz-albite-epidote-almandine subfacies of the greenschist facies that have been assigned tentatively to rock units similar to those in the Hølanda–Horg district. The rock units mapped are: (1) undifferentiated schists composed dominantly of quartz, chlorite, calcite, biotite, epidote, and hornblende; (2) quartzitic schists; (3) hornblende-quartz schists; and (4) trondhjemite now albite-quartz-garnet gneiss, and surficial material.

The ore minerals are pyrite, pyrrhotite, sphalerite, chalcopyrite, galena, cubanite, molybdenite, arsenopyrite, and tetrahedrite-tennantite. The gangue consists of individual grains and aggregates of quartz, feldspar, and chlorite; disturbed, folded undifferentiated and quartzitic schist partings; and angular fragments of calcite. The gangue minerals have the same characteristics as they do in the country rocks.

Three types of banding are present in the ore (1) magnetite banding, (2) banding caused by variations in pyrite grain size, and (3) banding caused by a change in ore to gangue ratio. Some pyrite contains "inclusions" of other ore and gangue minerals; some exhibits a series of cataclastic textures ranging from simple fractured pyrite to pieces of pyrite floating in matrix sulfides. Pyrite is elongated parallel to the foliation and in some localities is very fine-grained and not recrystallized.

Variations of ore minerals across the thickness of ore were observed. Pyrite increases in percentage from hanging to foot wall, pyrrhotite is most abundant on the foot wall, and chalcopyrite is more common on the hanging wall. Both sphalerite and galena are more abundant near the walls. Contouring vertical profiles of assay data shows trends in areas of high Cu, Zn, and S that correspond to the directions of minor folding.

The original origin of the ore deposit is uncertain. If it is epigenetic related to the trondhjemite, or if it is sedimentary, the structural and textural characteristics of the ore must have been the result of the processes of regional metamorphism. Various sulfide geothermometers give temperatures of crystallization consistant with highest possible temperatures of metamorphism.

Introduction.

The Folldal district in southern Norway lies among the Folla River Valley, Hedmark Fylke, at approximately 62° 9′ N. latitude and 10° E. longitude (Fig. 1) and is about 20 kilometers in length and 5 kilometers in width. The Nordre Gjetryggen Gruve, now the main mine of Folldalsverk A/S, is 11 kilometers by road or about 5 kilometers airline northeast of the village of Folldal.

In general, the topography of the region is representative of a mountainous area modified by Pleistocene glaciation. The mine is a little above timber line at 961 meters above sea level, on a moraine covered shelf or plateau. The geomorphology of the area is discussed by I. K. Streitlien in Marlow (1935).

Five mines are known in the Folldal district; Folldal Hovedgruve, Nordre Gjetryggen Gruve, and Søndregruve to the east and Nygruve, and Grimsdalsgruve to the west of the village of Folldal. This mining region has yeilded ore since 1748. A detailed history of the old mines can be found in *Folldal Verk gjennom 200 år*.

The Nordre Gruve ore body was discovered in 1917 but was not mined until 1935, when a flotation plant was built in Folldal to yield three concentrates; pyrite, copper, and zinc. Up to 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. From then until 1962, the mine has produced 65 thousand metric tons of raw ore per year. Information on the mining engineering can be found in Hjelseth and Einarsen (1957).

An area of approximately 4 kilometers by 3 kilometers around Nordre Gruve was mapped on a topographical base map with a scale of 1:10,000. Aerial photographs were obtained later. Figure 4 is based on the topographic map with slight adjustments for location made from the photo-

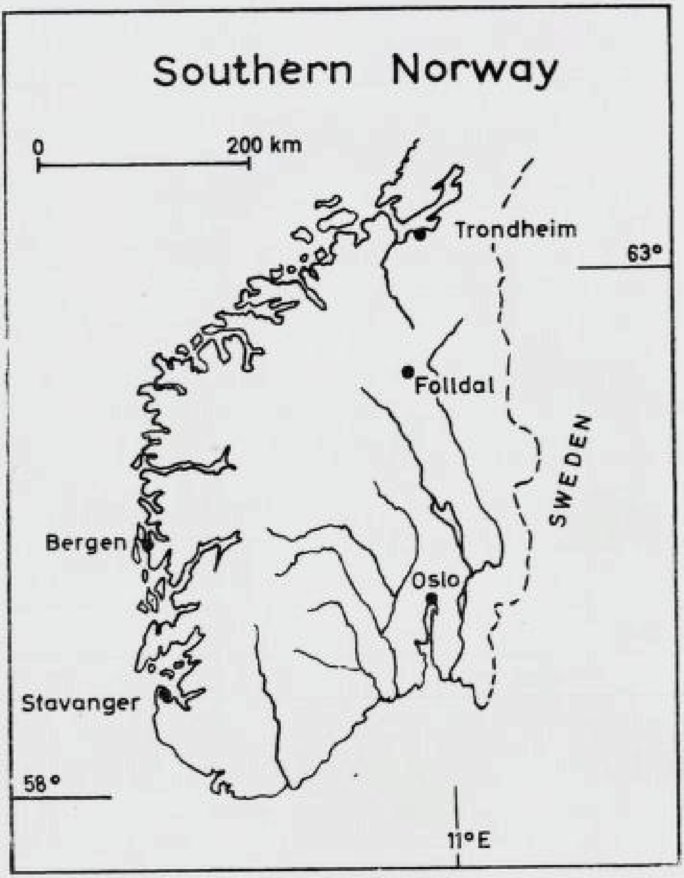


Fig. 1. Index map showing location of the Folldal district, southern Norway.

graphs. Aerial photographic coverage (scale; 1:20,000) is available for the region from slightly west of Folldalsverk to the eastern end of Gjetryggen between the Folla River and Grønko.

Regional geology.

The Folldal ore deposits lie 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 not well known. The first map of the Folldal area, made by K. O. BJØRLYKKE (1905) shows the

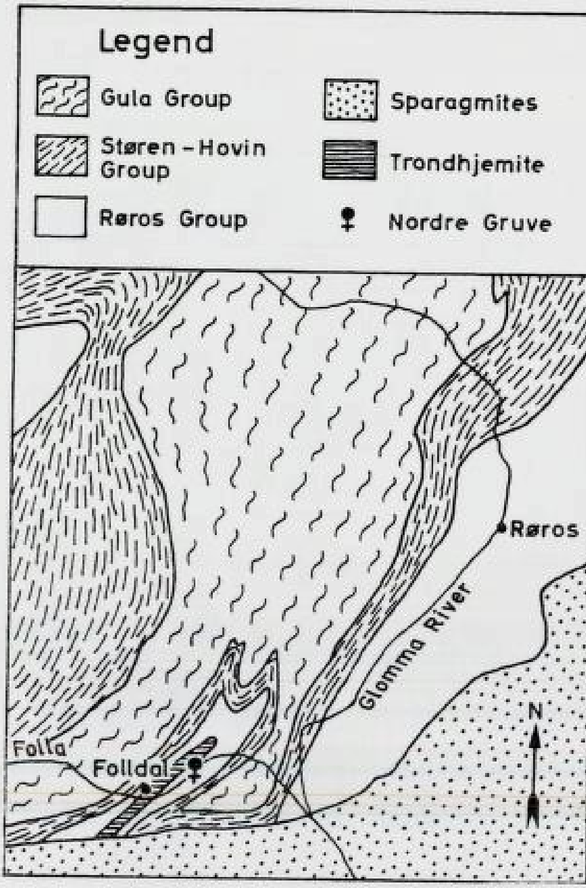


Fig. 2. Geological sketch map of the Folldal region, compiled from G. HOLMSEN (1918) and CARSTENS (1919).

contacts of granulite, mica schists, and phyllite trending northeast in alternating bands. CARSTENS (1919) mapped the area to the north and northeast of the Folldal quadrangle. He described "eruptive rocks", probably similar to Bjørlykke's granulite, passing through the Folldal area. G. HOLMSEN (1918) in his work on the ore belt in the Trondheimsfelt, included the Folldal area. He showed (1918, p. 171) the main structure of the Folldal quadrangle to be a northeastwards plunging anticline with a core of the Røros Group and limbs of Støren–Hovin and Gula Groups (Fig. 2). MARLOW (1935) mapped the Folldal quadrangle and made no structural interpretation. He merely indicated areas of out-

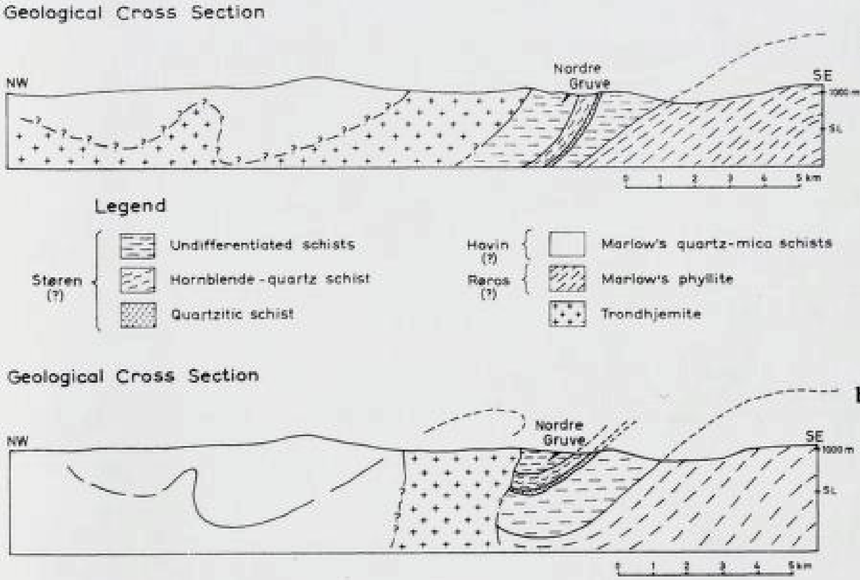


Fig. 3. Geological cross-sections through the area of Nordre Gruve.
a) authors interpretation, b) alternate interpretation.

crop, differentiated between different rock types, and recorded attitudes of foliation measured in the field.

Of the other quadrangles important for interpreting the regional structure, only the Tynset (Holmsen, 1943, 1950), part of the Sel (Strand, 1951), Opdal (P. Holmsen, 1955) and the northern part of the Dovrefjell quadrangles (P. Holmsen, 1955) have been mapped. Geis (1958) mapped a small region near Hjerkinn in the Dovrefjell quadrangle. A few generalized structures are indicated on the *Geologic Map of Norway* (Holtedahl, 1960). Vogt (1953, 1954) attempted to link structures of the Caledonian in Scotland with those in Norway and drew his northeast trending syncline II near the Folldal region. 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.

Detailed stratigraphy is known in the Hølonda–Horg district near Trondheim (Vogt, 1945). Holmsen (1950) 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 recognized in the Hølonda–Horg district. The information of Vogt and

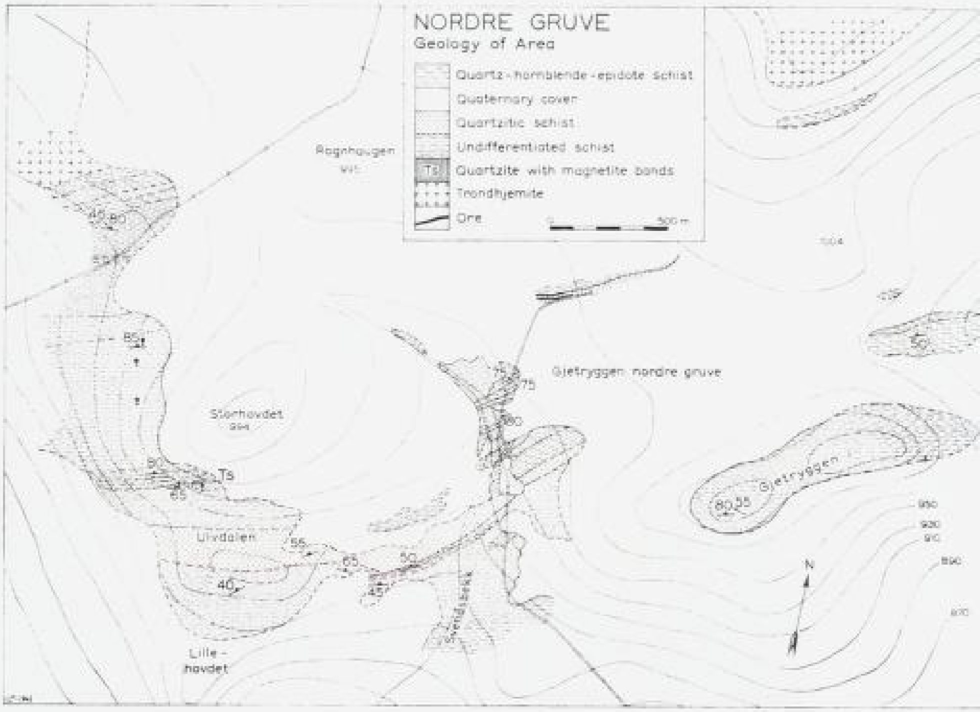


Fig. 4. Sketch map of geology around Nordre Gruve.

Marlow plus data gathered by the writer around the village of Folldal, allows a tentative structural, and a questionable stratigraphical, interpretation to be made of MARLOW's (1935) geological map. Figure 3 has been constructed using this data and presents a northwest cross-section through the Nordre Gruve ore body. Some of the rock units are taken directly from Marlow's work, while those in the vicinity of Nordre Gruve are from the author's surface mapping. The series of undifferentiated schists indicated on the cross-section includes chlorite-epidote schists with quartz-rich layers. The series, including undifferentiated schists, quartzitic schists, hornblende-quartz schists is approximately 2500–3000 meters thick. According to the stratigraphic section of the Hølonda–Horg district, (VOGT, 1945, p. 459), the Støren Group of meta-basalts interlayed with sedimentary beds is about 2500 meters thick. This suggests that the schist series could be assigned to the Støren group, while Marlow's large area of quartz-mica schists might represent part of the Hovin Group.

The structural interpretation is based on data taken from Marlow's map and reinterpreted by the writer. This structural interpretation shows Nordre Gruve on the southwest limb of a northeasterly plunging syncline which is probably part of a broad synclinorium. Other interpretations are possible if one assumes the trondhjemite and schist contact to be discordant, (Fig. 3 b).

General geology ot the Nordre Gruve area.

Lithology.

Five rock units were mapped on the surface (Fig. 4). From south to north these are; undifferentiated schists, quartzitic schists, hornblende-quartz schists, trondhjemite, and Pleistocene and Recent surficial materials. Underground several distinct beds of chlorite-epidote-garnet schist and chlorite schist were recognized within the undifferentiated schists. The distinct layers of hornblende-quartz schists were not observed underground.

Undifferentiated schists.

The undifferentiated schists are the most abundant rocks in the region mapped (Fig. 4). The general attitude is a northeast strike and a dip to the northwest at moderate to high angles.

The texture of the rocks of the undifferentiated schist series varies from fine-grained and foliated to banded, with distinct layers of the quartz-rich schists alternating with mafic-rich bands. In the southern portion of the map area, a phyllitic appearance characterizes the dominant rock, while in the middle to northern part of the map area, the same schists are interlayered with carbonate and hornblende-rich beds, glassy quartz lenses, and thin beds of pure quartzite.

Other horizons contain abundant garnets with or without hornblende. Intense folding and shearing disrupts the layers and lenses at various localities. Quartz and calcite lenses range from a microscopic thickness to 0.3 meter or larger. Characteristics of volcanic flows such as pillow structures or filled vesicles are not present. Modal analyses of undifferentiated schists are presented in Table 1.

Table 1. Modal analyses of undifferentiated schists.

	1	2	3	4	5	6
Quartz	40.7	29.0	29.4	18.3	52.6	35.5
Albite	0.0	0.0	0.0	tr.	0.0	4.6
Hornblende	0.9	tr.	53.7	1.5	1.6	15.5
Chlorite	16.5	29.2	11.8	67.5	13.6	14.3
Biotite	9.4	0.0	0.0	0.0	19.4	3.5
Muscovite	0.0	0.0	0.0	1.9	0.0	0.0
Epidote	11.3	35.8	3.5	5.3	4.5	25.9
Calcite	19.5	1.3	0.3	0.0	9.5	0.0
Garnet	tr.	0.0	0.0	0.0	0.0	0.0
Rutile	0.7	0.5	1.0	1.2	0.0	0.0
Apatite	tr.	tr.	tr.	tr.	0.0	0.0
Sphene	0.0	0.0	0.0	0.0	0.3	0.3
Zircon	0.0	0.0	0.0	0.0	0.1	0.0
Ore minerals	1.0	0.6	0.5	3.6	0.5	0.0

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.
6) Quartz-epidote-hornblende schist, Svendsbekk, Nordre Gruve.

Microscopically, the schist is composed of large subhedral to anhedral grains of quartz; some feldspar, full of small dusty inclusions; and chloritized hornblende set in a ground mass of micas, quartz, and epidote. In many specimens, the foliated is formed by trains of chlorite, biotite, and probably clinozoisite and by broken, sheared, or stretched feldspar crystals with quartz "tails" surrounded by the micas. These appear as clots and bumps on the outcrop.

The thin sections exhibit granulated and crushed grains as well as recrystallized areas. Quartz shows strained extinction under crossed nicols and the groundmass is usually finely granulated. Euhedral hornblende crystals form a matted mass without any grain alignment. Chlorite frequently occurs on altered edges of hornblende. The light brown, pleochroic biotite also shows alteration to chlorite. Calcite has a sieve texture with inclusions of quartz and muscovite. In some specimens, two generations of calcite in porphyroblasts could be recognized by grain centers showing extinction under crossed nicols in one position and edges showing extinction in another. In some places, secondary calcite fills in between grain boundaries and in fracture zones. Chlorite is the ubiquitous mineral of the undifferentiated schists. It occurs as an alteration product typical of retrogressive metamorphism.

A member of the epidote family occurs in subhedral crystals as twins on the (100) plane, isolated anhedral grains, and aggregated masses of granulated grains. In one determination, the optics of the minerals were $n_y = 1.725 \pm .002$, $n_z = 1.732 \pm .002$, $n_x = 1.719 \pm .002$, $X \wedge c = 0°$, positive, and large 2 V. It occurred in green elongated tabular prisms with a maximum length of 0.5 millimeter and a width of 0.1 millimeter. At other places, tabular prisms of a greenish gray mineral were found associated with glassy quartz lenses. An x-ray powder diagram showed the mineral to be a zoisite. 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 occurs as an euhedral mineral with numerous inclusions of quartz.

Zones of loose chloritic schists are exposed in the foot wall cross-cuts. These range in thickness from 0.3 meter to 2 meters or more. The zones have the appearance of having been highly sheared. Chlorite, usually in amounts of more than 85 percent by volume, is the dominant mineral in these zones. It has a $n_y = 1.615 \pm .002$, is optically positive and shows green pleochroic colors. Pyrite cubes, having and elongated axis parallel to the foliation, are sometimes present. They attain a length of 1 to 2 centimeters. In other zones, discrete crystals of a carbonate mineral with a $n_o = 1.695$ to 1.706 are found. It was determined by a x-ray powder pattern to be in the dolomite-ankerite group. From its refractive index, using a chart in KENNEDY (1947, p. 569), it is 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 and 260x and 330y, a distinct layer or bed of chlorite-epidote-garnet schist containing large amphibole blades up to 5 centimeters long was mapped. A similar distinct layer was observed in the Marie Louise shaft on levels 9 and 10. The undifferentiated schists in the foot wall of the western end of the lower levels of the mine also 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, mostly in rosettes of euhedral crystals, and minor amounts of quartz, calcite, and ore minerals. The garnet has a refractive index of $1.800 \pm .002$ and probably belongs to the almandine-pyrope family. The optical data of the amphibole are: $n_y = 1.676 \pm .002$, $n_z = 1.684 \pm .002$, $X \Lambda c = 12.5°$, X is yellowish brown, Y is greenish yellow, Z is dark green, positive, and $2V = 75°$. The chlorite is optically positive and has a $n_y = 1.623 \pm .002$.

Hornblende schists.

The hornblende schists are an easily recognized unit because of the contrast of dark hornblende needles, in places, 1 centimeter long, with the light gray groundmass of quartz, chlorite, epidote and occasionally almandinepyrope-garnet. Minor minerals in the rock are muscovite, orthoclase, albite, sphene, and in one place spinel. The refractive index of the garnet is $1.802 \pm .002$, which puts it into the almandine-pyrope series. The hornblende has the following optical properties: $n_z = 1.695 \pm .002$, $n_y = 1.686 \pm .002$, $n_x = 1.675 \pm .002$, positive, 2V less than 70°, and $Z \Lambda c = 18°$. 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 grains. Quartz grains have a granulated texture in some places. Some of the hornblendes have rims of chlorite suggesting retrogressive metamorphism. A modal analysis of this rock shows that it consists of quartz, 52.6 percent; albite, trace; chlorite, 6.2 percent; hornblende 29.9 percent; garnet, 2.3 percent; epidote, 7.7 percent and ore minerals, 1.3 percent.

Quartzitic schists.

The quartzitic schists generally form the immediate foot wall of the ore if thin selvages of chloritic schists are not present. They occur also as lenses and boudins in the undifferentiated schists.

The quartzitic schists range in composition from mica (muscovite and sericite) – quartz schists to glassy quartzite containing less than 5 percent accessory minerals. Table 2 presents modal analyses of the quartzitic schists.

Albite is most abundant in crests of folds in the schist. At some localities a foliation results from the alignment of phyllosilicates and streaks of ore minerals. The main ore mineral is pyrite in fine-grained cubic crystals together with minor amounts of chalcopyrite and pyrrhotite. In some

Table 2. Modal analyses of quartzitic schists

	1	2	3	4	5
Quartz	70.1	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	0.0	0.4	2.8	2.2	13.5
Sphene	0.0	tr.	0.0	tr.	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.

localities, the quartzitic schist is almost entirely glassy quartz bands or lenses, occasionally containing disseminated magnetite in bands concordant with the foliation, as for example the rock marked as Ts in figure 4. The larger grains of quartz generally show strained extinction and may be surrounded by many finer grains, suggesting that the quartz has been granulated. Lenses of large recrystallized quartz grains and some glassy quartz, stretched out parallel to the foliation are common. The average quartz grain size is 0.5 millimeter, while the larger grains average 0.8 millimeter.

The compositions of rocks with more than 60 percent quartz plus feldspar are compared with those of the quartzplagioclase gneisses in figure 5. As the quartzitic schists contain no feldspars, the author believes they represent metamorphosed equivalents of clayey sandstones, deposited during a period of relative stability, and are not the equivalents of metamorphosed quartz-keratophyres or acid tuff accumulations. The strained extinction, granulated textures, and foliation are evidence of tectonic movement after deposition.

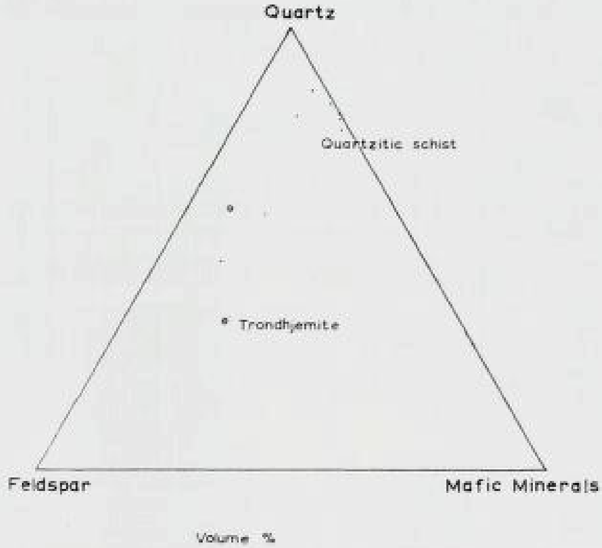


Fig. 5. Composition diagram for rocks containing more than 60 percent quartz plus feldspar.

Quartz-albite-garnet gneiss (trondhjemite).

The trondhjemite of Marlow is a pinkish-white to light gray, holocrystalline, foliated rock containing abundant porphyroblasts of garnets up to 0.5 centimeter in diameter. The author prefers to call this rock albite-quartz-garnet gneiss because of the genetic implications of the word trondhjemite. However, because it is labelled trondhjemite in the older reports, both terms will be used.

The trondhjemite outcrops of the surface in the northern part of the map area. At some localities, it contains scattered hornblende porphyroblasts. At others near the Hovedgruve, outside the present map area, it is cut by many veins of glassy quartz ranging up to 0.5 meter or more in thickness. Underground the quartz-albite gneiss (occasionally with a schistose texture) was mapped with undifferentiated schists unless it exhibited clear contacts with the other rocks and no gradiation into schistose rocks. In these cases it was mapped separately (pls. 1 and 2). The gneiss occurs as distinct bands which continue for short distances along strike as lenses, boudins, or indistinct bodies gradational to their surroundings. The distorted and folded lenses of this rock within undifferentiated schists are difficult to explain. They may have formed more continuous beds or lenses which were broken up during metamorphism and were engulfed in the other, incompetent, schists. However, the foliation is generally parallel to that of the surrounding schists, and it is difficult to see how the lensing could form if the gneiss were broken by tectonic movement. The bodies do not occur in a single definite stratigraphic zone and therefore are most likely lenses of reworked or water laid tuffs which had an irregular distribution in this sedimentary sequence.

The quartz-albite gneiss has an inequigranular allotriomorphic texture. Table 3 presents some modal analyses.

Table 3. Modal analyses of albite-zuartz-garnet gneiss.

	1	2	3	4
Quartz	33.9	51.4	47.2	57.7
Albite	46.2	27.9	40.0	26.2
Orthoclase	0.0	0.0	0.4	tr.
Muscovite	3.6	4.5	0.0	tr.
Biotite	0.0	0.0	0.0	1.7
Chlorite	0.7	0.0	2.1	3.6
Calcite	0.0	0.0	9.3	0.4
Hornblende	0.2	1.1	0.0	0.0
Epidote	2.9	1.6	0.4	8.1
Garnet	6.2	3.5	0.1	0.1
Zircon	0.1	0.2	0.0	0.0
Rutile	0.0	0.0	0.0	tr.
Sphene	0.0	0.1	0.1	1.8
Ore minerals	0.1	0.1	0.0	0.0

1) Albite-quartz-garnet gneiss, Haanesklekken, Nordre Gruve.
2) Quartz-albite-muscovite gneiss, near Hovedgruve, Folldal.
3) Quartz-albite gneiss, occurs as a lens, level 10, Nordre Gruve.
4) Quartz-albite schist, occurs as a continuous band, level 6, Nordre Gruve.

Albite in the rock is frequently twinned. Infrequently the albite is sericitized, giving it a dusty appearance. The porphyroblasts exhibit a sieve texture caused by numerous subhedral inclusions of quartz, muscovite, and epidote. Many inclusions are subhedral and unlike most such minerals in altered feldspar, have clear, sharp edges as seen under a high magnification. A few quartz grains also have similar inclusions. Garnets of the pyrope-almandine group (refractive index $1.796 \pm .002$) contain many inclusions of epidote and are occasionally rimmed with biotite. Calcite, a secondary mineral in most cases, fills in around grains along cleavage planes and in places expands into aggregates. It generally has a dusty color except in fractures where clear grains occur.

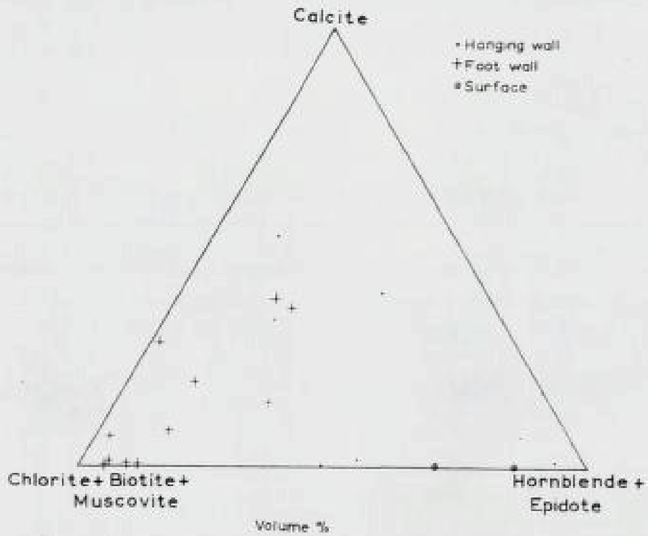


Fig. 6. Composition diagram for rocks containing less than 60 percent quartz plus feldspar.

Environment of deposition.

In figure 6 are recalculated modal analyses of all schists containing less than 60 percent quartz plus feldspar. The field occurance of each analysed specimen is designated by a special symbol. Those schists and gneisses with more than 60 percent quartz plus feldspar are presented in figure 5. Figure 6 presents the compositional variance of the more basic magnesium rich schists while figure 5 illustrates variations in the more siliceous rocks. The plots of the analyses cluster into two groups, one around the composition of trondhjemite and the other along the quartz-mafic composition line near 70 to 80 percent quartz.

The triangular diagram of the more basic rocks combined with the general geology of this region suggests interesting, but so far unproven, clues concerning the depositional environment of the original rocks forming the schists around Nordre Gruve. Since the schist series is not overturned, there was a change from argillaceous sedimentation, as illustrated by the modal analyses of the samples from 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 and finally the calcareous sediments of the hanging wall. This sequence is suggestive of conditions similar to the border of a basin. GEIS (1961) states that some massive sulfide deposits in the Folldal district occur on the flanks of a trough. The problems of sedimentary environment of the schists have only been revealed by the present work and have by no means been solved.

Grade of Regional Metamorphism.

The schists in the Folldal area have mineral assemblages characteristic of the quartz-albite-epidote-almandine subfacies, the highest of the greenschist facies (TURNER and VERHOOGEN, 1960, p. 539–541). Typical mineral assemblages are hornblende-albite-epidote-almandine-biotite-quartz and hornblende-chlorite-almandine. 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 rims of chlorite on hornblende crystals there is a suggestion of retrogressive metamorphism which is also implied by the amount of chlorite in the various modal analyses. As metamorphism and shearing movements during folding have destroyed most of the structures, textures, and probably minerals, of the original rocks it is difficult to postulate the premetamorphic character of these rocks. It is evident however that the schists around Nordre Gruve do not contain as abundant albite as do normal greenstones and graywackes. Their mineralogical composition is like that to be expected from calcareous clays metamorphosed to this degree.

Structure.

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 consistently trending bands of schist as indicated by BJØRLYKKE (1905) (Fig. 5). There are the two primary trends of minor folding that plunge northwest and northeast. The northeast trend is probably directly related to the thrusting movements from the northwest toward the southeast; while the northwest plunge is related to compression at right angles to the thrusting caused by the shape of the blocks involved in the tectonic movements. The aerial photographs and the change in strike of the thick quartzite bed 800 meters south of Nordre Gruve indicate a northwest trending warp of the general synclinal axis. The albite-quartz-garnet gneiss body shows the same relationship on aerial photographs. 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, when observable, are sharp except for the different mineral assemblages of the undifferentiated schists which give the appearance of gradual transitions, in some places. The variation in lithology appears to be actual bedding and not an effect of the regional metamorphism.

In summary, the various schists seem to be interfingering sedimentary rock facies, including water laid tuffs as well as non-volcanic debris. The quartzites represent periods of relative stability and weathering, while the undifferentited schists are manifestations of more rapid sedimentation and igneous activity in a broad synclinal downwarp, which was later thrust southwest out over the Sparagmites. At the same time the schists were being metamorphosed and folded isoclinally with the main fold axes trending northeast. Contemporary compressive forces, resulting from differential thrusting on different blocks, caused the axes of minor folding at approximately right angles to the main ore. The time of emplacement or deposition of the trondhjemite is not known, but the present mineral composition, internal structure and shape suggests it predated the metamorphism.

The ore deposit.

Introduction.

Plates 1 and 2 present the geology of the mine of all the presently explored levels (1961) except the eastern part of levels 3, 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 known ore by Folldalsverk; and from the author's mapping of levels 13, 12, and 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 no mapping of the attitudes of foliation, lineation, and minor folding. They are not responsible for the interpretations of structures indicated by the form lines on the map. To simplify the problem of the compiliation the same three main rock units were used in mapping as were used by the two previous workers.

In general, the hanging wall rocks of the ore body are the undifferentiated schist series, except in a few places where quartzitic schist occurs. Unfortunately, there is only one locality where a large hanging wall rock section is exposed. This is in the drilling cross-cut on level 10 at coordinates 450x and 580y. The immediate foot wall of the ore is generally composed of the quartzitic schists which grade southward from the ore into undifferentiated schists. 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 a few foot wall drifts. At some localities a quartz-albite gneiss or schist is also exposed in the foot wall. A very thin layer of loose chlorite-calcite schist appears on the immediate hanging and foot walls of the ore body.

Size and shape.

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 30° projection of Nordre Gruve (Fig. 7) illustrates the size and and attitude of the ore bodies in three dimensions. The projection is a simplified representation of a series of vertical cross-sections. Many of the complex branches and folds do not show in the diagram and any structures behind the plane of the foremost ore lens are obscured. The geologic map (Pls. 1 and 2) presents a more detailed picture. Figure 7 shows that the ore body is not one continuous manto or lens but is composed of five, or possibly four, separate ore lense, if one considers 1 and 7 to be interconnected. (The numbers of lenses used in this report are on figure 7). The main, and largest, lens in the eastern part of the mine, number 1, has four vertical upward branching lenses, numbers 2, 3, and 5 and possibly lens number 7. Lens 4 appears to be unconnected to lens number 1 and lies in front and to the north of the main ore zone. Lens number 6 branches off of lens number 7 and the smaller lens, number 9, is attached to lens number 8. The most westerly and first mined lens, number 10, appears to be separate from the other lenses, as

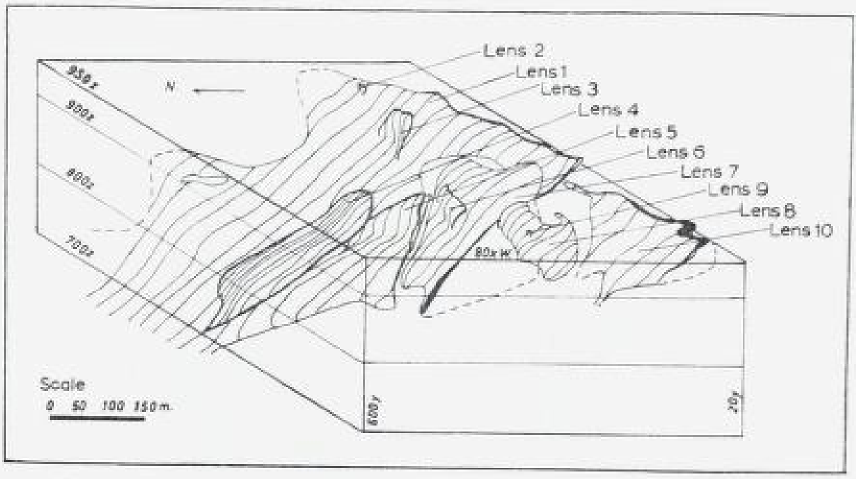


Fig. 7. Three-dimensional projection of the ten ore lenses of Nordre Gruve.

Fig. 8. Contour plot of thicknesses of Nordre Gruve projected to a vertical profile.

a drill hole through it shows a parting of quartz-mica schists between it and lens number 1.

The thickness of the massive sulfide ore, measured in the mine 664 times, 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. Of values measured, 44.4 percent fall below 1.1 meter while 87.6 percent fall below 3.0 meters. Since all of the thickness data were located on mine maps, it was possible to prepare a profile 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 (fig. 8). 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 to be controlled partially by intensity of folding.

Structure.

The ore 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 largest folds which can be observed on the projection, map, and cross-sections (Fig. 9) are flexures down the dip of the ore body and worps along the strike of the ore as emphasized by the curving drifts on the map. It can be seen in the cross-sections 1, 2, and 3 (Fig. 9), that these are not tight folds, and they are not structures one would expect to offer structure control. The present location of thick and thin ore appears to be controlled by the gentle warping and a tighter type of folding which is responsible for branching and lensing shown on the map and cross-section.

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, approximately N. 15–20° W., N. 80° E., or 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 directions are found.

Evidence of movement parallel to the ore zone is found in the foot wall cross-cuts where apparent shear zones exist, such as near the Marie

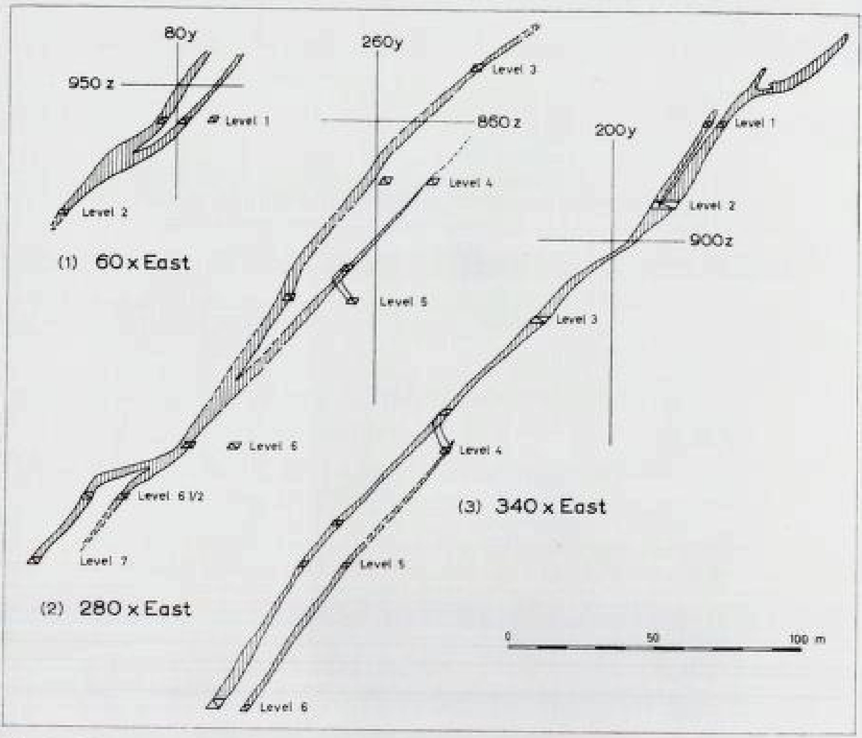


Fig. 9. Cross-sections of the ore body illustrating the branching and warping of the ore by folding. Ore is shown by vertical lines.

Louise shaft on level 11. 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 produced slickensides on the ore and in places in the immediate wall rock a loose chloritic schist envelope on both sides of the ore.

The ore 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. 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 may or may not have a breccia or crush zone. For example, a detailed study of the fault zone on level 11, (coordinates 500x and 640y) shows that the fault strikes N. 60° W. and dips 77° W. It has a breccia zone of about 0.3 meter thick composed of crushed and fractured fragments of massive pyrite ore in a crystalline carbonate matrix containing chloritic schist fragments. The massive sulfide fragments were fractured and later filled with crystalline calcite. When ore fragments are absent, the fault zones contain small quartz lenses and fragments. Specimens of the brecciated ore show there was no introduction of metals at this time. A fault zone on level 5 (coordinates 180 x and 280y) contains calcite, limonite, and goethite plus massive ore fragments. The secondary iron minerals may be much later than the faulting and associated with secondary descending oxidizing solutions.

The map suggests a possible relation between localization of ore and the thickness of the quartzitic schist in the foot wall, but upon further detailed study, such a relation does not prove to exist. 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. Ore is absent on either side of the fault. On the other hand on level 2 west the ore is 5 meters thick for a strike distance of about 75 meters, yet there is no quartzitic schist adjacent to the ore. On the lower levels, the ore pinches out in places as the drift approaches the more quartzose rocks.

The irregular lenses of ore appear to be essentially concordant with the enclosing wall rocks. However, a detailed scrutiny of the ore in relation to wall rock contact shows that the ore cross-cuts the foliation in places. Also underground there are many examples of small minor folds in which the ore has been folded or was introduced along a fold. 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 commonly corroded or embayed by massive sulfide ore.

Several examples on different scales, of this cross-cutting relation are given in figure 10. The minor fold on level 7 (fig. 10(a)) contains glassy quartz at its crest where the ore forms an intrusion into the quartzitic schists and contains undisturbed remnants of the chloritic schists. In figure 10 (c) the schists appear folded into the ore, the massive sulfides appear to have corroded the wall rock and pulled pieces of it out into a sulfide matrix. Figure 10 (d) (e), and (f) are additional examples of the cross-cutting relation.

On a smaller scale the study of discordancy can be shown in hand

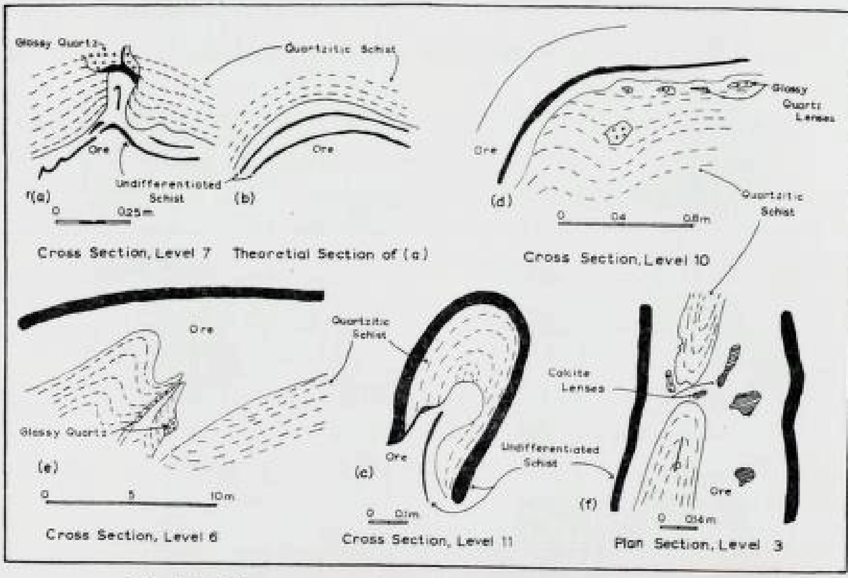


Fig. 10. Minor cross-cutting structures at the ore boundaries.

specimens and polished sections. On this scale there is no true concordancy of the wall rocks with the massive ore. At every contact, there are sulfides and silicate minerals transgressing the contact. In some specimens the ore is folded into the schists but exhibits cross-cutting relations to the foliation (Pl. 3 A). In other places, the schists, generally chloritic schists, are folded into the ore (Pl. 3 B). At other contacts of ore and schists, there is an apparent sharp contact, but less than a centimeter away in the schists, there are impregnations of pyrite, chalcopyrite, and pyrrhotite. 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 is the chief mineral of the schists in the gangue and pyrrhotite and chalcopyrite are the most frequent ore minerals in the schists.

The geologic map shows branches or prongs of ore extending from the main massive sulfide ore lenses. On the foot wall the majority of these point east, while on the hanging wall the larger number of branches or prongs point west. This relation holds for about 75 to 80 percent of the cases observed on the horizontal section. The folding in the hanging wall rocks corresponds to thickening and thinning of the ore zone, as for example on level 6, (coordinates 350x and 310y). Here the ore is thickest in the broader, less intense fold, plunging 55° NW, but the massive sulfide pinches out into a prong-like form in the more intense fold (Pl. 1).

The ends of the massive pyrite body vary from a gradual transition between the ore and pyrite-impregnated wall rock to an abrupt contact between the ore and quartz-rich wall rocks. This thinning of ore is accompanied, in some places for example level 5 west, by a splitting of the main ore into branches from a half a meter thick to microscopic in size. On level 13, at the western end of the massive ore, a taillike body looks as if it had been stretched and boudinaged into the quartz-rich schists.

Mineralogy and texture of the ore.

There are two different types of ore; one, a massive sulfide ore consisting mainly of pyrite, pyrrhotite, magnetite, sphalerite, chalcopyrite, and gangue; the other, a disseminated ore occurring in the wall rocks at the edge of the massive ore and along the strike extention of massive ore in some places. It 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. It occurs mostly in sheared zones either related to the main ore or isolated from it. It ranges from very sparse disseminations of single crystals of pyrite to occurrences approaching the concentration of sulfides in the massive ore.

Three types of massive banded ore can be distinguished; a magnetite ore, an ore showing variations in the gangue to ore mineral ratio, and an ore showing variations in the grain size of pyrite. Only the first type of ore can be followed for more than a meter underground because of the difficulties in distinguishing the other types of banding.

Ore minerals.

Magnetite.

The only primary oxide mineral in the ore is magnetite, Fe_3O_4) a relatively abundant constituent of the massive ore. One variety of the massive ore is the banded magnetite ore in which euhedral to subhedral magnetite crystals occur in the sulfides. The average magnetite grain size is 0.5 millimeters. The magnetite also occurs as lens-like aggregates or bands concordant with the foliation of the wall rocks. This is a discontinuous type of banding since each lens or band of solid magnetite extends along strike for only a few centimeters, but the zone of small lenses extends along strike for great distances. There are several examples of a conformable relation where the folded wall rocks control the thickness of the ore. Here the magnetite bands are in folds; in other places, the magnetite bands bend around lenses of glassy quartz. This type of ore is mixed with ore that shows banding resulting from a variation in the ore to gangue ratio.

The lenses or bands of magnetite banded ore can attain a thickness of 2 centimeters. In a couple of places, magnetite was replaced along its crystallographic growth boundaries by a carbonate mineral. This phenomena is uncommon in Nordre Gruve.

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 embay the magnetite grains suggesting an earlier age for magnetite. Small blebs of pyrrhotite are found within the magnetite in some cases.

Sulfides and sulfosalts.

The sulfide and sulfosalt minerals identified in the massive sulfide ore of Nordre Gruve are the following:

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
	Tetrahedrite-tennantite

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

Pyrite.

Pyrite is the ubiquitous mineral and is by far the most abundant mineral of the ore. It is also the most variable in size and shape. For this reason, a detailed study of pyrite grain shape and size was made using the cubic habit as a basis of measurement. In this case, grain shape and size are defined as the length and width of rectangular sections of pyrite with a

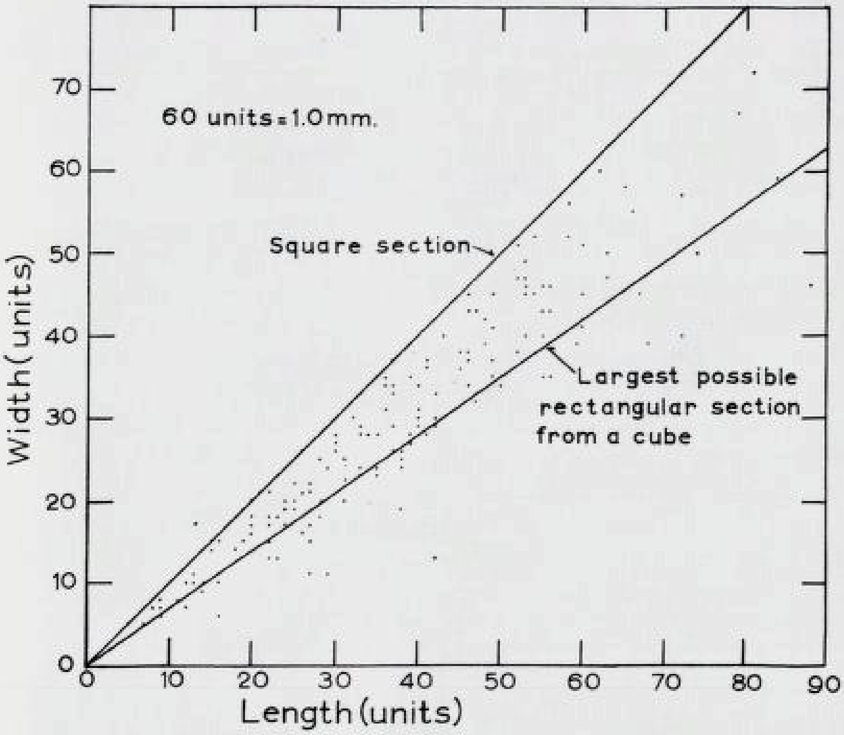


Fig. 11. Elongation of pyrite cubes shown by plot of length versus width of rectangular sections.

cubic habit as shown in polished sections. Some 200 rectangular sections were measured and plotted on a graph of length versus width. The mode of the maximum dimensions of the pyrite cubes is 0.67 millimeters squared and that of minimum dimensions of the cubes is 0.58 millimeters squared. The range was from the smallest measurable size to about 8 millimeters squared, although there are examples of euhedral pyrite in the disseminated ores with a maximum size of 2.5 centimeters and in places in the massive ore a much larger size.

If one takes a large number of randomly oriented cubes and passes a randomly oriented plane through the cubes (in practise 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. Although other sectionshapes are obtained, rectangular sections are used. 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 11. 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 form and tends toward an octahedral habit, or (3) the pyrite cubes have been elongated in one direction as a result of stresses either during or after deposition of the mineral. About 20 percent of the rectangles measured fall into the region of elongation, which suggests that case (1) is not the entire answer. There are no visual reasons for believing in case (2) from macroscopic specimens. Therefore, it would appear that elongation of the pyrite cubes is indicated.

The variation in grain size of pyrite gives rise to one of the three major sub-types of massive sulfide ore. It is characterized by a textural banding and lensing resulting from abrupt changes in grain size. This banding is generally conformable to the foliation of the immediate wall rocks but is impossible to follow underground for large distances. Thus its extent and importance is difficult to determine. This type of banding occurs not only by itself, but in the same specimen as banded magnetite ore and/or gangue to ore banded ore. Although the grain sizes and zones are shown in the specimens they are not of use in determining a succession of grain size bands throughout the mine because of the great variation in type of banding from one location to the next.

The subhedral and euhedral crystals of pyrite in polished section lie in a matrix of chalcopyrite, pyrrhotite, and sphalerite. Commonly 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 places, what appear to be inclusions of sphalerite, chalcopyrite, galena, and silicates are seen in the middle of euhedral pyrite crystals; pyrrhotite is sparse as "inclusions". 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 formation.

A three dimensional investigation was carried out in the following manner. Specimens which showed "inclusion" in polished specimen similar to those seen in Nordre Gruve sections were chosen from friable ore material from Bleikvassli. This material was used instead of Folldal ore because of the ease of recovering the pyrite without crushing the grains. They 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. One or two inclusions were observed after this, 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 these minerals to be true inclusions.

In many places, the pyrite crystals have been fractured along cleavage planes or crushed and therefore exhibit a cataclastic texture. 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. As the fragments are only slightly corroded, they reassemble to form the original crystals. At stages in between the extremes, the pyrite crystal is an entity but the cleavage fractures are filled with other ore minerals. There has been some replacement along the fractures and at the edges of pyrite crystals by the matrix minerals.

The greatest concentration of euhedral, non-fractured pyrite crystals, entirely free from "inclusions", appear in the crests of folds in the main ore that extend into the wall rocks. Also, 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, a pyrite of differing appearance occurs at certain localities. It is very fine-grained, less than 0.015 millimeter in diameter, and dusty because of the abundance of fine flecks of silicates in it. It is similar in grain size to that in the Løkken pyrite deposit which varies from 0.01 millimeter to 0.10 millimeter (Vokes, 1960). The main matrix mineral is sphalerite; pyrrhotite and chalcopyrite are rare in this type of ore. On level 10 at coordinates 540x and 690y, the hanging wall and foot wall areas are composed of medium-grained massive pyrite ore with normal amounts of matrix minerals. The generally euhedral pyrite crystals are well developed with few inclusions, while the ore in the center 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. It occurs within the ore body rather than in the hanging or foot wall portions.

Sphalerite.

Sphalerite occurs as one of the matrix minerals for pyrite. In some places where ore is relatively rich in magnetite, sphalerite is sparse or lacking, otherwise it is almost always present. It occurs as irregular masses or aggregates moulding around and embaying pyrite, as caries in pyrite, embaying chalcopyrite, and alone associated with silicate and carbonate minerals. It is extremely rare to find sphalerite associated with pyrrhotite. Sphalerite may segregate into large masses that appear as bands or zones in pyrite ore without other matrix minerals. The overall evidence suggests that sphalerite and chalcopyrite probably 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 almost completely destroyed. Sometimes the chalcopyrite in the sphalerite appears in no definite orientation but is more like an emulsion texture.

Chalcopyrite.

Chalcopyrite is found as a matrix sulfide in association with both sphalerite and pyrrhotite as well as with pyrite. There is a tendency for it to be most abundant on the foot wall of the ore bodies around inclusions of carbonate, and in chlorite schist partings. Chalcopyrite generally has mutual boundaries with other matrix minerals, but it embays pyrite and upon occasions forms veins in 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. Chalcopyrite and pyrrhotite are associated in veinlets and disseminations in chloritic schists of the hanging wall. The chalcopyrite is in irregular mouldings or groups throughout the ore but in far lesser amount than is sphalerite. It often appears to be replacing silicate minerals, especially amphiboles, along cross-fractures and cleavage planes.

Pyrrhotite.

Pyrrhotite is perhaps the third most abundant ore mineral. It has a tendency to be most abundant along wall zones in the chlorite schists immediately on the hanging wall, in chloritic schist partings in the ore, and around inclusions of glassy quartz and carbonate. Rarely it occurs as inclusions in pyrite as do the other matrix minerals. The texture of pyrrhotite is allotriomorphic and never shows crystal boundaries. The anhedral and rounded grains are in aggregates associated with chalcopyrite but rarely with sphalerite. Sometimes it shows strained extinction. Examples of pyrrhotite cross-cutting and embaying the other matrix minerals have been observed as well as the reverse relationship.

Galena.

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

Cubanite.

Cubanite is a rare mineral in the massive ore (observed in only two polished sections) and occurs only in copper rich areas where there is abundant magnetite and pyrrhotite. The magnetite in these places is usually partly replaced by chalcopyrite and pyrrhotite. Cubanite is found only in chalcopyrite as single lamellae or groups of lamellae having variable dimensions probably oriented along the $\{111\}$ planes.

Arsenopyrite.

Arsenopyrite was observed as euhedral grains in pyrite rich ore from samples taken near the hanging wall of the ore body. In most places, it was not corroded by other sulfide minerals, but some arsenopyrite grains were rounded, anhedral fragments giving the appearance of having been rolled.

Molybdenite.

Molybdenite was observed in two polished sections. It always occurs as small blades either in sphalerite or in pyrite. None of the blades were bent or twisted.

Tetrahedrite-tennantite.

A mineral occurring in small amounts in a few specimens was observed. It is isotropic, with a white to bluish-white color, and is harder than chalcopyrite, but softer than pyrrhotite. It was only observed in galena rich areas of the ore. Its properties seem to indicate that it is a member of the fahlerts group (tetrahedrite-tennantite) of 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.

Gangue minerals.

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 show 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 includes individual mineral grains and aggregates of quartz, feldspar as well as chloritic lenses, disturbed and folded undifferentiated and quartzitic schist partings, and angular fragments of carbonate. The gangue is composed of the same dominant minerals, quartz, calcite, and amphibole. Minor minerals are plagioclase (albite), epidote, garnet, biotite, chlorite, muscovite, and the common accessories found in the wall rocks. In some places, the amphibole was determined by optical methods to be an actinolite. It had the following optical data; $n_x = 1.628–1.633$, $n_y = 1.643–1.646$, $n_z = 1.654–1.658$; $Z \Lambda c = 13–15°$, negative, 2V about 80°, X very pale yellow, Z pale green, and Y yellow green. 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. Quartz grains generally show strained extinction and occasionally granulated and recrystallized textures. This is exactly analogous to the quartz observed in thin section from schists within the entire region of study. Calcite exhibits two generations of porphyroblasts, occurs as late secondary fillings in cracks and shear planes, and also is moulded around other silicate minerals. Plagioclase, occurring in a 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 showed in the country rocks.

On level 5 west at about coordinates 200x and 280 y, 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 stoped out, probably removing part of 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, mica, 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 were separated and identified by x-ray powder patterns as belonging to the dolomite-ankerite group. The n_0 refractive index was determined for these samples and found to range from 1.692 to 1.711. No dolomites or limestones have been reported in the Folldal district previously, but this could be due to the limited amount of geological investigations carried out in the area. The author believes that this dolomitic mass represent a thin bed of carbonate deposited in the original synclinorium.

Partings either of the undifferentiated schists or the quartzitic schists are found at all thicknesses ranging from microscopic to greater than 0.75 meter. They extend along strike for distances from microscopic to more than 50 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. They appear to be remnants of the original wall rocks.

Glassy quartz lenses or masses, infrequently surrounded by rims of chlorite, 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 places near the foot wall, there are 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 comproses angular, and somewhat rounded, carbonate fragments composed of aggregates of coarse crystals. These fragments are spread throughout the massive ore in 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 within the range 1.654 to 1.644±.002. High concentrations of magnetite or minerals of the pyrrhotite-chalcopyrite assemblage occur on the edges of these calcite fragments. Infrequent veins of matrix minerals cut the fragments along fractures and cracks. The general appearence of the fragments in the ore is that of a limestone breccia containing 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 ankeritic dolomite mass and that porphyroblasts occur in the loose chloritic schists. 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 possibility.

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

At one or two locations rounded lenses of quartz and feldspar were noted in which 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, there are thin plagioclase bands in the ore which consist dominantly of albite with minor quartz. These bands, about 0.5 centimeter thick, do not appear to be very common in the ore, nor do they have great areal extent. All of the gangue, except the schist partings which show characteristics resulting from tectonic folding movements, exhibit evidences of tectonic activity in the ore zone due to movements during folding and metamorphism or much later tectonic activity parallel to the ore zone. The manner in which sulfide minerals, particularly the matrix sulfides, are moulded around the gangue fragments provides only poor evidence for later tectonic movement as the cause of rounded fragments. A number of cases where ore containing a large number of rounded and rolled gangue fragments were found. This is similar to the "Durchbewegung" structures described in German and other literature.

Variations in composition of the ore.

Massive sulfide ore deposits similar to Folldal have been considered to be fairly homogeneous bodies as regards to mineralogical and chemical composition. In light of this concept, 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 which were then tabulated and plotted on triangular diagrams in all possible combinations in an attempt to find trends in mineralogical variation.

Table 4. 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		0.0– 0.5
Arsenopyrite	0.5	0.0– 0.2
Fahlerts		0.0– 0.3
Gangue	23.8	1.2–72.7

The mineralogical composition of the ore in volume percent is summarized in table 4. The gangue free composition of a limited number of sections is shown in table 5. Figures 12, 13, and 14 are triangular diagrams of gangue free massive sulfide ore. In Figure 12 the three components plotted are pyrite volume percent, pyrrhotite volume percent, and the volume percent of matrix sulfide minerals (chalcopyrite, sphalerite, galena, arsenopyrite, and tetrahedrite-tennantite). This shows that the Folldal massive ore is mainly a pyritic ore and that it is unlike certain others of the Caledonian sulfide ore bodies, for example Bleikvassli, which shows both a pyrrhotitic and pyritic ore type (Vokes, 1961, personal communication). 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. The association pairs, pyrrhotite and chalcopyrite and sphalerite and galena form the second and third apices. The diagram illustrates the domination of the pyrrhotite-chalcopyrite assemblage in ore volume percent over the sphalerite-galena assemblage. The third triangular diagram (Fig. 14) is plotted with the apices being

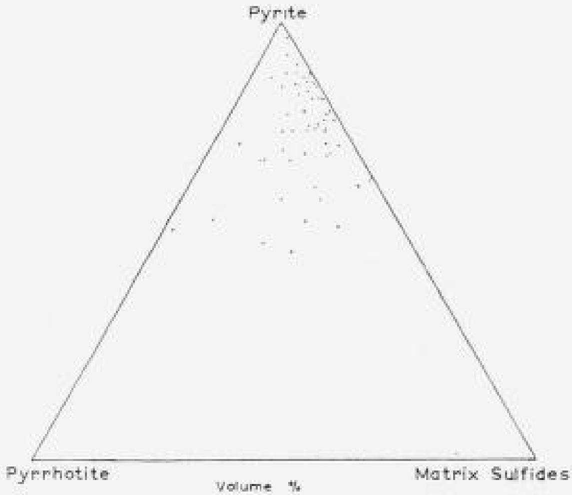


Fig. 12. Composition of ore expressed as volume percent pyrite, pyrrhotite, and matrix sulfide minerals.

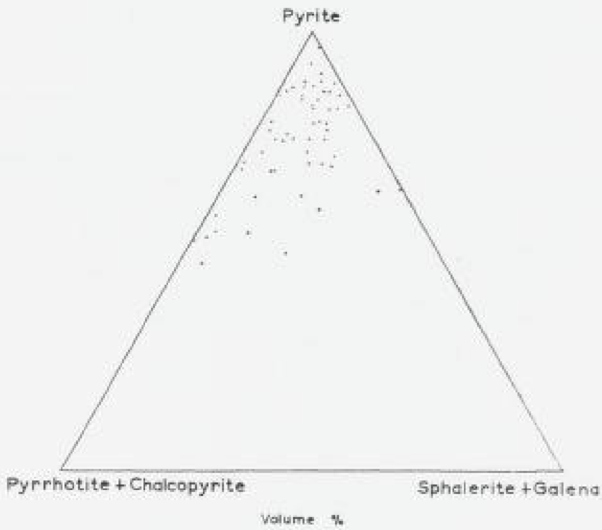


Fig. 13. Composition of ore expressed as volume percent of pyrite, pyrrhotite plus chalcopyrite, and sphalerite plus galena.

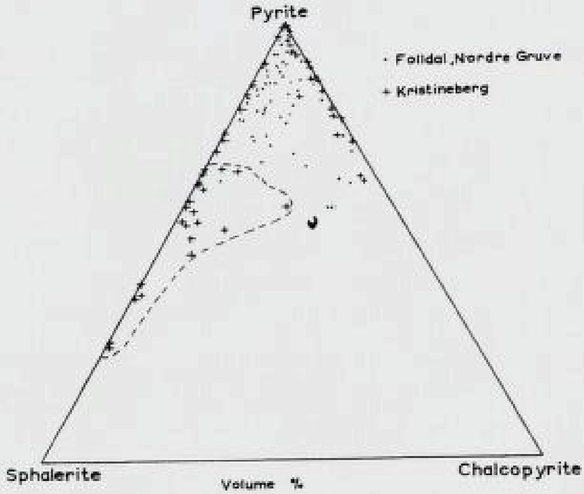


Fig. 14. Mineralogical composition of Nordre Gruve ore compared with that ore from Kristineberg, Sweden.

pyrite, sphalerite, and chalcopyrite. Analyses of Folldal ore are represented by the black points. Du Reitz (1951) gave 62 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 15 as black crosses. Except for the zinc ore of Kristineberg, which contains 10 percent galena, there is a very close similarity between the bulk composition of Kristineberg and that of Nordre Gruve.

Table 5 presents the results of 49 modal analyses of samples collected at 13 different locations as sections across the width of the ore body. Because thickness 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 analyzed sections ranges 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 basis. The average volume percent of pyrite for 49 analyses is 75.8; 7,6; for pyrrhotite; 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

Table 5. Analyses of orellocated with respect to wall rocks by percentage of thickness. (Pyrite-pyrrhotite-chalcopyrite-galena 100 %.)

Pyrite, gangue free (volume %)

Loc.	2 B	3 A	4 B	6 C	6 G	8 A	9 D	11 F	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	13.2
0.25						88.8	49.9	71.7	83.2	75.3	82.8	68.1	86.8
0.50	77.8		59.5	84.9	57.7	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	68.4	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	13.3	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	13.8	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	2 B:	240x,	150y;	thickness,	0.76 meter,	level 2.
Locality	3 A:	180x,	200y;	thickness,	0.80 meter,	level 3.
Locality	4 B:	330x,	250y;	thickness,	0.70 meter,	level 4.
Locality	6 C:	470x,	420y;	thickness,	0.61 meter,	level 6.
Locality	6 G:	310x,	350y;	thickness,	1.22 meters,	level 6.
Locality	8 A:	260x,	440y;	thickness,	0.72 meter,	level 8.
Locality	9 D:	300x,	490y;	thickness,	1.52 meters,	level 9.
Locality	11 F:	490x,	640y;	thickness,	0.91 meter,	level 11.
Locality	11 H:	460x,	640y;	thickness,	1.22 meters,	level 11.
Locality	12 G:	500x,	680y;	thickness,	2.50 meters,	level 12.
Locality	12 H:	540x,	690y;	thickness,	0.61 meter,	level 12.
Locality	13 A:	500x,	720y;	thickness,	2.00 meters,	level 13.
Locality	13 E:	470x,	680y;	thickness,	0.20 meter,	level 13.

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 the pyrite percentage decreasing from hanging wall to foot wall; two have pyrrhotite decreasing and three have matrix sulfides decreasing. In six sections, a 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 only for 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 give an overall generalization. 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

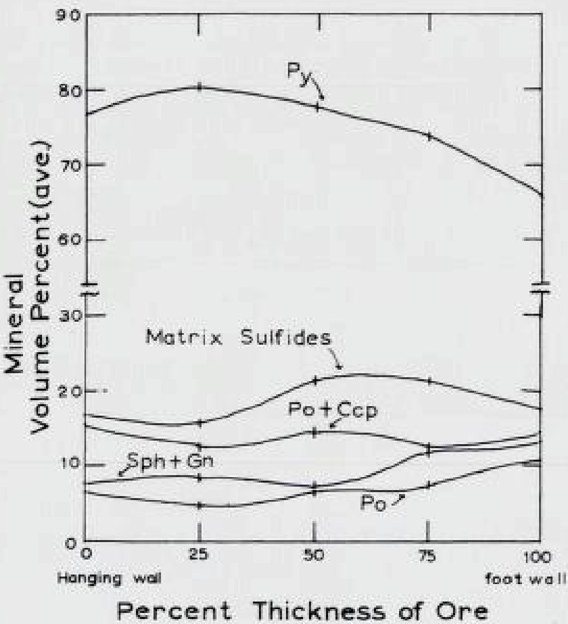


Fig. 15. Average mineralogical composition of the ore across the width of Nordre Gruve deposit. Pyrrhotite, Po; chalcopyrite, Ccp; sphalerite, Sph; galena, Gn; pyrite, Py.

for each of the five positions in the ore for each component. This may not be justified because of lack of analyses and lack of knowledge as to whether the samples, except those on the hanging and foot walls, correspond to each other in location; but such a summation as is presented in figure 15 is useful when used with the frequency diagrams of each component, to represent fairly well distributed samples in each population. In figure 15, 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 wall, 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 abundant on the foot wall than on the hanging wall and is at a minimum in the middle of the ore body. There generally seems to be a concentration of pyrrhotite near the contact of the ore with the wall rocks. In figure 12 the analyses which fall closer to the pyrrhotite apex than the majority of analyses are accounted for by this variation in pyrrhotite composition across the ore body. Sphalerite and galena are concentrated more toward the walls with a minimum concentration in the middle of the ore. Thus, sphalerite (this is the main component of sphalerite plus galena in which 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 Kristineberg, Sweden, showed a decrease in Fe percent and pyrite across the ore body 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.

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. 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 metamorphism than Nordre Gruve or it may be due to differences in the original conditions of depositions of the sulfides at the two different locations.

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 assay data above level 4, but below this there are 201 available assays all located with respect to the mine coordinates. Copper, zinc, sulfur, and occasionally iron were analyzed in the samples across the whole thickness of the ore body. Although traces of galena are found in polished sections, giving the ore a lead component, Folldalsverk has not analyzed for this metal. Table 6 presents a summary of modes, averages, and ranges for copper, zinc, and sulfur.

Frequency-distribution curves were drawn from the data (Fig. 16). 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.

Table 6. 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

An attempt was made to correlate copper versus zinc by using the product moment correlation coefficient (MORONEY, 1960) where the number of analyses equals 201; the average percentage of copper equals 1.25; the average percentage of zinc equals 5.35; and the standard deviation of copper equals 55.2; and that of zinc equals 219.6. Upon substitution, the correlation coefficient is found to be –0.32. A perfect straight

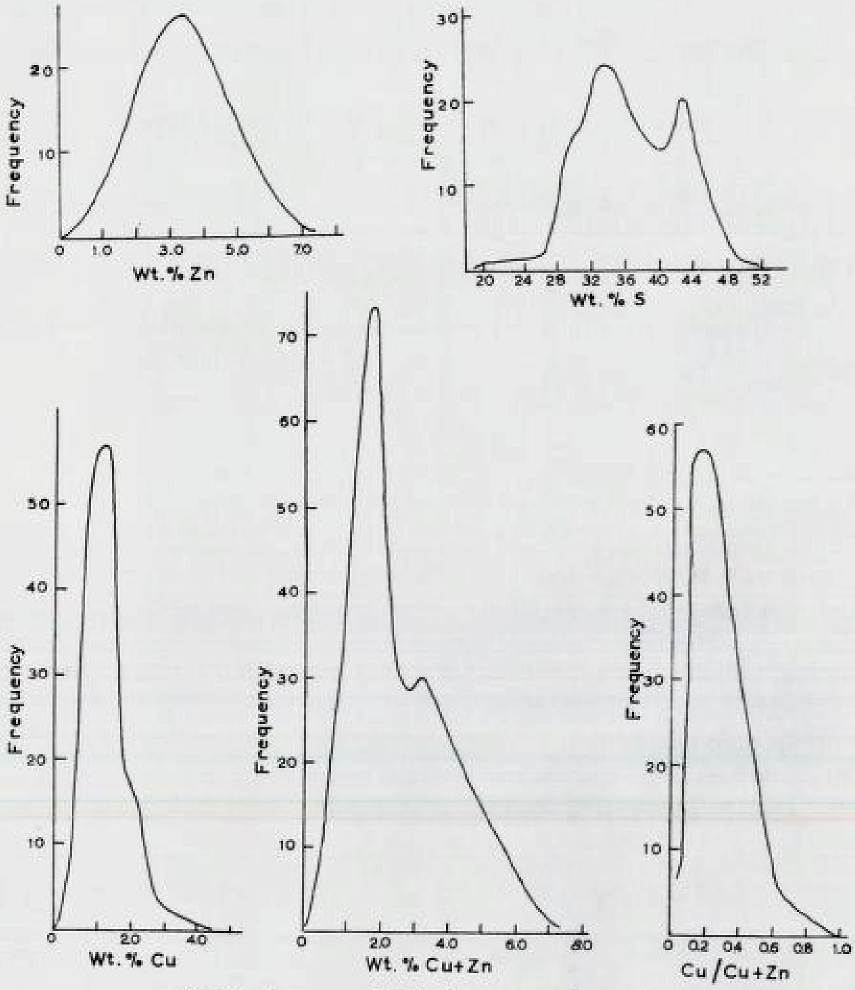


Fig. 16. Frequency distribution curves of assay data.

line correlation would have a coefficient equal to 1.0 and no correlation is represented by zero. 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. This means 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 which gave a normal distribution skewed toward the lower ratios (Fig. 16). This curve has a similar shape to one published by

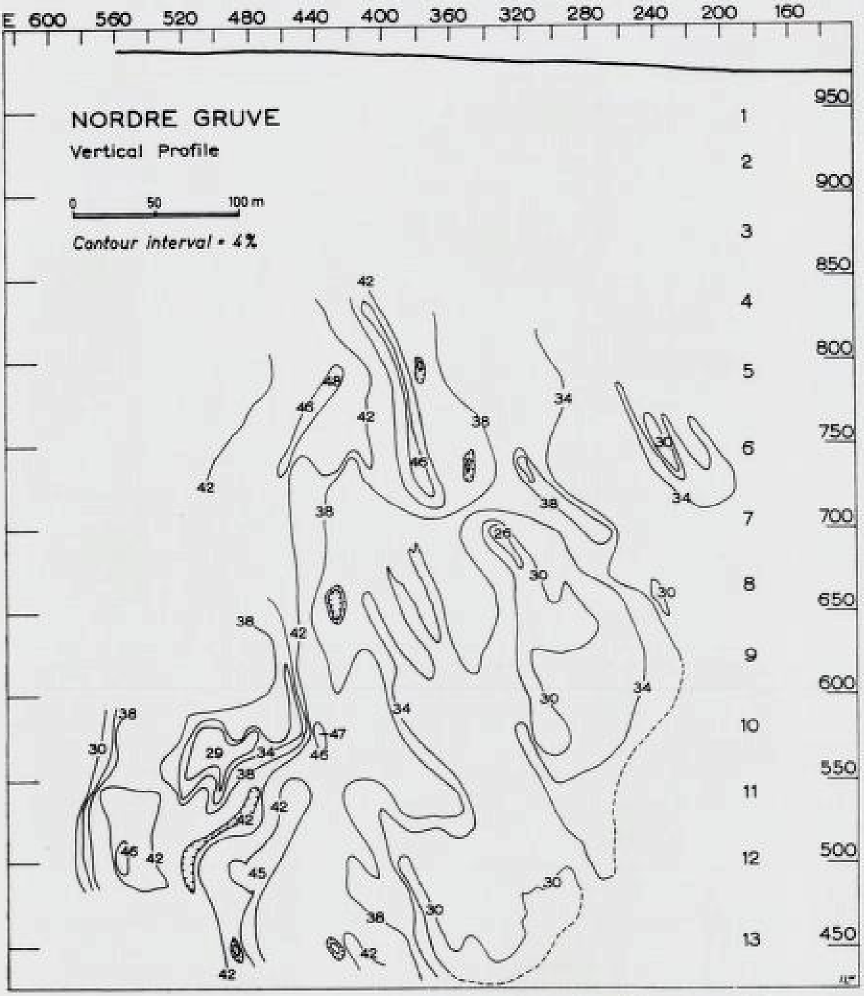


Fig. 17. Sulfur distribution in the Nordre Gruve deposit contoured by weight percentages on a vertical east-west profile.

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 understand better 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 profile and contoured. Figure 17 presents the sulfur distribution with a contour interval of 4 percent.

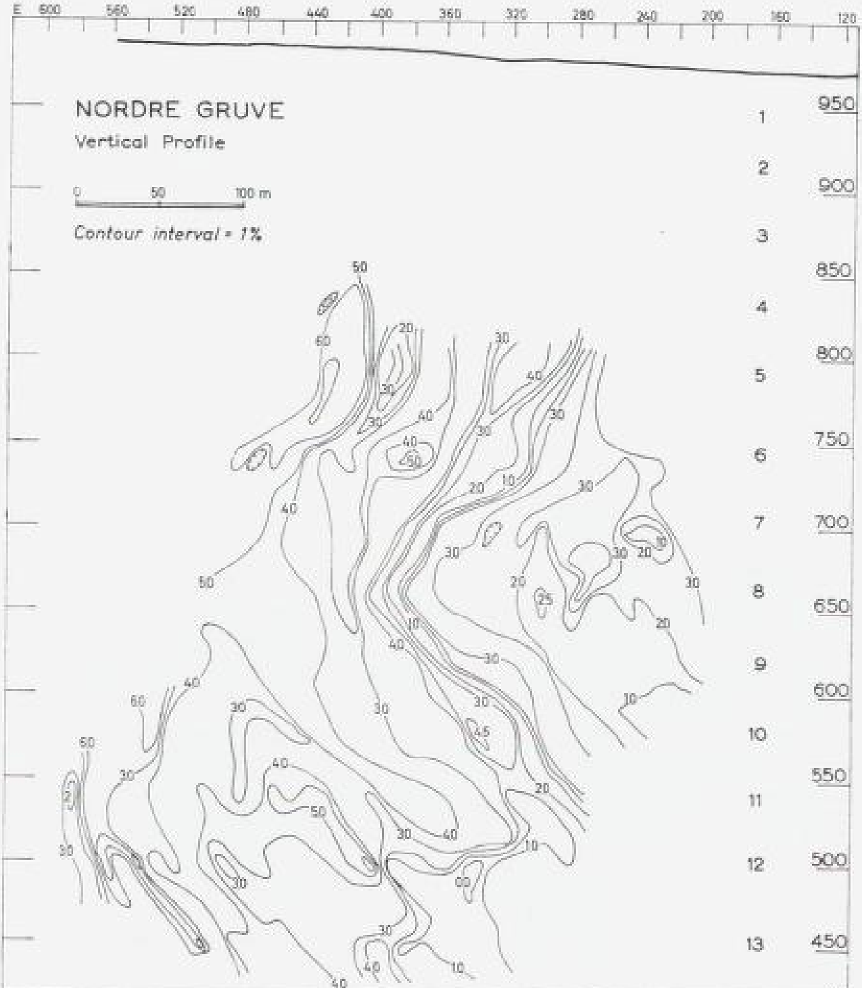


Fig. 18. Zinc distribution in the Nordre Gruve deposit contoured by weight percentages on a vertical east-west profile.

There are no readily apparent trends here, except that the sulfur precentage seems higher in the eastern part of the mine. Figure 18 is a similar diagram of the zinc percentages, interval 1.0 percent. One high zinc trend is readily apparent, plunging northeasterly with the trend of the ore. Another trend is discernible in the individual contour lines which seem to plunge northwesterly. In figure 19 of the copper distribution, one sees the same two trends, but they are more apparent. The areas

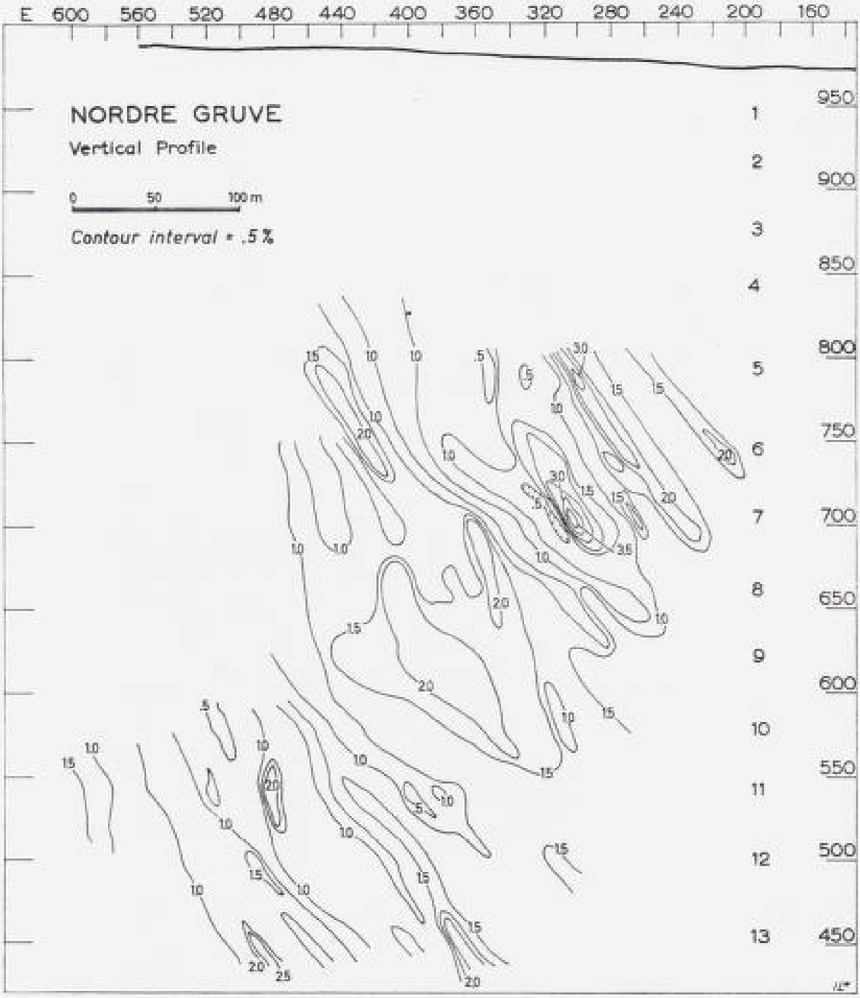


Fig. 19. Copper distribution in the Nordre Gruve deposit contoured by weight percentages on a vertical east west profile.

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 on 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

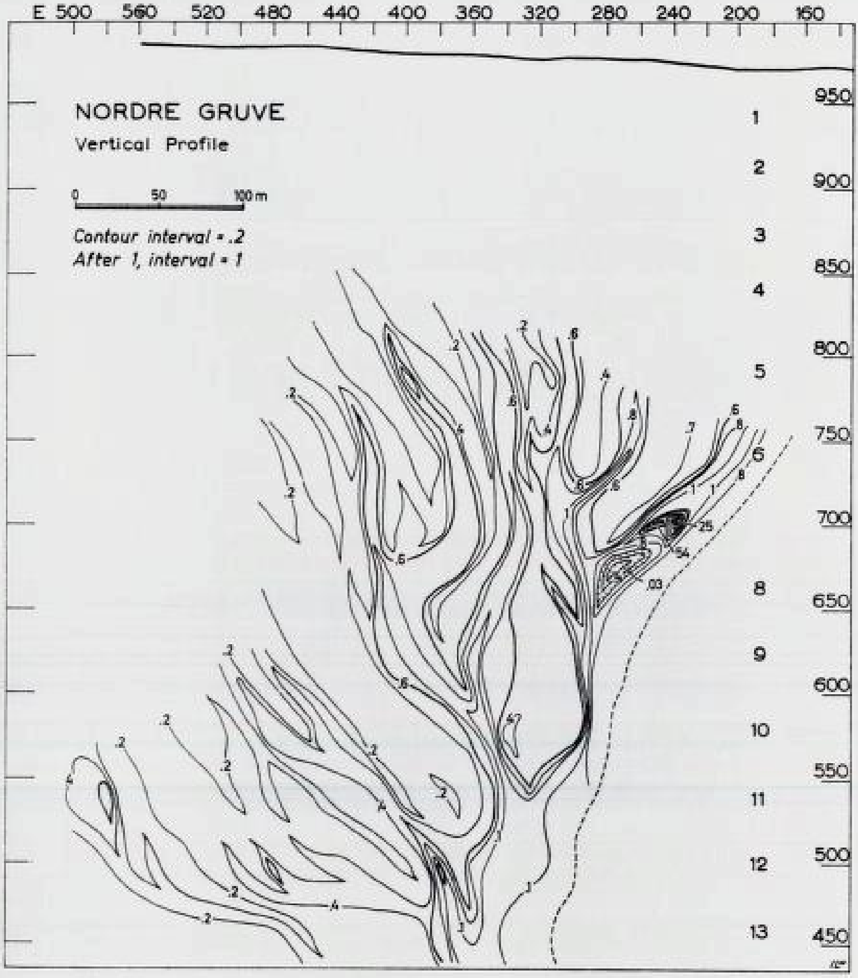


Fig. 20. Ratio of copper to zinc in the Nordre Gruve deposit contoured on a vertical east-west profile.

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.

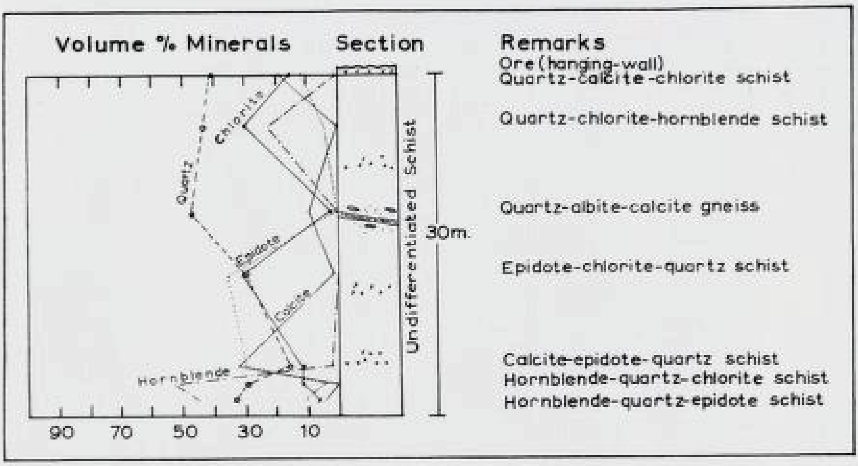


Fig. 21. Variation in modal mineral percentages on the hanging wall of the schists represents visible calcite, (x); quartz, (dots); glassy quartz lenses, (enclosed area).

The ratio of copper to zinc was also contoured in a vertical profile (fig. 20). All values of the ratio greater than 0.6, lie within the heavy black contour. This has a flamelike 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 receives 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. 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. The Bi reported in the analysis may be associated with the traces of tetrahedrite-tennantite found in the ore. Arsenic has been reported in analysis of Hovedgruve ore (Marlow, 1935) and probably occurs in Nordre Gruve. Any arsenic found in Nordre Gruve can probably be attributed to the minor amounts 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.

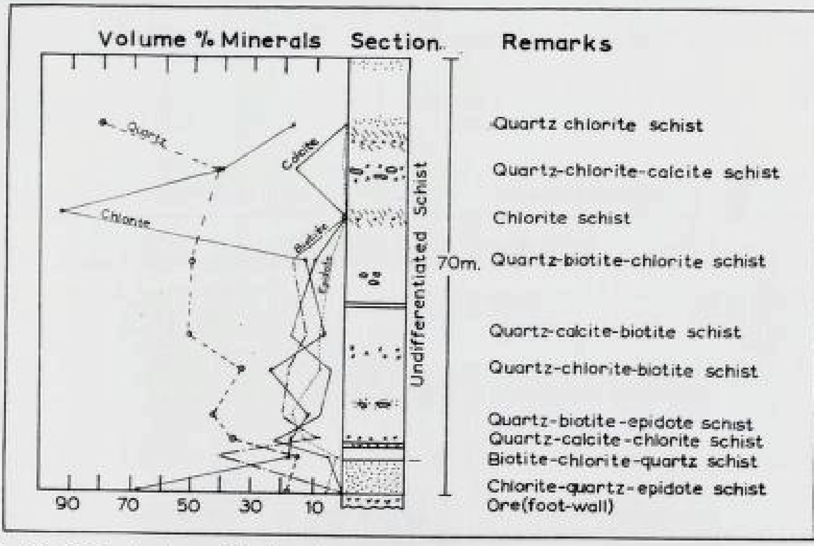


Fig. 22. Variation in modal mineral percentages on the foot wall of the schists represents visible calcite, (x); quartz, (dots); glassy quartz lenses, (enclosed area).

Wall rock alteration.

In ordre to determine if an alteration halo or zone exists around the ore body, a detailed mineralogical study of a hanging wall section on the undifferentiated schists was conducted. The results of this study were compared with wall rock samples collected in various other locations near the ore zone. Figures 21 and 22 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 plotted. It can be immediately seen that no simple trend or variation in mineral percentages with respect to distance from the ore zone exists. In part, this reflects the original heterogeneity of the undifferentiated schists, and in part, reflects probable results of varying metamorphic processes. But, it is not evidence for an alteration halo around the ore body. Chlorite, as a secondary alteration product, is present throughout 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.

Origin.

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 of 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 a later metamorphic concentration of scattered amounts of metals in the original rocks.

The final temperature of formation or recrystallization of the ore as indicated by various geothermometers is between 400 and 500° C. The lamellae of cubanite in chalcopyrite indicate a temperature of exsolution of 400 to 450° C (SCHWARTZ, 1927). While the temperature range given by BUERGER (1934) for the unmixing of chalcopyrite from sphalerite is 350 to 400° C. VOKES (1962) has analyzed two clean sphalerites from the zinc concentrates of Nordre Gruve and obtained temperatures of 462 $\pm$ 25° C. and 457 $\pm$ 25° C. at pressures of 1500 $\pm$ 1000 atmospheres. These are based on 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-pyrrhotite curve is still not completely established below temperatures of 600° C, but must be near to the solvus. This means that the amount of error expressed in Vokes' corrected temperatures must be greater than is shown. Also, since copper is present in the ore, the FeZnS system most probably does not represent true conditions of equilibrium. The Fe-As-S system has been presented in some detail by CLARK (1960). He states that the maximum temperature of pyrite-arsenopyrite association in nature must be 491 $\pm$ 12° C. This only applies to those specific localities in the mine where the association is found. There is a close similarity between the assumed maximum temperature of 550° C for the quartz-albite-epidote-almandine subfacies of the greenschist facies and the temperatures indicated by the geothermometers.

Observed facts which must be explained by a theoretical model are (1) the different types of banding, especially the magnetite banding, which are conformable with the folded wall rocks; (2) the non-existence of an alteration halo; (3) the gangue minerals lacking characteristics of introduced minerals but having properties similar to the same minerals found in the wall rocks; (4) the existence of "moved" or "rolled" gangue lenses and the existence of breccia-like structures formed by gangue and ore minerals ("Durchbewegung" structures); (5) the non-conformable rock to ore relations and the crests of folds in the wall rocks being broken by the massive sulfide ore; (6) the texture evidence of the pyrite cataclastic series which shows that there was continuous tectonic movement during or after deposition and which continued to a much later time; (7) the "inclusions" in the pyrite; (8) the concentration of matrix minerals, i. e. chalcopyrite, sphalerite, pyrrhotite near the walls of the ore body; (9) the occurrence of assay high areas of Cu and Zn corresponding with the directions of folding found in the wall rocks; (10) the elongation of the pyrite crystals; and (11) 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 complex series of events to explain simultaneously all of the observed facts for Nordre Gruve.

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 favourable horizon which was later replaced by sulfide minerals.

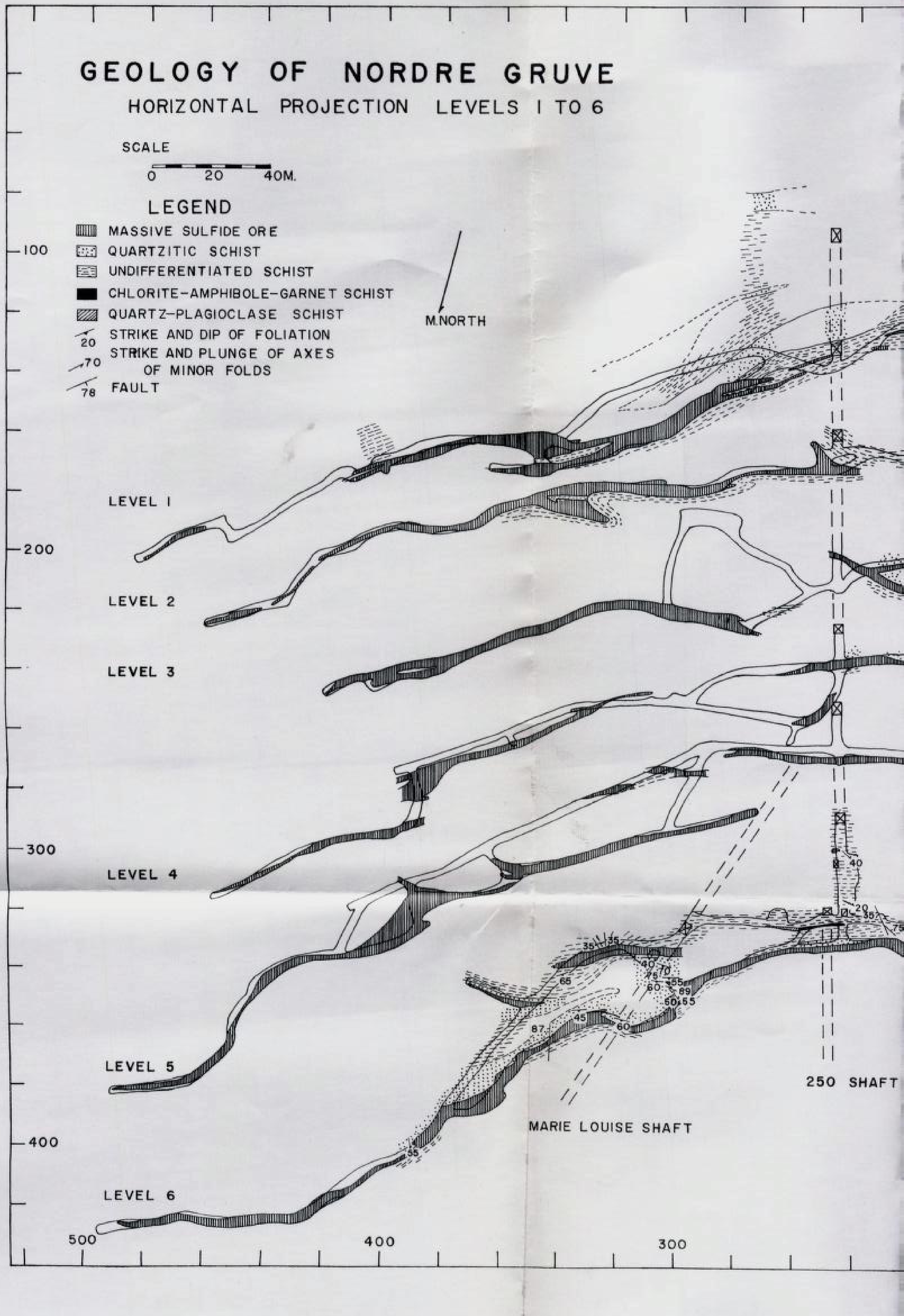
One may constrict a theoretical picture of the fold without the intrusion of the ore, ((b) of figure 11). Going from the foot wall to the hanging wall in the gentle fold, quartzitic schists, massive sulfide ore with chloritic schist partings, and chloritic schists occur. Upon more intense folding the 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 figure 11 (a). On the other band, it is difficult to picture the chloritic schist intensely folded before the emplacement of the ore with later replacement of all the schist except for the oriented folded partings by massive sulfides. The mass of glassy quartz in the crest of the fold, suggests this was an area of tension or low pressure where quartz could recrystallize from the quartzitic schists.

In some places, the fine-grained pyrite seems to be a result of intense shearing and granulation. In others, 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 holds only if one accepts the theory that the ore body was deposited earlier and then later involved in the regional metamorphism. When it occurs at locations where there are no visible evidence of post-ore movement, the origin of the fine-grained pyrite may be explained as being local areas of unmetamorphosed ore.

Using either of two possibilities of origin for the ore, sedimentary and epigenetic, one may arrive at the conclusion that the ore of Nordre Gruve has been metamorphosed. First, suppose the initial origin of the deposit is epigenetic, then the mineralizing fluids must have an igneous source at depth. The only rock which could be of magmatic origin within the area is the trondhjemite, which contacts the schists less than a kilometer away from the ore deposit at the surface. The relation of trondhjemites to nearby ore deposits has been published in Norwegian as well as foreign literature for many year. The trondhjemite contains the metamorphic mineral, garnet, and has been strongly foliated; both facts point to metamorphism. If one does not accept the trondhjemite as being of magmatic origin and the source of ore fluids, some mysterious, unknown source must be postulated. 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 would have been bent or moulded around the ends of the ore lenses. This would be expected had the "magma" been injected and forced the wall rocks apart to make room for itself to crystallize. The conclusions arrived at if the original origin is sedimentary are obvious. Because of the nature of this study, this argument is limited to this one deposit within the Folldal district, but from the nature of occurrences it probably could be applied equally well to that of Søndregruve and Hovedgruve and might be used for the other three deposits in the district. On the overall picture of similar deposits in the Norwegian Caledonides, the Norwegian Caledonides, the argument is probably not valid. 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 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 with an increase in the metamorphic grade of the rocks in which the deposit occur. This can be seen in any representative set of examples of Caledonian ores from the various regional metamorphic grades.

Other geologists are at the present time advocating the theory of metamorphosed ore deposits without regard to their original origin. 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 crest of the folds. He 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. 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 (1959, 1960) strongly supports the theories emphasizing the dynamic metamorphism of ore deposits. The photographs of massive sulfide ore from Russia are almost identical with similar textures found in polished sections of the ore of Nordre Gruve. BANNO and KANEHIRA (1961) attempted to build up a sulfide and oxide mineral facies and stability 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


GEOLOGY OF NORDRE GRUVE
HORIZONTAL PROJECTION LEVELS I TO 6
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20 STRIKE AND DIP OF FOLIATION
70 STRIKE AND PLUNGE OF AXES OF MINOR FOLDS
78 FAULT
M.NORTH
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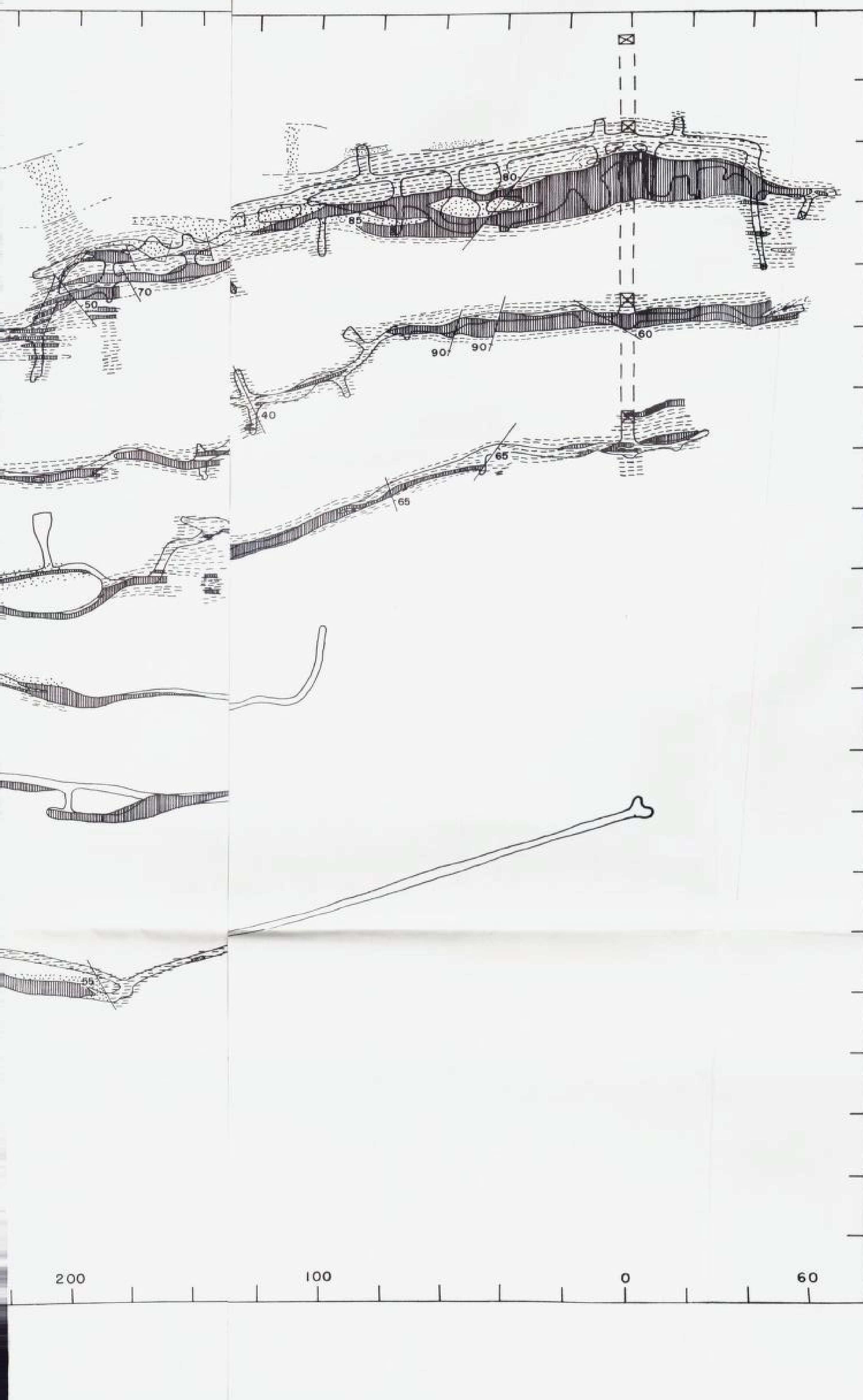

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list of work done in the past, as well as from numerous, unquoted publications, it can be noted that the metamorphism of ore deposits is a widely recognized phenomenon. However, the effects of metamorphic conditions on the ores are little known experimentally or in detail from the field. Textural evidence and criteria for mineral replacement, 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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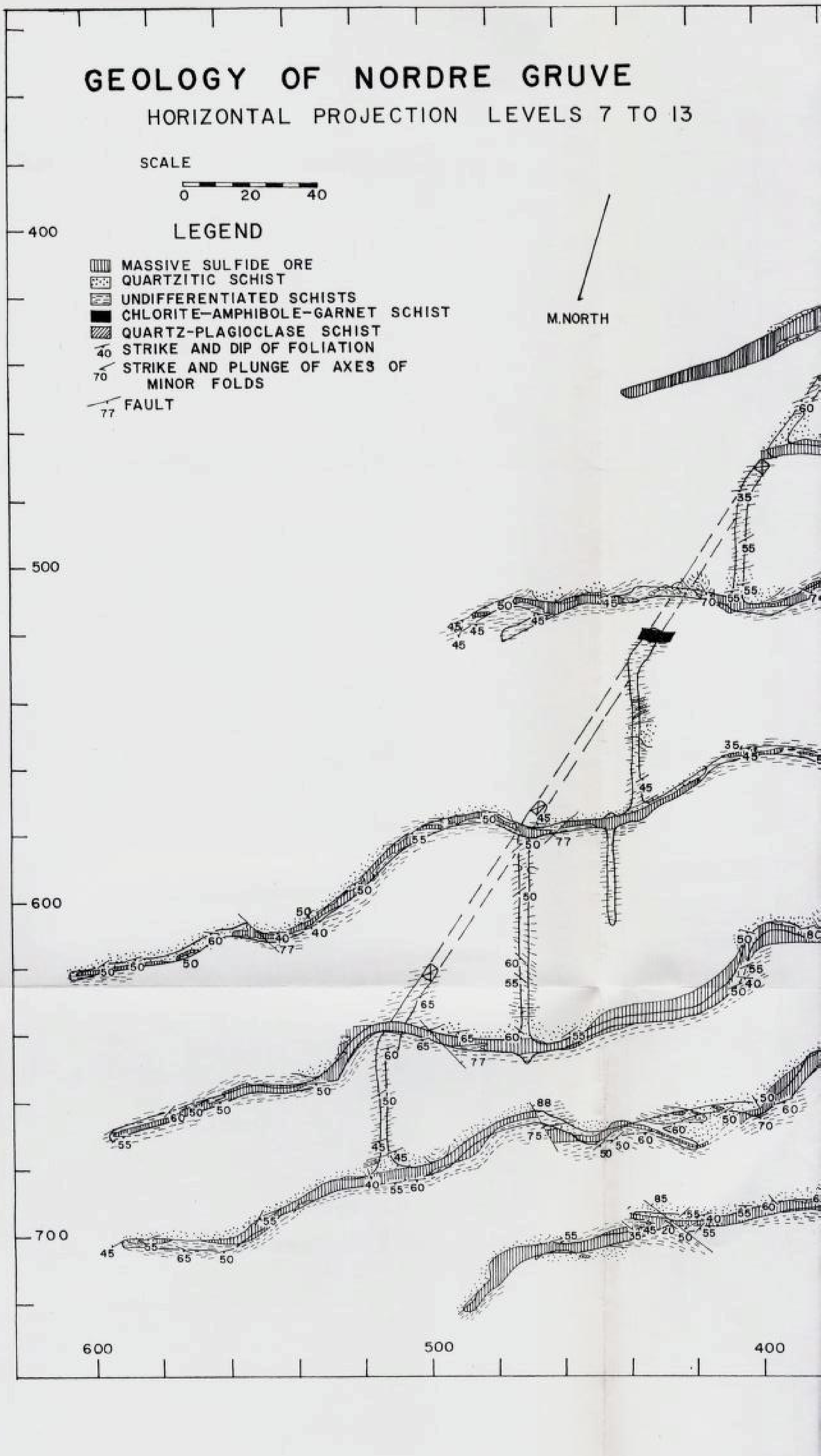
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SCALE
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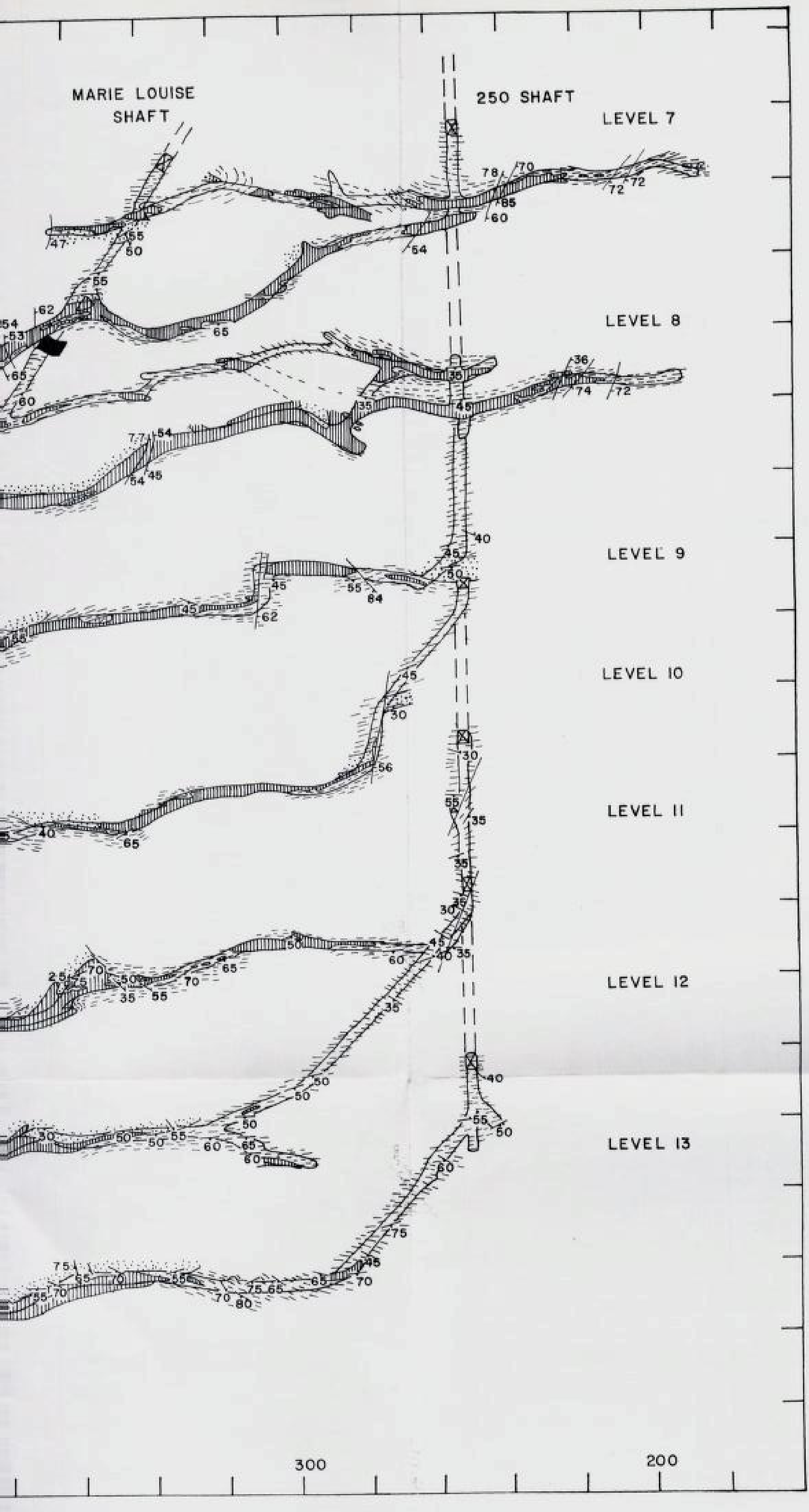

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