Caledonian Sulphide Deposits and Minor Iron-formations from the Southern Trondheim Region, Norway*

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Within the southern and central parts of the Trondheim region of the Norwegian Caledonides a great number of small, stratabound cupriferous pyrite deposits are confined to mafic metavolcanics of the Gula, Støren and Fundsjø Groups of the Lower Palaeozoic succession. The deposits occurring within, or in close contact with the metavolcanics are characterized by their association with minor manganiferous oxide/silicate iron-formations — better known as the 'vasskis' ore type — within the metamorphic low-grade areas. The iron-formations of the metamorphic higher grade terrains on the other hand, which are extensively developed within the Gula Group, are mostly of a pyrrhotitic sulphide/silicate type and sulphurization processes are thought to have played an important role during the metamorphism. The pyrite deposits occurring adjacent to the metavolcanics bear no relationship to the iron-formations. They are embedded in pelitic, often carbonaceous assemblages (Gula Group) or within tuffitic members of the volcanogene Støren Group, and they are thought to represent re-sedimented (reworked) deposits. The pyrite deposits display varying degrees of metamorphic reconstitution and a tectonic control has apparently determined their disc- or ruler-shaped morphology.

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Introduction

The Trondheim region of central Norway constitutes an important metallogenetic province of the Scandinavian Caledonides. A great number of metamorphosed pyritic base-metal sulphide deposits are confined to different but restricted formations of the Palaeozoic allochthon, the Trondheim Nappe of Wolff (1967). Rocks of the Gula Group underlie the central part of the region and have been considered to represent the oldest, assumed Late Precambrian/Cambrian member of the partly inverted stratigraphical succession, pre-dating the volcanogene Støren Group of probable Lower Ordovician age (Bugge 1954, Wolff 1967, Roberts et al. 1970, Rohr-Torp 1972, Rui 1972), although alternative oponions on the age of the Gula Group, based on geotectonic considerations, have been put forward in later years (Olesen et al. 1973, Gale & Roberts 1974).

The present paper gives an account of the ore mineralizations, and mainly those in the Gula, Støren and Fundsjø Groups of the southern part of the Trondheim region covered partly by the 1:250,000 map-sheet 'Røros' (Plate 1). They will be classified according to their specific geological environment, and special attention will be given to their association with minor iron-formations

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of the area and to their metamorphism. The nature of the deposits, as compared with other sulphide deposits occurring in the Scandinavian Caledonides, will also be discussed. A list of mines, prospects and showings is given in the appendix with information on their location and their ore mineralogy. Each ore deposit described or mentioned in the text has an adjacent number in brackets which refers the reader to the map (Plate 1) and to the list in the appendix.

General geology

THE GULA GROUP

Rocks of the Gula Group comprise fairly homogeneous lithological assemblages which have been recognized from the valley of Gudbrandsdalen in the south (the Heidal Group of Strand (1951)) to the Grong culmination in the north (including the Sonvatn Group of Wolff (1967)) over a distance of about 300 km. The sequence has been subjected to a varying metamorphism and deformation during the Caledonian orogeny, giving rise to distinctive metamorphic zones. A generally higher metamorphic grade and more intense deformation and plutonic activity within the different units of the Gula Group compared with the younger formations has made it difficult to establish a detailed stratigraphical succession for the group. The tectono-stratigraphic position of the Gula Group has been a much debated topic in recent years; a tectonic contact between the Gula and Støren/Fundsjø Groups is fundamental to Gale & Roberts' (1974) plate tectonic model for the central Norwegian Caledonides, while Gee & Zachrisson (1974) and Gee (1975) recognise a tectonized boundary only in the east, i.e., along the Gula–Fundsjø contact. In the Røros district Rui (1972) has described an apparently conformable contact, which is also the opinion of the present author, whereas in the southernmost part of the Trondheim region Guezou et al. (1972) have reported a major tectonic break at the Gula–Støren boundary.

A lithostratigraphical column for the Røros district was presented by Rui (1972) and later modified by Rui & Bakke (1975). A two-fold division of the Gula Group was proposed, a lower psammitic unit (the *Singsås Formation*) and an upper pelitic unit (the *Åsli Formation*), the latter apparently conformably overlying the volcanogene Hersjø Formation in a proposed inverted sequence. The two-fold division of the eastern part of the Gula Group was already recognized by Törnebohm (1896) who applied the names 'Singsås group' and 'Selbu skiffer group' to the lower psammitic and the upper pelitic units, respectively.

In the west the highest unit in the Gula Group, bordering the steeply dipping or inverted sequence of the Støren Group (Rohr-Torp 1972), is a pelitic, partly carbonaceous formation — the so-called 'Brek skiffer group' of Törnebohm (1896) — which will here be designated informally as the *Undal Formation.*

Thin horizons of mafic metavolcanics, the *Gula greenstone,* occur within the Singsås Formation and separate the psammitic unit from the eastern and western pelitic units, and confirms an apparent symmetry between the lith-

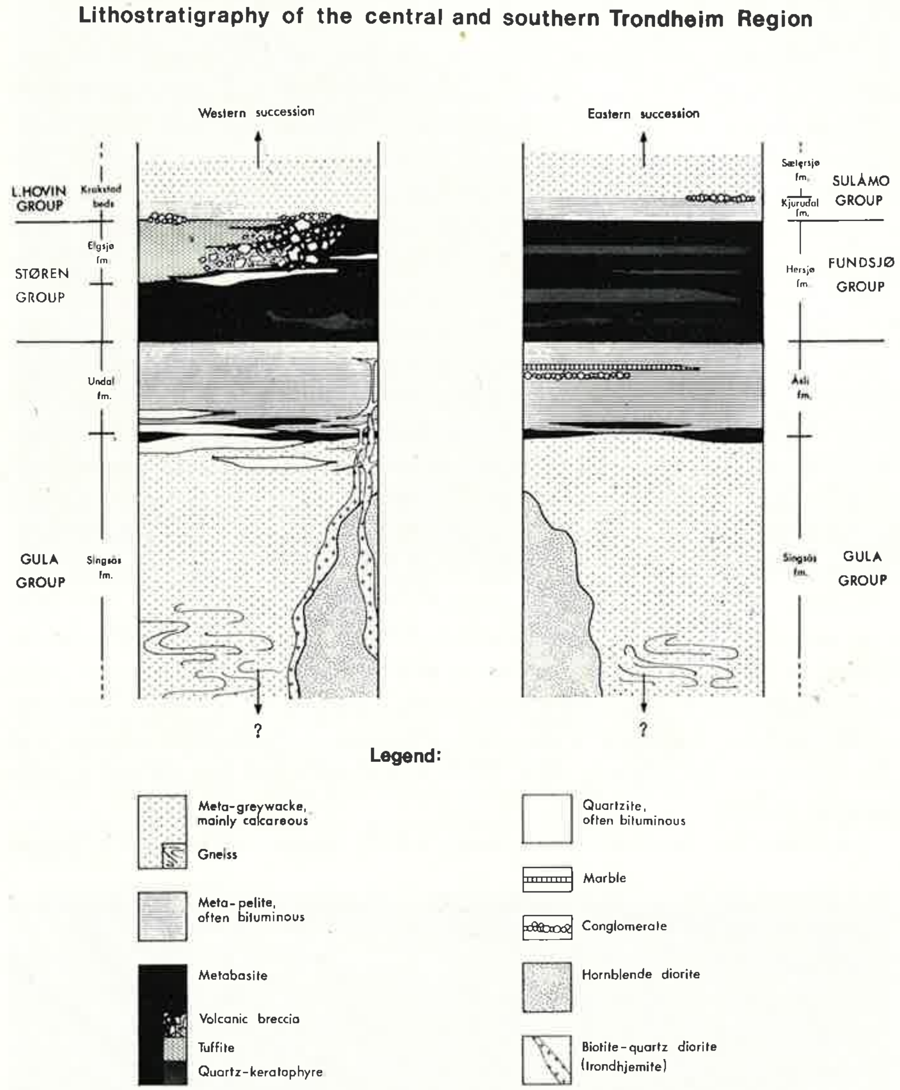


Fig. 1. Lithostratigraphical column of the central and southern Trondheim region.

ologies in the east and in the west. A correlation between the western Undal Formation and the eastern Åsli Formation is reasonable and is in accordance with the tectonic models of the Trondheim Nappe as proposed by Roberts et al. (1970) and Rui (in Rohr-Torp 1972). However, conflicting way-up evidence and datings have recently called the idea of a general inversion of the Trondheim region stratigraphy into question, and at the same time the enigmatic chronostratigraphical position of the Gula Group has been emphasized.

The psammitic and pelitic units of the Gula Group include more or less continuous horizons of metavolcanics, crystalline limestones, conglomerates, black schists and quartzites. Their exact stratigraphical positions, however, have been difficult to place. Fig. 1 shows the general lithostratigraphy of the Gula Group and of the younger formations which will be described below.

The Singsås Formation

A psammitic unit, the Singsås Formation, occupies the central part of the area underlain by the Gula Group and consists mainly of calcareous psammites which grade laterally into non-calcareous psammites including thin, bituminous horizons. The unit appears in different metamorphic and structural conditions throughout the region. The petrology and metamorphism of the calcareous metasediments were described by Goldschmidt (1915). Generally they grade from fine-grained calcite-bearing chlorite–quartz schists (in the Soknedal–Hauka area) into calc–silicate banded, garnetiferous biotite–quartz schists and gneisses in central and eastern districts. Transitions into high-grade diopside–microcline rocks occur associated with the composite major Caledonian intrusions of dioritic to trondhjemitic compositions within the central parts of the region, e.g. in the Kvikne and Singsås districts. The thermal influence upon the psammitic assemblages from minor diorite and trondhjemite dykes as well from large gabbroic bodies is evident from several locations within the Gula Group, and has been described from elsewhere within the region (Birkeland & Nilsen 1972, Olesen et al. 1973, Rohr-Torp 1974).

Locally, primary sedimentary structures such as graded bedding and load casts are preserved within the calcareous lithologies of the Singsås Formation (Figs 2 & 3), which seem to indicate a turbidite facies development for parts of the Gula Group. Throughout most of the Gula schists, however, prominent schistosity has erased most of the primary features in the original arenites, and the scanty way-up evidence (Rui 1972) is not sufficient enough for reliable tectonic analysis.

Less calcareous metasandstones occupy mainly the central parts of the Singsås Formation and are developed as grey, flaggy, biotite–quartz schists, often with discontinuous, thin intercalations of black schists. Apart from a different carbonate content, the main distinction between the calcareous and the non-calcareous units is seen in the general lack of bituminous intercalations in the former.

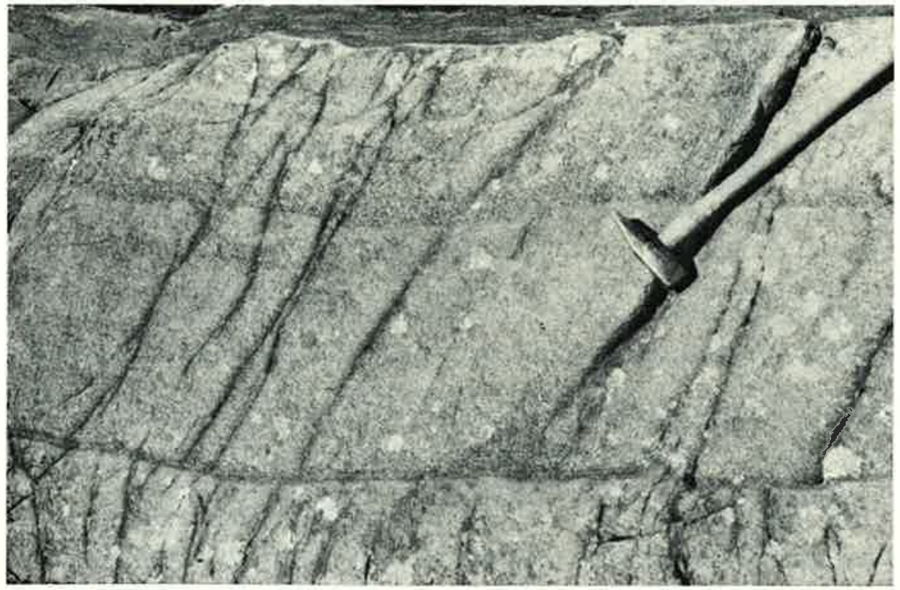


Fig. 2. Graded bedding in metagreywacke (calcareous biotite–qartz sandstone) from the Singsås Formation; Fjellsjøen, Dalsbygda (loc. 982 480, 1:50,000 sheet Dalsbygda).

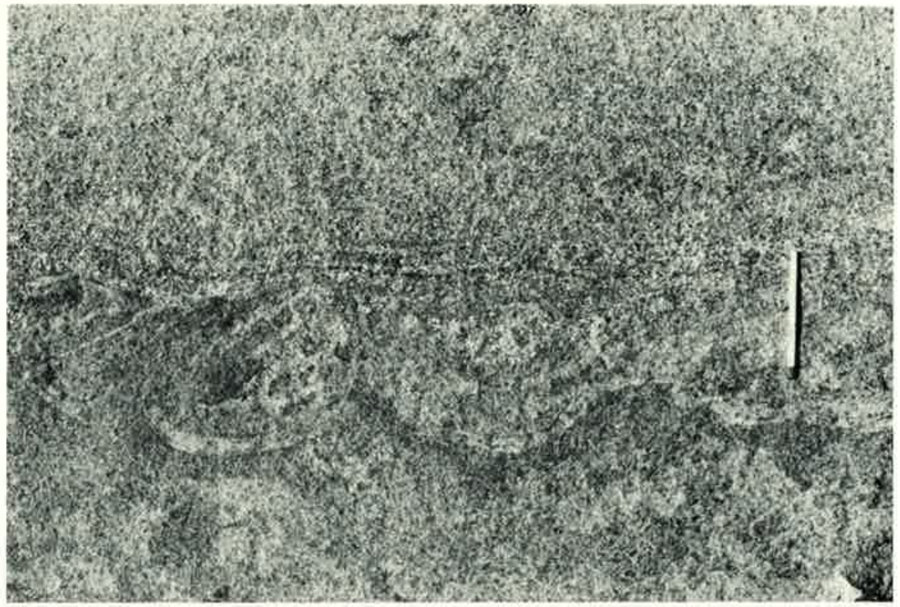


Fig. 3. Load casts and flame structures in metagreywacke from the Singsås Formation. Same locality as in Fig. 2.

Throughout the Singsås Formation and bordering this formation there occur thin but distinctive horizons of mafic metavolcanics which constitute *the Gula greenstone* (Nilsen & Mukherjee 1972, Nilsen 1974). The metavolcanics are mostly developed as dark, schistose amphibolites and are generally associated with horizons of black schists and banded carbonaceous quartzites which are extensively developed in the Gauldalen region. The sulphide mineralizations of the Gula Group are mostly confined to these lithological assemblages and will be treated in more detail in a forthcoming section.

The Åsli Formation

The Åsli Formation occurs in eastern areas of the Gula Group exposure and is mostly developed as fissile, grey to black phyllites. To the north they grade into less carbonaceous biotite schists in the Øyungen area, and further into pelitic Al–silicate-bearing schists and gneisses in the Haltdalen–Stjørdalen districts (Vogt 1941, Roberts 1968, Nilsen 1971, Rui 1972, Bøe 1974). Similar high-grade metamorphic equivalents of the Åsli Formation can be found in the Grimsdalen area and further to the south-west in the Dombås region (Guezou et al. 1972).

A discontinuous horizon of crystalline limestone, generally associated with a polymict conglomerate is included in the Åsli Formation and represents a southerly continuation of the Gudå conglomerate zone (Wolff 1964). This association can be followed more or less continuously along strike from the Haltdalen district to the Dovre region in the valley of Gudbrandsdalen (Pinna 1973).

The Undal Formation

The Undal Formation constitutes the western unit of the Gula Group, bordering against the volcanogene Støren Group. Like the Åsli Formation, the Undal Formation consists mainly of variably carbonaceous pelites. In the Soknedal–Støren and Orkelsjøen districts it is developed as grey and black chlorite–sericite phyllites, often with cm-thick intercalations of banded quartzite. To the north, in the Selbu district, the banded quartzites and phyllites of the Undal Formation have been described by Torske (1965) and Olesen et al. (1973) and have recently been interpreted as a separate nappe unit of Lower Hovin Group age on the 1:250,000 map-sheet 'Trondheim' (Wolff 1976). As no apparent tectonic or metamorphic break has been observed along the boundary between the Undal Formation and the Singsås Formation from Gauldalen to Gudbrandsdalen, the present writer considers it safer to regard the Undal Formation as belonging to the Gula Group.

In the Innset–Orkelsjøen district the phyllites of the Undal Formation grade into pelitic, garnetiferous biotite schists, passing southwards into grey, often calcareous biotite–sericite phyllites in the Fundin area. Further southwards, in the Dalholen–Hjerkinn area they appear again as flaggy biotite phyllites, locally with horizons of banded, often bituminous quartzites.

The Undal Formation lacks marker horizons such as limestone beds, but discontinuous layers of Gula greenstone occur frequently in northern areas, especially at the border to the Singsås Formation. A few psammitic horizons are included in the Undal Formation; at certain localities in the Soknedal region these take on the character of intraformational breccias. Thin, polymict conglomerate horizons, a few metres in thickness, occur locally in the southern Hjerkinn–Dalholen district.

THE STØREN GROUP AND HIGHER UNITS

The Støren Group constitutes the main volcanogenic rock unit throughout the western Trondheim Region. Within southernmost districts the metavolcanics comprise mainly mafic assemblages — mafic greenstone pillow lavas, pillow breccias and tuffites with minor intercalations of cherty layers and some volcanogenic sediments including conglomerates. Rhyolitic felsite of hypabyssal nature occurs infrequently in the Oppdal region and a few ultramafic pods, a few hundred square metres in outcrop, have been recorded within the greenstone layers

The greenstone lavas of the Støren–Rennebu area were first described by Bugge (1910) who pointed out their effusive nature with reference to the pillow structures and amygdaloidal textures. The pillow-lavas cover large areas in this district and Oftedahl (1968) considered the Soknedal area as the site of a submarine eruption centre.

To the south the outcrops of the Støren Group show a complicated pattern ascribed to lateral lithological variations as well as to tectonic disruption caused by polyphase folding and faulting and by the emplacement of the Innset intrusive complex. The lithological character of the metavolcanics changes gradually from the prominent pillow-lava facies in the north to a more volcanoclastic facies in the Oppdal area and further south. Here, pillow-lavas occupy a relatively minor part of the volcanic succession, while meta-hyaloclastites and other volcanic breccias with a pronounced sedimentary affiliation predominate. A similar lateral development of the Støren Group metavolcanics occurs to the north, as volcanoclastic products also occur in the Selbu district (Torske 1965).

The eastern branch of the Støren Group can be followed from the Rennebu area and through the Innset district as a sequence of pillow-lavas, interbedded with layers of tuffitic metasediments and banded, cherty layers. The pillow-lava constituents, which are metamorphosed into schistose amphibolites in the Innset–Orkelsjøen area, disappear southwards and the metavolcanics continue as a distinctive tuffitic volcanoclastic formation — informally designated as the *Elgsjø Formation* — from Orkelsjøen to Hjerkinn. These rocks appear as well-bedded, pelitic, green to greenish-grey sericite–chlorite phyllites, often vertically grading into thick (10–20 m) horizons of finely banded, greenish chlorite-bearing quartzites or green quartzose greywackes.

To the south the Elgsjø Formation is offset by the *Vinstra wrench fault*, but continues southwards along the eastern side of the valley of the Driva river.

An incipient porphyroblastesis of biotite and amphibole within the green phyllites indicates an increasing metamorphism towards the south, giving rise to biotite–muscovite garben-schists in the Hjerkinn district and coarse-grained garnetiferous garben-gneisses in the Driva valley. The associated fine-grained chloritic greenstone horizons are then represented by contorted bands of dark hornblende schists.

The boundary between the Elgsjø Formation and the adjacent younger metasediments to the west is transitional with diffuse layers of greenish greywacke appearing in the green phyllites. A thin, discontinuous horizon of a polymict conglomerate in many places acts as a marker horizon between the tuffaceous Elgsjø Formation of the Støren Group and the flysch-type greywacke lithologies. Rohr-Torp (1972) correlated the greywacke unit west of the Elgsjø Formation with the *Krokstad beds* of the *Lower Hovin Group* which overlies the Støren Group in the Hølonda district just to the north of Støren (Vogt 1945a, Chaloupsky 1970), and reported an inversion of the succession.

THE HERSJØ FORMATION AND HIGHER UNITS

The Hersjø Formation is the principal volcanogenic rock unit of the eastern part of the southern Trondheim region and represent the southern continuation of the *Fundsjø Group* in the Meråker district (Wolff 1967). The geology of some of the sulphide ore deposits of the Hersjø and contiguous formations has been described from the Røros district by Nilsen (1971), Rui (1972, 1973a) and Rui & Bakke (1975). In this account reference will be made only to a few points of general interest and to comparative features between the two major greenstone belts of the southern Trondheim region.

In contrast to the metavolcanics of the Støren Group, the Hersjø Formation has a more pronounced bimodal composition. Mafic metavolcanics of a tholeiitic composition predominate, but locally thick sequences of sodic quartz–keratophyres and gabbroic sills occur. The quartz–keratophyres show a wide compositional range. They grade from albitites to nearly pure quartzites and are frequently the host rocks to a great number of pyritic sulphide disseminations in the Røros–Alvdal area. Pillow-lavas, agglomerates and volcanic breccias are frequently met with in north–eastern areas. Generally the metamorphic grade of the metavolcanics of the Hersjø Formation is slightly higher as compared with the Støren Group assemblages; hence the original nature of the volcanism is harder to make out.

In the Alvdal–Savalen district the Hersjø Formation is exposed as the envelope of a dome structure (the *Einunnfjell anticline* — Berthomier et al. (1970), Mosson et al. (1972)) protruding through the surrounding inverted Gula Group sequences. Locally, palingenetic processes have affected the leucocratic constituents of the volcanic pile, giving rise to migmatites of quartz–dioritic compositions in the Savalen area. A few sulphide deposits are confined to the Hersjø Formation in this area; these will be considered further below.

The formations stratigraphically overlying the Hersjø Formation comprise an alternation of pelitic and psammitic lithologies with some metavolcanic members and one prominent serpentinite horizon. Descriptions are contained in Rui & Bakke (1975). The lithostratigraphical column of the south–eastern Trondheim region ends with the feldspathic quartzites of the *Hummelfjell Formation*. These lie in an inverted position, and are considered to be of Silurian age. Recent radiometric dating by Point et al. (1976), however, indicates a possible Precambrian age for the Hummelfjell Formation. In the present map area the rocks of the Hummelfjell Formation occupy the core of the Einunnfjell anticline.

STRUCTURAL DEVELOPMENT

The main structures of the southern Trondheim region can be attributed to at least three periods of deformation. The penetrative axial plane schistosity is related to an early phase (F_1) of isoclinal folding with a nearly horizontal NNE–SSW axial trend. A younger F_2 phase is defined by macroscopic tight to isoclinal folds and microscopic puckerings. Deformational effects, such as the rotation of garnet and biotite (Mukherjee & Sen 1971) and the parallel alignment of mineral aggregates (e.g. calc–silicate bands and ores), are ascribed to this phase. This conspicuous F_2 lineation is well developed throughout the region and generally has a NNW–SSW to E–W trend and an eastward plunge (see Fig. 18).

The doming in the Savalen area (Collomb & Quenardel 1971), gentle flexing in the Oppdal–Innset–Kvikne district and the formation of the open *Singsås synform* displayed in Gauldalen are considered to belong to a syn- or post-F_2 deformation phase. The Singsås synform has an axial trend parallel to the prominent F_2 direction and may be correlated in time with the main igneous activity of the region. This superimposed, NW–SE, open-styled cross-folding, as revealed by the Singsås synform, can be traced within the autochthonous–parautochthonous Late Precambrian 'sparagmite' sequence to the east and below the Trondheim Nappe proper, as noted by Grønlie & Rui (1976), and may post-date the nappe emplacement.

A later F_3 phase is revealed by cross-cutting, nearly horizontal planar structures in the marginal areas. Within the ores and rocks of the easternmost areas these are seen as flat-lying, closely spaced joints. In the north-west F_3 is revealed as a penetrative cleavage which transects and offsets the ore bodies, e.g. in the Ilfjellet district. This planar structure is associated with minor puckerings along a horizontal NNE–SSW axial trend in the easternmost parts of the Singsås and Åsli Formations.

A prominent set of steep NW–SE-trending faults occurs in the southern part of the region and represents the latest tectonic event. The Vinstra wrench fault is here a marked topographical feature. Congruent small-scale faulting and jointing has been observed in the Kvikne area to the north and this corresponds to the predominant direction of the streams of the region.

The sulphide deposits

The mining industry within the southern Trondheim region has long traditions. From the year 1632 when the Kvikne mines were put into operation and down to the turn of the 19th century, a great number of cupriferous sulphide deposits were discovered and exploited. In the central and western areas under consideration the chief activities took place within two periods during the 350 years since the Kvikne ores were discovered.

The first period was from 1650 to 1750 when three independent smelting works were established for the production of copper in the region, viz. at Kvikne, Soknedal and Budal. The ores from the *Rødalen mine* (100) were treated by smelters in the Alvdal district. The Kvikne works became the largest industrial enterprise in the region, operating a dozen smelters down the river Orkla during this first era. The last smelter in production, the Innset smelter in Næverdalen, treated the ores from the mines at *Kvikne* (71), *Nyberget* (31) and periodically from the mines at *Undal* (26) and *Bjørndalen* (60), until 1872. The furnace has now been restored (Thuesen 1960). Historical accounts of the development of the mining and smelting industry of the region have been given by Falck-Muus (1932), Enmo (1935) and Støren (1951).

After a standstill during the 19th century a second mining era was initiated at the beginning of the present century by the increasing demand for pyrite ore. The new era brought about a revival of some of the old mines at *Undal* (26), *Fos* (122) and *Rødalen* (100) and new mines as *Røstvangen* (90) and *Fløttum* (117) were put into production. In addition to the production of copper and pyrite ore, mining and smelting of iron ore took place on a limited scale in the Rennebu district at *St. Olaf* mine (21) around 1850.

The pyrite production of the several small mines ceased during the twenties and no mines were in production until the Undal mine was again reopened in 1952. It then closed down in 1971. In 1968 production started at the *Tverrfjellet mine* (7) at Hjerkinn which today contains the largest pyrite reserves of the southern Trondheim region.

Compared with the Røros and Meldal districts, the mines of the south-central Trondheim region have played a minor role in the total copper and pyrite production. The majority of the mineralizations do not reach ore grade, and the few workable ores — with the notable exception of the Tverrfjellet mine — can be considered as marginal deposits with ore quantities well below ½ mill. tons each. Apart from the active Tverrfjellet mine, the mine workings of the region are not accessible today and the present investigations of the ores were performed on material from excavations, adits and dumps and from the few diamond drill cores preserved.

Up to the present time, regional geological accounts of the sulphide deposits of the region are rather cursory. The surveys published by Helland (1873) and Foslie (1925, 1926) have, together with some local geological descriptions and technical reports, provided valuable information for the present compilation. From the southeastern Savalen district some of the ore deposits have been described by Vogt (1890), Aasgaard (1935) and Quenardel (1972), while deposits of the central Gula Group have been described by Brøgger & Vogt (1909), Falkenberg (1914), Theting (1935), Nilsen & Mukherjee (1972) and Rui (1973a). The deposits of the western part of the region have previously been described by Gulliksen & Vogt (1899), Bugge (1910), Brodtkorb (1926), Waltham (1968) and Lindberg (1971).

Most of the sulphide deposits of the central Trondheim region are clearly confined to distinct lithological units within the different formations described. They display most of the features characteristic of the metamorphosed stratabound 'Kieslagerstätten' type within the Scandinavian Caledonides, as reviewed by Vokes (1962, 1968, 1976), Vokes & Gale (1976) and Waltham (1968). Their stratabound nature is best revealed within the Gula Group since their distribution is restricted to thin, but mappable horizons of the Gula greenstone and associated graphite phyllite and graphite quartzites. The psammitic rocks of the Singsås Formation and the Krokstad beds appear to be totally barren of any sulphide mineralization.

A few deposits of non-stratabound type will be mentioned below. They comprise some cupriferous nickel deposits confined to ultramafic pods within the Gula greenstone, one chromite deposit and some vein-type Pb-py and MoS_2-mineralizations.

The deposits will be classified and described below according to the following scheme:

Gula Group	Støren/Fundsjø Groups
Kvikne type Sulphide deposits associated with the Gula greenstone and/or their adjacent oxide/silicate iron formations.	*Rennebu type* Sulphide deposits associated with Støren Group pillow lavas and their adjacent oxide iron-formations ('vasskis').
Budal type Sulphide deposits associated with graphitic schists and quartzites.	*Elgsjø type* Sulphide deposits associated with tuffaceous metasediments.
Olkar type Cu/Ni-deposits associated with mafic and ultramafic pods associated with the Gula greenstone.	*Saval type* Sulphide deposits associated with felsic and mafic metavolcanics of the Hersjø Formation.

The classification is based upon the different, characteristic lithological associations of the deposits in question and it should be pointed out that no specific genetic implications are inferred.

The polyphase tectonic and metamorphic processes to which the rocks of the region under consideration have been subjected have brought about particular textural and mineralogical changes and left specific imprints on each deposit. However, the examination of the ca. 120 deposits of the region has revealed that they have several features in common which may shed some light upon their history of emplacement.

DEPOSITS OF THE KVIKNE TYPE

The deposits of the Kvikne type are mainly restricted to the Kvikne area within the central part of the region where they constitute a sulphide belt from the *Rødalen mine* (100) through the *Røstvangen* district to the *Kvikne mines* (71). A few deposits of this type are restricted to the western Gula greenstone horizon, bordering the Undal Formation, viz. the *Breidvad prospects* (43, 44). The eastern Gula greenstone horizon bordering the Åsli Formation encompasses several minor deposits from south of Lake Savalen through *the Klett mines* (110, 111) to *Fos mine* (122) in the valley of Vangrøfta.

Massive pyritic bodies constitute the most important type of ores and are invariably associated with low-grade pyrrhotitic wall-rock disseminations of a more widespread occurrence. The massive pyritic ores occur as discrete, lenticular, ruler-shaped bodies, often arranged in an *en échelon* pattern within an ore district with sharp contacts to tectonically fragmented parts of the Gula greenstone. They do not differ markedly from the massive pyritic ores of the Budal type with respect to their morphology and composition, and their general affinity with the massive metamorphosed pyrite deposits associated with younger greenstone formations within the Scandinavian Caledonides is evident.

The massive pyritic ores are restricted to a few of the larger deposits of the region. In the eastern sulphide belt, massive pyrite ore has been mined at the *Fos mine* (122). It occurs here as a steeply dipping ruler-shaped body, less than

5 m in thickness (Foslie 1926). The southern deposits of this belt, including the larger *Klett mines* (110, 111), comprise mainly heavy pyrrhotite disseminations with minor pyrite, often associated with ferruginous oxide/silicate assemblages which will be treated below (e.g. *Haugen* (106), *Svartåsen* (105), *Lauvbekken* (116) and *Lomsjøvola* (114)).

In the central Gula Group area, massive pyritic ores have been mined at *Rødalen* (100), in the *Røstvangen area* (87–90) and at *Kvikne* (71). The pyritic bodies here usually pass laterally into massive, more cupriferous pyrrhotitic parts (e.g. northernmost *Helene Cathrine mine* at Rødalen) which have provided high-grade ores, e.g. at Røstvangen with more than 8% Cu (Rui 1973b).

No massive pyrite deposits of the Kvikne type have been recorded from the western sulphide belt of the Gula Group.

The general relationship between the different types of ores and wall-rocks from the Kvikne area was described by Nilsen & Mukherjee (1972) and holds for the majority of the sulphide deposits of the Kvikne type. In general the sulphide concentrations occur near, or at, the border between the Gula greenstone and the surrounding metasediments, as shown schematically in Fig. 4.

The massive pyritic ores have a simple mineralogy. Pyrite is the chief mineral component and occurs as aggregates of subhedral to euhedral cubes with a mean grain-size of 1–1.5 mm. Closely packed aggregates frequently display cataclastic features such as fracturing along cleavage planes at crystal contacts. Matrix consists chiefly of quartz (e.g. at *Rødalen* (100), *Børsjøhø* (87) and *Segen Gottes* (Kvikne) (71)) but pyrrhotite, chalcopyrite and sphalerite are common matrix sulphide components within all the pyritic ores. In general pyrrhotite constitutes the chief matrix sulphide, followed by chalcopyrite. Sphalerite occurs in minor quantities and is invariably associated with the chalcopyrite and pyrrhotite groundmass as amoeboidal intergrowths. In metamorphic high-grade ores from Røstvangen to Kvikne, sphalerite is frequently found as exsolved starlets and blebs in chalcopyrite, and sometimes chalcopyrite occurs as oriented exsolution blebs in sphalerite (e.g. Nilsen & Mukherjee 1972, Fig. 12). The ores of the eastern sulphide belt have generally a higher sphalerite content and ore grades between 1% and 3% Zn are common.

The matrix sulphides occur in varying proportions among the deposits and even within a single body. Great variations in ore grade occur due to the irregular distribution of ore components, as shown from the Røstvangen mine production (Rui 1973b) but the average lies in the range 1–3% Cu and less than 1% Zn, with lead in the range 0.02–0.05% for the majority of the pyritic ores of the Kvikne type. The matrix sulphides occur as faintly elongated, ragged mosaics, frequently filling in cracks and embayments of fractured pyrite porphyroblasts. Chalcopyrite occurs as larger irregular patches within single pyrrhotite grains.

Accessory sulphide components of the pyritic ores include galena, molybdenite, cubanite and mackinawite in decreasing order of abundance. Galena occurs as small, rounded inclusions in pyrite; molybdenite as sparsely distributed minute flakes among the gangue constituents. Cubanite and mackinawite are

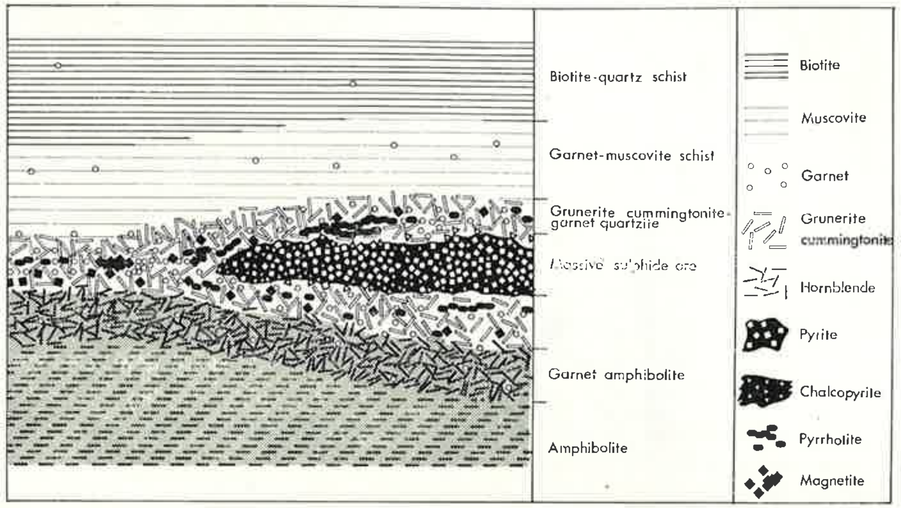


Fig. 4. The geological setting (schematic) of a pyrite ore of the Kvikne type at the border between the Gula greenstone and the surrounding metasediments.

recorded from the Kvikne, Rødalen and Klett mines as lamellar inclusions in chalcopyrite.

Magnetite and ilmenite are accessory constituents of the massive pyritic ores of the Kvikne mines, but are common ore components among the wall-rocks and iron-formations adjacent to the Gula greenstone.

Pyrrhotitic oxide/silicate iron-formation

The pyritic deposits of the Kvikne type are always accompanied by iron-rich rocks. These rocks constitute thin, stratabound horizons and are intimately associated with the Gula greenstone. Their relative stratigraphic position within the Gula Group justifies the term *iron-formation*. This term is here taken to include all the ferruginous rocks under consideration, provisionally with no reference as to their origin.

The iron-formations appear as thin layers, 1–5 metres in thickness, often tailing and uniting the discontinuous horizons of the Gula greenstone. Separate wedges are frequently seen within an envelope of garnet-muscovite schists. The iron-formations appear to have an asymmetrical position in relation to the Gula greenstone, but the isoclinal folding pattern of the metavolcanic succession has brought about a shuffling of the units involved due to slip folding. Fig. 5 gives the general relationship between the Gula greenstone, the pyritic ores and the associated iron-formation on a regional scale.

The iron-formations comprise a variety of metamorphosed lithologies, ranging from ultramafic rocks to ferruginous quartzites. The common assemblages include the following mineral components:
garnet, cummingtonite/grunerite, quartz, hornblende, biotite, magnetite, pyrrhotite and pyrite. Accessory components include some ilmenite, chalcopyrite, apatite, sphene, chlorite and rutile. The minerals occur in variable

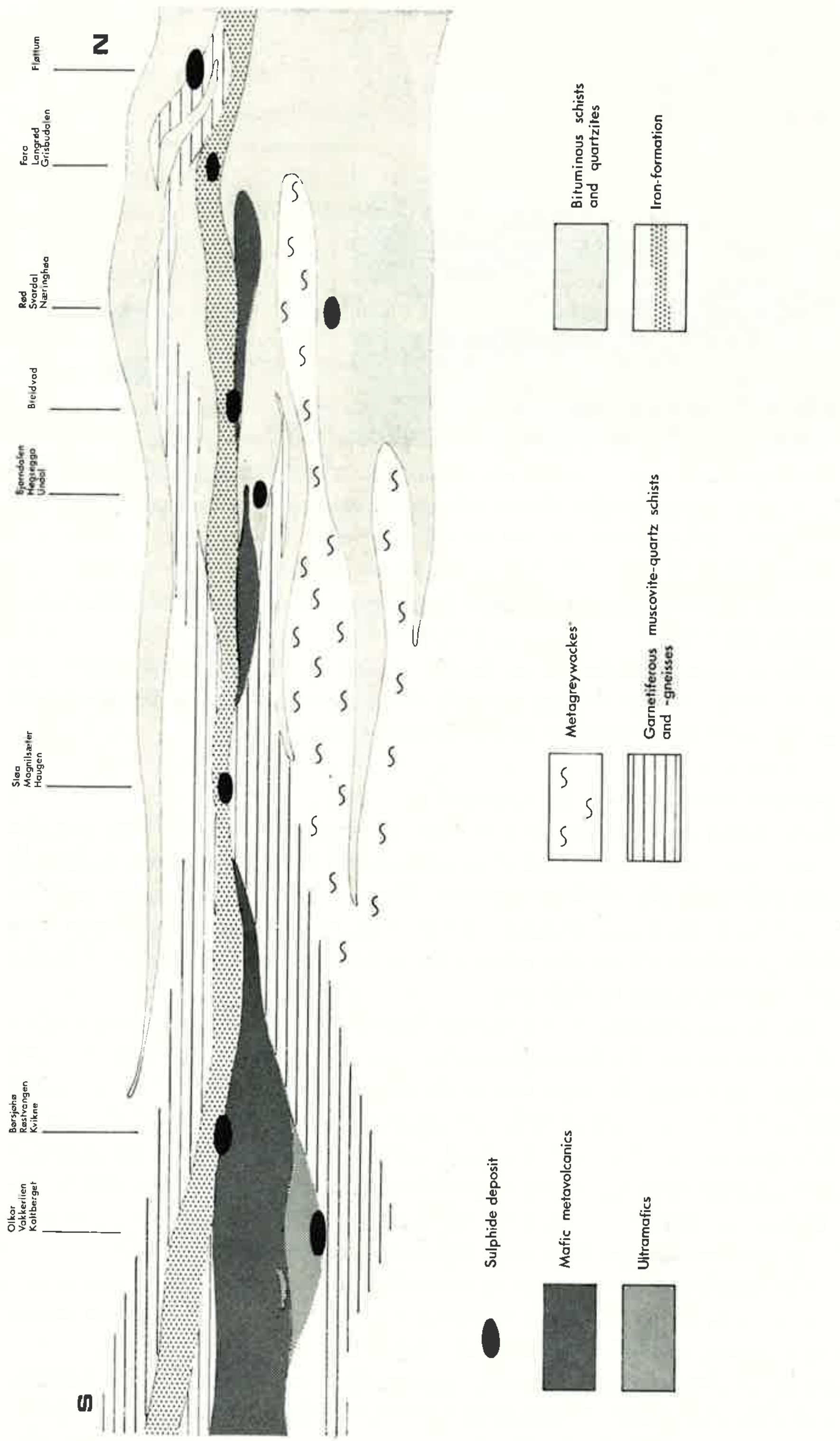


Fig. 5. The general relationship between the Gula greenstone, the associated iron-formation and the sulphide ores of the Kvikne and Budal types in a schematic N–S profile, showing the setting of some selected deposits.

proportions, but the following rock-types are commonly encountered in the field:

magnetite rock
magnetite quartzite
magnetite-grunerite/cummingtonite-garnet rock
magnetite-garnet rock
garnet-biotite rock
garnet quartzite
hornblende-garnet rock

The last-mentioned variety represents a transitional rock-type between the Gula greenstones proper and the associated iron-formation, as shown in Fig. 4.

The garnetiferous assemblages occur as medium- to coarse-grained rocks. In the central Gula Group they have an ochre-stained, crumbly appearance at the surface due to the decomposition of disseminated pyrrhotite. Within the metamorphic lower-grade south-eastern part of the region, e.g. in the *Lomnesvola* (113) and *Lomsjøvola* (114) districts, the iron-formation which accompanies the Gula greenstone consists of a fine-grained magnetite-biotite-garnet schist (Fig. 6) with numerous thin (1–2 cm) intercalations of pink, cherty garnet quartzite. Relics of similar, very fine-grained garnet quartzites

Fig. 6. Garnet–magnetite–biotite schist from the iron-formation at Lomnesvola (113). Plane polarized light. Scale bar: 100 μm.

Fig. 7. Pyrrhotite disseminations within magnetite–garnet–grunerite iron-formation at Gråhø (85). Note bundles of grunerite intersecting garnet porphyroblasts. Plane polarized light. Scale bar: 1 mm.

can be found as 'durchbewegte' fragments within the metamorphic higher-grade iron-formations of the central Gula greenstone belt from Rødalen to Budal.

Cummingtonite and grunerite are common components of the iron-formations. They occur in radiating bundles of prisms and fan-shaped aggregates with a grain-size from 0,1 mm to several mm (Fig. 7). Magnetite is a ubiquitous oxide component within the iron-formations and occurs as scattered subhedral grains, less than 0,5 mm across, which are often included in the silicate grains. A some places irregular layers of pure magnetite rocks are included in the iron-formations. At *Lomsjøvola* (114), *Drakjen* (Rødalen) (100) and *Røstvangen* (90) such layers occur as the immediate wall-rocks of the pyritic ore bodies.

A great number of small prospects and showings are confined to heavy sulphide disseminations within the iron-formations. Some of them were described from the Kvikne area by Nilsen & Mukherjee (1972) and from the Savalen district by Quenardel (1972). In neither area are they of any economic interest; however, they may have acted as prospecting guides for the associated pyritic ores of the region.

Pyrrhotite is the chief ore mineral component of these deposits and occurs as an irregular network between the silicate components, often filling cracks of shattered grains (Fig. 8). Under the microscope the sulphide component appears as a well-crystallized mosaic. Together with minute grains of ilmenite it is a common constituent of helicitic inclusion trails in garnet. Pyrite occurs in minor amounts in a few deposits as shattered, subhedral cubes. Chalcopyrite

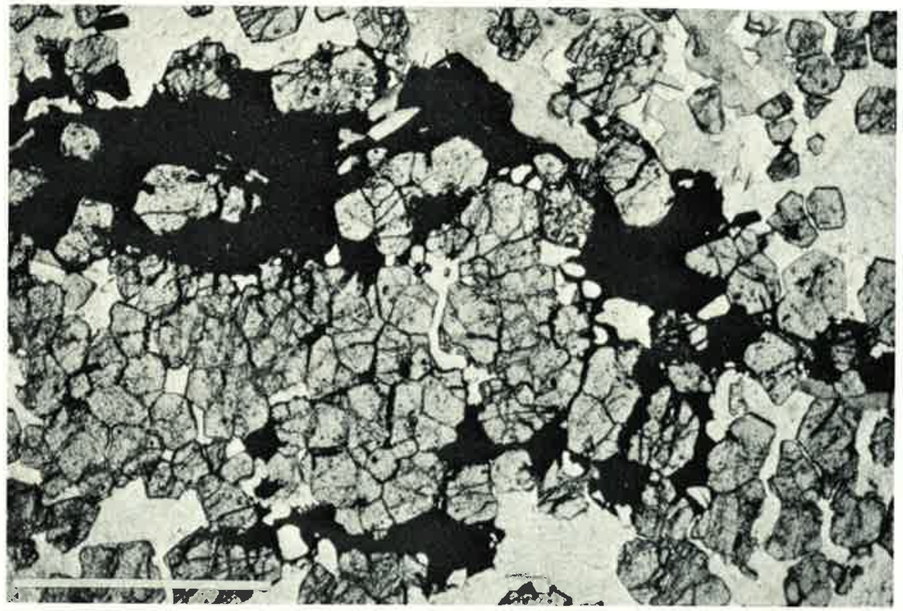


Fig. 8. Pyrrhotite dissemination within the garnetiferous iron-formation at Lomsjøvola (114). Plane polarized light. Scale bar: 1 mm.

is present in accessory amounts in nearly all of the deposits in question, occurring as minute blebs within pyrrhotite and crack-fillings in the gangue. Arsenopyrite has been found in minute quantities as idioblastic prisms in pyrrhotite ores at *Svartåsen* (105), *Lykkja* (84) and *Sæterfjell* (67). Sphalerite is virtually absent from the iron-formations of the Gula Group. While the sulphides occur both within the transitional zone to the metabasites (the hornblende-garnet rocks) and in the mica schists (the micaceous garnet rocks) (Fig. 4), the oxides are found exclusively in the latter.

The iron-formation at *Breidvad* (44) deserves special attention. Here, tectonically disrupted layers of pyrrhotite-disseminated garnet amphibolite, 1–2 m in thickness, occur embedded in the black schists of the Undal Formation close to the border of the Singsås Formation. Usually the rock displays a tectonic banding; schlieren of pyrrhotite-disseminated garnet aggregates alternate with bands of oriented wisps of green amphibole. Less schistose parts contain relics of fayalite and diopside, strongly replaced by green amphibole and cummingtonite/grunerite. The similarity with the so-called eulysites from the Precambrian of Sweden is striking and will be considered later.

Despite the extensive prospecting carried out along the iron-formations of the Gula Group, none of the occurrences has proved to be of any economical interest. Grab-sampling of the ores from nine of the deposits in question has revealed their low-grade character. Analyses give the following compositional ranges: Cu: 200–600 ppm; Zn: 100–300 ppm; S: 7–30%.

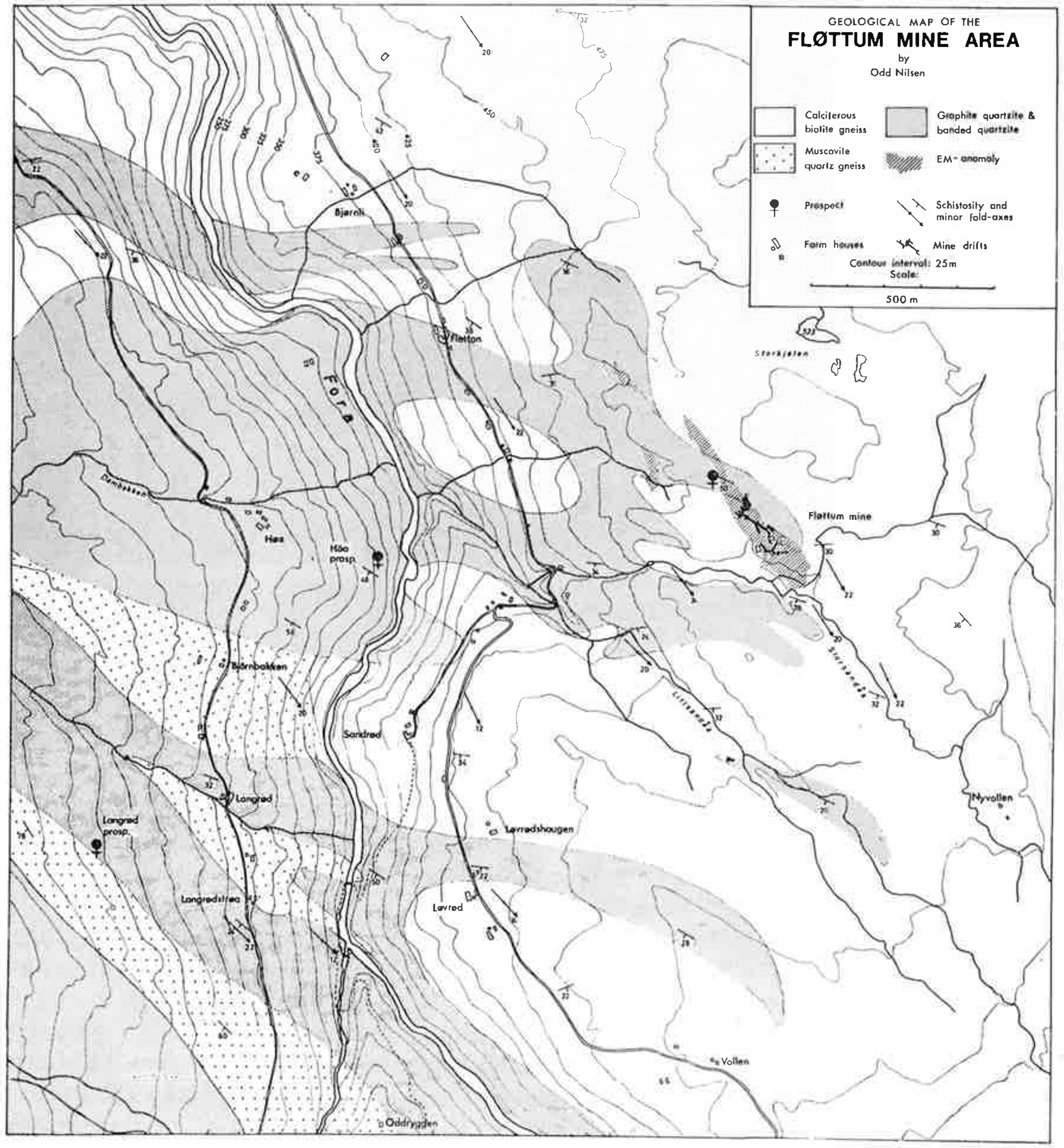


Fig. 9. Geological map of the Fløttum mine area, Fordalen.

DEPOSITS OF THE BUDAL TYPE

The deposits of the Budal type are characterized by their association with bituminous phyllites, schists and quartzites of the Gula Group. They are chiefly concentrated in the northern Soknedal-Fordalen districts, but some deposits within the bituminous assemblages of the Åsli Formation occur in the Ålen-Haltdalen districts outside the present map area. The deposits bear no apparent affiliation to the Gula greenstone, which is frequently encountered

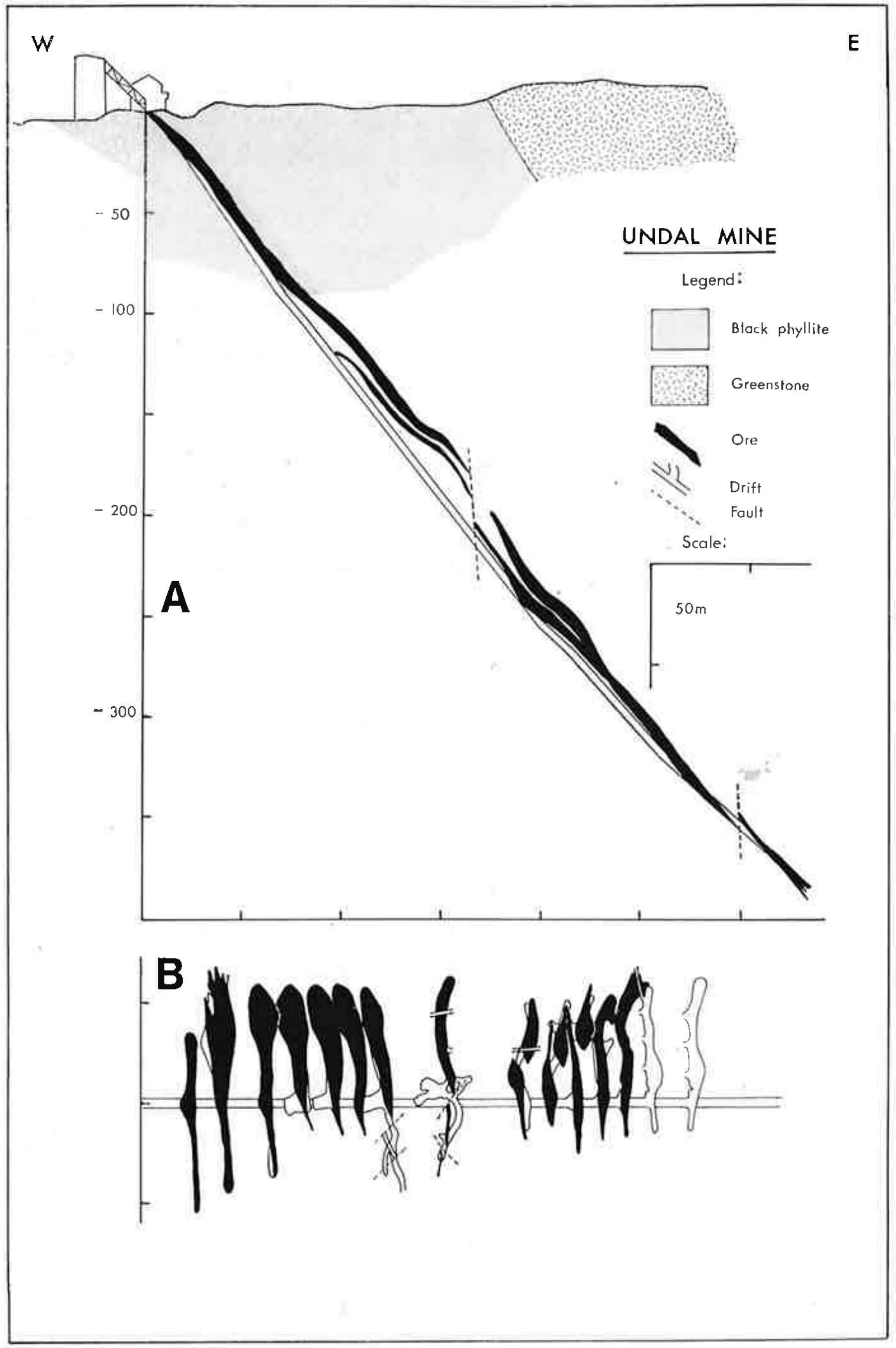


Fig. 10. Sections through the Undal mine, Berkåk.
A. Vertical profile along the ore axis.
B: Horizontal projections of the ore body at different levels. (From Lindberg (1971)).

as discontinuous and contorted layers within the different bituminous assemblages.

As in the case of the Kvikne type, the Budal type of sulphide deposits can be classified into massive pyritic deposits and disseminated pyrrhotitic deposits, though in this case the distinction between the two types in less clear-out. Here too, the pyritic deposis constitute the most important ores and have been the objects of intensive exploration at *Bjørndalen* (60), *Rogstad* (52), *Fløttum* (117), *Undal* (26), *Ilbogen* (16) and *Vasli* (29).

The pyritic bodies apparently display the same morphological features as do the other pyrite deposits of the Gula Group as revealed from the diamond-drill reports and workings at Fløttum (Ljøkjell 1953) and Undal (Brodtkorb 1926, Lindberg 1971) where exploitation and investigations have reached deeper levels of the ores. The ores occur as steeply inclined, ruler-shaped bodies. At Fløttum the main ore body is surrounded by several parallel-oriented satellites at the hinge-zone of a parasitic fold at the border between bituminous quartzite and the surrounding calcareous biotite gneiss of the Singsås Formation (Fig. 9). At Undal the pyrite body was followed for about 600 metres along its axis (Fig. 10). In the strike direction most of the pyrite bodies continue as pyrite- and pyrrhotite-disseminations within quartzitic bands in the black meta-sediments.

The pyritic ores of the Budal type have a simple mineralogy with the exception of the Fløttum ores which exhibit a rather complex mineral paragenesis. The pyrites of the deposits, confined to the metamorphic low-grade parts of the Undal Formation (e.g. in the Soknedal-Berkåk districts), are usually of a fine grain (0,01–0,5 mm) and exhibit textures indicating different, and in some places, overlapping stages of a progressive metamorphism, as shown by e.g. recrystallization by nucleation ('Sammelkrisallisation'), different stages of porphyroblastic growth and replacement by pyrrhotite, and progressive stages of deformation of primary sulphide layers, accompanied by neo-mineralization. The pyrites of the metamorphic higher-grade Budalen-Fordalen ores have a coarser grain-size (1–3 mm) and exhibit the same textural relationships against the other sulphides as for the Kvikne type of ores.

Sphalerite is an important constituent of the Fløttum ores and occurs as a minor component among the ores at Undal. At Bjørndalen it occurs in accessory amounts. At Fløttum it is locally concentrated together with chalcopyrite,, giving high-grade ores with 4–7% Zn and 1–2% Cu. It is here the dominant matrix sulphide component, associated with chalcopyrite along lobate grain boundaries. At Undal, sphalerite constitutes an important matrix component among the pyritic ores, though in lesser quantities and with a more equal distribution.

Chalcopyrite is virtually absent from most of the massive pyritic ores of the Budal type, but appears often together with pyrrhotite as veins and stringers within the wall-rocks – more or less conformable with the massive bodies. Chalcopyrite is a common minor component in the pyritic ore at Fløttum. Here the cupriferous ores exhibit the most variegated ore mineral parageneses; galena, tetrahedrite, mackinawite, pyrargyrite, a silver telluride, alabandite and native bismuth have been observed and confirmed by probe. Where present, chalcopyrite occurs as an accessory matrix component of the pyritic ores outside the Fløttum mines; at Undal it is intimately associated with pyrrhotite and/or sphalerite.

Most of the sulphide deposits of the Budal type occur as low-grade pyrrhotite disseminations in the black schists and the bituminous quartzites of the Gula Group. Many of the occurrences are concentrated in three districts, viz. the Budalen-Fordalen area, the Soknedal-Berkåk area and in the Ilbogen area on the eastern slope of the mountain Ilfjellet. A few deposits are found in the Undal Formation in the Orkelsjøen area and near Hjerkinn in the southern part of the map area.

In the Budalen-Fordalen area the mineralizations are confined to highly tectonized, black, often garnetiferous biotite quartzites as local pyrrhotite disseminations. Here, pyrrhotite is the dominant sulphide component and appears as a granoblastic web, often in a pronounced tectonic banding, enveloping and replacing the gangue constituents along cracks and crystal faces. Chalcopyrite has been found only as small stringers in the black schists at the prospect close to the adits at Fløttum (Fig. 9), but is virtually absent from the other deposits. Sphalerite is a common accessory component among the pyrrhotitic ores of this district, but the ore grade never attains values above 0,1% Zn.

Black phyllites and dark quartzites are the common host rocks of the pyrrhotitic sulphide ores of the Soknedal-Berkåk area. Compared with the metamorphic high-grade Budal-Fordalen district, this province is representative of a lower metamorphic grade (lower greenschist facies), which is reflected

Fig. 11. SEM-picture of framboidal pyrite in quartzite, Vora prospect, Berkåk. Scale bar: 5 μm.
Fig. 12. Pyrrhotite (darker grey) replacing aggregates of framboidal pyrite (paler grey), Høgsegga mine, Hauka valley. Plane polarized light. Scale bar: 10 μm.

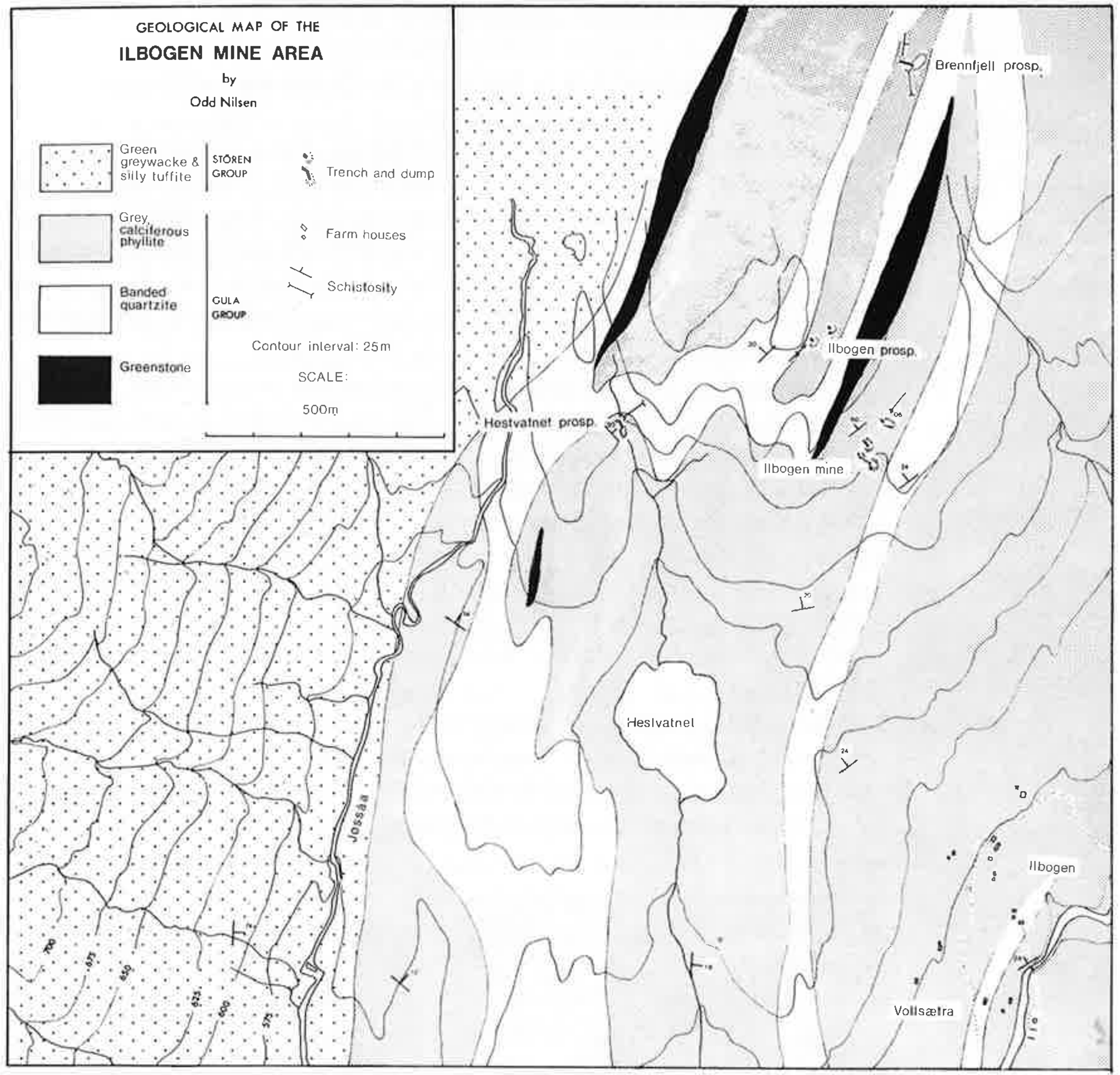


Fig. 13. Geological map of the Ilbogen mine area, Rennebu.

in the textures of the ores. The mineralizations are of a finer grain, and traces of a primary banding of the different components can be recognized in breccia fragments in some of the ores from the area. Here, pyrite is a common constituent and occurs in bands of scattered framboids (e.g. at *Vora* (24), Fig. 11) or close-packed framboidal aggregates replaced by pyrrhotite (e.g. at *Høgsegga* (53), Fig. 12). The fragments of the brecciated ores are healed by a granoblastic web of pyrrhotite and pyrite and in some deposits (e.g. at *Næringhøa* (39) and *Bjørkås* (28)) the pyrrhotite cement constitutes the matrix of a twisted and ball-textured breccia of black phyllite. In general in this area, pyrite and pyrrhotite appear as fine-grained and crenulated bands, 1–2 cm in

thickness, along the dominent axial plane schistosity of the black pelites of the Undal Formation.

The sulphide deposits of the Ilbogen area are clustered around the *Ilbogen mine* (16) and the *Vasli mine* (29) (Fig. 13). They are confined to the border between calcareous dark-grey phyllites and banded quartzites of the Undal Formation. The numerous excavations reveal low-grade, heavily brecciated pyrrhotite disseminations with a variable pyrite content. The ores appear as several steeply dipping sheets, 1–3 m i thickness, which are offset by numerous flat-lying faults. At Vasli, diffuse bands of massive pyrite ore, some 10 cm in thickness, are embedded in an ore zone, 15 m across, of a brecciated pyrrhotite ore.

As previously stated, the pyrrhotitic ores of the Budal type are economically of a very low grade character. Chalcopyrite and sphalerite are met with as occasional small splashes and blebs in the pyrrhotitic matrix, often bordering the present pyrite grains of the most reworked and recrystallized ores. Grab-sampling of eight deposits revealed the following ranges: Cu: 100–700 ppm; Zn: 100–800 ppm; S: 6–25%.

DEPOSITS OF THE OLKAR TYPE

The Olkar type of sulphide deposits encompasses a few Cu/Ni-showings associated with some minor mafic and ultramafic inclusions of the Gula greenstone and some alpinotype pods within the Singsås Formation, possibly derived from the same source.

The ultramafic rocks occur as small bodies, ranging in size from less than 1 m^3 to outcrops of some 100 m^2, usually enclosed within, or at the border of, the Gula greenstone. The rocks comprise serpentinites, talc-chlorite schists and hornblendites, and the less altered varieties show a lherzolitic composition. Their petrology and geochemistry were described by Nilsen (1974) together with comments on their sulphide mineralizations.

Sulphide ores occur generally as common accessory components among the different types of ultramafics within the Gula Group. They comprise pyrrhotite, chalcopyrite, pentlandite and pyrite, in decreasing order of abundance. At the prospects of *Vakkerlien* (75), *Olkar* (74) and *Kaltberget* (73) heavy cupriferous pyrrhotite disseminations occur within the brecciated border-facies of metagabbroic and ultramafic assemblages (Nilsen & Mukherjee 1972). Pentlandite occurs here either as exsolved flames in pyrrhotite or as discrete grains. Grab-sampling from the Vakkerlien and Kaltberget mines reveals ore grades at about the following values: Cu: 1–1,5%; Ni: 1–1,3%.

DEPOSITS OF THE RENNEBU TYPE

The sulphide deposits of the Rennebu type are confined to the metavolcanic assemblages of the Støren Group. The deposits are mainly located within, or at the border of the pillow-lavas and their metamorphic equivalents in the Rennebu-Innset districts. Like the deposits of the Kvikne type they are further characterized by an intimate association with iron-rich silicate/oxide rocks.

Fig. 14. SEM-picture of roe-textured pyrite ('Rogenpyrit') formed by coalescence of framboids, in stage of porphyroblastesis. From pyritic 'vasskis'-ore, Kalddalen prospect VII, Rennebu. Scale bar: 5 μm.

In the *Kalddalen* area (13,14) the sulphide ores appear as composite, fine-grained sheets or discontinuous layers, 1–5 m in thickness. They can be followed for almost 2 km along their strike direction, being emplaced between two piles of massive greenstone lavas, locally pillowed. Here they are always accompanied by, and rhythmically interbedded with, a fine-grained laminated black magnetite-chlorite rock – better known as *'svartfels'* ('black fels') among Norwegian geologists. The oxide/silicate association present is well known from other sulpide deposits within metamorphic low-grade Caledonian metavolcanics (e.g. Falkenberg 1914, Kurek 1931, Foslie 1926, Oftedahl 1958a, Torske 1965) and corresponds to the *Leksdal type* of sulphide deposits, a term introduced by Carstens (1920, 1924a). The colloquial term *'vasskis'* was, however, previously applied to this particular type of ore and is still in use, especially in the Løkken mine district north of Meldal.

In the *Hakefjellet* (13) and *Kalddalen* (14) deposits the sulphide layers consist of a very fine-grained mush of coalesced framboids, enveloping partly recrystallized cubes (Fig. 14). The pyrrhotite content is variable and constitutes a dominant matrix component of the ores of the northern Kalddalen prospects. A delicate mm-scale lamination of the ores is usually present due to differences in grain size, framboid/cube ratio and pyrite/pyrrhotite ratio. Thin ($<$1 mm) veins of recrystallized pyrite criss-cross the ores giving them a texture like the surface of a water-melon. Chalcopyrite and sphalerite are accessory components in very small amounts; where present they occur as small blebs in the vein-pyrite.

As with the majority of similar 'vasskis' deposits of the Caledonides of Norway, the sulphide ores in Kalddalen show a negligible content of copper and zinc (Carstens 1941). Representative samples from three of the deposits in question give the following values: Cu: 100–500 ppm; Zn: 50–400 ppm; S: 31–35%.

The pyritic sheets have sharp contacts to the interbedded 'black fels'. The latter has a neglible sulphide content, but magnetite constitutes about 50 vol% of the rock as anhedral grains, 7–10 μm in grain-size, enveloped by a felty mass of olive-brown stilpnomelane and minor interstitial quartz. Some carbonate and pale amphibole may occur. The oxides are often arranged in discrete laminae.

Another 'vasskis' zone is exposed at the *Ramfjell mine* (23) about 20 km SSW of the Kalddalen deposits. Here the zone can be followed as a steeply inclined sheet for about 50 m in a N-S direction. The sheet is bordered to the eastern greenstone complex via a thin (0,5 m) horizon of agglomerate. Fine-grained, black garnetiferous chlorite-magnetite quartzite constitutes the main host rock of the ore zone here, which was mined for iron ore during the 1850's. Pyritic layers are only locally developed as thin (30–50 cm) bands.

At the *St. Olaf mine* (21) and the adjacent *Sliper prospect* (20) in the Orkla valley, only oxide ores are present. Here, cherty hematite/magnetite layers of about 3 m in thickness occur at the border between the greenstones lavas and the tuffaceous metasediments, developed as flaggy, calcareous chlorite-quartz schists and impure, banded quartzites. At the St. Olaf mine, pure magnetite layers occur within a brecciated, fine-grained garnetiferous chert, while magnetite occurs as porphyroblasts in a chlorite-specularite schist at Sliper. The only sulphide species present are accessory bornite and blaubleibender covellite, both in very small amounts.

Analyses of the 'black fels' iron ores from the Ramfjell, St. Olaf and Sliper deposits reveal low Fe contents, ranging between 18 and 25% Fe. The ores were refined by a blast furnace at the farm Flå (The St. Olaf Iron Works) which over the years 1854–1862 produced 350 tons of pig iron (Hiortdahl 1877).

Prospecting for similar ores has been carried out at *Leverdalen* (1) on magnetite-disseminated quartzite.

The *Nyberget mine* (31) near Innset and adjacent prospects constitute some Rennebu-type sulphide deposits within a higher-grade metamorphic milieu. A lateral thinning of the greenstone units and an increasing influx of tuffaceous material is apparent here. A rapid vertical change of the volcanogenic units is conspicuous and the sulphide deposits are here invariably confined to the border between the thin greenstone horizons, metamorphosed into schistose, dark amphibolites, and the adjacent tuffaceous units, usually developed as impure, banded quartzites and biotite schists.

The ore body at Nyberget mine appears as a composite sheet, 0,5–3 m in thickness, conformably emplaced between two greenstone units and has been followed for about 300 m along its strike. Figs. 15 and 16 show the workings and the geological setting of the ores.

Fig. 15. Nyberget mine, Innset. View to the south. Note the inclined trench with rock pillars in the pyrite ore, and footwall amphibolite exposed in the lower part of the hillside.

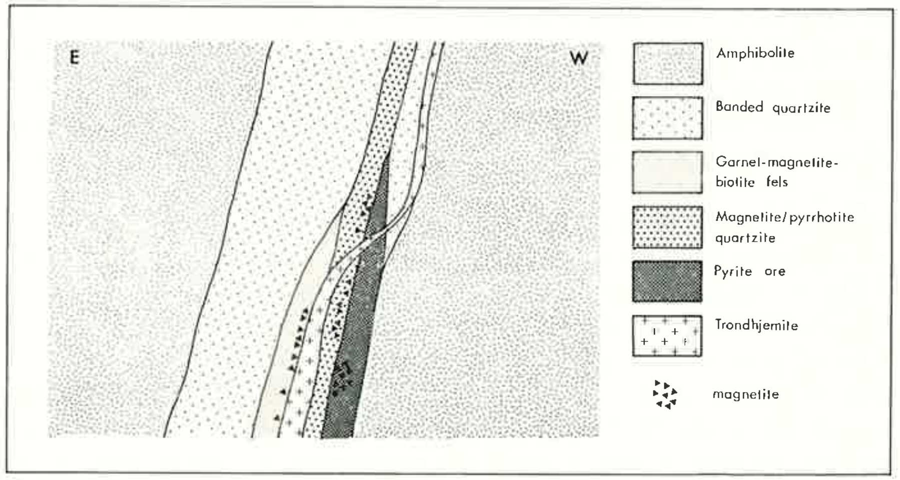
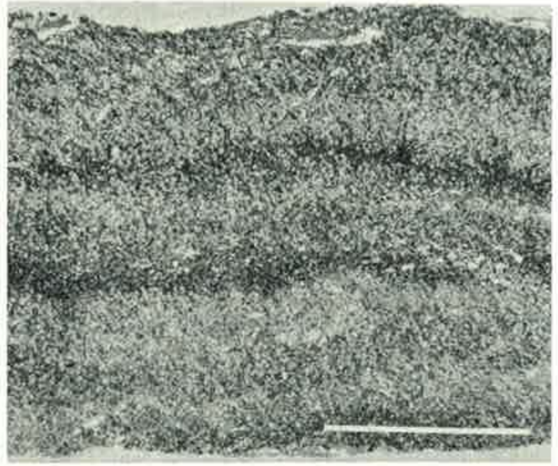


Fig. 16. Schematic vertical profile across the ore zone at Nyberget mine, Innset.

Massive, medium-grained pyrite ore is close to the greenstone and is chiefly composed of granoblastic pyrite with interstitial minor sphalerite and magnetite. Towards the hanging wall it grades into weak pyrrhotite- and

Fig. 17. Finely banded magnetite–garnet rock from the iron-formation adjacent to amphibolite of the Støren Group, Fjellbekken, valley of Inna, close to the Tverrfjellet prospect (36) (loc. 553 485; 1:50,000 map sheet Innset). Plane polarized light. Scale bar: 1 cm.



chalcopyrite-disseminations within the quartzites. Dark, garnetiferous biotite-magnetite rocks – partly disseminated with pyrrhotite – overlie the sulphide mineralizations. They are generally found as distinct layers, 5–10 m in thickness, close to the amphibolites in the area (Fig. 17). Pink, cherty inclusions are frequently found, and reveal their affinity with the black felses to the north. The magnetite of the wall-rock quartzite is locally replaced by pyrrhotite along the margins of the sulphide ore. Magnetite (± garnet ± epidote) is, furthermore, a common constituent as laminae between the quartzite bands of the banded quartzite of the area. Swarms of trondhjemite dykes have been conformably injected along the different units and cut through the ore body at Nyberget.

The oxide component of the Rennebu type of ores is quantitatively less developed in the *Skamfjell* (10) and *Jorfjell* (11) area. Here, fine-grained magnetite/ilmenite disseminations occur within the wall-rock amphibolite, enclosing thin, pyritic lenses.

In general, the deposits of the Rennebu type show many features in common with the Kvikne type of deposits when occurring in a higher metamorphic grade, as revealed from the Nyberget and adjacent deposits; the relationship between the sulphide and the oxide ores of these two categories will be considered further below.

DEPOSITS OF THE ELGSJØ TYPE

To the south of the Innset area, and intercalated between the lava flows of the Rennebu area, volcanoclastic rocks of the Elgsjø Formation of the Støren Group are hosts to several sulphide deposits. The associated deposits will consequently be classified as belonging to the Elgsjø type.

In contrast to the barren mafic lavas of the remainder of the Støren Group, the tuffaceous rocks of the Elgsjø Formation often carry weak pyrite disseminations, and in some places massive sulphides are present. These are mainly concentrated in the Fundin-Hjerkinn area, with the *Heimtjønnhø deposit* (50) being one of the biggest in the district. Mining and drilling operations during the years 1919–1922 revealed here a composite and highly elongated massive pyritic body, encompassing 1,6 mill. tons of probable ore (Foslie 1926). The ore body is emplaced conformably within the NNE-SSW-trending tuffaceous sericite-chlorite phyllites and the banded green quartzites of the area. According to Foslie (1937) and Waltham (1968), the ore body has a Z-shaped cross section, possibly due to tight or isoclinal folding. Thin (1–15 m) horizons of chloritic greenstone are present in the volcanic pile, close to the ore body.

The composition of the massive ores at Heimtjønnhø is very simple. Pyrite constitutes almost the only sulpide species present, and occurs as a fine-grained, close-packed mosaic (e.g. Waltham 1968, p.B158). Magnetite occurs occasionally, while pyrrhotite and chalcopyrite are rare. If present, they occur as small blebs (as with galena) within the pyrite.

The deposits of the *Elgsjøtangen* area (45–49) to the north of the Heimtjønnhø deposit display a similar geological setting. Only minor mining and drilling operations have been carried out here. A mineralized zone, only a few metres in thickness, can be followed for at least 3 km from the *Elgsjøtangen prospect* (45) to the *Elgsjøbekken prospect* (48). To the south it is offset by the major SSE-NNW-trending Vinstra fault. The zone strikes parallel to the axial plane of a tight, recumbent fold in the Elgsjø Formation, traced by a thin greenstone horizon. It is confined to impure quartzitic layers within the tuffaceous sericite-chlorite phyllites. Pyrite is the dominant ore component of these deposits and pyrrhotite may occur as a minor component. Chalcopyrite and sphalerite are accessory components in very small amounts.

At the *Hammersæter deposit* (22) in the Rennebu district, minor excavations have been made in a pyrite horizon, a few metres in thickness. This is embedded in banded, greenish quartz phyllites. The sulphide zone has been followed for about 200 m, just below a thin greenstone horizon. The ores have a composition similar to that of the Elgsjøtangen deposits.

The deposits in the valley of Driva to the north of Hjerkinn (4,5) are situated within the metamorphic high-grade equivalents of the Elgsjø Formation. Several pyritic lenses, which at the *Vårstigen prospects* (4) comprise about ½ mill. tons of probable ore, are confined to a sulphide zone which can be followed for at least 3 km. The mineralizations lie within coarse-grained garnetiferous garben gneisses and quartzites, close to the foot-wall of a composite amphibolite horizon.

The *Tverrfjellet mine* (7) lies in the southern continuation of the sulphide belt from Elgsjøtangen to Heimtjønnhø and contains the biggest sulphide ore reserves in the southern Trondheim region. The deposit has not been investigated by the present author, but it appears to have a similar geological setting as the other Elgsjø-type deposits as revealed from the present field-map. According to Geis (1961), Tysland (1974) and Husum et al. (1975) the sulphide bodies at Tverrfjellet appear as steeply inclined lenses, conformably embedded in the quartzites and green phyllites of the Elgsjø Formation in close proximity to the associated greenstone horizons of the area. The ore reserves

are of the order of 20 mill. tons of pyritic ore with an average grade of 1% Cu, 1,2% Zn and 32% S. Very low-grade banded magnetite/pyrite portions may, however, occur conformably within the ore lenses (Waltham 1968), which points to the presence of a Rennebu-type or a 'vasskis' component in the Tverrfjellet ore. Generally the tuffaceous metavolcanics of the Elgsjø Formation carry oxide ore as thin (<1 mm), banded disseminations of magnetite (locally as bigger porphyroblasts) and ilmenite, uniformly disseminated as minute flakes.

A very low copper content is a characteristic feature of the pyrite deposits of the Elgsjø type. Cobbed ores from the Heimtjønnhø, Elgsjøtangen and Vårstigen deposits reveal the following ranges: Cu: 40–400 ppm; Zn: 70–600 ppm; S: 30–40%.

DEPOSITS OF THE SAVAL TYPE

The deposits of the Saval type can be considered as representatives of the abundant stratabound pyrite deposits which are confined to the main volcanogene Hersjø Formation of the eastern Trondheim region. Here they represent a great diversity with respect to mineralogy, size and setting within the volcanogene lithologies of the formation.

The deposits are represented by three minor excavations in the Hersjø Formation of the Einunnfjell antiform at Savalen. At *Gressgodtvangen* (104) bands of heavy sulphide dissemination, 10–30 cm in thickness, occur conformably arranged within the highly tectonized amphibolites of the area. A coarse-grained pyrite ore with minor sphalerite is the dominant type, grading vertically into heavy sphalerite/pyrrhotite disseminations within the amphibolite wall-rock.

Discrete horizons of quartz-keratophyres of variable thickness (1 cm – 10 m) are commonly intercalated within the metavolcanics of the Hersjø Formation and constitute the host rocks of the sulphide mineralizations at the *Veslehøa prospects* (102, 103). Disseminations of pyrite and pyrrhotite occur here within a 3 m horizon of quartz-keratophyre, developed as a medium-grained, partly hornblende-bearing, chlorite-andesine-quartz rock. Single pyrite bands, 1–3 cm in thickness, may also be present.

ORE DEPOSITS OF NON-STRATABOUND TYPE

Within the present area a few ore mineralizations of a diversified, non-stratabound type occur (see appendix). They include a minor chromite deposit at *Svarthølhaugen* (3) in the Vinstra valley to the south of Oppdal. The chromite mineralization occurs as disseminations and veins within a lensoid serpentinite, emplaced at the tectonic border zone between the garben gneisses of the Elgsjø Formation and amphibolites of the external, western basal gneiss/flaggy quartzite complex. The serpentinite lens has a thickness of 10–50 m, and has been followed for about 300 m along its boundary. Similar alpinotype chromite-bearing ultramafic pods are frequently present in the amphibolite/mica gneiss division of the western, Precambrian, basal gneiss complex of the

Oppdal-Sunndal region (Rosenqvist 1943, Holtedahl 1950, Holmsen 1955). As previously mentioned, chromite-bearing serpentinites are also well known from the eastern part of the Trondheim Nappe where they make up a distinct 'soapstone horizon' from Røros to Folldal (Kjerulf 1879, Rui 1972, 1975). The question of a stratigraphical correlation of the ultramafics of the Oppdal area with the ultramafics of the eastern zone was already raised by Foslie (1925, p. 26). The actual chromite/serpentinite association is an alien element among the western Støren Group and higher lithologies. No chromite mineralizations have been found within the syn-volcanic ultramafic inclusions of the Gula greenstone either (Nilsen 1974). Thus the idea of a Precambrian age for the Svarthølhaugen and adjacent chromite deposits has much in its favour.

Within the Trondheim Nappe some sulphide mineralizations are confined to young pegmatite veins. At *Dølvad* (51) a system of steeply inclined joint fillings of coarse-grained quartz and calcite, each about 50 cm in thickness, follows a NW-SE trend. Pyrite and galena are found as coarse-grained aggregates in the pegmatite. Under the microscope accessory chalcopyrite, tetrahedrite and native bismuth have been found and confirmed by probe.

In the highly tectonized gneiss area of the upper Gauldalen district, pegmatites of trondhjemitic and granitic compositions are frequently observed as irregular dykes, often several metres in thickness, which transect the calc-silicate-bearing biotite gneisses. At one locality in northern Ledalen, disseminations of coarse-grained pyrite and molybdenite are found within a graphic granite pegmatite. Similar molybdenite mineralizations are known from the Haltdalen district, about 5 km to the east of the valley of Ledalen.

A weak pyrrhotite dissemination is often present within the migmatitic calc-silicate gneisses in the valley of Gauldalen. It may be detected by a conspicuous ochre-staining of the road-cut exposures. While the sulphur content of the calcareous biotite-quartz schists of the Singsås Formation to the south is nil, that of the migmatites lies between 0,5–2% which corresponds to a pyrrhotite content of about 1–3 vol.%. The pyrrhotite disseminations occur most frequently in areas of multiple injections of trondhjemite and around the Singsås igneous complex. Similarly, the hornfelses forming the contact aureole around the Øyungen gabbro complex locally show a marked sulphide enrichment as compared with the barren phyllites of the Åsli Formation to the south. A genetic relationship between the igneous activity and the apparent sulphurization of the host rocks of the district seems probable.

Comparative petrogenetic considerations

In the present paper the sulphide deposits of the southern Trondheim region are, by virtue of their clear stratabound nature, classified primarily on the basis of their stratigraphical setting, and secondly according to the specific lithologies with which they are associated. Several schemes of classification have been applied by Norwegian geologists to the Caledonian sulphide deposits, as reviewed by Vokes (1976). The present scheme does not intend to reform the existing classes which have been proposed over the years, but seeks to act as a basis for a comparison between deposits of different ages and geological settings. The fact that there exist great similarities between sulphide deposits of different geological settings has raised the question as to whether the deposits were derived from a common source and has drawn special attention to the effect of metamorphism upon the sulphide assemblages. In the case of deposits of the Rennebu and Elgsjø types, their origin is evidently related to different volcanic processes as revealed by their close affiliation to the adjacent pillow-lavas and volcanoclastic rocks, respectively. Within the Gula Group the ore deposits are located within a higher-grade metamorphic terrain, and more intensive, polyphase tectonic events and processes have erased their primary lithological relations. Here the metamorphic and tectonic processes have evidently brought about a remobilization and a redeposition of the primary ore components on a larger scale. The distinction between a *metamorphosed* ore and a regenerated or a *metamorphic* ore (Mookherjee 1970, Sangster 1971) can be difficult to make out, especially when investigations are locally restricted.

Some of the effects of metamorphism on the Caledonian stratabound sulphides have been reviewed by Vokes (1968) and with reference to the present deposits they will be discussed as the products of the following processes: (a) Structural changes; (b) Textural changes; (c) Redistribution of elements; (d) Formation of new phases; (e) Mineral and chemical zoning.

STRUCTURAL FEATURES

A conspicuous feature of most of the Caledonian sulphide deposits is their general elongate, lensoid morphology. To the extent that three-dimensional surveys have been carried out, the sulphide ores of the present region have been shown to display either ruler-shaped or ellipsoidal morphologies. The tectonic influence on the morphology of the Caledonian sulphide bodies was pointed out by Vogt (1945b, 1952) who demonstrated the congruence between the ore axes and the predominant 'flowage structures' present, caused by plastic movements and minor folding of the host rocks. The apparent tectonic control of some of the sulphide deposits of the easern part of the Trondheim region has been demonstrated by Rui (1973a, 1973b). Plots of the known ore axes from four of the deposits here under consideration are shown in Fig. 18; they are parallel to the trend of the F_2-lineations in the respective mine areas and emphasize the cogent tectonic control governing the metamorphosed ores in question. As with the ores investigated from the Røros area, fold hinges also appear to be favourable loci for the ores at Røstvangen and Fløttum.

Several workers have stressed the primary sedimentary control of the elongated, massive sulphide deposits in general, considering them as having been emplaced in narrow, trench-like depressions on the sea-floor (e.g. Oftedahl 1958a, Geis 1960, 1961, Anger 1966, Gräbe 1972). The apparent congruence between ore axes and the tectonic structural elements cannot be coincidental, however, irrespective of the shape of the original proto-ore. As

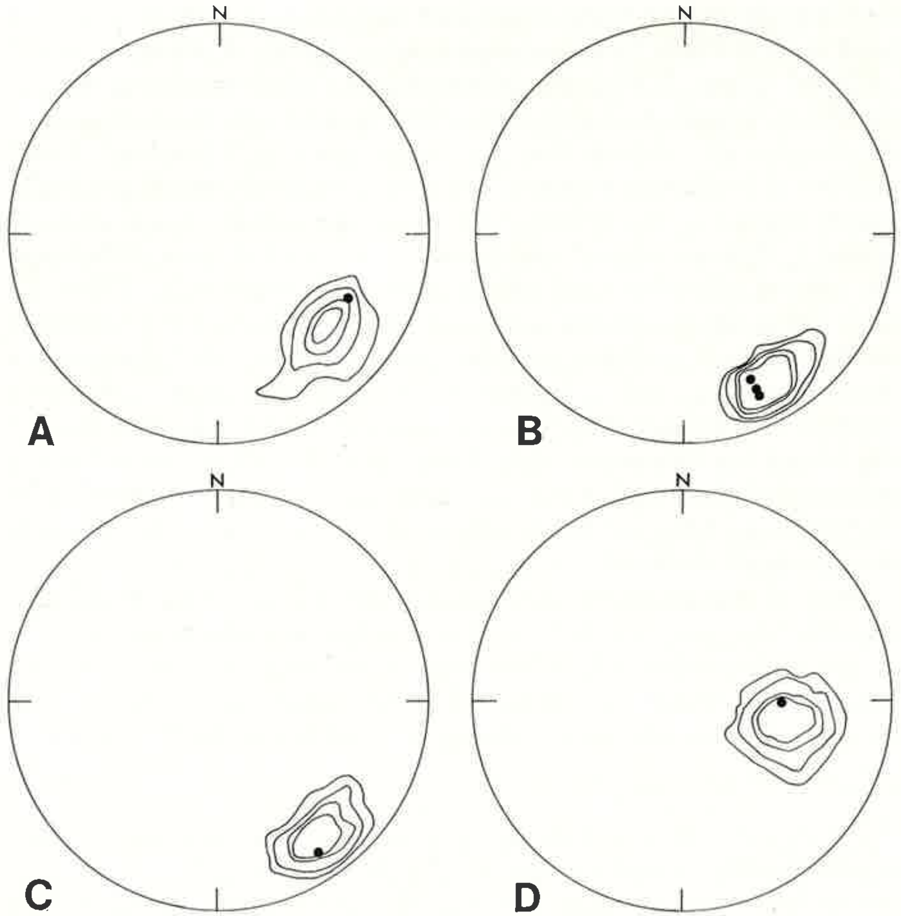


Fig. 18. F_2 lineations (linear preferred orientations of minerals and mineral aggregates) and minor fold axes of the: A: Kvikne mine area (106 obs.). B: Røstvangen mine area (56 obs.). C: Fløttum mine area (82 obs.). D: Undal mine area (35 obs.). Equal area projection; lower hemisphere: Contours: 5–10–20–25% per 1% area. Dots: Orientation of ore axes of the respective mines.

pointed out by Zachrisson (1971), with reference to the highly elongate Stekenjokk sulphide body in Sweden, the controlling agency of a primary elongate sulphide body is not likely to have had much influence upon the actual regional folding-pattern observed. However, the common *en échelon* pattern displayed by several sulphide ores may be ascribed to the tectonic contortion of one single, primary, elongate ore layer, although alternative explanations based on original sedimentological processes have been put forward (Geis 1976).

TEXTURAL AND MINERALOGICAL FEATURES

Original depositional features are rarely observed within the sulphide deposits under consideration. Metamorphism and tectonic processes have brought about

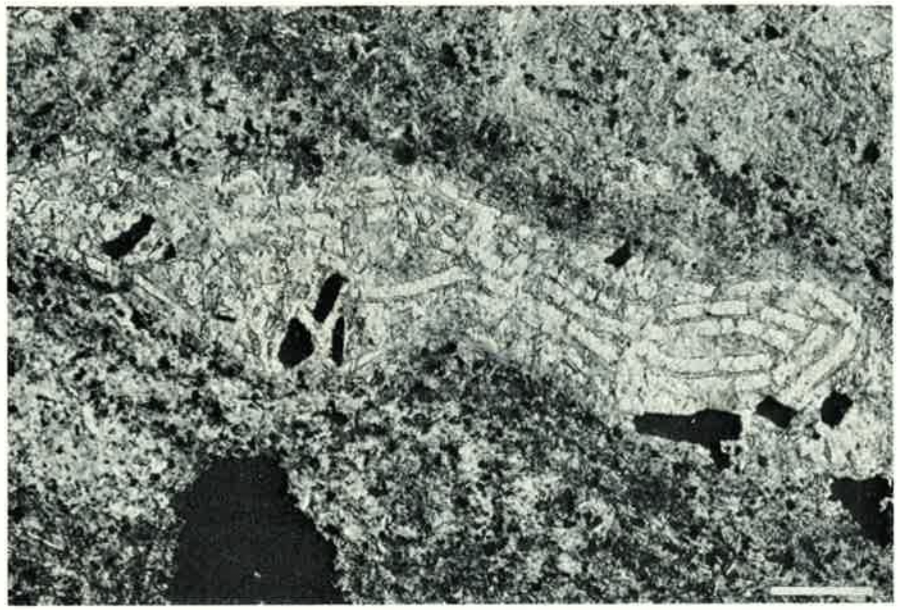


Fig. 19. Contorted, glassy microband of a probable colloidal origin. From the 'black fels' at Hakefjellet prospect, Rennebu. Magnetite (black) in a dark chloritic matrix. Plane polarized light. Scale bar: 100 μm.

profound textural and mineralogical changes within the ores. Due to the relatively great number of deposits investigated, it has been possible to record several different stages of the textural and mineralogical changes at different scales.

The Rennebu-type ores at Kalddalen (13,14) represent the least affected ores with respect to metamorphic and tectonic influence. On the megascopic scale their primary sedimentary nature is revealed by their delicate composite banding. Inclusions of collapsed glassy microbands within the 'black fels' point to a possible colloidal origin for at least some of the components of the ore. Colloidal textures of the sulphide components are described from similar 'vasskis' deposits in Grong (north of the Trondheim region) by Oftedahl (1958b). These correspond to a concentric variety of framboidal pyrite commonly observed in the Vora prospect (24). Usually the framboids occur as raspberry-like aggregates composed of several pyrite granules (Fig. 11). In the Kalddalen, Ilbogen and Høgsegga deposits framboidal pyrite is frequently met with as a roe-textured mush, corresponding to the *Rogenpyrit* of Fabricius (1961).

An initial pyrite porphyroblastesis takes place at the expense of the framboidal mush, which indicates an arrested state of growth (Fig. 14). The preservation of framboidal textures within pyrite porphyroblasts has been noted by Bernard (1964), Arnold et al. (1973) and Rickard & Zweifel (1975). A similar, partial recrystallization of mineral grains by an inward porphyroblastic growth with retention of an original texture has been reported by

Fig. 20. Tourmaline in the framboidal pyrite ore at Kalddalen prospect VII. SEM-picture. Scale bar: 100 μm.

Pittman (1972) in the diagenesis of quartz in sandstones. In this connection it is interesting to note that the framboidal texture seems to outlast the complete recrystallization of quartz shown by the granoblastic polygonal texture of quartz grains with straight boundaries and triple-points (Fig. 11).

Even if the formation of framboids is imperfectly understood with respect to their organic/inorganic affiliation (e.g. Kalliokoski 1974), their colloidal, sedimentary origin is favoured by most of the contributors in this field. A *possible* exhalite component of the ores in question is revealed by the abundant tourmaline in the sulphide portions of the Rennebu ore type (Fig. 20). The mineral appears to be a characteristic component of the ores in question, as it has been recognized by Smith (1927, 1950), and Carstens (1927, 1942b) from similar 'vasskis' deposits in the Meldal and Vassfjellet sulphide ore provinces of the Trondheim region.

An incipient tectonic influence on the sulphide assemblages can usually be observed within the ores of the Rennebu type as a brecciation on a very small scale; this has facilitated the formation of irregular veinlets of recrystallized pyrite. Successive stages of the brecciation can be seen in many of the ores of the Budal type from the western part of the region. Fine-grained sulphide layers are torn apart and cemented by recrystallized sulphides of a coarser grain. Among the deposits having banded quartzites as wall-rocks (e.g., the Innset deposits), massive granular pyrite ore often wedges in between the quartzite laminae. At Bjørndalen (60) the quartzite bands are completely offset, floating as twisted breccia fragments within a sulphide groundmass.

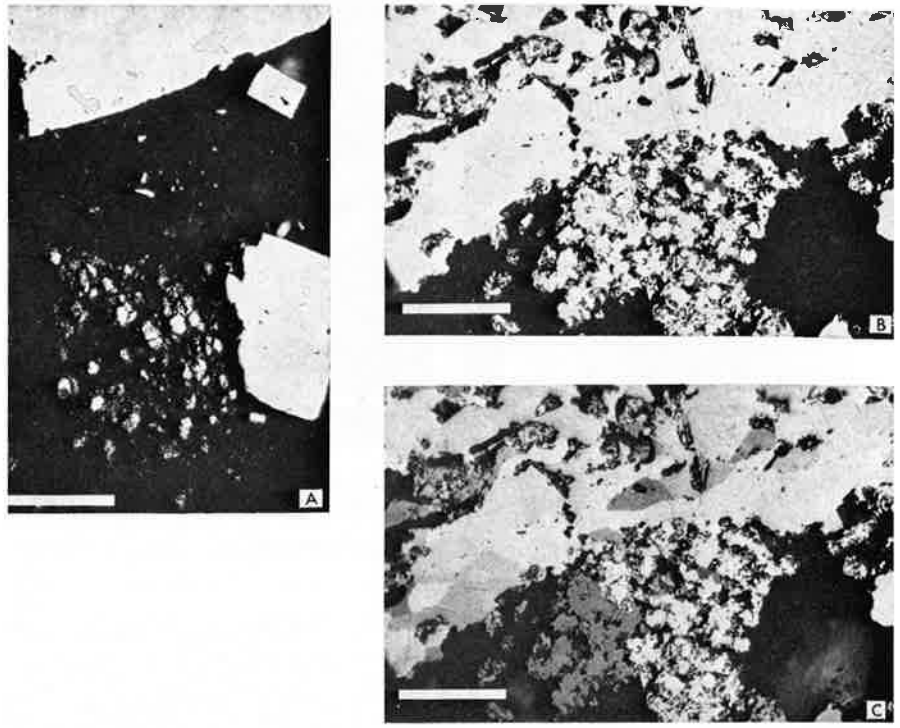


Fig. 21. Pyrite/pyrrhotite relationships of the sulphide disseminations at Hestvatnet prospect, Ilbogen area, Rennebu. Incident light, oil immersion.
A: Pyrite framboids within a breccia fragment of carbonaceous phyllite and pyrite porphyroblasts (with blebs of chalcopyrite). Plane polarized light. B: Pyrrhotite framboid pseudomorphs. Plane polarized light. C: The same as B, partly crossed nicols. Scale bars: 50 μm.

An incipient formation of pyrrhotite at the expense of pyrite very often accompanies the brecciation of the ores. The process can be seen among several of the ores in the Ilbogen area (15–18) and in the Vora prospect (24) as a complete isomorphic replacement of the framboidal pyrite aggregates (Fig. 21). Isomorphic replacement of recrystallized pyrite cubes into polycrystalline pyrrhotite grains has also been observed (Fig. 22). Within the more intensely deformed black schist ores, e.g. at the Høgsegga prospect (54), fragments of layers, originally consisting of a close-packed mush of roe-textured framboids, are transformed into a coarse-grained, strained mosaic of pyrrhotite with relics of a few pyrite granules (Fig. 12). The fragments are healed by a polygonal mosaic of equigranular pyrrhotite, often including idioblasts of pyrite.

By further deformation and metamorphism, as revealed by the ores of Næringhøa (39) and the Budalen–Fordalen districts, pyrrhotite becomes the most abundant sulphide species of the ores. The recrystallization appears to have taken place under static conditions as revealed by triple-point grain boundary relations (Stanton 1964, Spry 1969) and the absence of strain textures such as corrugation lamellae. However, fragments of the quartzitic rocks

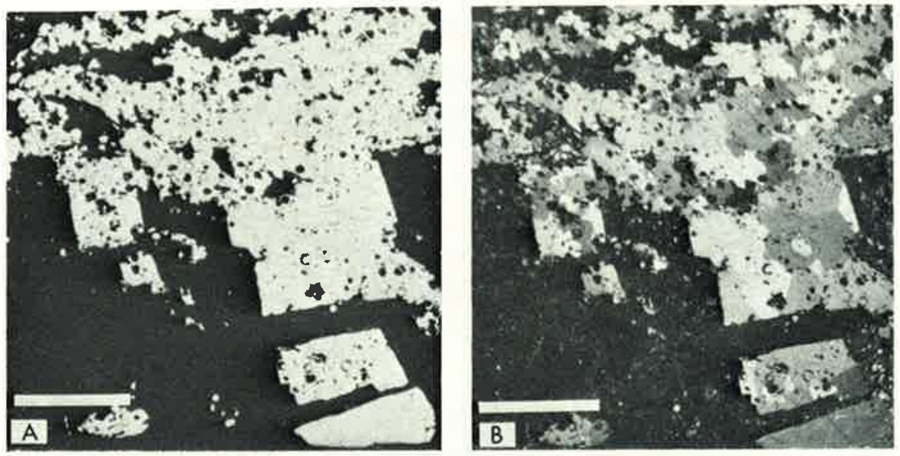


Fig. 22. Granoblastic pyrrhotite pseudomorphs after pyrite idioblasts with preserved spheroidal framboid inclusions and pits. From Storhøgda prospect, Budal. Incident light, oil immersion.
A: Plane polarized light. B: Partly crossed nicols. Scale bar: 100 μm.

and black schists are frequently balled up into a 'durchbewegt' texture, well known from several Caledonian sulphide ores (Vokes 1968, 1973). These textures point to a severe mechanical 'ground preparation' preceding the final sulphide crystallization. Apparently, an initial stress-induced pyrite/pyrrhotite transformation takes place during the initial deformation of the bedded ores in question which is accompanied by a static recrystallization within the space produced by the brittle failure of the beds. Depending on the cohesion of the fragmented host rocks, further tectonic movements tend to erase the breccia texture of the ores. The sulpides now tend to recrystallize along cleavage planes, frequently displayed as closely spaced microbands and streaks, often accenting a pre-crystallization puckering.

The base-metal sulphides present are usually confined to the recrystallized pyrrhotite portion of the ores as exsolved blebs and amoeboidal inclusions. It seems to be no mere coincidence that most of the copper and zinc present is confined to the highly tectonized pyrrhotite portions, marginally associated with the massive pyritic ores of the region, e.g. at Nyberget (31), Rødalen (Helene Cathrine) (100), Røstvangen (90), Bjørndalen (60), Gressgodtvangen (104), Klett (110) and Fos (122), to mention a few.

Minor deformational events, post-dating the main emplacement stage (i.e., post-F_2 stage), have locally shattered the present brittle pyrite crystals as well as the silicate gangue and brought about a redeposition of chalcopyrite and pyrrhotite along cracks and micro-fissures in most of the ores observed. Locally, coarse-grained granoblastic pyrrhotite displays strain-induced features such as corrugation lamellae and recurrent preferential growth, as revealed from the Kvikne mines (Nilsen & Mukherjee 1972).

THE EFFECTS OF SULPHURIZATION

It is evident from the preceding accounts that two distinctive mineral parageneses are encountered within the metamorphosed strata-bound ores of the southern Trondheim region. These correspond to the general *pyritic* and *pyrrhotitic* classes, respectively, as distinguished by Stanton (1960b) and applied to the Caledonian stratabound sulphides by Vokes (1962). They are shown to occur in different stratigraphical and geological settings and the present investigations reveal a close connection between the classes.

Desulphurization processes, as revealed from the incipient pseudomorphic pyrite–pyrrhotite transition of the western metamorphic low-grade deposits, represent apparently very important agents in a partial or complete metamorphic transformation of an original sulphide layer. Thompson (1972) concluded that during prograde metamorphism of pelites and bituminous schists, pyrrhotite forms at the expense of pyrite. Depending on the prevailing sulphur pressure, the pyrite–pyrrhotite transition proceeds by increasing temperature as demonstrated by the sulphide investigations in the Oslo district by Antun (1967). However, the attempt to establish pyrrhotite isograds (e.g. French 1968, Carpenter 1974) has often led to erroneous conclusions concerning the P-T conditions during the metamorphism of a sulphide province.

Desulphurization may have caused the apparent symmetrical zoning displayed by minor pyritic lenses and bands. Here, pyrite constitutes the common central component, while pyrrhotite is the prominent sulphide in the more chipped, flanking parts of the sulphide layer. A similar zoned pattern has been found in the Stekenjokk sulphide ore described by Juve (1974, 1977), who regards the actual transformation of pyrite to pyrrhotite as the most important metamorphic effect upon the original ore mineralogy. Depletion of ore elements in the space adjoining the ore bodies is obviously a matter of dispute, but an increased rock permeability in the neighbourhood of a sulphide body as suggested by Stanton (1960a) is not unlikely. The margins of a sulphide body will naturally be more susceptible to leaching processes during the metamorphism as compared with the central parts. Here, metamorphism will provide only a further recrystallization and a coarsening of the existing pyrite species.

The desulphurization processes which apparently have taken place during the progressive metamorphism of the ores under consideration may, on the other hand, lead to sulphurization processes affecting the adjacent wall-rocks. It has been shown experimentally that sulphurization of iron-rich ferromagnesian silicate assemblages yields sulphides and more iron-deficient phases (Kullerud & Yoder 1965). Several workers have regarded the sulphurization processes as possible ore-forming processes during diagenesis as well as during metamorphism (Lindroth 1946, Friedman 1959, Berner 1969, Clark 1969, Bachinski 1976), and the question of sulphurization of the Caledonian iron-rich assemblages of the 'black fels' type has been raised by Vokes (1970). The present investigations reveal that the idea of sulphurization of the minor iron-formations in question still has its attractions.

Evidence of sulphurization is scanty among the metamorphic low-grade deposits of the Rennebu type. Here, the ultra-fine-grained pyrite lies in close contact with sulphide-free iron-rich oxide/silicate bands. No metamorphic evidence of a pyrite/pyrrhotite transformation among the pyrrhotite-bearing 'vasskis' ores can be found, and the actual sulphide relations may be ascribed to the original depositional conditions. In the metamorphic high-grade Innset area, however, all transitions exist from granular, massive pyrite ores to pyrrhotitic disseminations within the garnetiferous magnetite rocks and quartzites. The latter represent sulphurized cherty layers. Sulphur deriving from a massive sulphide body, e.g. at Nyberget (31), may locally have transformed the hanging-wall oxide/silicate assemblages into the present sulphide-bearing quartzites (Fig. 16). Similarly, sulphurization has apparently transformed original oxide/silicate components of the Kvikne type deposits into the present varieties of pyrrhotite-bearing silicate assemblages.

According to the studies of Klein (1966, 1972) a mixture of primary ferruginous carbonates and cherts, as well as hydrous silicates such as stilpnomelane, greenalite and minnesotaite of an original volcanogene iron-formation, give way to abundant garnet and amphiboles of the cummingtonite–grunerite series during prograde metamorphism. Even pyroxenes and fayalite may form, as observed at the Breidvad prospect (44). Similar parageneses were described by Bonnichsen (1975) from the metamorphosed Mesabi Range, Minnesota. A pertinent publication is that of Carstens (1924b) who pointed out the great geochemical similarity between the enigmatic 'eulysitic' rocks of Sweden (Palmgren 1917, von Eckermann 1922, Geijer 1925) and the 'black fels' component of the Rennebu type ('vasskis') of Caledonian sulphide deposits. The eulysitic development of the Kvikne-type iron-formation at Breidvad represent conditions of low relative chemical potential of O_2 (Klein 1973), possibly caused by the enclosing graphitic pelites of the Undal Formation.

Cherty oxide components as found in the Rennebu-type iron-formation are shown to persist without any mutual reactions through high-grade metamorphic conditions. The coarse-grained magnetite-bearing quartzite bodies, frequently occurring as members of the Kvikne type iron-formation, may have escaped the process of sulphurization. Their coarse-grained, irregular appearance led the present author to the idea of an endogene hydrothermal origin for the actual quartzites of the Kvikne mine area (Nilsen & Mukherjee 1972), but the suggestion that they rather represent metamorphosed syn-volcanic cherty iron oxide deposits or 'oxide exhalites' made by Vokes & Morton (1973) is more plausible.

From the present considerations a convergence between the iron-formations of the Rennebu type and the Kvikne type is most likely when differences in metamorphic grade are taken into account.

ASPECTS OF THE IRON AND MANGANESE CONTENTS OF THE IRON-FORMATIONS

Bulk chemical analyses have been made of the different characteristic assemblages of the Rennebu-type and the Kvikne-type iron-formations. As was to be

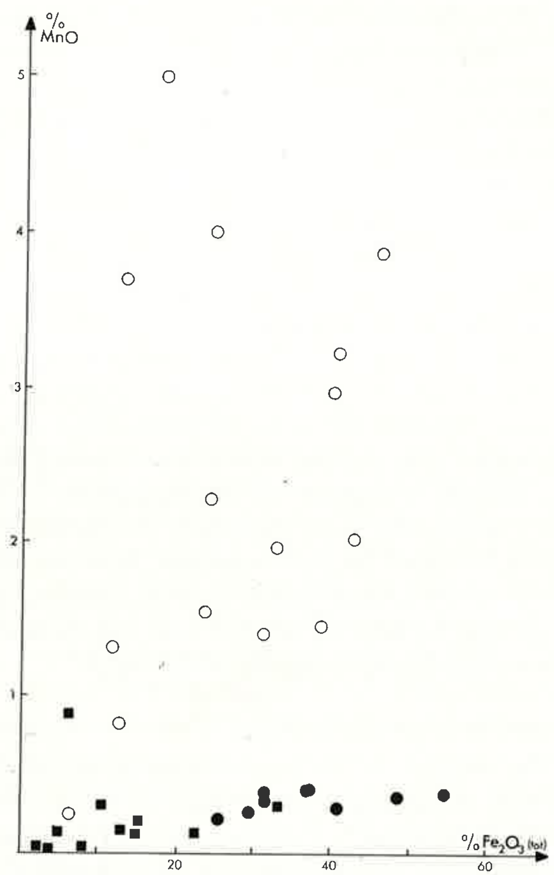


Fig. 23. The relationship between iron and manganese from different ferruginous assemblages within the iron-formations of the southern Trondheim region. Open circles: Gula Group assemblages. Dots: Støren Group assemblages ('black fels' and cherty iron ores). Filled squares: Støren Group assemblages (Cherts).

expected from their variable mineralogy, quite a wide compositional range was found. However, the geochemical investigations in progress reveal significant differences in the contents of iron and manganese in the iron-formations. As shown in Fig. 23, the iron-formations of the Kvikne type are characterized by high and variable Mn-contents, while the Mn-content of the 'black felses' and cherts of the Rennebu region is low and nearly constant, corresponding to the average manganese content of the adjacent pillow-lavas (Loeschke 1976, Rohr-Torp pers. comm. 1977). The higher manganese content of the Rennebu type ('vasskis') ores on the whole, as compared with the massive pyritic ores of the Caledonides (Carstens 1942a), may be attributed to the 'black fels' component of the former. Locally it has been shown that cherty layers within the lavas of the Støren Group may attain exceptionally high manganese values (Oftedahl 1967).

The varying Mn/Fe-ratios found within the different iron-formations of the world may be due to the primary differential solubilities of iron and manganese under various conditions of pH and Eh during deposition (Krauskopf 1956, 1957). The Mn/Fe ratio as an indicator of the depositional conditions of some stratabound sulphide ores has been discussed by Richards (1966) and Whitehead

(1973). However, the high but variable manganese content of the Kvikne-type iron-formation may equally well be attributed to the varying degrees of sulphurization during metamorphism. Leaching of iron from an original ferromanganiferous oxide/silicate/carbonate assemblage during sulphurization, and redeposition of the sulphides formed, leads in all probability to a higher Mn/Fe ratio of the residue as the sulphide compounds of iron become stable at somewhat higher Eh and pH values. According to the Eh/pH conditions of the provenance area the manganese will be fixed in the ferromagnesian silicate phases present (e.g. garnet, cummingtonite and grunerite) or within the sphalerite lattice or separated as alabandite under the most reducing conditions, e.g. within the present bituminous assemblages. Alabandite has been observed (and confirmed by probe) as an accessory component within Kvikne-type iron-formations embedded within the bituminous schists and quartzites of the Budalen–Fordalen area, together with accessory manganiferous sphalerite. The analyses performed on sulphide-free samples from the Kvikne-type iron-formations (Fig. 23) support the above hypothesis of a metamorphic adjustment of the Mn-Fe distribution of the iron-formations. However, detailed geochemical investigations of the different phases involved are required to get an idea of the mutual reactions between the sulphide ores and the associated iron-formations during the prograde metamorphism of the region.

GENETIC CONSIDERATIONS

The majority of the massive sulphide deposits of the southern Trondheim region are invariably associated with minor iron-formations of a great lateral extent. Separated in time and space and subjected to varying degrees to metamorphic and tectonic processes, they constitute members of volcanic associations well known from eugeosynclinal belts from Precambrian to Recent. The term 'iron-formation' has been applied here in the most general way to include all stratigraphic units of bedded rocks that contain more than 15% of iron and where the structure of the rocks conforms with the structure of the adjacent sedimentary, volcanic or metasedimentary rocks (Gross 1959). In the Precambrian belts they constitute the so-called *Algoma-type* of iron-formations (Goodwin 1962, Gross 1965). Compared with the Clinton- and Superior-types of iron-formations, they are economically of minor importance. Volcanogene, often manganiferous iron-formations, however, constitute important marker beds in several major sulphide-bearing sequences around the world. They comprise the *polvo hematites* of the Iberian pyrite belt (Schermerhorn 1975), the *Perapedhi formation* of the Troodos Igneous Complex (Hutchinson & Searle 1971) and the ferruginous beds (*Kosaka-tetsusekiei*) of the Kuroko deposits (Horikoshi 1969) and elsewhere (Richards 1966, Besson 1972, 1973, Stanton 1972, Ferrario & Montrasio 1976).

With reference to their intimate association with mafic metavolcanics and laterally persistent iron-formations, the massive sulphide deposits of the Rennebu and Kvikne types represent in all probability *in situ* deposits of a volcanogene/sedimentary origin. In this respect the Caledonian iron-ore province of the Fosen peninsula, NW Trondheim region, apparently provides another example of a similar depositional environment in the Scandinavian Caledonides (Carstens 1955).

Being enclosed within different pelitic and volcanoclastic assemblages, respectively, the deposits of the Budal and Elgsjø types do not show any intimate association with extensive ferruginous layers. Though their geological settings in time and space differ, their proximity to minor lava horizons points to a possible common mode of emplacement. Apart from the general absence of conformably embedded oxide/silicate assemblages, their mineralogical and textural conformity with the pyritic ores of the Rennebu and Kvikne types suggests a common kindred. As discussed by Jenks (1971), sulphide ores deposited in a submarine volcanic environment are, as with their enclosing sediments, susceptible to transportation downslope as dense turbidity currents or slides. In a poorly consolidated state, autochthonous sulphide layers originally deposited within a strictly volcanic environment and interbedded with or overlain by (cherty) ferruginous sediments may be transported into regions of mixed clastic and volcanoclastic material and even of shaly clastics alone. Some of the major ore bodies within the Iberian pyrite belt (e.g. Tharsis North Lode) are embedded in local basins adjacent to the effusive centres and enveloped by pelitic, partly carbonaceous sediments (Strauss & Madel 1974). The resedimented nature of these ores is revealed by delicate sedimentary structures, similar to those commonly encountered in barren turbidites. In a similar manner, the deposits of the Budal and Elgsjø types may have been redeposited into their volcanoclastic and clastic environments, respectively, in proximity to their exhalative centres within the Gula and Støren groups. By the process of transportation and resedimentation their associated ferruginous beds (which might have been in a colloidal or gel-like state) may have separated from the sulphide mush and been dispersed or resedimented in the adjoining metasediments. Some of the pyrrhotitic Budal-type disseminations (e.g. Grisbudalen (119) and Langrød (62)), affiliated as they are to black, garnetiferous quartzites, may represent primary fragmented satellites of an original Kvikne-type oxide/silicate iron-formation. Minor magnetite portions of the massive pyritic ore bodies at Undal (26) and Tverrfjellet (7) may similarly represent adhering fragments of an originally associated oxide iron-formation. Unfortunately, structural and metamorphic effects imposed on the pyritic bodies in question would have erased any confirmatory primary structures which are assumed to have been present. In this context the presence of framboidal pyrite indicates only their resistance against mechanical forces, and a possible sedimentary origin for at least some of the ores of the Budal type.

From a consideration of the ubiquitous sulphide disseminations found in the graphitic pelites of the Gula Group, the role of sulphate-reducing bacteria in providing significant quantities of sulphides cannot be excluded. A syn-sedimentary sulphide formation is likely within the anoxic-reducing primary environment with a probable supply of volcanogene metal fluxes.

Conclusions

The sulphide deposits of the southern Trondheim region comprise a variety of conformable pyritic and pyrrhotitic mineralizations. A consideration of their distribution indicates their location within a few restricted and specific geological environments within the Gula, Støren and Fundsjø Groups of the Trondheim Nappe. According to their lithological setting, they can be regarded as:

(1) Primary, autochthonous, massive pyritic deposits intimately associated with distinct horizons of mafic metavolcanics and iron-formations of a limited vertical but wide lateral extent.

(2) Primary, allochthonous, massive pyritic deposits, resedimented and embedded within clastic and volcanoclastic assemblages adjacent to the magmatic source.

The sulphide-Fe-oxide/silicate association commonly found and the few synsedimentary features observed within the ores of the Gula and Støren Groups favour an original exhalative-sedimentary origin for the deposits in question, as proposed by Oftedahl (1958c) for the majority of the Caledonian sulphide deposits of Norway. Their affiliation to mafic volcanism associated with variable thicknesses of volcanoclastics, flysch-type quartz-wackes and carbonaceous pelites indicate deposition of deep-water accumulations adjacent to either a land mass or volcanic islands. Regarding their geological evolution, possibly within an island-arc setting, they fit well within the *Besshi-type* of stratabound sulphides as discussed by Mitchell & Bell (1973).

Tectonic and metamorphic processes have regenerated the deposits to different degrees and brought about a mechanical and chemical redistribution of the primary ore components on a local scale. A short-range S-metasomatism has apparently been an important process in the chemical and mineralogical mutual reconstitution of the ores and the ferromagnesian mineral components of their wallrocks.

Mineralogically and chemically, the stratabound deposits do not show any apparent correlation between the ore type (in terms of the Cu:Pb:Zn ratios) and the nature of the host rocks. However, a distinct bimodal nature of the metamorphosed massive ores is recognized, irrespective of their stratigraphical and lithological setting. As revealed by several Caledonian deposits (e.g. Vokes 1962, Saager 1967, Nilsen 1971, Juve 1974, Rui & Bakke 1975) they can be grouped into:

(1) Massive pyritic ores

(2) Massive to disseminated, brecciated pyrrhotite–chalcopyrite ores with or without minor pyrite.

Variations in the pyrite/pyrrhotite ratio of the metamorphic low-grade pyritic deposits in all probability reflect original differences in the partial sulphur pressure during deposition, but the great diversity of ratios encountered from the higher-grade areas is ascribed to the metamorphic and tectonic processes. During the Caledonian orogenic movements the ore bodies, irrespective of their original shape, have been remoulded into their present elongate and partly dissected shapes through the various stages of tectonic deformation and metamorphism.

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Appendix

Mines and prospects of the southern Trondheim region, listed according to the reference numbers on the geological map (Plate 1).

Abbrevations:

Map sheet 1:50,000

A – Alvdal 1619 III
B – Budal 1620 IV
D – Dalsbygda 1620 II
E – Einunna 1519 I
H – Haltdalen 1620 I
Hj – Hjerkinn 1519 III
I – Innset 1520 II
K – Kvikne 1620 III
Ks – Kvikneskogen 1619 IV
O – Oppdal 1520 III
R – Rennebu 1520 I
S – Snøhetta 1519 IV
T – Tynset 1619 I

Type:

B – Budal type
E – Elgsjø type
K – Kvikne type
O – Olkar type
R – Rennebu type
S – Saval type
1 – Within basal gneiss complex
2 – Pegmatite vein type

Mineralogy:

Po – Pyrrhotite
Py – Pyrite
Cp – Chalcopyrite
Sl – Sphalerite
Gn – Galena
As – Arsenopyrite
Mt – Magnetite
Hm – Hematite
Il – Ilmenite
Cr – Chromite
Pn – Pentlandite
Mo – Molybdenite

● – Major component
o – Minor component
x – Accessory component

Type of aggregate:

D – Dissemination
M – Massive

Foslie no.:
Reference numbers according to Foslie (1925).

No.	Mine/prospect	Map sheet 1:50,000	UTM grid ref.	Type	Mineralogy Po	Py	Cp	Sl	Gn	As	Mt	Hm	Il	Cr	Pn	Mo	Aggr.	Foslie no.
1	Leverdalen	O	362 564	R	x	x					●						D	
2	Skjørdøla	O	350 427	R		●					●						D	
3	Svarthølhaugen	S	326 291	1										●			D	154
4	Vårstigen	S	334 138	E	x	●							x				M	152
5	Skåkbekken	S	324 117	E	x	●											M	
6	Kongsvoll	S	318 066	R	●		x										D	
7	Tverrfjellet	Hj	270 997	E,R	o	●	o	o	x		x						M	
8	Øyabekken I	Hj	336 950	B	●	o				x							D	
9	Øyabekken II	Hj	334 951	B	●												D	
10	Skamfjell	R	373 805	R	o	●					x		x				D	108
11	Jorfjell	R	419 806	R	o	●					x		x				M	106
12	Mærk	R		R		●											M	111
13	Hakefjellet	R	506 794	R		●					●						M	
14	Kalddalen I–VIII	R	513 799	R	o	●	x				●						M	
15	Hestvatnet	R	511 775	B	●	o		x		x							D	
16	Ilbogen	R	516 775	B	o	●		x		x							M	112
17	Ilbogen prosp. I–II	R	515 778	B	o	●											D	
18	Brennfjell	R	516 782	B	●	o											D	
19	Vasli	R	509 725	B	●	o											D	116
20	Sliper	R	473 696	R							o	●					D	113
21	St. Olaf	R	478 680	R							●	o					M	114
22	Hammersæter	R	488 661	E	o	●		x									M	118
23	Ramfjell	R	441 621	R		o					●						M	115
24	Vora	R	526 605	B	o	●											D	121
25	Nertjønna	R	567 618	B	●	x											D	
26	Undal	R	536 660	B	o	●	o	x			x						M	119
27	Nylykkja	R	535 674	B	o	●											D	
28	Bjørkås	R	553 705	B	●		x	x		x							D	
29	Aunerøa	R	508 723	B	o	●											D	
30	Innsetlia	I	563 538	R	o	●											M	127
31	Nyberget	I	560 535	R	o	●	x	o			x						M	128
32	Bergstjern III	I	557 529	R		●					o						D	
33	Bergstjern I–II	I	563 522	R	●	●	x	x									D	
34	Langfjellet	I	564 508	B	●		x	x					x				D	
35	Litlfjell	I	561 500	B	o	●	x	x		x							D	129
36	Tverrfjellet pr.	I	555 476	R	●	o	x										D	
37	Kletten	I	558 462	B	●												D	
38	Bustaden	I	524 436	R							x						D	
39	Næringhøa I	I	496 402	B	●			x									D	134
40	Næringhøa II	I	493 400	B	●												D	
41	Orkelsjøen	I	447 338	B	●	o	x				x						D	
42	Orkelhøa	I		B	●	o											D	135
43	Breidvad III–IV	I	595 477	K,B	●		x										D	
44	Breidvad I–II	I	595 480	K	●		x						x				D	
45	Elgsjøtangen I	E	445 149	E		●			x		x						M	149
46	Elgsjøtangen II	E	445 148	E		●					x						M	
47	Elgsjøtangen III	E	441 143	E		●											M	
48	Elgsjøbekken	E	427 128	E	o	●			x							x	M	150
49	Steindalkollen	E	415 114	E	●	o											D	
50	Heimtjørnhøi	E	403 083	E	x	●	x	x			x					x	M	151
51	Dølvad	E	594 301	2		●			o								D	
52	Rogstad	B	682 856	B	o	●											D	123
53	Høgsegga	B	694 803	B	●	●	x										M	124
54	Høgsegga prosp. I–III	B	695 796	B	●	o	x										D	
55	Rød	B	647 752	B	●	o	x		x								D	

No.	Mine/prospect	Map sheet 1:50,000	UTM grid ref.	Type	Mineralogy Po	Py	Cp	Sl	Gn	As	Mt	Hm	Il	Cr	Pn	Mo	Aggr.	Foslie no.
56	Svardal	B	732 748	B	●	o	x										D	
57	Sæter prosp.	B	730 744	B	●	x	x	x	x								D	
58	Sæter	B	728 744	B	●	x		x									D	
59	Storhøgda	B	725 713	B	●	o	x										D	
60	Bjørndalen	B	701 668	B	o	●	o	o	x								M	125
61	Rauhammeren	B		K	●													274
62	Langrød	B	857 748	B	●	x	x	x	x								D	
63	Høa	B	864 756	B	●	x	x		x								D	
64	Grubehøgda	K	674 560	B	●		x		x								D	126
65	Falninga	K		B		●												130
66	St. Hallvard	K	744 407	K	●		x			x	x		x				D	131
67	Sæterfjell I–II	K	747 414	K	●	o	x						x				D	
68	Svartsjøen	K	752 395	K	●	o	x		x		x		x				D	132
69	Russu	K	752 398	K	●	o											D	
70	Vang	K	731 370	K	●		o										D	133
71	Kvikne: Gabe Gottes	K	735 364	K	●	o	●	o			x		x				M	133
	Segen Gottes	K	735 365	K	o	●	o	o	x		x		x			x	M	133
	Banken	K	735 366	K	o	●	o				x		x			x	M	133
	Mine 1707	K	735 366	K	●	●	o	o			x		x			x	M	133
	Dalsgruben	K	734 370	K	●	o	●	o			x		x			x	D	133
	Kojan I–II	K	731 362	K	●		x				x		x				D	133
	Odden I	K	733 371	B	x												D	133
	Odden II	K	734 371	K	●												D	
	Odden prosp.	K	731 375	B	●		x										D	
	Storbekken	K	736 369	K	●								x				D	
	Gjøkåsen	K	737 368	K	●	●	o	o									M	
	Estensvangen I	K	730 365	K	●		x						x				D	
	Estensvangen II	K	733 366	K	●		x				x		x				D	
	Grubeåsen	K	731 360	K	●		x						x				D	
72	Berstjern I–III	K	728 354	K	●	x	x						x				D	139
73	Kaltberget	K	711 351	O	●		o								●		D	138
74	Olkar	K	700 357	O	●		●								o		D	137
75	Vakkerlien	K	653 339	O	●		o								o		D	136
76	Eidsfjellet	K	737 319	K	●	x							x				D	142
77	Magnilsæter I	K	800 315	K	●								x				D	
78	Rundhaugen	K	808 351	K	●	o	x	x									D	
79	Støa	Ks	719 304	K	●		x						x			x	D	141
80	Magnilsæter III	Ks	799 308	K	●												D	
81	Magnilsæter II	Ks	801 305	K	●						x		x				D	
82	Bjørkeng	Ks	714 286	K	●		x										D	
83	Mysmørdalen	Ks	755 264	K	●												D	
83	Lykkja	Ks	698 253	K	●	o	x	x	x	x							D	143
85	Gråhø	Ks	686 228	K	●						o		x				D	
86	Børsjøhø prosp.	Ks	676 217	K	●		x										D	
87	Børsjøhø	Ks	665 203	K	x	●	o	o	x							x	M	147
88	Hamdal	Ks	659 201	K	o	●	o	o	x							x	M	
89	Finnhaug	Ks	663 196	K	x	●	o	x	x								M	
90	Røstvangen	Ks	712 179	K	o	●	o	o			o					x	M	145
91	Røstvangen prosp.	Ks	715 181	K	●						x						D	
92	Gløta	Ks	702 171	K							●						D	
93	Gløtlisæter	Ks	715 170	K	●												D	
94	Lykkjevangen	Ks	708 155	K	●						x						D	
95	Loken	Ks	708 153	K	●						x						D	
96	Søgardsvangen	Ks	702 136	K	●						x						D	
97	Strålbergsætra	Ks	686 082	K	●						o		x				D	

No.	Mine/prospect	Map sheet 1:50,000	UTM grid ref.	Type	Mineralogy Po	Py	Cp	Sl	Gn	As	Mt	Hm	Il	Cr	Pn	Mo	Aggr.	Foslie no.
98	Ulvdalen I	Ks	685 075	K	●						o						D	
99	Ulvdalen II	Ks	684 074	K	●						o						D	
100	Rødalen: Drakjen	Ks	684 071	K		x	x				●						D	181
	Helene Cathrine	Ks	683 070	K	●	x	o	x					x			x	M	181
	Nygruben	Ks	683 070	K	o	●											M	181
	Gammelgruben	Ks	683 069	K		●	o	x			x						M	181
	Klettgruben	Ks	682 068	K	o	●	o	x									M	181
101	Gruvkletten	Ks	684 059	K	●												D	
102	Veslehøa I	Ks	703 075	S	●	o	x										D	
103	Veslehøa II	Ks	703 075	S	●	o	x										D	
104	Gressgodtvangen	Ks	778 094	S	x	●	x	o									M	
105	Svartåsen	Ks	809 049	K	●		x			o			x				D	195?
106	Haugen	Ks	830 100	K	●		x			x	x		x				D	
107	Klettvang I	Ks	832 107	K	●												D	
108	Klettvang II	Ks	832 110	K	●												D	
109	Klettvang III	Ks	835 118	K	●												D	
110	Klett I	Ks	837 120	K	●	o	o	o	x								M	199
111	Klett II	Ks	839 123	K	●	o	o	o	x								M	199
112	Rødhammer	Ks	839 145	K	●						x						D	
113	Lomnesvola	A	737 992	K	x		x										D	
114	Lomsjøvola	A	764 001	K	o	●	x				o		x			x	M	193
115	Galtbekken	A	769 006	K	x						x						D	
116	Lauvbekken	A	772 010	K	x												D	
117	Fløttum	H	875 757	B	o	●	o	o	x	x							M	273
118	Fora	H	893 725	B	●	o	x	o									D	
119	Grisbudalen	H	911 770	B	●	x	x	x									D	
120	Svartåsen	H		B		●											D	272
121	Røhovde	H	027 627	K	●												D	
122	Fos	D	009 388	K	o	●	o	o	x								M	211
123	Litlvola	T	933 262	K	●												D	