STRATABOUND SULPHIDE MINERALIZATION
IN THE KJØLI AREA, RØROS DISTRICT,
NORWEGIAN CALEDONIDES*

INGOLF J. RUI & INGE BAKKE


Two important sulphide ore-bearing formations have been recognized in the Cambro-Silurian succession of the Røros district. One is composed of submarine greenstones and quartz keratophyres (the Hersjø Formation). The other one, which is studied here, consists of a heterogeneous series of banded meta-argillites and meta-greywackes with subordinate thin green interlayers of probable volcanogenic origin (the Røsiø Formation). These two formations are embedded in a thick succession of various clastic sedimentary rocks which have undergone metamorphism and folding during the Silurian orogeny. The numerous sulphide deposits which occur in the Kjøli area are largely confined to the Røsiø Formation. The sulphide bodies are chiefly composed of massive pyrite and/or pyrrhotite showing variable chalcopyrite and sphalerite grades. The massive sulphides often occur as thin, extensive sheets, locally as irregular, small lenses which rarely exceed one metre in thickness. It is probable that the sulphides have been precipitated primarily on the sea-floor, but there is no clear evidence of a volcanogenic origin. Local discordant relationships between the massive sulphides and the wall rocks are ascribed to metamorphic mobilization of the sulphides. The thicker sulphide lenses may themselves represent mobilized portions of thinner sulphide-rich units.

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The Kjøli area is located in the Røros district in the central Scandinavian Caledonides of Norway, about 30–40 km to the north of the town of Røros (approx. 62°35'N, 11°23'E) (Fig. 1).

The Cambro–Silurian rocks of the Røros district make up the southeastern limb of a large and complexly folded synformal structure composing the Trondheim Region (cf. Strand & Kulling 1972). These rocks are correlated with Koli of the extensive Seve–Köli Nappe Complex of the Swedish Caledonides (Gee & Zachrisson 1974). To the north-east of Røros, near Rien and Langen, a zone of intensive mylonitization delineates the base of the Trondheim/Seve–Köli nappe complexes, where they override the older Eocambrian and Precambrian rocks of the Sylane window (Fig. 1).

The Røros district (Rui 1972) is composed of volcanic rocks (greenstones and quartz keratophyres), and a thick clastic succession dominated by meta-argillites and meta-arenites. These were intensely folded, metamorphosed

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and thrust during the Silurian orogeny. The supracrustals are locally heavily intruded by pre-metamorphic gabbros and younger syn- to post-metamorphic trondhjemites.

The geology of the Kjøli area is divided into two parts by the Tydal Thrust (new name, Figs. 1 & 2). This has been mapped as far south as the Sextus-Kongen area, where we have not been able to trace it further. To the north it has been mapped across the valley of Tydal just beyond the map limit in Fig. 1, and about 10–15 km further north (Wolff 1967). Lithostratigraphical relationships in other parts of the Røros district indicate that displacement along the thrust plane probably does not exceed a couple of kilometres. This is in agreement with the conclusion reached by Olesen et al. (1973), based on studies in the Tydal-Selbu area.

In the Kjøli area, the sequence dips westwards and is at least partly in-
verted. This conclusion is based on locally well-preserved sedimentary structures in the south-western part of Kjølifjellet (Rui 1972), where the Gula Group youngs eastwards into the Hersjø Formation (Fig. 2). This supports the assumption of a general regional inversion of the eastern Trondheim Region favoured among others by Wolff (1967) and recently by Olesen et al. (1973).

The copper mining industry in the Røros district dates back to 1644 when the Gamle Storwartz Mine was discovered; it was put into production the next year. Mining activity, which entailed periods of intensive search for new ores, resulted in the location of a number of mineralizations. The sulphide bodies are mainly massive, and are classified with the stratabound type of ores which are commonly recognized in eugeosynclinal orogenic regions. They are both pyritic and pyrrhotitic in type, and usually carry variable amounts of chalcopyrite and sphalerite. Today there are two mines in production, Killingdal and Lergruvbakken (Fig. 1), both located south of the area dealt with here.

In the Kjøli area a great number of small, abandoned mines and prospects delineate an extensive zone of abundant sulphide mineralization along the strike between Øvre Gauldalen and Tydal. Most of the deposits were discovered and ultimately exploited during the 18th and 19th centuries. The Kjøli Mine is the largest; it was discovered in 1766 and worked intermittently until it was finally abandoned in 1941. The total production from this mine was only about a quarter of a million tons (Table 1). The other

Table 1. Chemical analyses of massive pyritic ores from the Kjøli area.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Cu wt.%</th>
<th>Zn wt.%</th>
<th>S wt.%</th>
<th>Fe wt.%</th>
<th>Ag/Au ppm</th>
<th>Tot. prod.</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ag 40</td>
<td>X 1000 tons</td>
</tr>
<tr>
<td>Kjøli</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Au 0.8</td>
<td>ca 250</td>
</tr>
<tr>
<td>1</td>
<td>2.35</td>
<td>0.17</td>
<td>45.90</td>
<td>43.80</td>
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<tr>
<td>2</td>
<td>2.04</td>
<td>0.025</td>
<td>46.77</td>
<td>46.04</td>
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<tr>
<td>3</td>
<td>1.91</td>
<td></td>
<td>42.80</td>
<td></td>
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</tr>
<tr>
<td>Midtgruben</td>
<td></td>
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<td>4</td>
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<td>0.90</td>
<td>48.75</td>
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<td>Røros Menna</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2.15</td>
<td>5.5</td>
<td>39.0</td>
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</tr>
<tr>
<td>8</td>
<td>1.30</td>
<td>9.3</td>
<td>39.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Svensk Menna</td>
<td>9</td>
<td>1.37</td>
<td>1.80</td>
<td>42.46</td>
<td>43.68</td>
<td>ca 8</td>
</tr>
</tbody>
</table>

1. Shipping analysis, March 1921. 2. Production analysis, February 1921. 3. Average of shipping analyses, 1905–1920. 4.–9. Sample analyses. Analyses Nos. 1–5 and No. 9 are quoted from Aasgaard (1927). The others are performed by the laboratory of the Killingdal Grubeselskab A/S.
deposits are much smaller, and altogether have probably not produced more than about fifteen to twenty thousand tons of ore.

The sulphide deposits in the Kjøli area have been studied by Helland
(1873), who stressed the stratabound nature of the ores. Later Aasgaard (1927) surveyed most of the old mines and sulphide showings in the Álen–Tydal region. He gives valuable information concerning the earlier history, exploration activity and exploitation of the deposits. More comprehensive studies of the Rødhammeren and Killingdal mines in neighbouring areas have recently been given by Nilsen (1971) and Rui (1973).

Stratigraphy

The succession in the Kjøli area is divided into six formations (Fig. 2). As a result of the present investigations and additional field mapping carried out by Lieungh (1973) further south in the surroundings of Kongens Grube (Fig. 1), it is clear that a more detailed subdivision of the original lithostratigraphical scheme for the Røros district (Rui 1972) is required. In the revised stratigraphical column (Fig. 3), two new formations are distinguished between the Kjurudal and Røros formations of Rui (1972). Lieungh (1973) named them the Røsjø and Fjellsjø formations.

In the Kjøli area, parts of the lithostratigraphical succession are evidently missing, the entire Sætersjø Formation being cut out by the Tydal Thrust. Moreover, only remnants of the dark phyllites of the Kjurudal and Fjellsjø formations remain along the thrust zone in the southern and central parts of the area, and they are completely missing further north. Since the lithologies of the dark phyllites occurring immediately above the thrust plane are quite similar to those occurring below it, they are given the same symbols on the map (Fig. 2). The stratigraphical relationships further south require that the phyllites occurring above the thrust zone should be correlated with the Kjurudal Formation, whereas those occurring below it represent the Fjellsjø Formation.

Short descriptions of the stratigraphic units are given below, with emphasis being placed on the petrography. The different formations are described successively from the Gula Group to the Hummelfjell Formation, i.e. from the oldest to the youngest beds in the supposed inverted succession. Since the rocks above the thrust plane, especially the rocks from the Gula Group, have been dealt with in more detail elsewhere (Rui 1972), they are only briefly reviewed here.

The Gula Group. – The Gula Group crops out on the barren, high mountain areas to the west of the Tydal Thrust (Figs. 2 & 4). The rocks are mainly composed of fine-grained, brown weathering quartz–biotite schists. Locally there are more quartz-rich, arenaceous types, which sometimes exhibit various types of primary sedimentary structures, particularly grading and load casts (Rui 1972).

The metamorphism increases towards the west and north-west. Staurolite- and kyanite-bearing meta-argillites have been described by Kisch (1962) in his ‘Heimvola zone’ to the north-west of Falkfangarvola (Fig. 2). To the
west of the lake Veunsjøen, the Gula schists grade into andalusite- and cordierite-bearing rocks bordering the Hyllingen gabbro complex (Fig. 1). The contact zones here are overprinted by regional amphibolite facies metamorphism (Birkeland & Nilsen 1972).

The upper part of the Gula Group is composed of mica schists, greenish meta-marls, and green tuffitic bands in rapid alteration, suggesting the onset of volcanic activity. The uppermost Gula unit is a strongly deformed quartzite conglomerate, which is locally associated with a calcite marble. Similar conglomerate beds have also been found to the south of Veunsjøen, lower down in the Gula schists.

The Gula Group of rocks in the present area should be correlated with the upper eastern part of the Gula Group in the Tydal–Selbu area (Olesen et al. 1973), which contains similar conglomerate beds and marbles. The conglomerates are in turn correlated with the Gudå Conglomerate further north in Meraker (Wolff 1967).

*The Hersjø Formation.* – The meta-volcanics of the Hersjø Formation crop out along the eastern slope of Kjølifjellet, Blåhamaren and Falkfangarvola. The main rock types are green hornblende schists (greenstone), occasionally interbanded with light grey, quartz–albite schists (quartz keratophyres).

The greenstones are fine-grained and chiefly composed of acicular hornblende and sodic plagioclase. Chlorite, epidote minerals, and calcite are usually present in subordinate amounts; biotite is rare.

*The Kjurudal and Fjellsjø Formations.* – Within the map area the two formations have not been differentiated. The rocks consist of dark, rather homogeneous phyllites. These constitute the base of the steeply rising Kjølifjellet, partly occurring above, and partly below, the thrust plane between Menna and the Grønskar mine area.

Essential constituents are quartz, biotite, chlorite, and muscovite. Black graphitic varieties are frequently encountered. Calcite, epidote minerals, and sodic plagioclase may be present in subordinate amounts.

*The Røsjø Formation.* – The Røsjø Formation is composed of two members. In the lower part, near the dark phyllites, finely banded and laminated grey to greyish brown meta-argillites predominate. Characteristic are thin, but distinct, green interlayerings, which are usually less than one cm thick.

The meta-argillites are chiefly composed of quartz and biotite with subordinate amounts of sodic plagioclase, clinozoisite, and chlorite. Hornblende, garnet, muscovite, carbonate, sphene, and rutile may be present as accessories. The thin green beds consist of hornblende and sodic plagioclase + quartz in varying proportions. Clinozoisite/epidote are usually abundant, together with minor to accessory chlorite, biotite, and sphene. It remains uncertain whether these latter bands represent volcanoclastic sediments or contemporaneous pyroclastic volcanics.
In the higher parts of the Røsjø Formation the beds usually become increasingly massive, and consist mainly of meta-greywackes. The chief constituent is quartz, but sodic plagioclase may be present in substantial amounts. The variable distribution of the dark coloured minerals, i.e. notably hornblende, epidote minerals, and chlorite, are responsible for the variable grey to greenish colour of the rocks. The hornblendes are commonly developed as tiny, needle-shaped porphyroblasts, often about one cm long.

Green beds of hornblende-rich schists, from a few cm to a few dm in thickness, are also found within this part of the succession. Petrographically they are similar to the greenstones from the Hersjø Formation.

The Røros Formation. — Extensive areas to the east of the Røsjø Formation are underlain by a series of calcareous, argillaceous to subarenaceous mica schists. More rarely, the beds pass into more massive arenaceous types. These rocks were early recognized and named Røros skifer by Kjerulf (1871), and later precisely defined and outlined in the field by Tørnebohm (1896). This formation is apparently transitional into the Røsjø Formation.

The Røros Formation often exhibits a weak to distinct compositional banding related to variations essentially in the quartz and carbonate contents. The individual beds usually range from about 0.5–10 cm in thickness, though several dm-thick, quite massive layers may occur. The colours of the rocks usually vary from grey to light grey, or greyish green.

In addition to quartz and biotite, the ordinary Røros schists usually carry abundant, though variable, amounts of muscovite, chlorite, and carbonate and lesser amounts of sodic plagioclase and epidote minerals. Biotite, hornblende and garnet are frequently developed as larger porphyroblasts.

Detailed petrographical descriptions of the Røros schists have been given by Kisch (1962: 42), including the typical biotite porphyroblast-bearing Stuedals-skifer (Reusch 1890), and the hornblende-graben schists. Chemical analyses of the rocks have been presented by Carstens (1929) and Bryn (1960).

The Hummelfjell Formation. — This formation comprises the uppermost part of the supposed inverted lithological succession. The rocks are largely composed of rather massive feldspathic quartzites which commonly show light grey to yellowish grey colours, often with faint shades of green or red.

The meta-sandstones tend to split up in dm-thick beds along thinner bands enriched in mica or carbonate. Impure marbles, mica schists, and quartzitic beds are more conspicuous towards the contact with the Røros Formation. This contact is locally strongly mylonitized.

An essential constituent of the rocks is quartz; sodic plagioclase is usually abundant. Microcline, biotite, muscovite, chlorite, carbonate, epidote/clinozoisite, and hornblende may be present in variable, but usually subordinate, amounts.

Just to the north of the lake Grønsjøen, a small serpentinite body occurs
near the boundary between the Røros and Hummelfjell formations. This provides further confirmation of the stratabound character of the serpentinites in the eastern Trondheim Region (Rui 1972).

Caledonian intrusions

Various types of gabbroic rocks, mostly of clearly intrusive origin, are frequent in parts of the mapped area. They will be described in the following order: Equigranular and porphyritic meta-diabases largely occurring in the western parts above the Tydal Thrust; saussuritic gabbros, most common in the Røros Formation; dark amphibolites confined to the Hummelfjell Formation; scattered occurrences of trondhjemites.

The equigranular and porphyritic meta-diabases. – These rocks occur as swarms, particularly in the Gula Group, but they are also observed within the Hersjø Formation. They are occasionally recognized below the Tydal Thrust, notably in the Kjøli Mine area.

The meta-diabases are fine- to medium-grained and usually occur as sills ranging from a few dm up to about 10–15 m in thickness. Discordant sheets have been noticed more rarely (Rui 1972: 16).

The main difference between the porphyritic and the equigranular varieties depends on the presence of abundant phenocrysts of plagioclase in the former. The maximum size of these may be about 10 mm in diameter but most often they are about 5 mm or less. Chilled margins are often easily observable, especially among the porphyrites, where the frequency of phenocrysts diminishes towards the contacts.

Identical rocks from neighbouring areas are described by Vogt (1941), Kisch (1962), and Nilsen (1971). According to Kisch (p. 29) the average composition of ‘eight blastoporphyritic and nine equigranular amphibolites’ shows: 49% hornblende, 48% plagioclase, including 5% zoisite/clinozoisite, 2–3% titanite, and minor amounts of biotite and chlorite.

Though the plagioclase phenocrysts and groundmass laths frequently show zoisite alteration, they are often well twinned and exhibit compositional zonation ranging from about An_{60} (cores) to about An_{80} (rims).

The saussuritic meta-gabbros. – Conformable sheets and lenses of fine- to coarse-grained saussuritic gabbros are well known throughout the Røros district. The rocks are usually quite massive but often show fine-grained, schistose contacts. In the Kjøli area these meta-gabbros predominate in the Røros Formation.

The meta-gabbros are mainly composed of the same minerals as the meta-diabases described above, but the plagioclases are always altered to aggregates of albite/oligoclase and clinozoisite or more extensively recrystallized into a granoblastic mosaic. Ophitic textures may still be recognizable. Petrographical descriptions of the rocks are given by Kisch (1962: 56) and by
Carstens (1929), who also presents one chemical analysis of the meta-gabbro at Quintushøgda near Røros.

In the meta-gabbro to the east of Guldal Mine there are two lenticular ultramafic bodies situated near the north-eastern margin of the intrusion. These are a couple of metres wide and a few tens of metres long. They are essentially composed of antigorite and talc, and lesser amounts of carbonate, chlorite, and oxides. Pseudomorphs of antigorite after olivine are well preserved.

*The amphibolites in the Hummelfjell Formation.*—These amphibolites differ from the ordinary meta-gabbros in being darker greenish to black in colour though they sometimes show a diffuse lighter banding. The rocks are also usually definitely more schistose and exhibit fine to medium-grained nematoblastic textures in thin section.

The dark amphibolites are essentially composed of sub- to euhedral hornblende and anhedral plagioclase (ca An$_{20-40}$) usually in approximately equal amounts. Epidote/clinozoisite is usually present in lesser amounts and, more rarely, carbonate, chlorite, and biotite. Some varieties are extremely enriched in hornblende, which may account for about 80–90 vol. % out of the total silicates, whereas lighter coloured bands may contain as much as about 80 vol. % plagioclase.

An amphibolite variety of unusual composition was found just to the south of the small outliers of the Røros Formation, which rest upon the Hummelfjell Formation to the north north-west of Grønsjøen. The chief constituent is colourless tremolite, whereas abundant green spinel and remnants of olivine characterize the rock. Small amounts of chlorite, talc or sericite, and opaques are also present.

The amphibolites occurring within the Hummelfjell Formation are associated with comparatively high aeromagnetic anomalies which distinguish them from the other, much less magnetic, mafic intrusions of the area.

*The trondhjemites.*—Scattered occurrences of trondhjemite intrusions are largely confined to the areas above the Tydal Thrust and to the northern part of the Røros Formation. They usually occur as thin, concordant and cross-cutting sheets up to a few metres in thickness. Two larger bodies are found; one to the south-west of Falkfangarvola, the other to the west of the Menna Mine area. The trondhjemites to the north of the Kjøli Mine show clear discordant relationships to the dark phyllites and greenstones (Fig. 8).

The rocks are usually fine- to medium-grained, greyish white in colour; sometimes they are faintly reddish. Essential minerals are sodic plagioclase and quartz together with subordinate muscovite, biotite, chlorite, and epidote/clinozoisite.

In the adjoining Tydal area, trondhjemites and related leucocratic rocks have been studied by Kisch (1962: 78), and Olesen et al. (1973). Based on
<table>
<thead>
<tr>
<th>UNIT</th>
<th>ROCK TYPES</th>
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<tr>
<td>Hummel Fjell Formation</td>
<td>Feldspathic Quartzites</td>
</tr>
<tr>
<td>Røros Formation</td>
<td>(Interlayers of Graphitic Schist) Serpentinite Bodies</td>
</tr>
<tr>
<td></td>
<td>(Conglomerate/Marble)</td>
</tr>
<tr>
<td></td>
<td>Calcareous Grey and Greenish Mica Schists</td>
</tr>
<tr>
<td>Røsjø Formation</td>
<td>Banded Brownish-Grey Schists with Thin Green Volcanogenic Interlayers; Grey and Greenish Meta-Arenites</td>
</tr>
<tr>
<td>Fjellsjø Formation</td>
<td>Graphitic Phyllites</td>
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<td>(Satersjø Formation)</td>
<td>(Effusive Greenstone / Quartz Keratophyre)</td>
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<tr>
<td>Kjurudal Formation</td>
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<td>Dark Phyllites, Partly Graphitic (Polymic Conglomerate)</td>
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<td>Effusive Greenstone and Quartz Keratophyre</td>
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<td>Cambrian Group</td>
<td>(Dictyocemata Shale at Nordanevoll) Marble/Quartzite Conglomerate</td>
</tr>
<tr>
<td></td>
<td>Calcareous Grey Meta-Arenites, Often with Interlayers of Graphitic Schist</td>
</tr>
</tbody>
</table>

Fig. 3. Lithostratigraphy of the Røros district, revised from Rui (1972). Units in parentheses are not found in the area described here.

Structural relationships the latter workers favour a syn- to post-metamorphic age for the trondhjemite intrusions.

Structures
The Tydal Thrust divides the Kjøli area into two structural units which exhibit pronounced differences in tectonic style. The Gula and Hersjø units above the Tydal Thrust are deformed by tight to isoclinal folds and show
Fig. 4. Geological sections showing the supposed inverted lithological succession in the Kjøli area. Locations of sections are shown in Fig. 2. (1) Gula Group, (2) Hersjø Formation, (3) Kjurudal & Fjellsjø Formations, (4) Røsjø Formation, (5) Røros Formation, (6) Hummelfjell Formation, (7) Trondhjemite intrusions.

Fig. 5. Fold axes from the central and southern part of the Kjøli area. The beds above the Tydal Thrust are characterized by tight to isoclinal folding. The gently undulating strata below the thrust are generally deformed by folds of more open style which also appear to have deformed the thrust plane itself and the succession above it.
comparatively steep, mainly westerly dips of schistosity and bedding surfaces (Fig. 4). The axial trends of regional folds are parallel to the axes of minor folds (Fig. 5), which in turn show parallelism with the elongation direction of the deformed Gula Group conglomerates (Rui 1972: 18). Variation in the orientation of the minor fold axes is due to a superimposed gentle flexuring of the strata.

East of the Tydal Thrust the beds are more flat lying, gently undulating with dips frequently between 10–20 degrees. Minor folds are generally more open in style showing axial trends about NW–SE to NNW–SSE in the Menna–Kjøli area, turning N–S further to the north. The flexuring of the thrust plane and the units above it may be related to this stage of gentle folding.

The thrust zone is often well exposed and is seen as a steep wall in the topography. It consists of dense and dark, well-jointed mylonites and ultramylonites. Irregular mm-thick, reddish-violet veinlets of submicroscopic material are characteristic.

The discordant nature of the thrust zone is easily recognized, both in relation to the dark phyllites of the Kjurudal and Fjellsjø formations in the south, and to the Røsjø Formation in the Grønskar–Allergot area in the north.

Mylonitic zones are also frequently developed below the main thrust, most often in the Røros Formation or at the border between the latter and the Røsjø Formation. These zones are often expressed in the terrain as low ridges which may be several kilometres long. Sections through such ridges show that they consist of mylonites in the core often flanked by intensely crumpled schists on the flanks which pass gradationally into normal country rocks (Aasgaard 1927: 23). To the north of Midtgruben a series of sheet-like meta-gabbro intrusions occurs in one of these mylonitic zones. The meta-gabbros themselves are mylonitized but no discernible displacement of the rocks has been recognized.

The contact between the Røros and Hummelfjell formations is generally characterized by strong deformation and disharmonic folding. To the west and north of Lauvøyvola the border is clearly discordant and mylonitized.

Ore geology

Valuable information about the size and extension of the old mine workings, ore types, and wall rock relationships has been collected by Aasgaard (1927). In later years, geophysical surveys and diamond drilling, largely carried out by the Killingdal Grubeselskab A/S, have added much new data regarding the lateral extension, shape, and dimensions of the mineralized zones outside the underground workings. Unfortunately most of the mines are flooded and have collapsed; along with weathering of the outcrops, this has impeded a systematic study of the orebodies and the immediate wall rocks.
Types of ores. – The sulphide orebodies in the Kjøli area are of the massive stratabound type. Similar deposits are common throughout the Røros district, as well as in the Caledonides in general.

The sulphide deposits are dominated by either pyrite or pyrrhotite, or a mixture of these constituents. They usually contain abundant chalcopyrite, while the sphalerite content is highly variable. Galena is rare. Disseminated or massive magnetites are commonly associated with the sulphides.

Based on the content of the principal iron sulphides, we have distinguished between pyrite-dominant ore types and pyrrhotite-dominant ore types. It is characteristic that the gangue silicate fraction in the ores increases with the pyrrhotite content. In the pyritic ores the silicates do not generally exceed 10% of the mode. The pyrrhotite ores, however, are characterized by abundant inclusions of green coloured silicate aggregates in which ferromagnesian minerals strongly predominate. These silicate inclusions frequently constitute between 20–50% of the mode, giving the ores a breccia-like appearance (Fig. 6).

The pyritic ores. – The Kjøli orebodies contain the most pyrite-rich mineralization of the area. It consists of a dense aggregate of fine-grained, sub- to euhedral pyrite with interstitial chalcopyrite, pyrrhotite, and minor sphalerite. In addition there are scattered grains of subhedral magnetite. The pyrite grains usually show evidence of cataclastic deformation.

The gangue silicate fraction, mainly quartz and chlorite, in a typical ore specimen from the Kjøli Mine amounts to about 5% by volume. The scattered quartz grains show extreme undulatory extinction. The chlorite may occur as small flexed flakes, but more often as crumpled aggregates. Muscovite is more rare.
Massive magnetite with subordinate amounts of sulphides is locally present and is exposed in the south-western outcrop of the Kjøli I orebody (Fig. 8). Bands of massive magnetite have also been recognized underground, usually next to the hanging wall, but also within the massive sulphides (Aasgaard 1927: 125).

In the massive ores from Svensk Menna, Røros Menna, Godthåb, and Midtgruben the pyrite grains are embedded in, and often isolated from each other by, abundant pyrrhotite, which occurs together with chalcopyrite and sphalerite as a matrix. Small grains of arsenopyrite and galena are occasionally noticed.

The pyrite is relatively coarse-grained, often cataclastic, with grains approx. 0.2–0.4 mm in diameter, but scattered individuals may sometimes measure one centimetre or more. The pyrite crystals often appear to be strongly corroded (rounded) by the groundmass sulphides.

The more pyrrhotite-rich pyritic ores (Svensk Menna, Røros Menna, Godthåb, Midtgruben) often contain almost pure spherical aggregates of granoblastic quartz. These are sharply delineated from the sulphide masses and may measure up to about 1–2 cm in diameter. Similar quartz ‘eyes’ are even more common in the pyrrhotitic ores.

The pyrrhotitic ores (Svensk Menna, Røros Menna, Godthåb, Midtgruben) are grouped with the massive pyrrhotitic type of ores. The pyrrhotitic ores are characterized by abundant inclusions of green silicate fragments and glassy quartz ‘eyes’ of the same kind as recognized in the pyrrhotite-rich pyritic ores. The silicate inclusions are cemented by a groundmass aggregate of pyrrhotite and chalcopyrite, and lesser amounts of sphalerite (Fig. 6 A). Subhedral grains of pyrite and magnetite may also occur. The chalcopyrite often tends to be clustered adjacent to the silicate fragments. Available copper analyses of the pyrrhotitic ores (Aasgaard 1927: 125)
are greatly variable, which makes it difficult to give any reliable estimates of the ore grades.

The green silicate fragments in the pyrrhotitic ores exhibit almost invariable signs of being bent, twisted, and rotated—apparently as a result of extensive plastic flow of the enclosing matrix sulphides. The silicates are also frequently heavily dissected by the sulphides along highly irregular branching veinlets.

Green silicate fragments in the ores from Guldal are chiefly composed of entangled masses in which any one of chlorite, biotite, or bluish green hornblende may predominate. Lens-shaped aggregates of granoblastic quartz occur sporadically, whereas garnet and sometimes sericite may be present as accessories. The hornblende needles are often flexed and broken. Hornblende and garnet may be slightly chloritized.

In hand specimens the silicate inclusions in the pyrrhotitic ores from Grønskar appear quite similar to those which were studied at Guldal. The one thin-section examined, however, showed a dense aggregate of chlorite with scattered porphyroblasts of a colourless, partly chloritized amphibole (tremolite), instead of the bluish green hornblende usually encountered. Isolated broken fragments of this amphibole are also moulded in the sulphides as are clusters of chlorite and biotite, and scattered grains of quartz.

Magnetite is quite often associated with the pyrrhotitic ores. Specimens from the Guldal Mine may show scattered subhedral magnetite grains which are more or less evenly dispersed through the massive sulphides. The bulk masses of magnetite, however, are concentrated as darker massive bands showing only subordinate amounts of sulphides. In some cases an intimate alternation has been observed between thin parallel magnetite and silicate-rich laminae, which resemble primary depositional banding (Fig. 6 B).

The silicate bands consist of deep bluish green hornblende (approx. 20–30% by volume) and subordinate amounts of quartz. The hornblendes are arranged subparallel to the banding.

In the Grønskar and Allergot deposits, magnetite occurs in much the same way as in the Guldal Mine, but there are also massive magnetite ‘beds’ which are not directly connected to any visible sulphide bodies (Aasgaard 1927: figs. 39, 41 and 42). One thin section of magnetite ore from Grønskar showed the same silicates as the specimen from Guldal, roughly estimated to about 10% of the mode. According to Helland (1873: 27), some of the Grønskar deposits have been worked for iron ore.

Wall rocks. – The sulphide deposits in the Røros district are usually surrounded by haloes of chlorite-rich schists. Such zones may be several metres thick fading outwards into ordinary, less chloritic schists. Sometimes internal zones of abundant muscovite, e.g. the Killingdal Mine (Rui 1973), or muscovite plus chlorite, may occur next to the massive sulphides. The deposits in the Kjøli area are no exception; Aasgaard (1927) frequently comments on the presence of soft, green, chloritic schists adjacent to the orebodies.
Fig. 7. Geological map of the Menna-Guldal area with superimposed magnetic and electro-magnetic anomalies. Anomalies above the Kjurudal and Fjellsjø Formations are omitted. Heavy lines in the cross-sections (lower left) indicate the attitude of mineralized zones. Note that each line may consist of one or more closely spaced ore zones. Aero-magnetic survey by Terratest AB, Stockholm, Sweden. Electromagnetic ground survey by P. Singsås, Norges Geologiske Undersøkelse, Trondheim, Norway.

Studies of the immediate wall rocks are confined to a few thin-sections from Kjøli, Midtgruben, Grønskar, and Allergot. In summary, all the specimens show abundant quartz and chlorite, the latter being far above the aver-
age for the normal enclosing country rocks. Many of the samples are also relatively rich in muscovite, which usually occurs in an intimate lamellar intergrowth with chlorite.

Other minerals which may occur in the chlorite zones in subordinate to accessory amounts are sodic plagioclase, epidote, carbonate, sulphides, and relics of biotite and garnet. The latter two are often strongly chloritized. It should be noticed that both feldspar and epidote minerals are rather common in the Røsjø Formation, while muscovite is rare.
Shape and distribution of the sulphide deposits. – The map (Fig. 2) clearly shows that the mineralization frequency in the Kjøli area is conspicuously high within the Røsjø Formation. The other lithological units are almost barren, showing only a few minor prospects near the upper and lower contacts of the volcanogenic Hersjø Formation, and a mineralization in the Røros Formation to the east of the Kjøli Mine.

The massive pyrrhotite at the Gamle Folldal prospect in the south-western part of the area is limited to a zone of iron-rich epidote skarn at the border between the Gula Group and the Hersjø Formation. The ore and the skarn rock are probably formed through metasomatic replacement of marble, which occurs in this position.

To the north of Kjøli several small mineralizations are bound to a rust zone near the border between the Hersjø Formation and the underlying dark phyllites (Fig. 8). Richer chalcopyrite impregnations or more massive pyrrhotitic lenses sometimes occur near trondhjemite dikes cutting through the greenstone/phylite border. Outside the map area the Killingdal Mine and possibly also the Rødhammeren Mine occur at, or near, this same stratigraphical level (Fig. 1).

A combination of geological mapping, comprehensive geophysical measurements, and reconnaissance diamond drilling has shown that most of the sulphide mineralizations are confined to the Røsjø Formation. (The geo-
Fig. 9A. Geological map of the Grønskar area.
Fig. 9B. Geological map of the Allergot area.
physics includes: Regional airborne electro-magnetic surveys (two plane rotary field method) carried out by ABEM, Stockholm in 1959; helicopter-borne magnetic and electro-magnetic measurements between the Menna and Grønskar areas by Terratest AB, Stockholm in 1970; Turam measurements in the Kjøli-Midtgruben area by Geofysisk Malmleting, Trondheim in 1955, and in the Menna-Guldal area by Norges Geologiske Undersøkelse in 1971. Additional slingram surveys were carried out by the Killingdal Grubeselskap A/S in the sixties. The geophysical surveys were initiated by the Killingdal Grubeselskap A/S, with the exception of the turam measurements at the Kjøli-Midtgruben area, which were financed by the government.) The sulphides usually occur as thin discrete zones or sheets which may show considerable lateral extension in different, often closely spaced, stratigraphic levels. There are no indications of repetition by isoclinal folding. Sometimes the sulphide zones swell into irregular lenses which occasionally exceed one metre in thickness (e.g. maximum 2-3 m in the Kjøli Mine, and 2 m in the Svensk Menna). These small sulphide bodies formed the basis of the earlier mining activity in the area.

Because of the moraine cover and the general lack of any distinct marker horizon within the Røsjø Formation, it has not been possible to prove if the thin sulphide units are truly stratiform over more than a few metres along strike although the geophysical data indicate that they probably are.

Aasgaard (1927: 139, 144) stated that clear cross-cutting relationships between the massive sulphides and the wall rocks were observed at Guldal, Grønskar, and Allergot. These local discordanices, however, may very well be of secondary origin – accomplished by the plastic flow of the sulphides due to faulting and folding (cf. Clark & Kelly 1973, Gill 1969). A convincing example of the tectonic mobilization of sulphides was recorded in a core sample from drill hole no. 1, located about 800 m to the north of Røros Menna (Fig. 7), where pyrrhotite and chalcopyrite had been injected along a minor, steep-dipping fault plane for several centimetres.

The complex EM-anomaly pattern in the Menna area (Fig. 7) reveals different, partly overlapping, conductive zones. The extensions of the thicker sulphide masses in the old mines appear to be rather limited, even though they may be mutually interconnected by thinner, non-conducting zones of disseminated sulphides. Diamond drilling to the north and north-west of Røros Menna (drill hole nos. 1–3 and I–III) showed that the complex anomaly pattern in this area is due to a number of thin, essentially massive pyrrhotitic units of variable chalcopyrite grades. Graphite-bearing rocks were not encountered. The thicknesses of the different sulphide zones range from only a few millimetres up to a very local maximum of about 85 cm in drill hole no. 1, but they are usually about 2–10 cm thick. In drill hole no. 3, for instance, three pyrrhotitic zones occur at 6.36, 6.8, and 7.27 m depths. They are respectively 8, 2 and 36 cm thick. An additional two bands, 2 and 0.5 cm thick, were traversed between 37.14–37.19 m depth (cross-section in Fig. 7).
Conditions in the Kjøli–Midtgruben area (Fig. 8) are quite comparable with those in the Menna area. The comparatively large pyritic lenses at the Kjøli Mine quickly thin out towards the periphery of the old workings – as inferred from the old drilling nos. I–VI (Aasgaard 1927: 119). Drill hole nos. 1–3, performed by Killingdal Grubeselskap in 1965, did not penetrate the ore zone.

Reconnaissance drillings at the north-eastern edge of the wide EM-anomaly orientated towards Midtgruben, cut across several parallel zones dominated by pyrrhotite–chalcopyrite impregnations ranging from about 2–25 cm in thickness. In addition, 10 cm of massive pyrite occurs in drill hole no. 3. One of the two drill holes just to the north of Midtgruben (Aasgaard 1927: 135) pierced two 15 cm thick pyritic bands in the space between the two anomaly zones (cross-section in Fig. 8). It thus appears that more or less continuous sulphide mineralizations occur from the Midtgruben prospects towards the Kjøli Mine. The gap in the EM-anomaly closer to the old workings at Kjøli, does not necessarily imply that the sulphide zones are absent; they may be more dispersed. The helicopter-borne magnetic and electro-magnetic measurements indicate elongated mineralized zones further to the south-west of the Kjøli Mine, which may join the anomaly zones in the Menna area.

In the Grønskar area (Fig. 9 A), numerous mineralizations involving both the Grønskar and Flogruben mines have been tested along a main sulphide horizon. In addition there are three or four less distinct, parallel zones, which in part are characterized by abundant magnetite.

To the west of the Menna area the Røsjø Formation disappears below the Tydal Thrust. Detailed mapping, however, has clearly shown that the same strata reappear above the thrust plane to the south-west of Killingdal (Fig. 1). From here the Røsjø Formation continues southwards into one of the most productive mining areas in the Røros district. It comprises the old Mugg, Sextus, Fjellsjø, and Kongen mines, and also the recently developed Lergruvbakken Mine (Rui 1974: 709).

Summary and conclusions

It has been shown that the abundant sulphide mineralizations in the Kjøli area are largely related to the Røsjø Formation, as are also the important mineralizations in the Kongen–Mugg area further south. The Røsjø Formation is thus one of the most important ore-bearing units in the entire Røros district. The other important mineralized unit is the volcanogenic Hersjø Formation, which contains three relatively large deposits (Killingdal, Hersjø, and Rødhammeren) and several small ones (Fig. 1). Important exceptions to these two ore associations are the major deposits at Olav and Storwartz, which occur in the Røros Formation to the north-east of Røros.

The sulphides in the Kjøli area are frequently developed as thin, apparently largely concordant, sheets, which often occur on several different
levels. The enclosing Røsjø Formation consists of banded meta-argillites and more massive meta-greywackes. These rocks are in part characterized by thin green layers of probable volcanogenic origin. They might be of pyroclastic origin, but might equally well represent volcanoclastic sediments, thus not being indicative of contemporaneous volcanicity.

The mode of occurrence of the sulphides and the finely laminated nature of the associated magnetite where this is developed locally, indicate that they were precipitated on the sea-floor during the deposition of the Røsjø Formation.

Sulphide–graphite schists indicative of stagnant waters and reducing conditions have not been recorded. Neither are there any clear relationships between the ores and the thin green banded units, which might have favoured an exhalative sedimentary origin in the sense of Ofteadal (1958). The common occurrence of the ores in greywacke type sediments, however, indicates changing conditions and rather rapid sulphide-oxide precipitation.

Studies of naturally and artificially deformed sulphide ores indicate that some sulphides like pyrrhotite, sphalerite, chalcopyrite, and galena are remarkably weak and extremely ductile compared to the common rock forming minerals. Clark & Kelly (1973) showed that the transition from brittle to plastic behaviour of pyrrhotite and sphalerite takes place far below the P–T field of regional greenschist facies metamorphism. They emphasized that the field of brittle behaviour of these minerals may be even more restricted in natural systems where extremely slow strain rates and the presence of fluid phases have to be taken into consideration.

It is therefore likely that mobilization of primary sulphide phases in the presence of metamorphic fluids takes place to varying extents during metamorphism and folding, depending on the intensity of these events. Metamorphic mobilization might therefore have been responsible for local discordant relationships between the massive sulphides and the wall rocks as was reported by Aasgaard (1927). In one instance such a discordance was also clearly recognized in a drill-core from the Menna area, where pyrrhotite and chalcopyrite had been injected along a fault plane. The ‘durchbewegte’ brecciated structure of the pyrrhotitic orebodies may similarly be explained as mobilized portions of thin, closely spaced sulphide- and silicate-rich bands. The silicate bands were torn apart by the moving sulphides, twisted and finally moulded in the massive ores.

Metamorphic mobilization may thus be the prime cause of local thickening of the sulphides, which in turn would impoverish the primary thinner sulphide mineralizations. This is indicated by the electro-magnetic measurements and the diamond drillings, which show that the thicker sulphide lenses of the area are of limited extension and usually isolated from nearby much wider, but thinner mineralizations, e.g. particularly well demonstrated at the Kjøli Mine but also in the Menna area (Figs. 7 and 8).

Lateral metamorphic mobilization and concentration of the sulphides would most likely happen where the beds of the Røsjø Formation have been
subjected to more pronounced flexuring as for instance in the Menna–Guldal area and at the Kjøli Mine. Accompanying metamorphic fluids could have caused chloritization (± sericitization) of the immediate wall rocks.

In other more intensely deformed parts of the Røros district there are many examples of close relationships between the geometry and location of sulphide deposits and fold structures. This is clearly demonstrated in the descriptions of the Killingdal and Røstvangen mines (Rui 1973). Thus, although the stratabound character of the mineralizations is apparent and their genesis during accumulation of the volcano-sedimentary sequence is probable, the formation of orebodies appears to be related to secondary thickening of the sulphides during orogeny.

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