SULPHIDE MINERALIZATION AND WALL ROCK ALTERATION AT RØDHAMMEREN MINE, SØR-TRØNDELAG, NORWAY*

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The present paper deals with the geological setting and the petrology of the wall rocks and ores at Rødhammeren pyrite deposit, Haltdalen, Sør-Trøndelag. The sulphide mineralization has taken place in the southern part of a narrow zone of sillimanite-bearing biotite schists, near the border of enclosing metavolcanics (amphibolites and quartz keratophyres). There are two principal ore bodies: a lens-shaped upper pyrite body and a lower, irregular and veined pyrrhotite-chalcopyrite body. The wall rocks are affected by a Mg metasomatism which has transformed the biotite schists into cordierite-bearing anthophyllite-gedrite rocks and the quartz keratophyres into cordierite quartzites. An epigenetic origin is suggested and the deposit is classified as being of the 'Falu type'.

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Introduction

The Rødhammeren mine is situated in the Haltdalen district in the eastern part of Sør-Trøndelag, Norway. (Latitude 62°56'N, longitude 11°25'W.) The mine is part of a belt of sulphide deposits in the eastern Trondheim region, running in a NNE–SSW direction from Folldal in the south, through the Røros district, to Meraker in the north, and having an extension of about 220 km (Fig. 1).

Most of the sulphide deposits in the Haltdalen area were found late in the 18th century, and the mining operations flourished in the first part of the 19th century. However, the output from the numerous mines and prospects is negligible when compared with those in the Røros district. At the end of the 19th century the mines in the area were abandoned.

Rødhammeren mine was the biggest in the Haltdalen district. Rødhammeren mountain consists of three small knolls lying about 1000 m above sea level between the mountains Trælsåfjell and Skjelåfjell, just above the timber line. The deposit is on the eastern slope towards the river Skjelåen (Figs. 2 and 4).

The deposit was found in 1774, and mining operations took place with several interruptions until the beginning of the 20th century. Thorough exploration and diamond drilling were undertaken as early as 1917, and in

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later years extensive geological and geophysical investigations have taken place. Today the workings are completely flooded, and any further examination of the ore bodies would be difficult. However, available drill cores and good exposures around the mine made the geological setting clear.

Previous work

Geologically, the Haltdalen district lies in the eastern part of the Trondheim region. A review of the geological investigations made previous to the last decade in this part of the Norwegian Caledonides was published by Wolff (1967).

The first detailed geological description of the Haltdalen area was given by Hørbye (1861). Aasgaard (1927) made a survey of the geology between Haltdalen and Meraker together with a description of the mines and prospects. Vogt (1940) gave a detailed description of the fossiliferous black shale locality at Nordaunevoll, and accompanied it with a geological map of the Haltdalen area. In the later years Kisch (1962) gave an exhaustive petrographical description of the Tydal district, just north of the area investigated. Towards the end of the decade, the areas south and southeast of the Haltdalen district were mapped and described by students from the University of Oslo. The main tectonics and stratigraphy are being published by Rui (pers. comm.).

A detailed survey of the mines and prospects in the Haltdalen district, including the Rødhammeren mine, was given by Aasgaard (1927). Here the outline of the ore and the wall rocks was given, based upon the diamond drillings done in 1917. In his monograph, Carstens (1920) gives a brief survey of the deposit which becomes the mother locality of the 'Rødhammer type' in his classification scheme of the Caledonian sulphide deposits. The mine is mentioned by Foslie (1926) also in his survey of the Norwegian pyrite deposits and in an unpublished thesis from Norges Tekniske Høgskole, Trondheim (Steenstrup 1946).

General geology

The bedrock in the Haltdalen district belongs to the older Cambro-silurian beds of the Trondheim region. The following rock units can be separated, and fit well within the lower parts of the stratigraphical column proposed by Wolff (1967):

Lower Ordovician	Støren group	Metavolcanics
Cambrian	Gula-schist-group	Black shale (2eα) Polygenous quartz conglomerate Crystalline limestone Pelitic schists

Acidic and basic plutonic rocks have intersected the sediments and volcanics at a later stage, and will be mentioned briefly after the following descriptions of the groups.

GULA-SCHIST GROUP

This unit comprises the metasediments of non-volcanic origin in the area, and includes mainly pelitic schists with intercalations of black schists, a conglomerate horizon and a marble horizon.

In the area west of Trælsåfjell mountain the pelitic schists are kyanite- and/or staurolite-bearing garnet-biotite-quartz schists. Staurolite and kyanite often occur as small knots or pods in a fine-grained groundmass of quartz, biotite and plagioclase. Varieties of this rock were suitable for millstones, and quarrying in a large scale took place in the Selbu district in the last century.

East of the central gabbro complex a metamorphic zoning of the metasediments has taken place. A contact zone of sillimanite-bearing hornfelses encloses the eastern margin of the body. Further to the east a belt of andalusite-bearing biotite schists runs in a NNE–SSW direction. Around Veunsjøen lake the schists are finer grained and chlorite-bearing, and at Kjøliskarvene transitions to weakly metamorphosed sandstones occur.

In the west the schists are folded together with the metavolcanics and form and antiform with a N-S axis plunging gently to the south.

A polygenous quartz conglomerate is intercalated within the kyanite-bearing mica schists in the west. The conglomerate, known as the 'Bukkhammer conglomerate', is a southern extension of the Gudå conglomerate zone in the Meraker district (Wolff 1964, 1967).

A crystalline limestone horizon, the Bukkhammer limestone, accompanies the conglomerate horizon.

Black schists occur now and then as thin intercalations within the mica schists. They occur very frequently near the border between the metasediments of non-volcanic origin and the metavolcanics. At Nordaunevoll a fossiliferous black shale containing undeformed specimens of *Dictyonema flabelliforme* was found by J. H. L. Vogt in 1888, and the locality was described by Th. Vogt in 1940. It represents the oldest fossiliferous horizon known from the Trondheim region, and dates the boundary between the Cambrian Gula-schist group and the overlying volcanic formation to the base of Ordovician (2eα) (Størmer 1940). Usually the bituminous metasediments are developed as sulphide-bearing graphite-sericite schists.

STØREN GROUP

Metavolcanics can be traced for hundreds of kilometres in the eastern part of the Trondheim region (Fig. 1). They overlie the Gula-schist group, and can be correlated with the Støren group of lower Ordovician age (Wolff 1964, 1967). In the Haltdalen area the metavolcanics as well as the metasediments of non-volcanic origin appear in a higher metamorphic grade compared to the regions north and south of the area.

The metavolcanics in the area include more or less schistose oligoclase/andesine amphibolites with some intercalations of quartz keratophyre. The amphibolites consist of plagioclase (usually an oligoclase or an andesine) and a bluish green hornblende in roughly equal amounts. Quartz, biotite, chlorite and ore occur in minor amounts.

The quartz keratophyres occur as 0.5–5 m thick layers, conformably intercalated with the amphibolites. They are well exposed on Trælsåfjell mountain west of Rødhammeren mine (Fig. 3).

Their mineralogical composition varies. Quartz and albite constitute 70–90% of the volume, and garnet, biotite, muscovite, hornblende, staurolite,

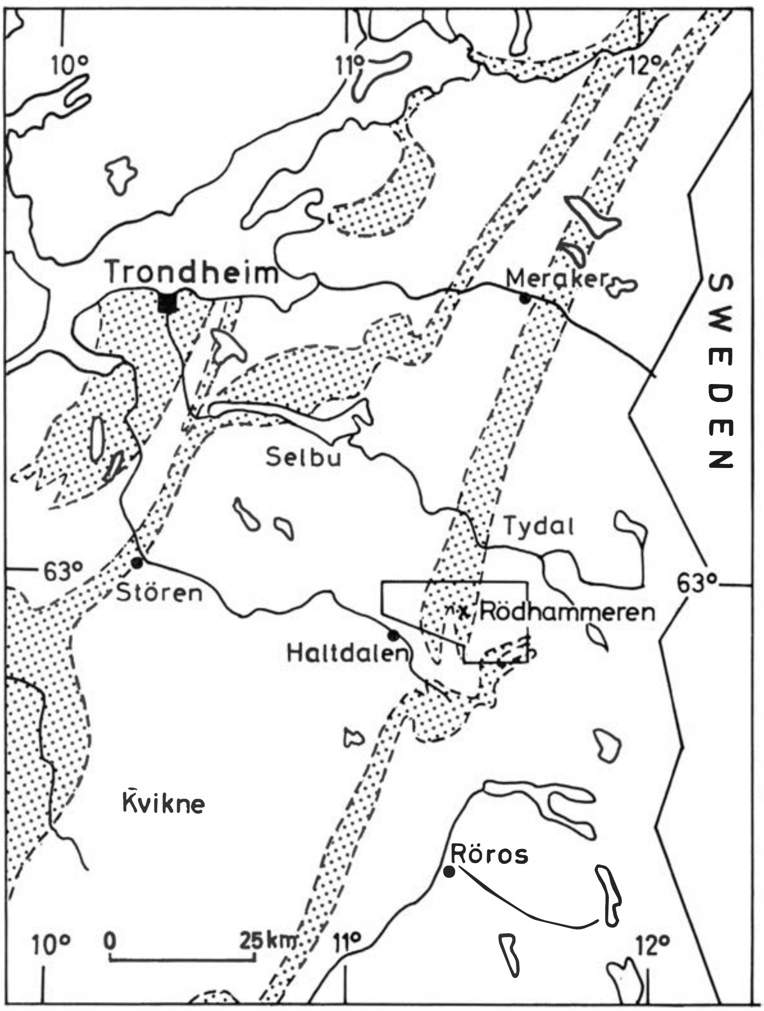

Fig. 1. Key map indicating the investigated area within the Trondheim region. Grey: The metavolcanics of lower Ordovician age (Støren group).

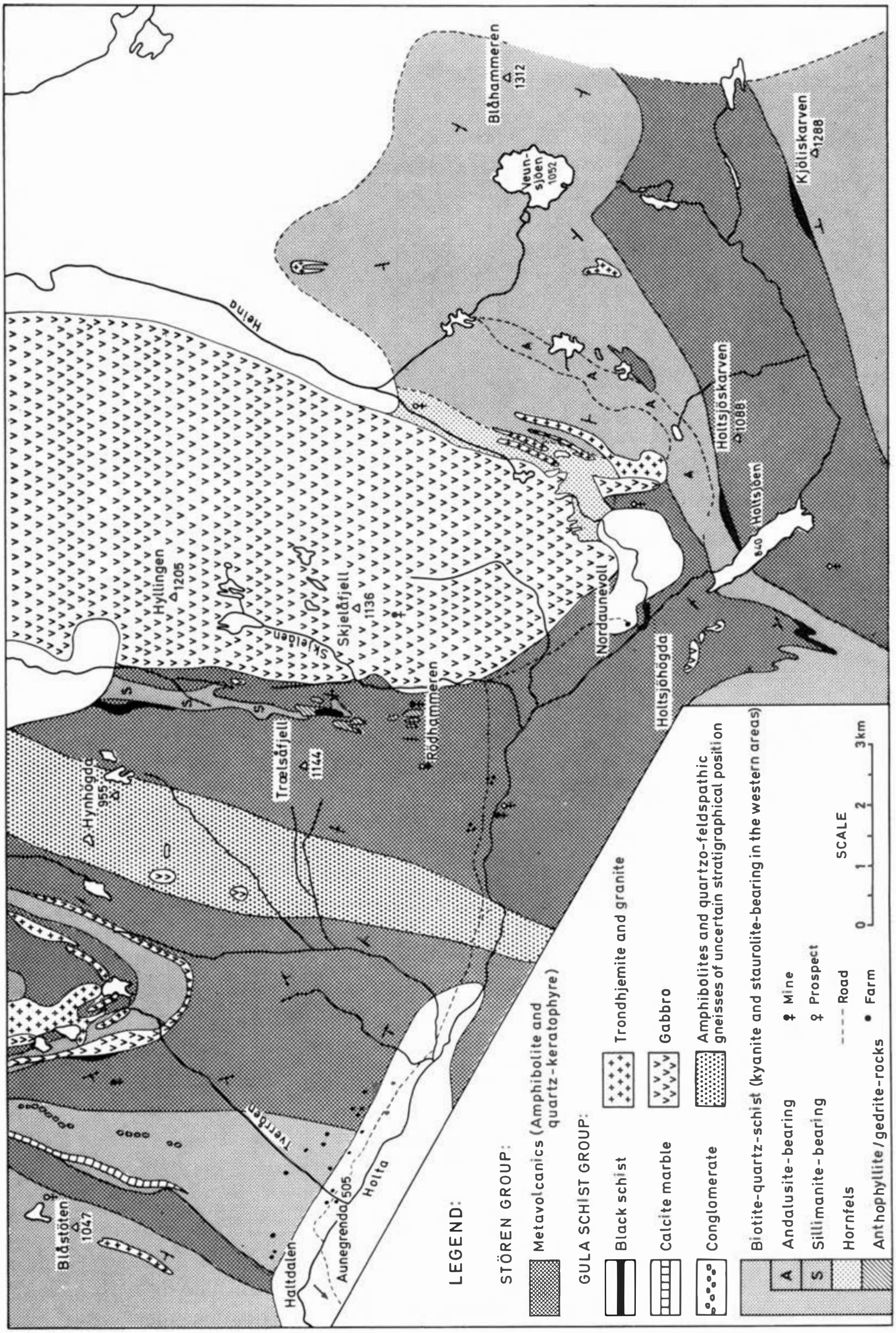

Fig. 2. Geological map of the Haltdalen-Kjøli area.

Fig. 3. Layers of quartz-keratophyre alternating with massive amphibolites and porphyrites at the mountain Trælsåfjell, west of Rødhammeren.

zircon and apatite occur in minor amounts. A single keratophyre layer can be followed for only 10–50 m along the strike before it wedges out.

INTRUSIVES

A gabbro complex ('Hyllingen gabbro complex') forms a central part of the area. The complex is the southern part of the larger Fongen gabbro massif, which extends about 40 km northward from the Haltdalen district. The Hyllingen gabbro complex is a plate-formed body with conformable boundaries to the metamorphic rocks. It shows different stages of differentiation, from basic and ultrabasic rocks (olivine gabbros and peridotites) to diorites and monzonites.

The gabbro complex is accompanied by swarms of porphyritic amphibolites of hypabyssal origin, especially near its western border. The porphyrites intersect the gabbro complex, and a genetic relationship is suggested.

The porphyrites often grade into equigranular amphibolites when thinning out, and are difficult to distinguish from the less schistose metavolcanics in the Trælsåfjell-Rødhammeren district.

The porphyrites contain plagioclase, a greenish grey amphibole and clinozoisite as major constituents. Plagioclase occurs as phenocrysts, some mm across, and very often shows zoning.

As can be seen from the map (Fig. 2), acidic plutonic rocks are concentrated near the core of the western antiform and as an eastern border facies of the Hyllingen gabbro complex. In the western antiform they include massive bodies of equigranular, medium-grained quartz diorites (trondhjemites) and granites. Their porphyritic equivalents occur as sills within the pelitic schists.

The acidic plutonic rocks on the eastern side of the Hyllingen gabbro complex are monzonites, grading into granites to the east. They have a definite genetic relationship to the complex, and it is suggested that they are the end product of the differentiation of the gabbro complex.

The ore deposit

GEOLOGICAL SETTING

As seen from the map (Fig. 2) the Rødhammeren sulphide deposit lies within the metavolcanics near the southern tip of a wedge of sillimanite-bearing biotite schists. The rocks are intensively folded, and the metamorphic grade in this zone is high close to the gabbro. The presence of black schists as intercalations between the metavolcanics and the pelitic schists

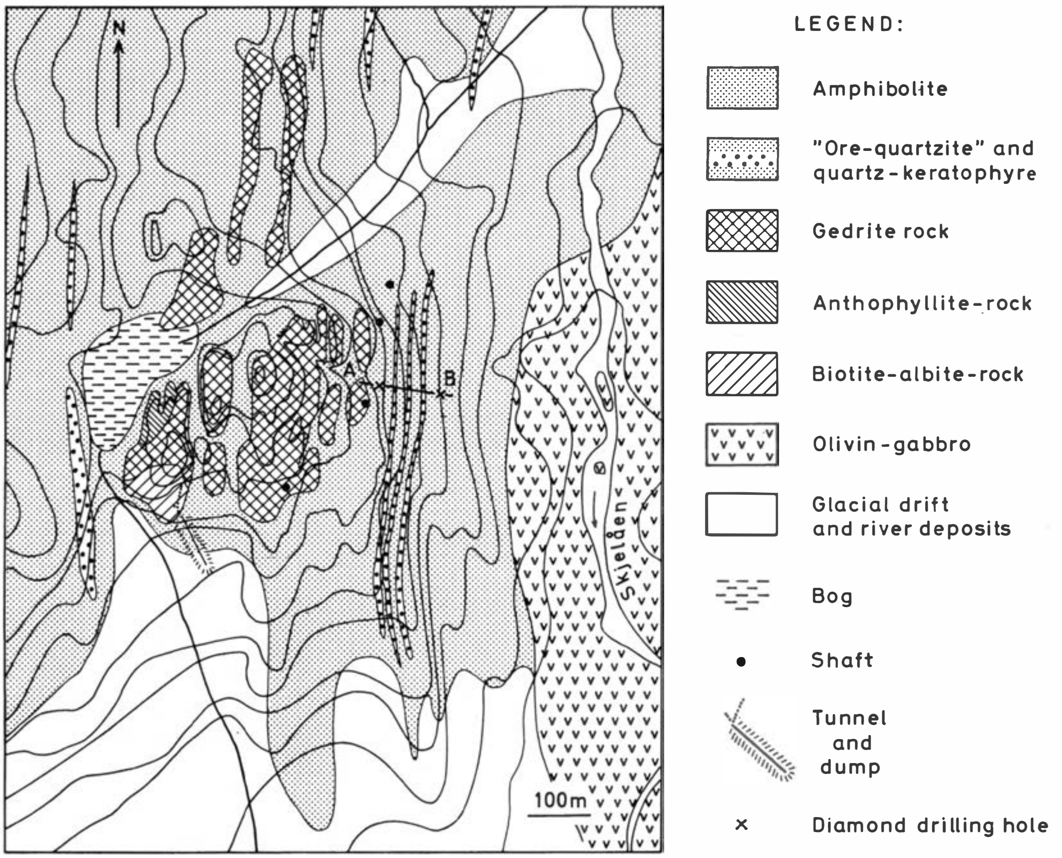

Fig. 4. Geological map of the Rødhammeren area. The line A–B indicates the vertical section between diamond drilling holes 14 and 13 respectively, as shown in Fig. 5. Contour interval: 5.5 m.

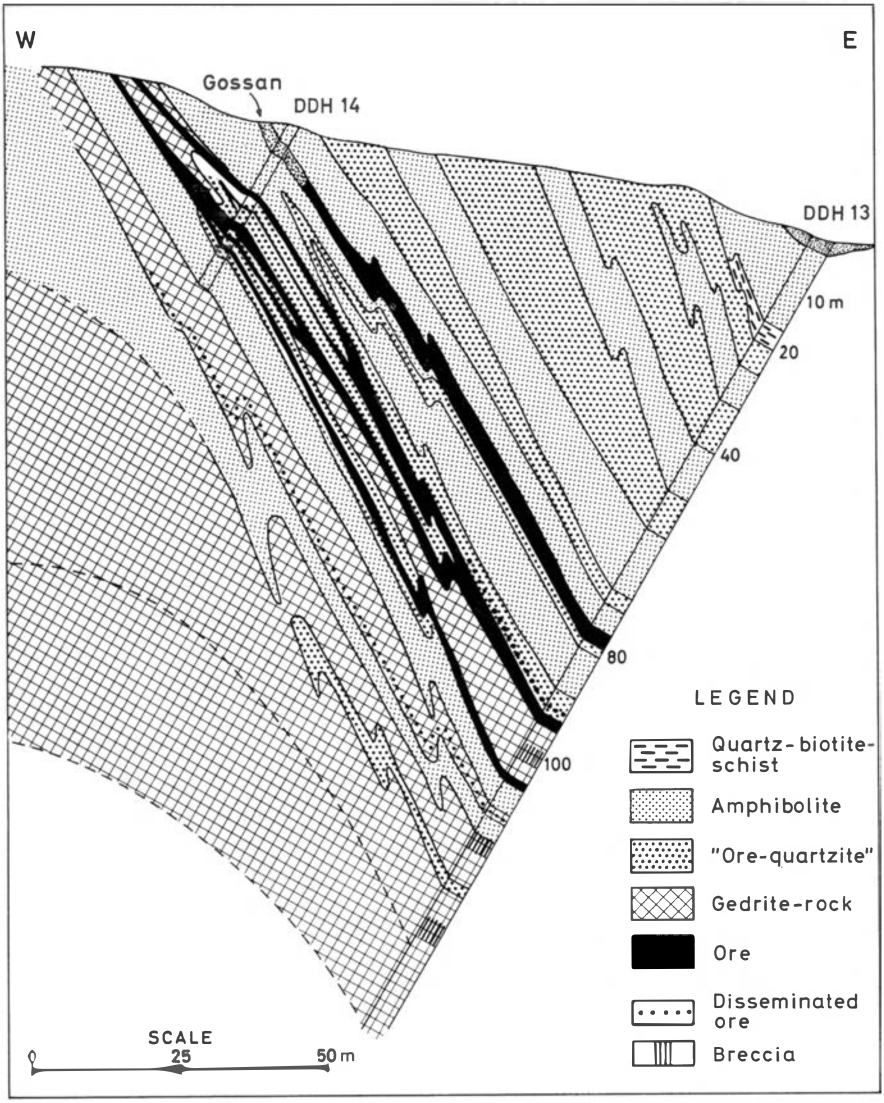

Fig. 5. Vertical section (schematic) through the Rødhammeren deposit along the line A–B indicated on Fig. 4.

points to the fact that the sillimanite-bearing zone must be a down-folded part of the Gula schists in the west.

To the south the zone of sillimanite schists wedges out, and small, isolated ridges and knolls consisting of massive gedrite rocks seem to represent the southern continuation.

The sulphide mineralization in Rødhammeren mine has taken place at the border between a ridge of gedrite rocks and the enclosing metavolcanics (Figs. 4 and 5). In the following sections the ore and the different types of wall rocks will be described.

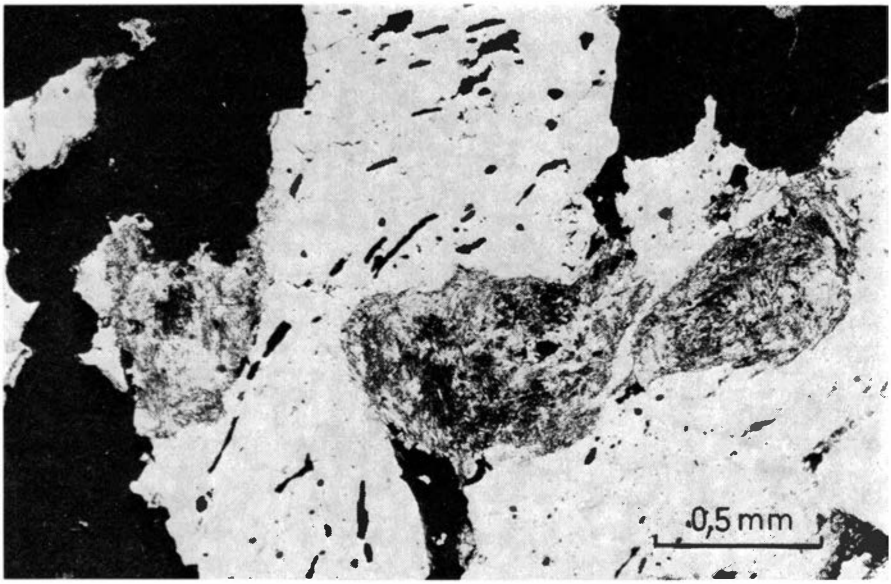

Fig. 6. Pinite-globules (grey) and ore (black) in a fine-grained ground-mass of quartz. From the upper ore-body, Rødhammeren mine. Plane polarized light.

THE ORES

Diamond drilling operations in 1917 and 1954–1956 revealed two main ore bodies in Rødhammeren: (1) An upper pyritic ore body associated with the metavolcanics; and (2) a lower chalcopyritic ore body associated with the gedrite rocks.

The upper pyritic ore body. The upper pyritic ore body is a regular, elongated plate or lens, lying apparently concordant with the more or less schistose country rocks (i.e. strike: north-south, dip: 60–80°E). It has an average thickness of 3.5 m, and can be traced for about 300 m in the strike direction.

Pyrite is the dominant ore mineral, and occurs as rounded single grains, 0.5–2 mm across, and as small irregular aggregates evenly distributed in a groundmass of quartz and fine-grained aggregates of micaceous minerals (pinite) (Fig. 6).

Pyrrhotite and chalcopyrite are accessory constituents and occur usually in cracks or in between the pyrite individuals in the aggregates. The pyrite often shows cracks filled with the gangue minerals.

No banding or other depositional features can be seen in the ore mined out. However, a closer look at a larger section of the ore in the mine would probably reveal textures valuable in the interpretation of the nature of the ore.

The copper content in the ore is low (0.1–0.5% Cu), while the sulphur content is about 35%.

Fig. 7. An outcrop of the upper ore-body at Rødhammeren. A white, spongy skeleton is developed and the ore minerals are weathered out.

The outcrops of the upper ore body are exposed mainly in trenches, excavations and around the shafts. The rust zone has a characteristic appearance. At the surface it appears as a white, sponge-like skeleton of quartz (Fig. 7). Here the single pyrite grains are completely weathered out, but in the deeper trenches the ore zone appears as an ordinary gossan – the pore holes partly filled with iron oxides and some pyrite.

Similar leached oxidation zones have been reported from a few Norwegian sulphide deposits. They are known from Skorovass mine in Grong, N. Trøndelag and from Bjørkåsen mine in Ofoten, Nordland (Bjørlykke 1960) and from Båsmo and Bleikvassli mines, Nordland (Vokes 1963). At Rødhammeren mine the oxidation zone is 5–10 m thick.

The lower chalcopyritic ore body. The lower ore body (or bodies) is comprised of a network of thin, irregular layers lying within the gedrite rocks, close to the metavolcanics in the east. Contrary to the upper ore body, the lenses and layers of the lower body very often show a tendency to branch and split. The ore often cuts across the main foliation in the area. The thickness of the single layers or lenses has a range of a few cm to about 4 m. The ore zone as a whole is about 20 m thick.

The ore has a high Cu content compared with the upper ore body, and has a lower sulphur content (0.5–1.5% Cu; 20–30% S).

The ore consists of chalcopyrite, pyrrhotite and pyrite in a medium-grained, brownish-grey gedrite rock. Magnetite, ilmenite and hematite occur as minor ore constituents. The sulphide aggregates replace the gedrite rock, and polished sections reveal that the single ore minerals often replace the gangue minerals along cracks and crystal faces.

Chalcopyrite and pyrrhotite are the dominant ore minerals in the lower body, and occur usually in intimate intergrowths as irregular 'clouds', often enclosing pyrite and oxide ore. In some outcrops pyrrhotite is the only sulphide ore. Pyrite occurs as small, single euhedral cubes or as resorbed anhedral individuals, enclosed by pyrrhotite and chalcopyrite.

Ilmenite and magnetite occur in minor amounts (2–3 vol. %), and are evenly distributed in the ore. Ilmenite – the dominant oxide ore – often shows exsolutions of hematite in the form of parallel oriented strings or elongated blebs.

The oxide ore minerals are apparently older than the sulphides which usually enclose the oxides forming a typical 'caries' texture.

THE WALL ROCKS

As stated earlier, a thorough study of the ore and wall rocks at Rødhammeren mine is unfortunately difficult due to the works being water-filled, and also to the small number of drill cores available. However, samples from the surface and from the drill cores provide material that gives a general view of the environment of the ore.

The following rock types accompany the ore, and will be treated separately:

Sillimanite-biotite schist
Amphibolite
Ore quartzite
Gedrite/anthophyllite rocks
Phlogopite-albite rocks with pegmatite

Sillimanite-biotite schist. The southern continuation of the narrow, N-S running zone of sillimanite-bearing Gula schists north of the mine is only observed in the drill cores as a few, thin, lenticular layers or bands. As wall rocks of the ores they play a minor role. However, their connection with the ore deposit is so close that their petrography is worth mentioning.

The rocks north of the deposit usually appear as massive resistant rocks of a greyish brown colour. At some places a poor schistosity is developed. A conspicuous feature is the large porphyroblasts of prismatic sillimanite. The mineral does not show any preferred orientation, and occurs as prisms 1–3 cm in length and 3–4 mm across. On a weathered surface the prisms stand out owing to their great resistance to weathering (Fig. 8). The grain boundaries are generally sericitized.

In addition, sillimanite occurs as fibrolitic aggregates, formed largely at the expense of biotite (Fig. 9). A similar occurrence of sillimanite within the Gula schists has been reported from the Gudå area, 55 km NNE of the area investigated (Roberts 1968).

Generally the groundmass of the sillimanite-biotite schists has a granoblastic texture. It is composed mainly of quartz, plagioclase, biotite and muscovite. Kyanite and/or staurolite occur sparsely and in minor quantities, and apatite, tourmaline, zircon, ilmenite, magnetite and graphite occur as accessory constituents.

Plagioclase and quartz constitute about 40–50 vol. % of the rock, and occur as an allotriomorphic mosaic with a grain size of 0.1–1 mm. The plagioclase, usually an andesine, often shows a diffuse zoning. A core with composition An_{41-46} and a rim with composition An_{28-31} are commonly observed.

A reddish-brown biotite occurs as small, poorly oriented flakes, about 0.5 mm in length. Usually the rims are converted into tassels of fibrolite (Fig. 9).

White mica occurs as poikiloblastic porphyroblasts without any preferred orientation. Thin needles of sillimanite and thin flakes of biotite are often enclosed within the mica, oriented parallel to (001) of the mineral.

The oxide ore occurs as single, rounded grains and as irregular, fine-grained aggregates within the clusters of fibrolite. Their formation may have been due to the breakdown of biotite. Flaky ilmenite and graphite are often interbedded parallel to the (001) of the biotite.

Kyanite occurs now and then as homoaxial intergrowths with sillimanite.

Fig. 8. Porphyroblasts of prismatic sillimanite. From sillimanite-biotite schists, north of Rødhammeren.

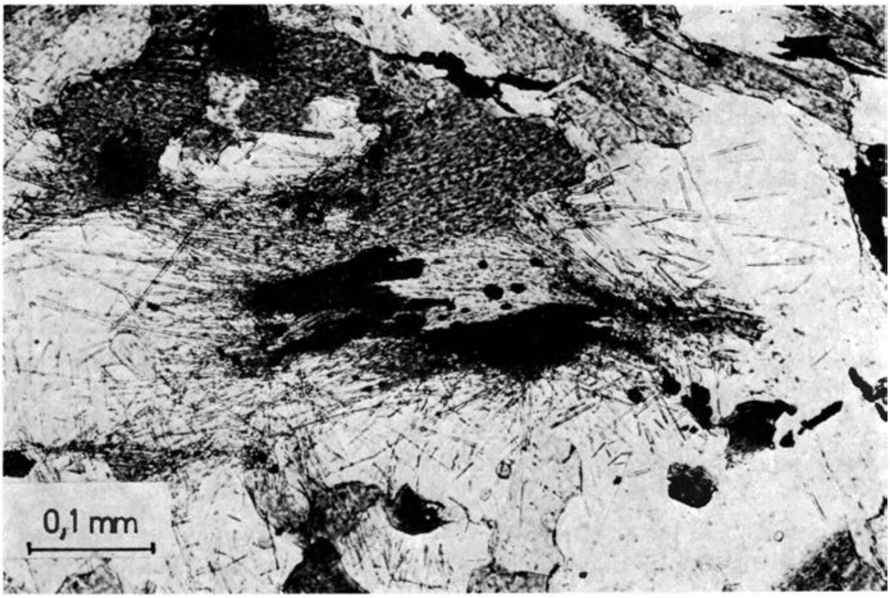

Fig. 9. Fibrolite and iron-ore formed at the expense of biotite (upper left). From sillimanite-biotite schist north of Rødhammeren. Plane polarized light.

Amphibolite. Equigranular and porphyritic amphibolites (porphyrites) are the common wall rocks of the upper ore body. Amphibolites are not as frequent as wall rocks of the lower ore body. As stated earlier, the distinction between the intrusive nature of the porphyritic amphibolites and the effusive nature of the equigranular amphibolites is masked in the area due to folding and metamorphism.

The amphibolites have developed a very weak foliation; usually they occur as massive, fine-grained rocks of a greyish-green colour, alternating with thin, N-S running layers of ore quartzite.

The mineralogy of the amphibolites does not differ much from that of the other amphibolites of the area, and shows the least sign of alteration in connection with the sulphide mineralization.

Plagioclase and olive-green hornblende are the major constituents and occur in equal proportions. Biotite, ore, apatite, sphene and quartz are accessories.

Plagioclase attains a grain size of 1 cm in the porphyritic varieties, but usually the grain size is 0.1–0.3 mm. The An content varies between An_{35}–An_{60}. The phenocrysts in the porphyrites show a marked zoning. A phenocryst from a porphyrite from the south side of Rødhammeren shows a core with composition An_{55} and a rim of An_{35}. Usually the phenocrysts of the porphyritic amphibolites have a higher An content than the equigranular plagioclase. The An content of the phenocrysts is usually higher than that of the plagioclase in the groundmass. The phenocrysts are usually sericitized or saussuritized.

Olive-green hornblende occurs as ± 0.2 mm long prisms and does not show any pronounced preferred orientation. Outside the mine area (e.g. 3 km north of the mine) cummingtonite-bearing amphibolites are observed. The Ca-poor amphibole can be seen in homoaxial intergrowths with the green hornblende (Fig. 10). Otherwise the mineralogy does not differ from that of the normal amphibolites in the area. The cummingtonite-bearing amphibolites cannot be distinguished from the normal ones in the field, but they seem to be connected to the zone of metavolcanics running parallel to the sillimanite schists. Thus they have been recorded by Kisch (1962) from Hynhøgda to Hilmo in Tydal (pp. 36 ff.). Outside this amphibolite zone, cummingtonite-bearing varieties of the amphibolites have not been observed by the present writer. The presence of cummingtonite as reaction rims around hornblende in some of the amphibolites in this zone seems to be the only sign of a possible hydrothermal alteration of these rocks.

Ore quartzite. At the eastern slope of Rødhammeren layers of a fine-grained, quartzitic rock 1–5 m thick are intercalated within the amphibolites. In hand specimen the rock resembles the ordinary quartz keratophyres in the area, but their petrography differs in many respects from ordinary acid metavolcanics.

The rocks are related to the immediate vicinity of the ore bodies, and occur as wall rocks of the upper ore body at Rødhammeren. Thus the term 'ore quartzite' is proposed in order to distinguish them from the ordinary quartz keratophyres in the area.

They are fine-grained rocks with a granular texture and have a greyish-white colour which can vary according to the presence of minor minerals such as biotite and ore.

Quartz and cordierite occupy 70–80 % vol. of the rock. White mica, phlogopite, chlorite and ore occur as minor constituents, and plagioclase, gedrite, sillimanite (fibrolite), staurolite, zircon and kyanite are accessory minerals.

Quartz and cordierite occur as interlobate intergrowths with an even grain size of 0.5–2 mm. Usually the cordierite is altered to a felty mass of yellowish or light brownish flaky minerals, known as pinite (or falunite). They form globular aggregates in which the minerals display a radiating texture. The globules have sharp boundaries to the enclosing quartz grains which may reflect the original shape of the cordierite individuals (Fig. 6).

The alumina silicates occur in varying amounts, and always in small aggregates, the sillimanite as tassel-formed aggregates (fibrolite) and the kyanite as clusters of small sericitized prisms.

In some ore quartzites phlogopite and colourless mica occur as scattered flakes, 0.5–3 mm in length without any preferred orientation. Plagioclase occurs as an accessory constituent ($<$ 1 vol. %) and has a cloudy appearance.

The opaque ore consists of pyrrhotite, pyrite, magnetite and chalcopyrite as small (± 0.3 mm) anhedral individuals. In the impregnated zones pyrite

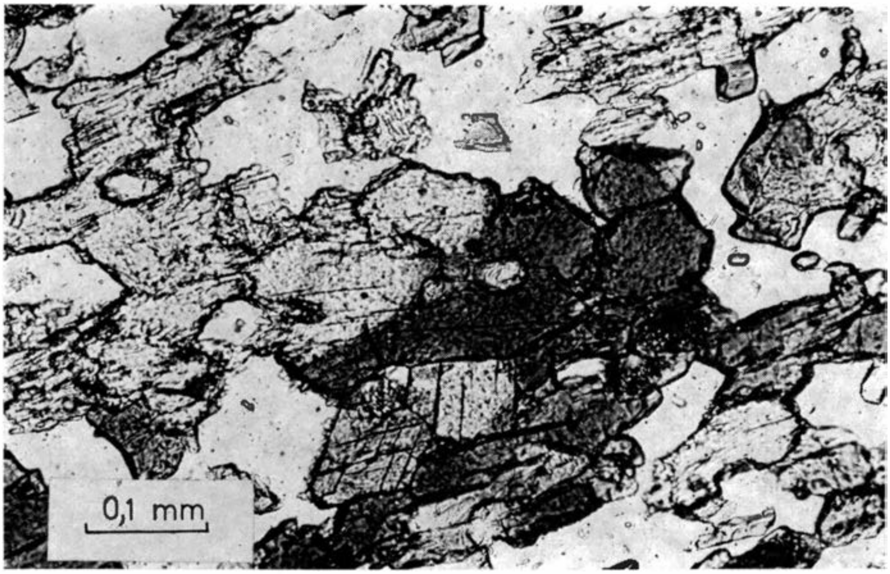

Fig. 10. Homoaxial intergrowths of cummingtonite (light grey) and hornblende (dark grey) from cummingtonite-bearing amphibolite north of Rødhammeren. Plane polarized light.

occurs in greater quantities, and in the upper ore body pyrite makes up over 50% volume of the rock.

Gedrite/anthophyllite rocks. The most conspicuous rocks in the Rødhammeren area are the resistant gedrite/anthophyllite-bearing rocks. They form the three elongated intrusive-like knolls which have resisted erosion more than the enclosing metavolcanics. The rocks are massive, medium-grained and have a brownish-grey colour.

On the western ridge at Rødhammeren a yellowish-grey, monomineralic anthophyllite rock has developed. Here anthophyllite occurs as fan-shaped clusters, the single anthophyllite needles attaining a length of from 2–3 cm.

The two eastern ridges consist of more fine-grained, darker gedrite rocks. Near the eastern border, the gedrite rocks become brecciated, and chlorite and garnet replace the rhombic amphibole in many places. Here an enrichment of chalcopyrite and pyrrhotite has taken place, forming the lower ore body at Rødhammeren.

Rhombic amphibole constitutes more than 50% volume in these rocks. Quartz, cordierite, kyanite, garnet, staurolite and chlorite occur in varying amounts. Zircon, phlogopite, plagioclase and ore occur as accessory constituents.

The rhombic amphibole is usually a gedrite. The refractive indices indicate iron-rich varieties (40–53 mol. % Fe gedrite). The gedrite usually occurs as radiating fan-shaped clusters and rosettes up to 5 mm in diameter (Fig.

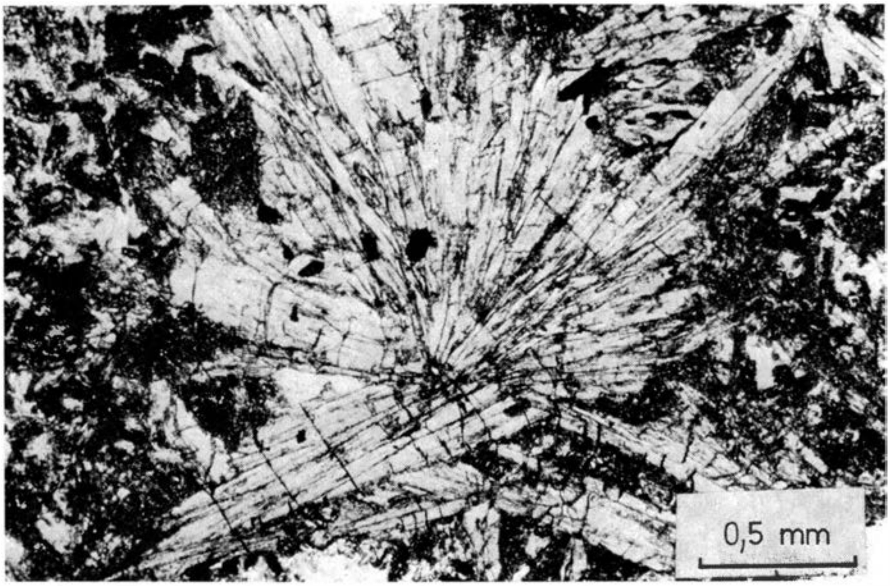

Fig. 11. A rosette of gedrite within a groundmass of quartz and heavy sericitized clusters of fine-grained kyanite. From DDH13/160 m, Rødhammeren. Plane polarized light.

11). No preferred orientation of the amphibole needles can be seen; the rock therefore has a massive, intrusive-like appearance.

Cordierite and quartz occur as a granular groundmass within and around the amphibole aggregates. Anhedral, small (± 0.2 mm) prisms of kyanite occur in small clusters, usually within a felty mass of chlorite and/or sericite. Staurolite occurs as an accessory constituent in some of the gedrite rocks, forming anhedral prisms up to 1 mm in length. The mineral is always heavily replaced by chlorite (clinochlore).

A reddish-brown garnet occurs in some places in great quantities, especially near the eastern border of the gedrite rock massif. It has a poikilitic texture, and is usually smeared out as elongated, anhedral individuals with ragged outlines, within a fine-grained matrix of quartz. This textural feature, together with the frequent occurrence of rounded and elongated aggregates of quartz and cordierite, points to strong deformational events in the ore-bearing border zone of the gedrite rock complex.

As mentioned earlier, the sulphides of the lower ore body often replace the gangue minerals along cracks and crystal faces; the deposition of the lower ore body therefore seems to be later than the formation of the gangue.

Phlogopite-albite rocks with pegmatite. The gedrite/anthophyllite rocks in the western ridge grade into fine-grained, massive feldspathic rocks to the south. They are well exposed in a tunnel running about 140 m in a NNE direction from the southern tip of the ridge.

The rocks are chiefly composed of plagioclase, quartz and phlogopite. Kyanite, sillimanite and colourless mica occur as minor constituents.

The plagioclase is an albite with composition between An_{06} and An_{09}. The plagioclase and quartz form a granular, saccaroidal texture, and the grain size is between 0.2 and 2 mm.

Phlogopite and white mica occur as small (± 0.5 mm) flakes without any preferred orientation. Kyanite and sillimanite (fibrolite) occur together with a felty mass of chlorite in small aggregates with a rectangular outline. The alumina silicates occur in intimate, homoaxial intergrowths. The rectangular outline of the aggregates possibly reflects the idiomorphic crystal habit of former prismatic sillimanite porphyroblasts.

A muscovite-albite pegmatite-veinlet was found in the tunnel, running in a NW-SE direction through the phlogopite-albite-rock. The veinlet runs across the main tectonic lines of the area, and is suggested to be of a late, hydrothermal origin.

The nature of the wall rock alteration

Cordierite- and anthophyllite/gedrite-bearing rocks have a very limited distribution in the Trondheim region. In the Haltdalen-Tydal area kyanite-bearing anthophyllite rocks are described from Heinvola, Tydal by Kisch (1962) and were found by the present writer south of Heinvola. They occur within the hornfels zone near the eastern border of the Hyllingen gabbro complex, and are suggested to be a contact-metamorphic facies of the Gula-schists.

The literature dealing with the origin of cordierite-anthophyllite/gedrite rocks is voluminous, and a number of different theories have been put forward to explain the enrichment of iron and magnesia in these rocks.

Eskola (1914) in his classic monograph on the Orijärvi district was the first to point out the close relationship between sulphide ore and cordierite-anthophyllite rocks in Finland and Sweden (p. 234 ff.).

The ferro-magnesian enrichment of the rocks accompanying the ores at Rødhammeren should thus be looked upon in the light of the discussion which Eskola's paper brought about in the following decades.

In Norway Precambrian cordierite-anthophyllite-rocks of the 'Orijärvi type' are described from the Kongsberg-Bamble-formation by Brøgger (1934), Bugge (1943) and Jøsang (1966), and from the basal-gneiss area of western Norway by Sørbye (1964). The only sulphide deposit of Caledonian age connected to cordierite-anthophyllite/gedrite rocks is described from Birtavarre, Troms, by Vokes (1957).

In Sweden cordierite-anthophyllite/gedrite rocks have been extensively investigated. They occur mostly in association with the iron ores of central Sweden and are especially connected with the sulphide ores of the 'Falu' type (Magnusson 1953, 1970).

A common geochemical feature of these rocks, whether they occur in connection with ore or not, is their relatively high magnesia content (10–20% MgO), a high FeO content, and the low content of calcium and alkalies. This chemical composition was according to Eskola (1920) uncommon to 'normal' rocks of sedimentary or eruptive origin, and their chemical composition was explained as a result of a metasomatic process. Iron-magnesia metasomatism is now generally accepted as a mechanism for the formation of cordierite-anthophyllite/gedrite rocks.

In the field, the cordierite-anthophyllite/gedrite rocks have an igneous appearance, and this seems to be a general feature for the rocks of the 'Orijärvi' type (Eskola 1914, p. 253, Vokes 1957, p. 150). The intrusive-like knolls of Rødhammeren may be interpreted as altered ultrabasics. Serpentine bodies occur frequently within the metavolcanics of the Støren group in the Røros district, south of the area investigated. Anthophyllite rocks can originate as a high-temperature alteration of serpentine in contact with siliceous country rocks (Phillips & Hess 1936). However, the formation of quartz-bearing cordierite-anthophyllite/gedrite rocks from a preexisting ultrabasic rock requires a disproportionally great supply of SiO_2.

The occurrence of sillimanite, kyanite and staurolite in the gedrite rocks is the best argument against a preexisting ultrabasic. The relics and pseudomorphs of alumina silicates point to a pelitic origin for the host rock. An idea which immediately suggests itself is that the cordierite-bearing gedrite rocks at Rødhammeren originated by introduction of magnesia and iron into the southern part of the sillimanite-biotite schists, thereby altering the original pelitic rock into intrusive-like bodies of cordierite-anthophyllite/gedrite rocks.

Depending on the P, T conditions and the magnitude of the water pressure, minerals such as chlorite (clinochlore), cordierite, anthophyllite and gedrite will originate at the expense of the alumina silicates already present. A supply of Si and Al besides Mg and Fe was necessary for the formation of the cordierite-anthophyllite rocks of the Orijärvi region (Eskola 1920). At Rødhammeren a supply of Al and Si should not be necessary for the formation of the gedrite rocks because of the high concentrations of alumina and silica already present in the original argillaceous metasediment.

The mobile components, the alkalies, which were chiefly tied to minerals such as plagioclase and biotite, were in all probability leached out of the original rock in areas of intensive permeation by the hydrothermal solution, thus causing an albitization, sericitization of alumina silicates and formation of the phlogopite-bearing albite rocks in the peripheral areas. A similar displacement of alkalies within an area affected by Mg-metasomatism is described from several iron-ore deposits in central Sweden. In the Bjørnberg district, central Sweden, quartz-albite rocks form a transition zone between unaltered host rock (i.e. leptite) and cordierite-gedrite quartzites. The enrichment of sodium in these rocks is explained by Gavelin (1935) as an effect of the greater mobility of potassium as compared with sodium during the metasomatic process. This is in accordance with the scheme set up by Korshinskij (1965, p. 33) showing the relative mobility of components during infiltrational metasomatism.

At Rødhammeren most of the potassium in the original metasediments may have been conveyed out of the system affected by the metasomatism, now being dispersed in the country rocks or accumulated in cross-cutting pegmatite veins. Thus the phlogopite-bearing albite-quartz rock may remain as a transitional metasomatic rock, enriched in sodium, between the original sillimanite-biotite schist and the cordierite-anthophyllite/gedrite rock.

The texture and mineralogy of the ore quartzites at Rødhammeren have strong resemblances to those of the ore quartzites of Orijärvi (Eskola 1914, pp. 209, 256) and of Falun (Geijer 1917, p. 112). The distinctive features of these rocks are a fine-grained granular texture, the frequent occurrence of disseminated pyrite and their mineralogy (quartz, cordierite, pinite). From their field relations, it is evident that they represent altered layers of quartz-keratophyres within the metavolcanics. The development of cordierite at the expense of plagioclase indicates an influx of magnesia. The reaction between plagioclase and magnesia occurs in the following way (Bugge 1943):

I $4NaAlSi_3O_8 + 2MgO \rightarrow Mg_2Al_4Si_5O_{18} + 7SiO_2 + 2Na_2O$
II $2CaAl_2Si_2O_8 + SiO_2 + 2MgO \rightarrow Mg_2Al_4Si_5O_{18} + 2CaO$

In most places the cordierite is altered to a felty mass of micaceous minerals known as pinite (or falunite). The microscopic identification of the different mineral species within the aggregates is difficult due to the extremely fine-grained size. Schreyer & Yoder (1959) and Deer, Howie & Zussman (1967, p. 86) have shown that pinite can be formed by hydrothermal breakdown of cordierite to chlorite (amesite) and pyrophyllite. Near 450°C and $P_{H_2O} = 2$ kb. the following reaction occurs:

III $\underset{\text{cordierite}}{2Mg_2Al_4Si_5O_{18}} + 6H_2O \rightarrow \underset{\text{amesite}}{Mg_4Al_4Si_2O_{10}(OH)_8} + \underset{\text{pyrophyllite}}{2Al_2Si_4O_{10}(OH)_2}$

The quartz set free by reactions (I) and (II) can be seen as small blebs within the pinite globules.

No metasomatic minerals have been observed in the amphibolites of the Rødhammeren area. As with the amphibolites of Birtavarre (Vokes 1957, p. 170) the amphibolites seem to have been 'protected' against the magnesia metasomatism. The only indication of a metasomatic alteration of the metabasites can be seen in the cummingtonite-bearing amphibolites described earlier. The formation of cummingtonite at the expense of an ordinary hornblende points to a de-calcification due to Mg-metasomatism. A similar alteration of amphibolites was described by Eskola (1914, p. 257) and Bugge (1943, p. 100). However, a complete transition hornblende-cummingtonite-gedrite is not found in the area investigated.

The enrichment of magnesia in the wall rocks of the Rødhammeren deposit is not necessarily due to an influx of magnesia-bearing solutions. Tuominen & Mikkola (1950) suggest that the cordierite-anthophyllite rocks at Orijärvi represent a residue, enriched in stable components as alumina, magnesia and iron and deficient with respect to the more mobile components (i.e. calcium and the alkalies). The displacement of the components took place during penetrative tectonic movements along slip-planes, and was most effective around fold-hinges. Thus the cordierite-anthophyllite rocks now occur as phacolite-like core-fillings of tight folds. An analogous mode of formation was advanced by Brøgger (1934) to explain the genesis of the cordierite-anthophyllite rocks in the Bamble area.

The Rødhammeren area has been affected by strong tectonic movements, and the metasomatic rocks may well represent altered core-fillings of tightly isoclinal folds. However, fold-hinges may act as channelways for influx of hydrothermal solutions from a distant source as well as for an outflow of fluids from the area affected by a metamorphic differentiation of the type postulated by Tuominen & Mikkola.

If one accepts the idea that the metasomatic alteration of the rocks at Rødhammeren was due to an influx of Mg-bearing solutions, the solutions may have emanated from an igneous source. The Orijärvi rocks are thought to have originated by means of a pneumatolytic introduction of Mg and Fe from a cooling oligoclase-granite (Eskola 1914, 1919). This was in accordance with the theories advanced by Sundius (1935). However, as stated by Tilley & Flett (1930), Brøgger (1934) and Reynolds (1946), residual solutions from a granitic magma will not contain sufficient concentrations of magnesia and iron for bringing about Mg-metasomatism on a regional scale.

In the Rødhammeren area it is difficult to assume a genetic relationship between the Hyllingen gabbro complex and the metasomatic rocks. Unaltered mica-schists are found less than 20 m from the gabbro contact.

Reynolds (1946, 1947) suggests granitization as a source of Mg- and Fe-bearing solutions: 'It is thus an established fact that the granitization displaces material rich in Fe, Mg and K and sometimes Na together with the minor constituents Ti, P and Mn, and that these constituents are fixed in a zone beyond that of granitization' (Reynolds 1946, p. 434). In spite of the fact that no sign of granitization processes can be observed in the Haltdalen area, one must assume that a mobilization of certain elements to a certain degree has taken place at depth during the metamorphism of the area. As opposed to Al_2O_3, SiO_2 and CaO, MgO acts as a fully mobile component during a high- and medium temperature metamorphism at shallow and medium depths (Korshinskij 1965, p. 85). Thus it is reasonable to assume that magnesia was among the first components to be leached out of the basic rocks (amphibolites, greenstones and gabbros) by palingenetic processes during the Caledonian orogeny. These processes may have been set in motion by igneous activity in the area. A process similar to this was suggested by Bugge (1943) for the formation of the cordierite-anthophyllite rocks of the Bamble area.

The solutions may have migrated upward and outward via slip-planes and thrust-zones and fixed within favorable zones, thereby causing mineralogic rearrangements in the original rocks.

The relationship between the ores and the wall rocks

The depositional features of the two ore bodies at Rødhammeren differ much with regard to mineralogy and texture. However, the deposition of the ores seems to have a close connection with the metasomatic alteration of the wall rocks, and an epigenetic origin is suggested.

Textural evidence points to emplacement of the lower ore-body later than the metasomatic alteration of the host rock – a pre-metallization change known as 'ground preparation' which is known from many epigenetic deposits (Park & MacDiarmid 1964). Crosscutting veins of ore, the filling of cracks and the replacement of the gangue minerals points to a later introduction of the ore-bearing solutions as compared with the solutions responsible for the metasomatic alteration of the silicate rocks.

With regard to the upper pyritic ore body, the relation between ore and host rock is not so simple. As mentioned earlier, the gangue minerals, especially quartz, often fill cracks and fissures in the sulphide ore, indicating that the ore was subjected to silification or recrystallization of the gangue after the ore emplacement. Cross-cutting structures are not observed, and the ore seems to be associated with well-defined layers within the metavolcanics. The absence of any mineral banding parallel to the ore walls, and the gradual lateral transition into massive pyrite ore may indicate a remobilization and a redeposition of a pre-existing sulphide layer within the metavolcanics. A similar interpretation was put forward by Koark (1962) for the origin of the sulphide ore in Falun mine, Sweden. However, his evidence for an exhalative sedimentary origin of the Falun ore was rejected by Geijer (1964).

The sulphide enrichment in the upper ore body is so closely connected to the metasomatic host rocks, that the emplacement of the ore seems to have been brought about by means of the same mechanism that caused the metasomatic alterations. But, as in Birtavarre, it is clear that Mg-metasomatism took place before the introduction of sulphides. In spite of the differences of texture and mineralogic and chemical composition between the two ore bodies, they seem to have originated contemporaneously. The sequence of events leading to their formation will be discussed in the following section.

The sequence of the events – a recapitulation

The Rødhammeren area provides an example of a polymetamorphic subprovince where metasomatism and ore deposition were among the latest events in the metamorphic history. The sequence of events leading to the formation of the ores and the country rocks in Rødhammeren may be set up as follows:

1. During the Caledonian orogeny the sequence of Ca-poor argillaceous sediments and volcanics in the Haltdalen area was subjected to folding and metamorphism. In the Rødhammeren area the supracrustals were folded into tight, isoclinal folds and subjected to a high-grade Barrovian metamorphism (i.e. within the sillimanite-almandine-orthoclase subfacies of Winkler (1967)).

2. The intrusion of the Hyllingen gabbro complex may be contemporaneous with the deformation of the wall rocks; the swarms of porphyrite dikes accompanying the intrusion are folded together with the supracrustals, and neither the gabbro nor the porphyrite is seen intersecting the folded supracrustals.

3. After the emplacement of the gabbro, the area was affected by a low-pressure Mg-metasomatism which took place near zones of great permeability for hydrothermal solutions (e.g. near fold-hinges and at the contact between the different rock types). The metasomatism may be divided into three stages:

The initial metasomatism caused a removal of Ca and alkalies from the rocks, and Mg was introduced, causing the formation of cordierite-, gedrite-, and anthophyllite-bearing rocks. ('Ground preparation').

In the next stage, iron, copper and sulphur were introduced to the altered rocks, possibly through the same channelways, and deposited in favorable locations, forming the principal ore bodies. As for the solutions responsible for the metasomatic alterations of first stage, the content of mineralizers in the solution may have been derived from metavolcanics and gabbros undergoing palingenetic processes at depth. Iron and sulphur may have been conveyed from horizons of black shale and layers of sedimentary sulphides (e.g. 'vasskis').

The introduction of the sulphides was probably contemporaneous with a deformation of the rocks, causing migration and redeposition of the ore material.

In the latest stage H_2O was introduced – an event that caused an alteration of cordierite to micaceous material (pinite) and a mobilization and a recrystallization of SiO_2. In the lower ore body the introduction of H_2O caused a chloritization of the cordierite-bearing gedrite rock along thrust zones.

The classification of the Rødhammeren ores

The sulphide deposits in the Trondheim region were classified by Carstens (1920) into six principal groups – the Røros type, the Skjækerdal type, the

Lillefjell type, the Leksdal type, the 'impregnation' type and the Rødhammer type. Each type could be identified according to the mineralogy, the geological setting and – to a lesser extent – the genesis of the ore.

In later works, this classification scheme was changed, and the number of classes was reduced to four (Carstens 1932, 1936) (the Røros type, the Leksdal type, the Fløttum type and the Rødhammer type).

The Rødhammeren mine became the type locality of the ores of the 'Rødhammer type'. In contrast to the other types, the 'Rødhammer type' comprises a well-defined group of sulphide deposits. The ores of the 'Rødhammer type' of Carstens are characterized by the following two criteria:

Pyrite is the dominant sulphide mineral – chalcopyrite is subordinate.

The ore is genetically connected to 'white granites' (trondhjemites and related rocks) and occurs as a rule on the contact between the 'white granites' and the enclosing rocks. Often the ore occurs within the 'white granites'.

In his interpretation of the 'Rødhammeren type' as an epigenetic type, he regards the trondhjemitic rocks as the ultimate source of the circulating ore-forming solutions (Carstens 1936, p. 29). Obviously he refers to the features of the upper pyritic ore body in his description of the 'Rødhammeren type'. However, the genetic implications are, in the present writer's opinion, somewhat misleading. Trondhjemites and related rocks ('the white granites') do not occur in the Rødhammeren area. The quartz-keratophyres and ore quartzites of the Rødhammeren area are of effusive origin, and their mineralogy and field relations differ from the true trondhjemites. Trondhjemites and related rocks occur as minor sills and small bodies within the Tverråantiform in the west, but it is doubtful whether they represent the ultimate source of the ore-bearing solutions responsible for ore-deposition at Rødhammeren.

The relationship between ore and acid intrusives is not evident, and the term 'Rødhammer type' in the sense of Carstens may be misleading from a genetic point of view.

However, the upper ore body at Rødhammeren displays mineralogical and textural features which are known from a great number of sulphide deposits within the Caledonides of Norway. The term 'Bjørkåsen type' was proposed by Foslie (1933) for a similar ore type, rich in pyrite and quartz, and low in copper. Saager (1967) proposed the term 'Pyrittyp' for similar sulphide ores in the Mofjell area, northern Norway.

Actually, the Rødhammeren ore deposit is representative of *two* distinctive sulphide parageneses, known as the *pyritic* and the *pyrrhotitic*, respectively, in the twofold classification scheme of Stanton (1960). The nature of the two ore types was discussed by Vokes (1962), based on observations from sulphide deposits of the Caledonides of Norway. The ores of Rødhammeren fall well within the two principal classes, which, according to Vokes (op. cit. pp. 894, 896) have the following characteristics:

The ores of the pyritic type – '. . . are massive sulfide ores in which pyrite is the dominant ore mineral. The textures vary from fine- to coarse grained and are as a rule characterized by sub- to euhedral pyrite grains, in between which occur the other sulfides and the gangue minerals in an allotriomorphic intergrowth. Mineral banding, generally parallel to the ore-walls, may or may not be present. The ore bodies as a whole are largely concordant with the layering or schistosity of the country rocks, though in some thicker ore lenses cross-cutting of the country rock structures is a marked feature. The ore lenses or plates are generally, though not always, elongated in the lineation direction of the surrounding schists.'

The ores of the pyrrhotite type – 'Texturally these pyrrhotitic ores show considerable differences from the massive pyrite ores considered above. They are essentially breccia ores, full of fragments, of all sizes, of the surrounding country rocks, with a general fine to medium grained matrix of pyrrhotite and chalcopyrite. The latter mineral is generally present in very variable amounts as irregular streaks or patches. Irregularity of tenor is a characteristic of this type of ore in contrast to the first type. The ores occur as flat, irregular plates lying generally concordant to the layering of the metamorphic schists that form the country rocks. However, this general concordance does not hold in detail, and branching and crosscutting of the ores are a marked feature of this type.'

These characterizations of the two principal classes of sulphide deposits hold for the upper ore body (the 'Rødhammer type' sensu stricto) and the lower ore body at Rødhammeren respectively.

However, the most distinctive feature of the Rødhammeren ores is their association with cordierite- and anthophyllite-gedrite rocks, formed by means of an extreme Mg-metasomatism of metamorphic supracrustals. As stated earlier, the ore deposition at Rødhammeren mine must be seen in connection with this process.

The Rødhammeren sulphide deposit differs from most of the sulphide deposits in the Caledonian mountain chain with respect to its geological setting. Thus, the concept of a 'Rødhammeren type' of sulphide deposits is, in the writer's opinion, still justified, but in another sense than that of Carstens.

An analogy with the Swedish term 'Falun type' is evident from the definition of Magnusson (1953, p. 186): 'Sulphide ores which have been formed through Mg-metasomatism can be classified as sulphide ores of Falu type.'

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