

The stratabound sulphide deposits in the Folldal area, Southern Trondheim Region, Norway

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Five strata-bound massive sulphide deposits are situated at three different stratigraphic levels in the volcanogenic Fundsjø group in the Folldal area. The deposits are hosted in metabasalts, metarhyodacites and volcanoclastic rocks and belong to the Cu-Zn class of volcanic-associated massive sulphide deposits. The metal content of the deposits indicates that the sources of metals are underlying strata, possibly with a contribution from intrusives. Wall rock alteration varies according to differences in host rocks, and is probably a result of chemical variations of the host rocks, temperature differences and proximity to the hydrothermal vent. The clustering of deposits in the Folldal area is considered to be due to the occurrence of a large subvolcanic trondhjemitic intrusion which acted as the major heat engine for convection. The small size of the deposits might be related to the shallow level of the intrusion.

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Introduction

The Folldal area was, next to the Røros District, the most important sulphide ore producer in the Southern Trondheim Region (Foslie 1925; Bugge 1978). Four mines in the area produced 4.45 million tons of ore during the period 1748–1970 (Internal reports, Folldal Verk A/S). A fifth deposit, which is the largest in the area, has never been mined because of its low grade.

The extensive mining activity led to both regional and more local investigations in the area by several workers (e.g. Bjørlykke 1905; Marlow 1935; Janes 1955; Page 1963; Waltham 1968; Heim 1972; Pedersen 1979 and geologists employed by Folldal Verk A/S). New data presented by Bjerkgård & Bjørlykke (1994) form the basis for interpretations and understanding of the environment for deposition of sulphides in the area.

The orebodies belong to the Cu-Zn type of stratabound massive sulphide deposits and are found in volcanic sequence with a geochemical island arc signature. The deposits are situated at different stratigraphic levels in this sequence and in different host rocks. They show differences in content of both base and trace metals, as well as the extent and types of wall-rock alteration. Mineralization is densely clustered within an area of only about 80 km² and there must be a reason for this clustering of deposits in such a restricted area.

This article deals mainly with the geological setting and structure of the deposits, including zonations in metal content and wall-rock alteration. The intention is to discuss why the deposits in such a restricted area are so different with respect to metal chemistry and wall-rock alteration. The work has been done mainly on drill cores, since the mines are now inaccessible. The methods used are core logging accompanied by analysis of metal content (base and trace metals) in addition to field work.

Studies of wall-rock alteration by geochemistry, radiogenic isotopes on both host rocks, altered wall rocks and sulphides, as well as microprobe analyses of minerals are in progress.

Geology

The Folldal area in the northwestern part of Hedmark County comprises lithologies belonging to the Upper Allochthon of the Trondheim region (Fig. 1). The lithologies are mostly semipelitic garnet-chlorite-mica schists of the Gula Group and volcanic rocks, volcanoclastites and minor sedimentary rocks belonging to the Fundsjø Group. The units are structurally inverted, so that the Gula Group overlies the Fundsjø Group.

In Folldal (Fig. 2), the Gula Group consists, in the stratigraphically lower part, of turbidites of the Singsås Formation, followed upwards partly by graphitic, semipelitic garnet-chlorite mica schists of the Åsli Formation.

The Fundsjø Group starts at its base with metabasalts and -gabbro, which are overlain by tuffitic rocks with intercalations of metasediments. A large trondhjemitic body has intruded the metabasalts as shown by apophyses in the basalts and mafic xenoliths near the top of the trondhjemitic. Extrusive equivalents to the intrusion are found in the tuffitic unit. Both apophyses and xenoliths have been deformed by the first phase of deformation in the area, which shows that the trondhjemitic must have intruded prior to this deformation. This is supported by a U-Pb zircon age of 488 ± 2 Ma on the intrusion (Bjerkgård & Bjørlykke 1994).

The Fundsjø Group is characterized by a large amount of volcanoclastites with subordinate continent-derived sediments, especially to the south of Røros (Guezou 1978; Pedersen 1979; Grenne 1988; Bjerkgård & Bjørlykke

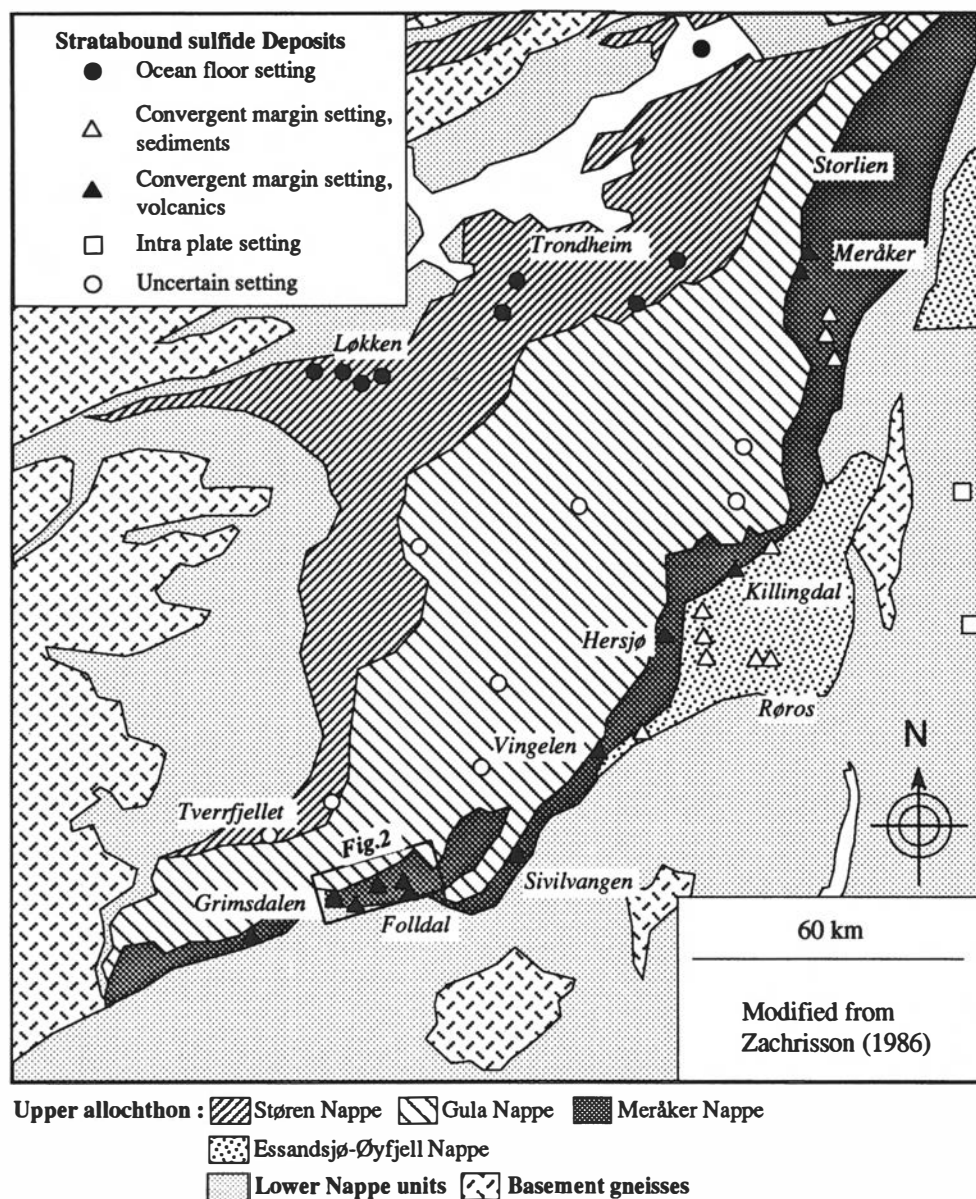


Fig. 1. Classification of stratabound ore deposits in the Upper Allochthon of the Trondheim Region Caledonides in relation to terranes and nappe units. The Folldal area (Fig. 2) is outlined.

1994). This is also the case for the lower volcanic units in the Gjersvik area of the Grong District (Lutro 1979) and the Stekenjokk area of Sweden (Stephens 1982), both of which have been correlated with the Fundsjø Group (Stephens & Gee 1989).

The geochemistry of the Folldal volcanic rocks indicates formation in an island arc setting. This is similar to the corresponding rocks in the Røros–Meråker area (Fig. 1); in the latter area, however, rocks with MORB affinity are also found (Grenne & Lagerblad 1985; Grenne 1988). This suggests a development with rifting of the arc or even a pristine marginal basin formation northwards. High concentrations of Cr and Ni in the island arc basalts indicate mixing with a more primitive magma (e.g. boninite). Together with a low content of K and Rb in both the mafic and felsic volcanites, this is an indication of an ensimatic setting. However, intercalations of sedimentary rocks such as quartzites indicate proximity to a continent.

In contrast to the Fundsjø Group, the Lower Ordovician Støren Group metabasalts in the west (Fig. 1) are dominated by mafic metavolcanites, while felsic rocks are very subordinate. Further, no continent-derived sediments have been found in this unit. Geochemistry shows a clear MORB-affinity in the volcanites (Gale & Roberts 1974; Grenne & Lagerblad 1985) and they might therefore represent part of the Iapetus sea floor or a back-arc basin to Iapetus (Sturt & Roberts 1991).

Observations between Grimsdalen and Sivilvangen, show that the Gula–Fundsjø contact is primary (Bjerkgård & Bjørlykke 1994). Gradual transitions between the units, as well as intercalations of tuffites in the Åsli sedimentary rocks, are found. Further, there are no differences in deformation or a metamorphic break across the contact. Corresponding observations have been made in the area between Tynset and Meråker (Wolff 1967; Rui 1972; Rui & Bakke 1975; Fox et al. 1988). Conglomerates containing volcanic rocks, as well

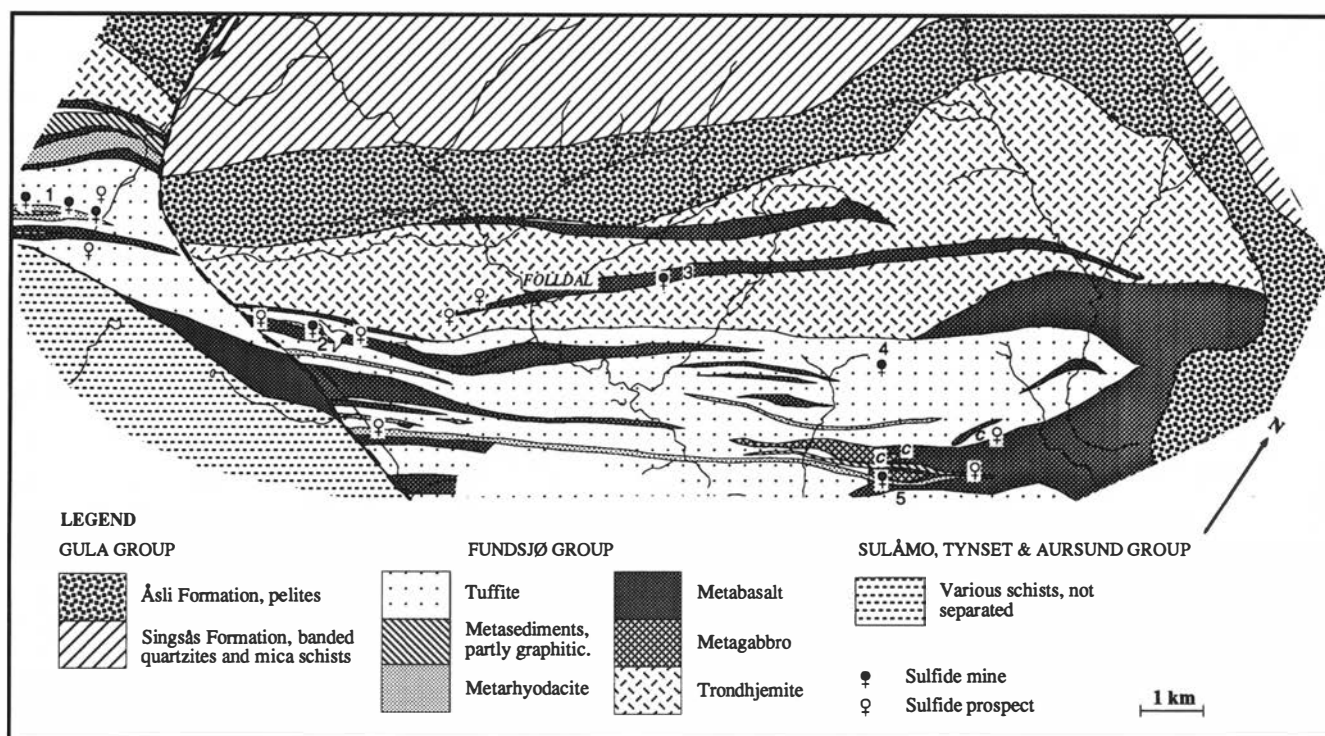


Fig. 2. Geology and ore deposits in the Folldal area. The deposits are: (1) Grimsdalsgruva (eastern part of the Grimsdalen deposit); (2) Nygruva; (3) Hovedgruva; (4) Nordre Geitryggen; (5) Søndre Geitryggen. c = garnet-quartz rocks (coticles).

as various gneisses and quartzites, are found at this level in the Otta–Dombås area (Bøe et al. 1993).

The upper part of the Gula Group is Tremadocian (488–505 Ma) based on the presence of the graptolite *Dictyonema Flabelliforme Sociale* at Nordaunevoll (Vogt 1889; Gee 1981) in the Åsli Formation very close to the Fundsjø Group (Rui 1972). The age of the Folldal trondhjemite is, as mentioned above, 488 ± 2 Ma. These ages give further support to a continuous stratigraphy from the Gula Group and upwards through the Fundsjø Group.

The Singsås Formation has been metamorphosed to a higher degree than the overlying units (Wolff 1979). A possible syndeformational trondhjemitic intrusion in this formation at Vakkerlien has been dated by the U-Pb method on zircons to 509 ± 5 Ma (Klingspor & Gee, referred to in Stephens et al. 1985). The trondhjemite cross-cuts a nickeliferous metagabbro (Boyd & Nixon 1985), possibly comagmatic with the Gula Greenstones (Nilsen 1974), and thus provides a minimum age for the unit. The age fits with the metamorphic Sm/Nd age of 505 ± 18 Ma of the Seve eclogites (Mørk et al. 1988). Thus it is possible that both Seve and Gula have been through the same tectonic event at around 505 Ma. From this it follows that the nature of the Singsås–Åsli contact is of major importance for the stratigraphy and geodynamic modelling of the Trondheim region.

Sulphide deposits in the Fundsjø Group

Massive sulphide deposits are found in the Fundsjø Group, all the way from Meråker in the north to Dombås

in the south (Fig. 1). Most of the deposits are very small ($< 100,000$ t); among the larger are Killingdal, Hersjø, Vingelen, Sivilvangen, the deposits in the Folldal area and in Grimsdalen.

The deposits in the Fundsjø Group are found in different host rocks. Some deposits are associated mafic volcanites (metabasalts), as are the Killingdal (Rui 1973; Birkeland 1986) and Folldal Hovedgruve deposits, some, such as the Vingelen and Sivilvangen deposits, are related to mixed volcanic and sedimentary rocks or tuffites whilst others are associated with felsic volcanites as is the case for several smaller deposits in the Tynset–Alvdal area.

The extent and character of alteration phenomena associated with the mineralizations vary. Some deposits, e.g. the Sivilvangen and Vingelen deposits, have no alteration zones. Others such as the Killingdal deposit (Birkeland 1986) are underlain by stringer mineralizations in strongly altered rocks, showing zonations in alteration mineralogy. Alteration types related to the Fundsjø Group deposits include chloritization and/or sericitization.

The Folldal deposits

General

The deposits in Folldal are situated at several stratigraphic levels and in different host rocks. Proximity to the different types of volcanic and intrusive rocks also varies. This provides a unique possibility to investigate what these factors mean with respect to metal ratios,

Table 1. Overview of the Folldal deposits regarding ore production, mineralogy, host rocks and wallrock alteration.

Deposit	Production years	Size (mill. t)	Production, Cu:Zn (%)	Massive ore, drillhole data Cu:Zn:Pb:Ag:Au*	Host rock	Alteration
Nordre Geitryggen	1920–26 1936–70	2.5	1.3:3.2	1.63:4.51:0.31: 31:273	Tuffite	Limited; chl → qz + ser → cc + qz + /-amf
Søndre Geitryggen	1770–1847 1952–65	0.5	0.80:2.4	0.67:2.72:0.15: 27:350	Metarhyodacite	Extensive; chl → qz + ser → tc + do + qz + chl → cc + qz
Hovedgruva	1748–1940 (discontinuous)	1.15	1.90:1.10	1.94:1.21:0.0023: 21:187	Metabasalt	Extensive; chl → chl + ser + qz → qz + /-amf + /-ep
Nygruva	1783–87 1842–45 1940–52	0.3	0.85:3.50	1.96:5.01:0.45: 48:350	Tuffite and Metarhyodacite	chl & → cc + qz qz + ser
Grimsdalen + Grimsdalsgruva	Explored, no production	6.64 + 1.65 ⁽¹⁾	0.41:2.58 ⁽¹⁾ + 0.93:1.40	0.37:2.62:0.19: 19:246 + 0.85:1.63:0.042: 12:168	Tuffite (Metarhyodacite)	Limited; chl → cc + qz

* Cu, Zn, Pb in %, Ag in ppm and Au in ppb.

⁽¹⁾ Refers to size and content of proved massive mineralization.

Alteration is described in direction inwards against the massive ores.

alteration phenomena and primary mineral zonation of deposits in a restricted area (Fig. 2).

History

Table 1 gives a list of the deposits with information on ore production, mineralogy, host rocks and alteration. Hovedgruva was the first deposit discovered in the area and mining started in 1748. This deposit as well as Søndre Geitryggen and Nygruva were mined discontinuously for copper on a small scale until 1845–47, when all the mines were closed down for economic reasons. A new era began around the turn of the century, when pyrite became an important source of sulphur. Hovedgruva was reopened and test mining was carried out at Grimsdalsgruva. Nordre Geitryggen was found in 1920, but mining was very problematic there because of the swampy terrain. Demand for zinc made it possible to open this deposit for regular mining in 1936 and, in turn, Nygruva and Søndre Geitryggen were also reopened. Mining in the Folldal area lasted until 1970, when Nordre Geitryggen was closed down. All activity was then concentrated on the Tverrfjellet deposit at Dovre, belonging to the Støren Group (Fig. 1). This deposit was abandoned in 1993.

Host rocks and structure

Schematic lithological columns with alteration zones around each of the deposits in Folldal are presented in Fig. 3. Detailed sections and profiles of the deposits based on drill hole data can be seen in Figs. 4–8.

Metabasalts, rhyodacites and volcanoclastic rocks or tuffites are the host rocks of the deposits. The meta-

basalts are dark green, fine-grained and weakly schistose, consisting of millimetre-thick streaks of quartz and albite in a matrix of chlorite and amphibole. The rhyodacites consist of albite and quartz, occurring as phenocrysts and irregular aggregates respectively, in a fine-grained matrix of the same minerals (Fig. 11a). Porphyroblasts of garnet and needles of amphiboles are common. The trondhemite at the base of the Fundsjø Group has a similar mineralogy, but lacks any fine-grained matrix. The tuffites are generally greyish green chlorite schists with a pronounced schistosity. They consist of alternating calcite-quartz laminae, fine-grained lenses of quartz-albite and thicker chlorite layers, which define a characteristic lamination on a millimetre to centimetre scale. Quartz, albite, chlorite, epidote and calcite are the main phases, muscovite and amphibole are usually subordinate. The tuffites are classified as mafic or felsic on the basis of the ratio between mafic phases such as chlorite, epidote and amphibole and the felsic phases quartz and albite. Mafic chlorite-rich tuffites dominate.

The rocks of the area have been subjected to at least two phases of folding and some later fracture and fault zones (Birkeland 1986). The D₁-phase of isoclinal folding has led to a penetrative schistosity which affects all units, while D₂ has led to folding on a meso-scale of a more open style. The deformation phases have also affected the ores.

Hovedgruva is stratigraphically the lowermost deposit, hosted in partly pillowed metabasalts which have been intruded by the Folldal Trondhemite. Associated with the deposit are lenses of metagabbro as well as trondhemitic aplites (Fig. 4a). The aplites close to the mineralization are variably altered to quartz-sericite rock. Where the rock is less altered it consists of euhedral phenocrysts of albitic plagioclase up to several millimetres in size in a

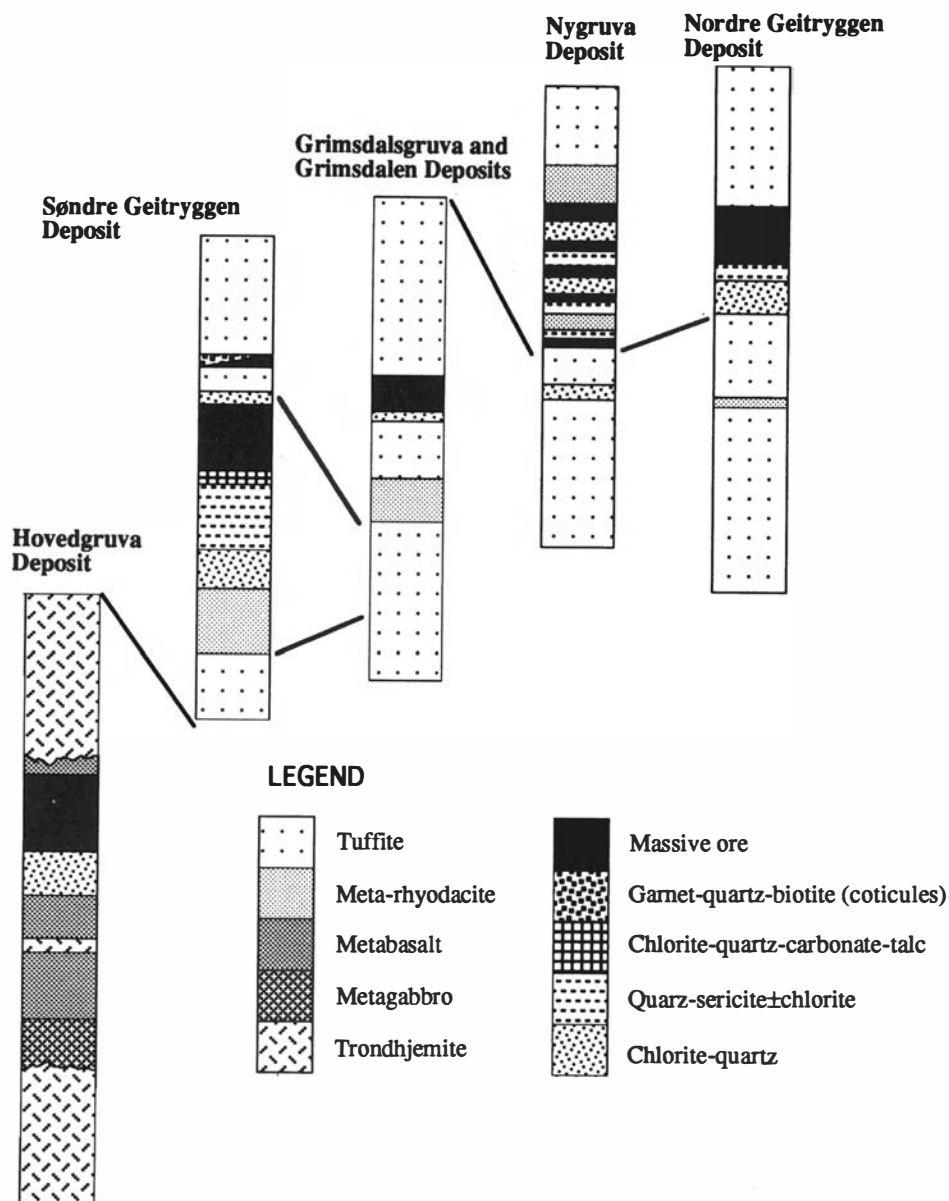


Fig. 3. Schematic stratigraphic columns of host rocks and wall-rock alteration related to the Folldal deposits. The thicknesses of the ore and alteration zones are exaggerated compared to host rocks. The lines between the columns show stratigraphic relationships between the deposits.

very fine-grained matrix of quartz and albite. Euhedral garnet and green amphibole are common subordinate phases. The metabasalts are generally weakly foliated amphibolites with green hornblende, chlorite, epidote and albite as main phases. In places, often close to the ore, the metabasalts are heavily studded by plagioclase phenocrysts.

The ore occurred in four separate lenses of variable thicknesses, the result of isoclinal folding and boudinage under F_1 and the later influence of the more open folds of phase F_2 (Fig. 4b). The massive mineralized zone has a length along strike (discontinuous) of about 900 m and descends to a depth of about 600 m with a dip around 55° NW. The ore is usually massive (60–90% sulphides) and homogeneous without any banding.

Søndre Geitryggen is situated at a slightly higher level on the southern limb of a large synformal structure and lies stratigraphically right-way up. It is situated in the upper parts of a 20–50 m-thick, extensive horizon of

rhyodacite, in contact with overlying tuffites (Fig. 5). An extensive horizon of graphitic phyllite and greywacke occurs intercalated in the tuffites (Fig. 2). The tuffites include both felsic (i.e. rich in quartz and albite) and mafic (rich in chlorite, biotite and amphibole) types. The mafic tuffites dominate and are typically banded or laminated with chlorite-rich and quartz-calcite-rich bands alternating on a millimetre to centimetre-scale. The tuffites occasionally contain subordinate graphite. Eastwards the tuffites wedge out and metabasalts and -gabbros dominate.

The deposit consisted of a relatively small lens-shaped body of massive Zn-Cu ore with an axis trending due north and plunging at about 65° . It had a maximum strike length of 195 m and maximum thickness of 25 m (at 100 m below the surface), gradually narrowing downwards. This structure is due to isoclinal folding, probably mostly controlled by D_1 .

Nordre Geitryggen is hosted in tuffitic, banded, chlorite schists in the core of the synform and thus at a higher

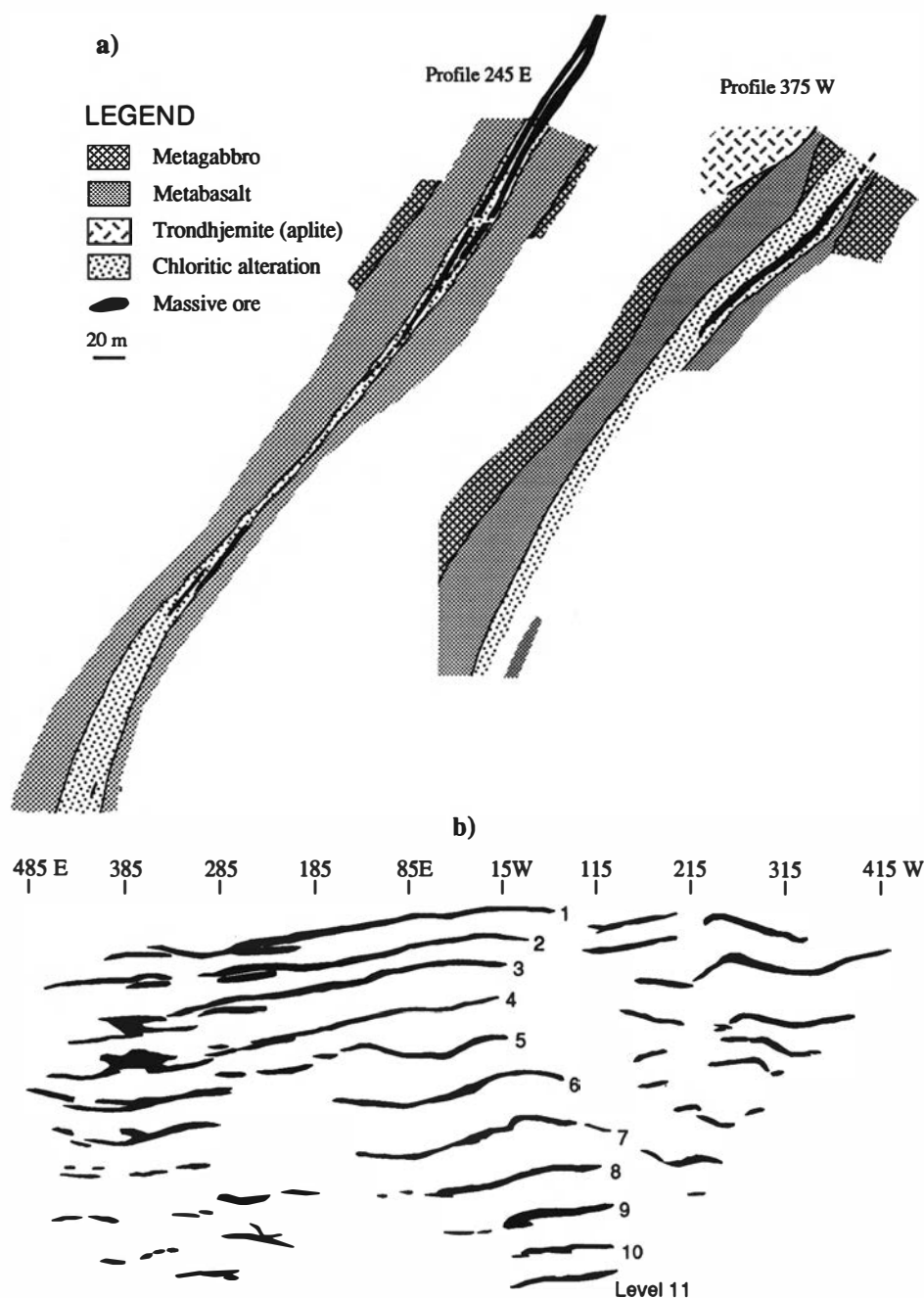


Fig. 4. The Hovedgruva deposit: (a) vertical sections; (b) horizontal projection of the massive ore at the different levels.

stratigraphic level than Søndre Geitryggen. Thin lenses of rhyodacite are intercalated in the tuffites (Fig. 6a) and also thin, extensive horizons of graphite schists. Owing to heavy overburden and limited thickness, these schists are mappable mainly by geophysical methods such as by resistivity and magnetometry. As in the case of Søndre Geitryggen, the tuffites around Nordre Geitryggen are dominantly mafic. Page (1963) described these rocks as undifferentiated schists, or, with an increasing content of amphibole and epidote, as quartz-hornblende-epidote schist.

The ore zone has a strike length of about 420 m and has been followed to a vertical depth of about 550 m. It strikes N042°E and dips about 40°NW. The main ore axis has a plunge of about 45°NE. Because of strong deformation and folding due to the D₁-phase the ore

occurred in ten partly interconnected lenses (Fig. 6b). By contouring the thickness data of the ore from the drill cores on a vertical profile, Page (1963) was able to show that the thicker part of the ore at Nordre Geitryggen corresponded to fold hinges of minor F₂-folds. The fold axes plunge about 40°W, which fits the arial observations (Bjerkgård & Bjørlykke 1994).

Nygruva is situated at a stratigraphic level similar to Nordre Geitryggen, at the border between tuffites in the stratigraphic footwall and rhyodacites in the hanging wall (Fig. 3). Horizons of rhyodacite are locally intercalated in the ore. The tuffites are generally mafic and may be described as quartz-calcite-banded chlorite schists. Amphibole or biotite is locally abundant and the rocks are sometimes grey in colour, due to graphite. The rhyodacites are mostly altered and replaced by a schistose

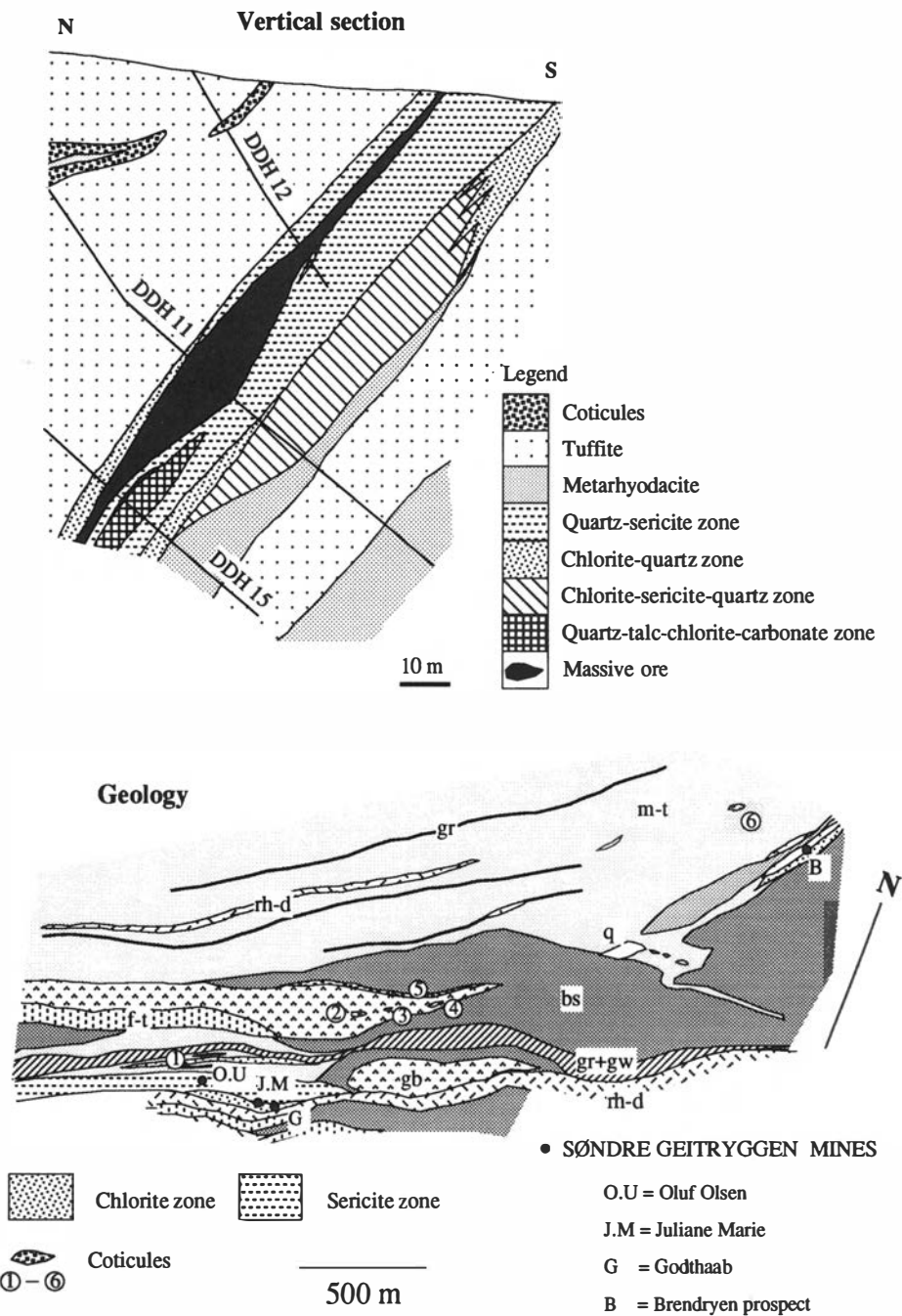


Fig. 5. The Søndre Geitryggen deposit: vertical section and geology of the area around the deposit. Abbreviations: q – quartzite, gr – graphite schist, gw – greywacke, m-t – mafic tuffite, f-t – felsic tuffite, rh-d – rhyodacite, bs – basalt, gb – gabbro.

quartz-sericite (\pm chlorite) rock with lesser amounts of albite. Unaltered varieties show no foliation and have abundant millimetre-sized phenocrysts of albite.

The ore has the shape of a very flat-lying ruler with an axis plunging only 15° W (Fig. 7a). This is very similar to the direction of the axis to the Grimsdalen orebody (see below). The dip of the ruler is about 70° NW and the strike ENE–WSW. The thickness is on average 3 m (max. 7 m). A normal fault has displaced the ore about 140 m. After the continuation west of the fault was found in 1940 (Carstens & Engzelius 1946) the ore was mined for a length of about 680 m until another fault of unknown character (possible large strike-slip component) cut it again. The possible continuation of the ore-zone west of this fault has not been found.

In addition to the main ore lens, several discontinuous massive mineralized lenses occur in the stratigraphic footwall of the deposit, associated with extensive quartz-sericite alteration of metarhyodacite. Chloritic alteration is limited. The lenses have thicknesses reaching a maximum of 1 m, which are too thin to be exploited. Because of the variation in lithologies and alteration in comparison with the main orebody, the lenses are considered to be primary and not the result of folding and/or faulting.

The Grimsdalen–Grimsdalsgruva orebody is situated in a large unit of tuffites (Figs. 2 and 8). A thick unit of partly altered rhyodacite is found in the stratigraphic footwall 0–40 m below both deposits. In Grimsdalen in particular, the tuffites contain 5–16 m thick horizons with clasts of both rhyodacite and basalt. The clasts are

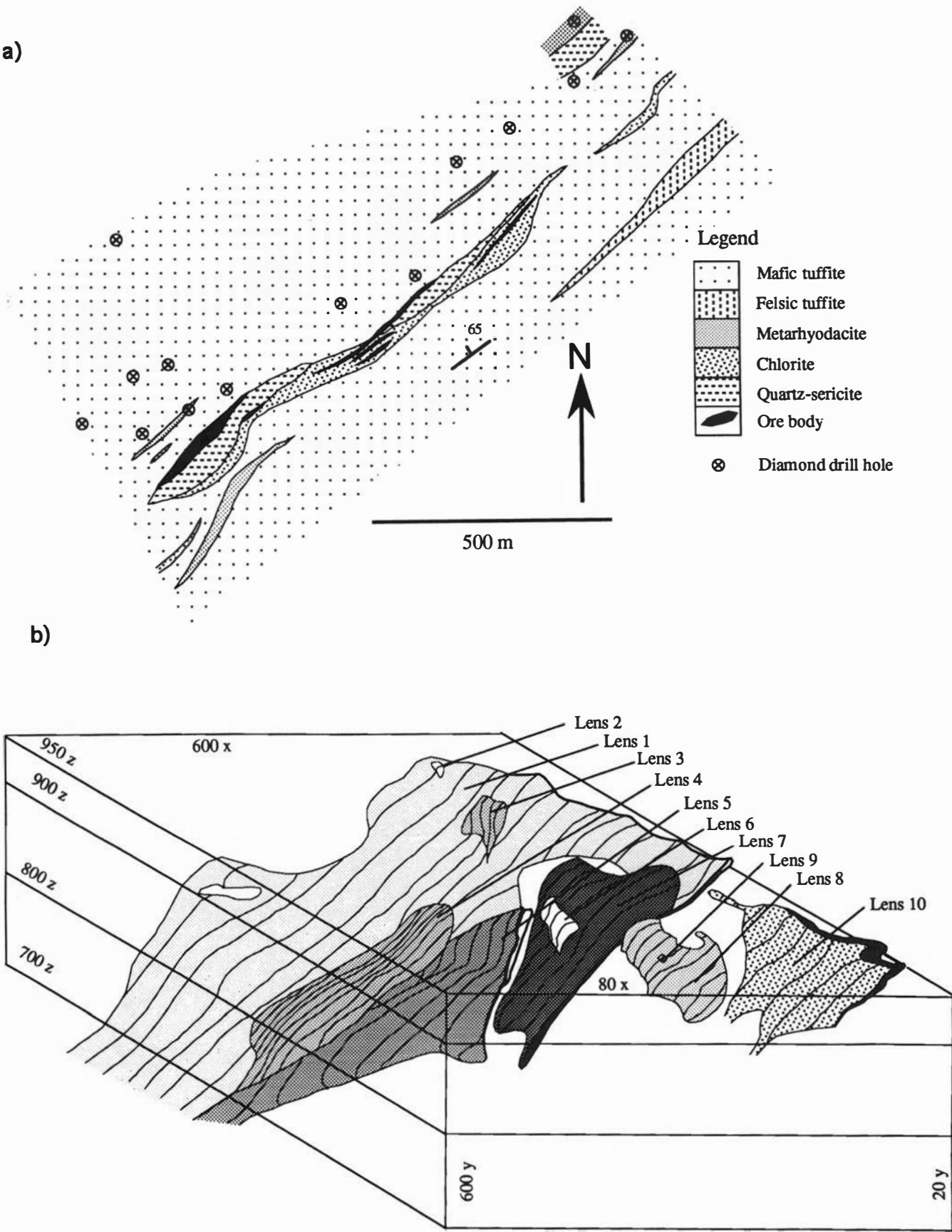


Fig. 6. The Nordre Geitryggen deposit: (a) horizontal section (at surface) based on drillholes; (b) 3D projection of the massive ore lenses at Nordre Geitryggen (from Page 1963).

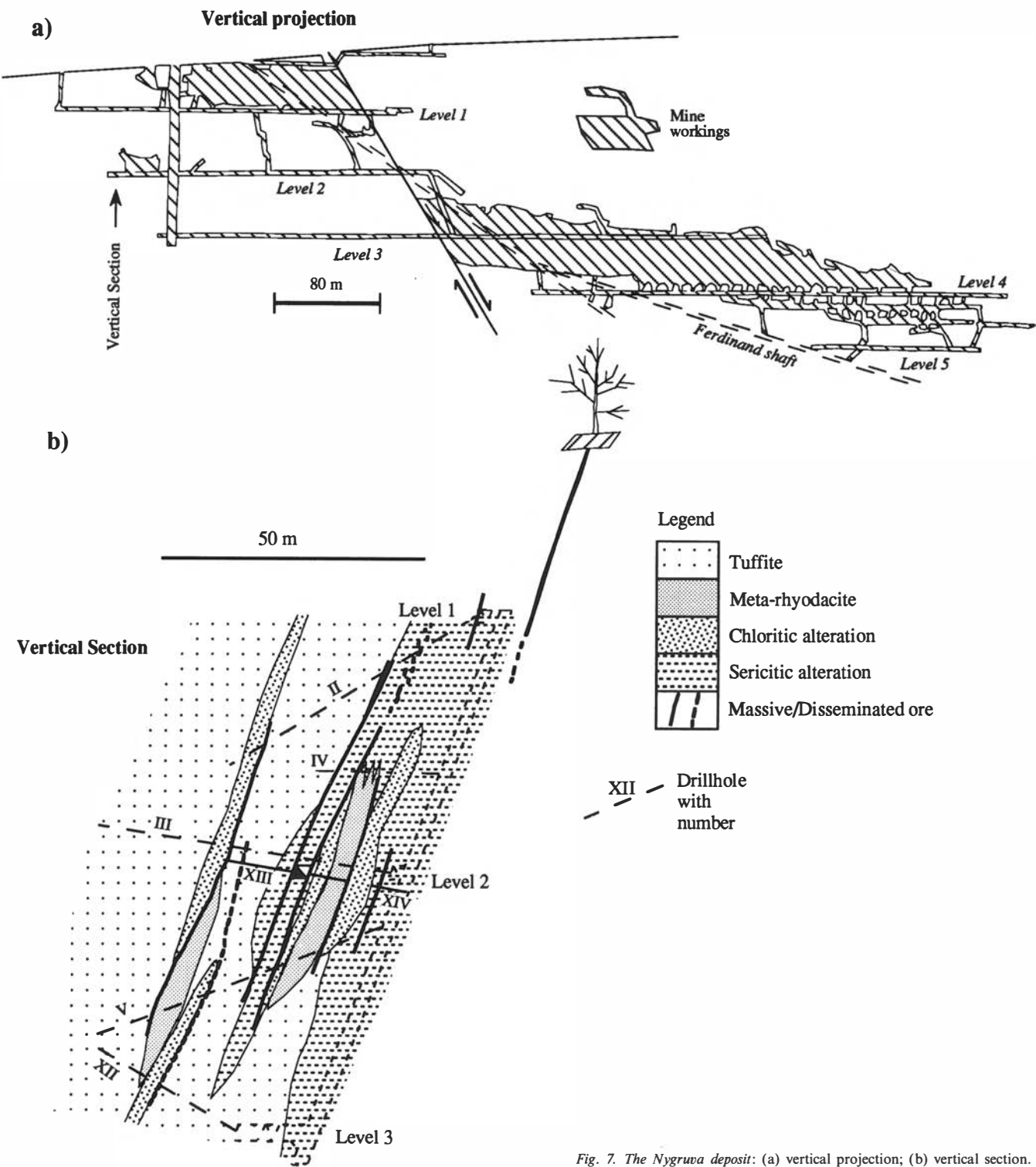


Fig. 7. The Nygruva deposit: (a) vertical projection; (b) vertical section.

variable in size, from <1 to >5 cm in diameter, and are partly angular. These tuffitic rocks have probably formed because of a considerable topographic relief, such as a fault-controlled basinal structure. Several thin, but extensive horizons of graphite schist (revealed by geophysical methods) are intercalated in the tuffites.

The combined length of the ore is nearly 9 km and the width is a maximum 1000 m. The thickness is on average

3 m. This makes the Grimsdalen orebody the largest in the Folldal area with a probable ore tonnage of 13 mill. t, but with a grade too low to be mined. A large fault divides the orebody in two separate deposits and has displaced the ore horizon right laterally for about 700–800 m (Pedersen 1979).

The ore at Grimsdalen is close to isoclinally folded about an axis plunging around 15°W, giving two inter-

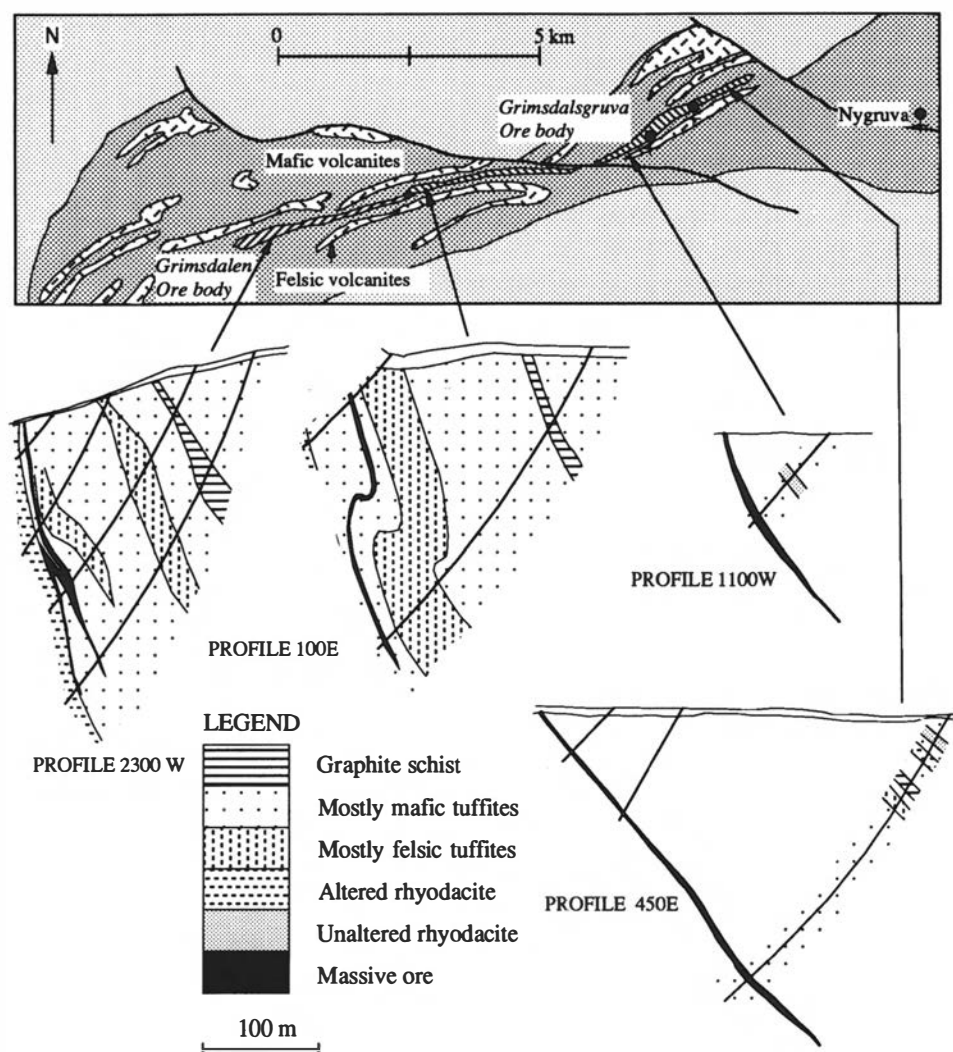


Fig. 8. The Grimsdalen deposit: Geology (modified from Nilsen & Wolff 1989) and vertical profiles. On the geological map the orebodies are projected to surface.

sections of ore in some drill holes. This axial direction and fold style correspond closely to those of F_2 -folds observed in the area around Grimsdalsgruva. A later open phase with axial direction about 70°N has led to an undulation of the ore plane. Further, the plunge of the F_2 -axes changes to an easterly direction in the eastern part of the Grimsdalen orebody. These later structures are due to drag along the large fault. The Grimsdalsgruva part of the orebody has not been folded and has the shape of a ruler, similar to the Nygruva deposit.

The massive mineralizations

All the deposits have a stratigraphically upper stratabound massive mineralization ($>30\%$ S or more than 50% sulphides), underlain by disseminated ore. The extent and character of the dissemination depends on the intensity and type of associated wall-rock alteration (see below).

There are variations in thickness and extent of the massive ores. The tuffite-hosted deposits have thin extensive blankets of massive sphalerite-pyrite ore, typically with a delicate banding. This is especially evident at the

Nordre Geitryggen and the Grimsdalen deposits, which have dimensions of more than 0.5×0.4 km and 9×1 km, respectively, and typical thicknesses of <3 m and 2–4 m outside fold hinges. This is in contrast to the felsite-hosted Søndre Geitryggen deposit, which, even after removing the effect of folding, has a thickness of at least 12 m, but a limited extent (0.2×0.4 km).

The mineralogy of the massive mineralizations (Table 2) generally consists of porphyroblastic pyrite in a recrystallized matrix of pyrrhotite, chalcopyrite and sphalerite. The texture of the ores is mainly the result of deformation and metamorphism. A diffuse banding on a centimetre-scale due to variations in the content of sphalerite and pyrite may be a primary feature. Banding due to zones enriched in magnetite is present in the Nordre Geitryggen and Grimsdalen deposits.

There are clear differences, especially between tuffite- and volcanite-hosted deposits, in the content of both sulphides and gangue. The content of pyrrhotite is higher and the ratio pyrite/pyrrhotite much lower in the tuffite-hosted than in the volcanite-hosted deposits (12–19% and 4–5 vs. 3–5% and 11–17%, respectively). The content of magnetite is also higher in the tuffite-hosted

Table 2. Average and range (in parentheses) of modal mineral contents of the massive ore in the Folldal deposits, based on estimates from polished thin sections.

	Nordre (n = 8)	Søndre (n = 16)	Hovedgruva (n = 12)	Nygruva (n = 10)	Grimsdalen (n = 4)	Grimsdalsgruva (n = 12)
Pyrite	46 (30–65)	53 (35–75)	68 (50–90)	52 (35–65)	58 (50–70)	56 (25–80)
Pyrrhotite	17 (1–35)	5 (0–15)	4 (0–15)	13 (3–35)	12 (5–16)	19 (3–44)
Chalcopyrite	13 (5–20)	9 (1–20)	15 (5–30)	12 (5–20)	12 (1–20)	10 (3–25)
Sphalerite	19 (5–35)	32 (12–50)	12 (1–45)	19 (6–45)	16 (5–25)	7 (3–15)
Magnetite	5 (0–20)	0	2 (0–25)	3 (0–15)	3 (0–10)	9 (0–20)
Galena	7 of 8	15 of 16	0 of 12	10 of 10	3 of 4	4 of 12
Gangue						
Quartz	26 (3–75)	44 (10–80)	70 (10–95)	26 (5–65)	14 (0–35)	45 (15–85)
Calcite	58 (10–95)	39 (0–90)	12 (0–70)	57 (15–80)	79 (65–90)	42 (0–75)
Other	am, mu, chl	chl(10%) mu, bi	am(9%), chl mu	mu, chl, plg	am, chl	chl, bi, plg, am, mu

n = number of samples. Values in volume percent, except for galena, which refers to numbers of sections in which the mineral has been found.

deposits. Galena is very rare in the Hovedgruva deposit, while in the other deposits it is present in accessory to subordinate amounts, and is more abundant in ore rich in sphalerite.

Tellurides including hessite, altaite and Bi-tellurides are occasionally associated with, and partly included in galena (identified by SEM). They are especially abundant in the Søndre Geitryggen deposit. Molybdenite is present in all the deposits and is found as minute laths in sphalerite. Arsenopyrite occurs as euhedral diamond-shaped crystals in the tuffite-hosted deposits of Nordre Geitryggen and Nygruva. The mineral has not been found in the other deposits, which accords with a much lower arsenic content in these (see below).

Quartz and carbonate (mostly calcite) constitute 80–90% of the non-sulphides in the massive mineralizations (Table 2). In the tuffite-hosted deposits the average carbonate content is around 60%, while it is 12% in the basalt-hosted and 39% in the rhyodacite-hosted deposit. The opposite is the case as regards quartz; the basalt-hosted Hovedgruva deposit has a much higher content of quartz than the other deposits. There is also a tendency to a higher content (and abundance in more samples) of chlorite and amphibole in the mafic and tuffite-hosted deposits. Chlorite is, almost without exception, Mg-rich (colourless, normal grey interference colours and optically positive, also confirmed by SEM). Muscovite seems to be enriched in the felsite-hosted Søndre Geitryggen deposit, and talc is present in the lowermost part of the massive mineralization in this deposit together with calcite and dolomite (see below).

Chlorite and/or amphibole seem to be associated with ore rich in chalcopyrite and pyrrhotite, while carbonate is typically associated with ore which has a higher content of sphalerite and pyrite.

Pyrite has grown by aggregation of smaller grains, as shown by regular trails of 'dust' and inclusions of the matrix sulphides and silicates, defining the old grain boundaries. Especially in the tuffite-hosted deposits, pyrite is present with 'cloudy' cores of other sulphides, silicates and undefined 'dust'. These pyrites have also partly resorbed inclusions of pyrrhotite. Similar textures were described by Pedersen (1979) from the Grimsdalen de-

posit. This might indicate that pyrite has been formed at the expense of pyrrhotite or as a result of recrystallization.

Pyrrhotite is typically recrystallized into a granoblastic or foam texture with equant grains. Pyrite shows a similar texture when the pyrite content is high, as in Hovedgruva and Grimsdalen. Chalcopyrite occurs as aggregates of partly equant grains and with abundant twin lamellae.

Magnetite is usually closely associated with pyrrhotite, occurring as loose aggregates of subhedral to euhedral porphyroblasts in a matrix of pyrrhotite. The porphyroblasts very often have rounded inclusions of pyrrhotite. These might either be primary inclusions or a result of metamorphic recrystallization (i.e. poikiloblastic growth). The latter suggests that magnetite formed at the expense of pyrrhotite.

Later deformation has led to fracturing to both porphyroblastic pyrite and magnetite. The fractures have been filled by the more ductile sulphides chalcopyrite, galena and occasionally tellurides. Locally, and especially in Nygruva, where thin shear zones cross-cut the ore, pyrite occurs both heavily fractured and as rounded porphyroblasts floating in a matrix of mostly pyrrhotite ('durchbewegung'). The pyrrhotite is recrystallized at a later stage to a granoblastic texture.

Textures resulting from deformation and recrystallization of the gangue closely follow corresponding textures in the sulphides. Thus in zones where the sulphides are well recrystallized, quartz and carbonate occur in granoblastic texture with distinct triple junctions. Carbonate shows only few deformation twins. In zones where the sulphides are deformed (e.g. heavily fractured or even rounded pyrite), quartz shows typical mortar texture and undulating (nearly twinned) extinction under crossed nicols in the microscope, whilst carbonates are very deformed and twinned.

The extent of remobilization of the ores is difficult to decide from drill cores only. Samples from dumps at Nygruva show late veining of chalcopyrite cross-cutting both the banded ore and the quartz-sericitic wallrocks. These veins are up to 1 mm thick and extend about 5 cm away from the massive mineralization into the wall rocks. The veins consist of chalcopyrite with subordinate pyrrhotite, galena, arsenopyrite and sphalerite. Included

Table 3. Metal content of the massive ore in the Folldal deposits.

Element	Søndre Geitryggen (N = 25)	Hovedgruva (N = 15)	Nygruva (N = 18)	Nordre Geitryggen (N = 25)	Grimsdalsgruva (N = 10)	Grimsdalen (N = 25)
S	31.5 (13.2–43.2)	44.3 (21.7–51.5)	36.8 (12.3–50.4)	35.6 (33.0–43.0)	36.7 (17.5–42.1)	29.3 (19.3–40.7)
Ag	27 (<5–78)	21 (<5–41)	48 (11–120)	31	12 (3–26)	19 (3–37)
As	85 (28–190)	37 (6–120)	396 (<2–1600)	292 (33–710)	46 (26–67)	n.a.
Au	350 (71–1100)	187 (<5–420)	350 (33–770)	273 (71–670)	168 (48–377)	246 (97–390)
Ba	<100 (<100–200)	<100 (<100–200)	<100 (<100)	<100 (<100–200)	<100 (<100–200)	n.a.
Bi	16 (<3–49)	>3 (<3–6)	27 (<3–40)	21 (<3–71)	18 (3–28)	n.a.
Co	26 (<5–62)	437 (46–1300)	136 (46–440)	152 (<5–480)	71 (19–160)	n.a.
Cr	100 (20–230)	164 (90–350)	97 (30–220)	179 (110–370)	101 (60–180)	n.a.
Cu	0.67 (0.09–2.21)	1.94 (0.22–4.04)	1.96 (0.08–10.55)	1.63 (0.40–3.68)	0.85 (0.16–3.92)	0.37 (0.15–1.09)
Mo	26 (6–58)	30 (18–41)	31 (18–53)	24 (<5–44)	9 (<5–23)	n.a.
Ni	<100 (<100)	<100 (<100–200)	<100 (<100–100)	<100 (<100)	<100 (<100–200)	n.a.
Pb	1515 (202–7700)	23 (13–50)	4451 (118–11300)	3059 (126–18300)	421 (24–2870)	1925 (1300–4000)
Sb	1.4 (0.2–10)	<0.2 (<0.2–0.3)	2.9 (<0.2–9.6)	4.0 (<0.2–30.0) [4.0]	<0.2 (<0.2–0.4)	n.a.
Se	44 (<5–94)	64 (8–170)	80 (40–240)	30 (19–190) [80]	58 (39–86)	n.a.
Ti	<0.01 (<0.01–0.02)	<0.01 (<0.01–0.04)	<0.01 (<0.01–0.05)	<0.01 (<0.01–0.07)	<0.01 (<0.01)	n.a.
Sn	<10 (<10)	<10 (<10–15)	<10 (<10)	<10 (<10)	<10 (<10)	n.a.
U	1.7 (<0.5–5.1)	0.8 (<0.5–1.3)	2.5 (0.6–5.0)	2.5 (0.9–7.0)	0.8 (<0.5–2.0)	n.a.
Zn	2.72 (0.21–6.62)	1.21 (0.01–8.09)	5.01 (1.16–13.04)	4.51 (0.64–9.38)	1.63 (0.35–8.61)	2.62 (0.36–4.85)

The numbers refer to weighted average (against length of drillcores) and range (in parentheses) (Cu, Zn and S in %, Au in ppb, the other elements in ppm). N = number of analyses. S. analysed by XRF (Folldal Verk A/S), Bi, Cu, Pb, Sn, Ti, Zn by ICP, and the others by INAA (both ICP and INAA by X-ray Assay Labs, Canada).

are also small grains of native gold, native bismuth and tellurides (hessite and altaite). The gangue in these veins is carbonate.

Page (1963) describes several examples of ore cross-cutting the foliation in the wall rocks and ore introduced along fold structures at Nordre Geitryggen. The cross-cutting structures described have lengths of <5 m. Further, the content of Zn and especially Cu were shown to be increased in the fold hinges of F_2 -folds.

Metal variations

The deposits have quite different content of both the base metals Cu, Zn and Pb and trace metals (Table 3). This is best seen on a spider plot (Fig. 9a). The tuffite-hosted deposits Nordre Geitryggen and Nygruva have the highest content of Zn and Pb and are also relatively rich in Cu. These deposits also have the highest (Cu + Zn)/S-ratio, indicating a relatively low content of pyrite. They have the highest content of As, Bi, Sb, Se and Ag. The content of As is notable, since it is 5–10 times the values of the other deposits.

The basalt-hosted Hovedgruva stands out with a Cu/Zn-ratio >1 and an extremely low content of Pb. The high pyrite content is shown by a low (Cu + Zn)/S-ratio and a high content of S. Compared to the other deposits, Hovedgruva has a much lower content of As, Ag, Au and Bi, while the content of Co is 5–10 times higher.

The felsite-hosted Søndre Geitryggen is much lower in base metals than the tuffite-hosted deposits, but the ratios between the elements are quite similar (Fig. 9b). However, the iron-sulphide to base metal ratio is higher and close to the value of the Hovedgruva deposit. The contents of Co and As are very low compared to both the tuffite- and the basalt-hosted deposits, while the contents of Ag and Au are high (Fig. 9b).

The Grimsdalen–Grimsdalsgruva deposit also has felsic volcanics in the stratigraphic footwall and with respect to the main metals the ratio is quite similar to the Søndre Geitryggen deposit, even though the contents are lower. The deposit has not been fully investigated with respect to trace metals (especially not the Grimsdalen part), but at least the ratios between Au, Ag and Pb are similar to those at Søndre Geitryggen.

Zonation of metal values

Because of limited analyses during production, drill hole data are, in most cases, the only source of information on zonations in the ores. The holes have, in many cases, been drilled from abandoned adits into the wall rocks and only intersect parts of the ore. Thus, zonations both along and across the ores are not known in detail, especially at Søndre Geitryggen, Hovedgruva and Nygruva, the oldest mines.

At Nordre Geitryggen there was a systematic increase in Cu/Zn-ratio westwards and into the deeper part of the ore (Page 1963). Similarly, the content of Zn and especially Cu increased in the fold hinges of F_2 -folds (see above).

The Grimsdalen–Grimsdalsgruva orebody has been extensively drilled from the surface and more than 70 holes intersect the combined 9 km-long orebody. A zonation with higher Cu/Zn-ratio eastwards is evident, such that the eastern part of Grimsdalsgruva has the highest values (Fig. 9c). Also the content of sulphur in the massive mineralization is considerably higher in Grimsdalsgruva (on average 36.5 vs. 26.6%) while the content of Pb is higher in the Grimsdalen part (0.2 vs. 0.06%). These features indicate that the Grimsdalen part is more distal relative to a feeder system than Grimsdalsgruva.

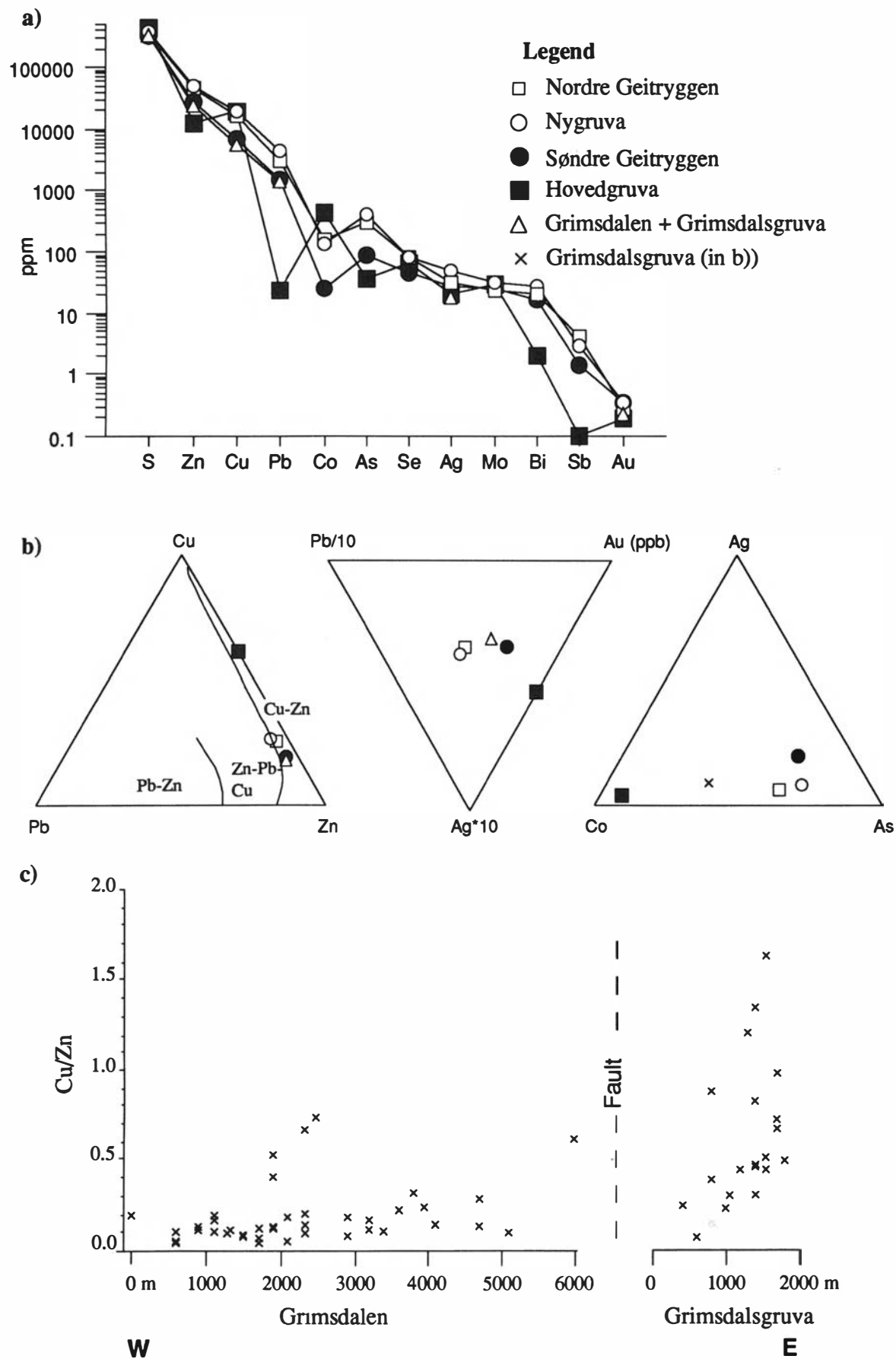


Fig. 9. The massive mineralizations of the Folldal deposits: (a) average metal content; (b) metal ratios (classification lines from Franklin 1986 in the Cu-Zn-Pb plot); (c) lateral variations in Cu/Zn ratios of the Grimsdalen/Grimsdalsgruva orebody.

Very little is known about the content of Cu and Zn in the *Hovedgruva* deposit, as only a few drill holes intersected the ore. From the early days of mining a high content of Cu (up to 2.5%) was observed in the upper part of the ore. This was interpreted to be the result of secondary enrichment (Aasgaard 1935).

Very few drill holes intersect the main ore lens at *Nygruva*. Based on old production reports the content of both Cu and Zn seems to be quite constant: in 1944–50 the production figures of mined ore were Cu 0.81–0.89%, Zn 3.33–3.67% and S 26.66–30.70%. According to old reports the ore mined east of the fault before 1900 had a higher content of Cu (1.3%) and S (\approx 44%). The massive zones or lenses stratigraphically below the main lens (see above), show no systematic zonation and are locally rich in either Cu (up to 10.6%), Zn (up to 13.0%) or both.

Late stage and distal mineralizations

Massive pyrite mineralization is found intercalated in the tuffites about 80 m above the main orebody of Søndre Geitryggen (Fig. 5, no. 1). This contains 0.16% Cu, 0.55% Zn, 41.6% Fe and 35.2% S. This mineralization seems to grade into a rock consisting of alternating quartz-biotite-garnet and quartz-albite. The extent of this zone is at least 200 m along strike and a thickness of \leq 12 m. Similar rocks occur 500–700 m northeast of the Søndre deposit, in several small bodies along with a more extended horizon, slightly higher in the stratigraphy (Fig. 5, nos. 2–6). With some uncertainty because of intense folding in the area, these rocks are interpreted to be at the same level as the massive pyrite above the Søndre deposit.

The bodies consist of irregular lenses dominated by very fine-grained garnet (up to 70%, size <0.01 –0.1 mm), separated by quartz and biotite-rich lenses and sometimes lenses with chlorite and amphibole. The lenses have thicknesses up to a decimetre scale. Ilmenite is present as an accessory phase, associated with biotite.

The extended horizon can be followed for nearly 1000 m along strike and has a thickness of \leq 50 m. In contrast to the bodies, the horizon has a higher content of quartz, lower content of garnet and contains plagioclase, muscovite and magnetite. The content of garnet and magnetite decreases stratigraphically upwards in the horizon and in the upper part the rocks may be classified as volcanoclastic or tuffitic. A fine rhythmic banding on a millimetre to centimetre scale is present between relatively coarse-grained quartz-biotite-chlorite bands and fine-grained muscovite-garnet-biotite+/-plagioclase+/-chlorite bands. At other places garnet-quartz+/-plagioclase bands, biotite-magnetite+/-garnet+/-muscovite bands and quartz+/-garnet+/-magnetite bands alternate. The banding is probably a primary feature.

The high content of phyllosilicates and plagioclase and the gradational transition from garnet-magnetite-quartz

rich rocks to typical tuffites upwards in the horizon indicate mixing between exhalites and tuffites. In contrast, plagioclase and muscovite have not been found in the small bodies in the vicinity of the Søndre Geitryggen deposit. Also, the content of garnet is essentially higher in the latter.

The compositions of garnet, biotite and amphibole have been determined by microprobe. The very fine grained (<0.01 –0.1 mm) garnet shows zonations from grossular-spessartine-almandine cores (18–40% sps) to more almandine-rich rims (Fig. 10a). Biotite is Fe-rich and occurs together with stilpnomelane at one of the localities. Amphibole varies between colourless cummingtonite-grunerite, blue ferro-hornblende, green actinolite and actinolitic hornblende. Chlorite is Fe-rich according to optical properties.

Whole rock analyses (XRF) have been made of samples of garnet-quartz-biotite rocks from localities (2), (4) and (6). As shown there is good concordancy in chemistry between the different localities, but also some systematic variations: the Mn content increases away from the Søndre Geitryggen deposit, while the Fe content decreases. The content of Pb, Zn, Cu as well as K and Rb decreases along with Fe.

Whole rock data can be used to determine source components of garnet-quartz rocks as discussed by, e.g., Wonder et al. (1988) and Spry (1990). The garnet-quartz-biotite rocks from Folldal are compared with tuffites and graphite schist from the same area (Table 4) and pelitic schists from the Åsli Formation (data from Ellevold 1976). In the SiO_2 vs. Al_2O_3 plot (Fig. 10c), all the garnet-quartz samples from Folldal plot in the field of hydrogeneous sediments, while the tuffites plot as deep-sea sediments. This might indicate that the garnet-quartz rocks represent mixing between hydrothermal sediments and tuffites. The hydrothermal character of the graphite schist might be due to a locally high content of quartz. On the Fe/Ti vs. $\text{Al}/(\text{Al} + \text{Fe} + \text{Mn})$ plot (Fig. 10d), the samples follow a mixing curve similar to that between East Pacific Rise metalliferous sediments (EPR) and terrigenous sediments (TS). In Folldal, the Åsli and/or graphite schist in the Fundsjø Group represents the sedimentary end member. The tuffites have variable contents of terrigenous material and spread out along the same mixing curve. In the ternary Fe-Mn-Co + Cu + Ni plot (Fig. 10b) both tuffites, schists and garnet-quartz rocks plot in the hydrothermal field.

Rocks dominated by quartz and manganese-rich garnet have been termed coticles (Renard 1878; referenced in Spry 1990). Such rocks generally occur in pelitic schists as discontinuous layers above, below, or along strike from base metal mineralizations (Spry 1990). They are regarded as distal facies of the massive sulphide mineralizations, forming haloes around the deposits (Stumpfl 1979; Wonder et al. 1988). Similar manganese haloes are known from modern sea-floor deposits, but with manganese occurring in carbonates, oxides, oxyhydroxides and as amorphous matter (Rona 1988).

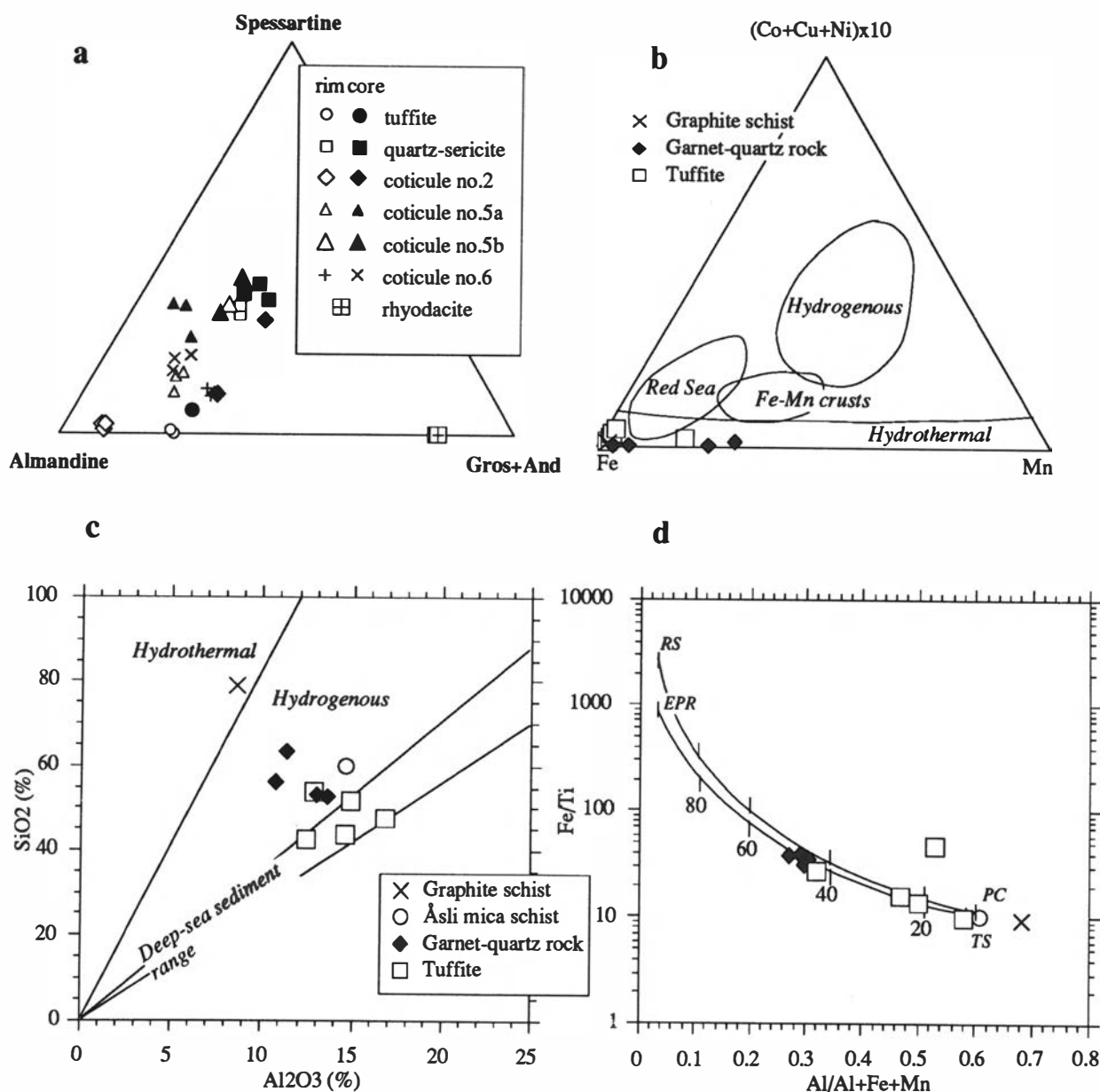


Fig. 10. (a) The composition of garnets in coticules compared to other lithologies. The analyses have been done by electron microprobe (Gros + And is Grossular + Andradite). (b–d): classification of the garnet-quartz rocks (coticules) of the Søndre Geitryggen deposit. (b): Ternary (Co + Cu + Ni)-Fe-Mn plot. The fields of Red Sea, Fe-Mn crusts, hydrogenous and hydrothermal sediments as defined by Spry (1990). (c): SiO₂ vs. Al₂O₃, boundaries between hydrothermal, hydrogenous and deep-sea sediments are taken from Bonatti (1975). (d): Fe/Ti vs. Al/(Al + Fe + Mn). The curves (from Spry 1990) show mechanical mixing of hydrothermal sediments from the East Pacific Rise (EPR) and the Red Sea (RS) with terrigenous sediments (TS) and pelagic sediments (PS) (legend as in plot c).

Based on their high Mn content, the intimate relationship between the garnet-quartz rocks and the Søndre Geitryggen deposit and on geochemical data on these rocks and the surrounding sediments, the garnet-quartz rocks are interpreted to represent distal facies of the Søndre Geitryggen deposit. This implies a hydrothermal origin, which is also shown by the cherty, very fine-grained garnet laminae, despite metamorphic influence. The hydrothermal sediments have been mixed with tuffites and sediments of possibly terrigenous origin. The decrease in content of base metals and in Fe/Mn ratio indicates increasing distance from the hydrothermal vent. On this basis the garnet-quartz rocks are classified as coticules.

Wall-rock alteration

Alteration of the immediate host rocks has been recognized in all the deposits in Folldal, though it varies from being absent or very limited to extensive (Figs. 3–8). The most common alteration types are quartz-sericite and chlorite-quartz, which generally occur in the stratigraphic footwall of the deposits. With the exception of the Søndre Geitryggen deposit, chlorite-quartz alteration is related to the mafic rocks (tuffites and basalts), while quartz-sericite alteration is related to felsic rocks (trondhjemite and rhyodacite). In the Søndre Geitryggen deposit, rhyodacite has also been altered to chlorite-quartz.

Table 4. Whole-rock analyses of garnet-quartz rocks, tuffites and metasediments in the Søndre Geitryggen area.

Gangue/Rock	SiO ₂	TiO ₂	Al ₂ O ₃	FeO(t)	Fe ₂ O ₃ (t)	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅		
MAIN ELEMENTS													
Åsli-sch.	59.8	0.82	14.6	6.4	n.a.	0.08	5.0	0.6	1.9	2.90	0.21		
graphite-sch.	79.1	0.38	8.6	2.8	n.a.	0.04	0.7	0.1	0.2	2.77	0.06		
tuffite	54.0	0.74	12.8	15.1	n.a.	3.50	2.2	3.4	2.6	0.78	0.24		
tuffite	47.8	1.04	16.8	8.0	n.a.	0.12	5.2	5.9	5.5	0.04	0.16		
tuffite	42.6	0.79	12.5	9.6	n.a.	0.18	7.6	11.2	2.7	0.23	0.09		
tuffite	43.9	0.91	14.6	9.7	n.a.	0.14	10.0	6.7	3.2	0.45	0.11		
tuffite	51.7	0.24	14.9	8.7	n.a.	0.12	6.6	5.1	4.8	0.36	0.06		
coticule loc.2	53.0	0.72	13.0	n.a.	23.3	0.76	2.2	2.8	0.1	2.64	0.25		
coticule loc.4	52.7	0.76	13.7	n.a.	22.4	1.49	2.0	4.8	0.1	0.70	0.42		
coticule loc.6	63.3	0.54	11.4	n.a.	15.1	4.52	0.9	4.0	0.1	0.12	0.14		
coticule x	55.9	0.47	10.8	13.7	n.a.	6.02	1.7	5.3	0.3	0.10	0.29		
Rhyodacite	80.7	0.22	10.5	1.6	n.a.	0.09	0.3	2.3	3.6	0.13	0.06		
Gangue/Rock	Mo	Nb	Zr	Y	Sr	Rb	Pb	Cu	Zn	Cr	Co	Ni	V
TRACE ELEMENTS													
Åsli-sch.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	81	296	30	222	101
graphite-sch.	7	9	84	8	22	61	31	18	30	269	3	9	188
tuffite	6	17	123	35	70	55	17	277	113	292	54	87	105
tuffite	1	1	69	26	111	4	12	10	114	619	43	191	239
tuffite	3	2	26	22	223	7	18	249	115	509	38	110	299
tuffite	3	4	44	21	101	11	16	66	121	483	36	102	289
tuffite	2	0	27	8	95	9	13	22	176	226	31	31	186
coticule	4	15	128	37	14	88	12	6	114	265	14	46	157
coticule	5	13	143	34	17	27	10	4	82	267	19	44	134
coticule	6	20	95	21	2	7	7	0	18	359	26	25	82
coticule	7	15	86	28	57	12	12	140	53	293	34	43	49
Rhyodacite	13	5	64	24	155	4	3	0	29	86	2	1	7

The data of the Åsli schist is from Ellevold 1976. All analyses have been carried out at the University of Oslo. The *coticule x* is not related to any known ore deposit. n.a. – not analysed.

The quartz-sericite alteration is similar in all deposits, occurring as schists with millimeter thick lenses and layers consisting of alternating sericite or muscovite and quartz. Quartz is typically recrystallized in a granoblastic, coarse-grained texture. Where the alteration is less intense, the lenses with quartz and sericite are separated by original rock, in the case of Søndre Geitryggen by fine-grained quartz-albite matrix and partially resorbed albite phenocrysts of the rhyodacite (Fig. 11b).

The chlorite-quartz alteration varies somewhat in correspondence with the host rocks. Generally it is schistose, consisting of alternating layers of chlorite and quartz (Fig. 11c). Quartz is, as is the case for the quartz-sericite alteration, recrystallized in a granoblastic texture. The chlorite layers vary from monomineralic to varieties with abundant porphyroblasts of biotite and occasionally amphibole. Also typical are wedge-shaped crystals of sphene. Where alteration is less intense, domains of unaltered rock occur, such as fine-grained quartz-albite matrix with partially resorbed albite phenocrysts. Chlorite is generally Fe-rich in the volcanite-hosted deposits Søndre Geitryggen and Hovedgruva, while in the tuffite-hosted deposits it is more Mg-rich. Further, calcite is abundant in the chlorite-quartz alteration in the tuffite-hosted deposits. What distinguishes the chlorite-quartz alteration from the tuffitic chlorite schists is the lack of muscovite, quartz or calcite in the chlorite layers of the former, which are generally also thicker than in the

tuffites. The alteration also has a higher quartz content and a much lower content of muscovite and usually contains disseminated sulphides.

The *Hovedgruva* deposit, which is the only deposit hosted by metabasalts, is totally dominated by chloritic alteration. The alteration is mostly found at the stratigraphic footwall of the massive ore, while the hanging wall usually consists of metabasalt, often with plagioclase phenocrysts. Locally, aplitic trondhjemite is associated with the ore. This is partly altered to chlorite-sericite-quartz rocks, and consists of alternating chlorite and quartz-sericite-albite in millimetre to centimetre bands. The chloritic alteration consists in places of nearly 100% chlorite with some quartz and shows thicknesses of up to at least 25 m. The alteration rocks typically contain disseminated pyrite and subordinate chalcopyrite, sphalerite and pyrrhotite.

The *Søndre Geitryggen* deposit, hosted by metarhyodacite, is underlain by an extensive and well-developed, zoned, wall-rock alteration. There is a cross-cutting relationship between the alteration and rhyodacite in the stratigraphic footwall, but because of deformation the contact is almost concordant with the surrounding strata (Fig. 5). The alteration can be divided into roughly three types, depending on the main products. From the footwall of the massive mineralization these are: (1) quartz-chlorite schist, (2) quartz-sericite schist, and (3) quartz-talc-chlorite-carbonate schist. The different alteration

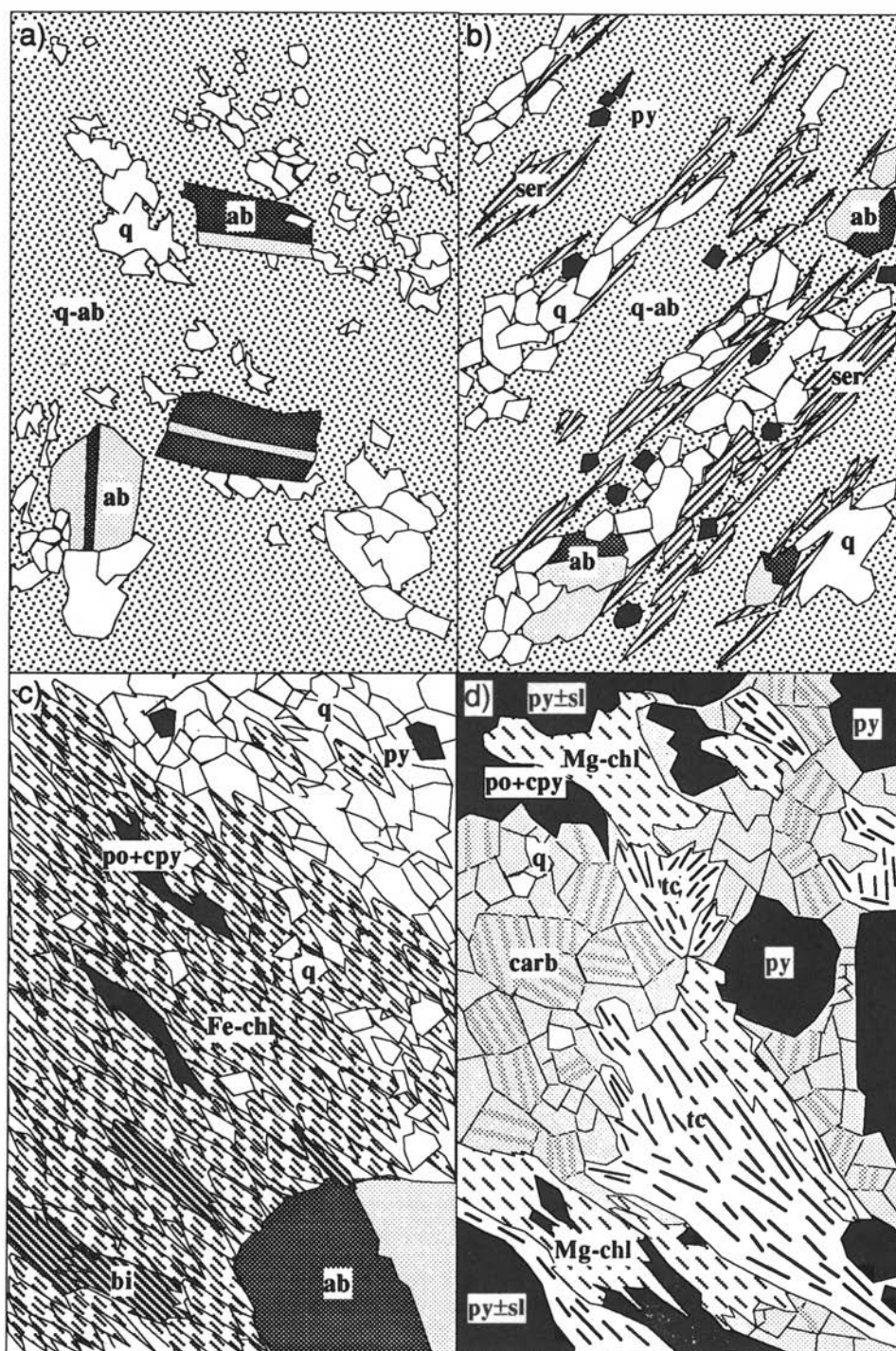


Fig. 11. Wall-rock alteration in relation to the Søndre Geitryggen deposit. Drawings from photographs. (a) rhyodacite; (b) quartz-sericite; (c) chlorite-quartz; (d) quartz-chlorite-carbonate-talc. Legend: *q* = quartz, *ab* = albite, *q-ab* = fine-grained quartz-albite matrix, *ser* = sericite, *bi* = biotite, *Fe-* and *Mg-chl* = Fe- and Mg-rich chlorite, *carb* = carbonate, *tc* = talc, *py* = pyrite, *po* = pyrrhotite, *cpy* = chalcopyrite, *sl* = sphalerite. Scale: Horizontal part of section is 3.5 mm.

types are displayed in Fig. 11. The quartz-sericite alteration dominates and extends 1100 m westwards from the deposit. The maximum thickness of total alteration is about 110 m.

The quartz-chlorite schist occurs mostly to the east of the massive mineralization, with a transitional contact to the rhyodacite or tuffite. Westwards it grades into a quartz-sericite-chlorite schist. A quartz-chlorite schist is also found in the hanging wall of the ore, but with a chlorite richer in Mg. The rock is always dominated by green, Fe-rich chlorite, while quartz, biotite and locally calcite are subordinate. Sphene commonly occurs in up

to 1 mm wedge-shaped crystals. Pyrrhotite and chalcopyrite are the main sulphides, often appearing in massive lenses. Pyrite is found in weak disseminations. The Søndre Geitryggen deposit was first mined for Cu in this zone.

Upwards and westwards, i.e. towards the massive ore, the quartz-chlorite schist grades into an extensive quartz-sericite alteration zone, which also more or less surrounds the massive mineralization. The alteration crops out in a creek as much as 1100 m W of the deposit as an approximately 10 m thick zone with weak pyrite-dissemination. In addition to quartz and sericite, chlorite and

occasionally calcite are found in subordinate amounts, while sphene is accessory, and associated with chlorite. The sulphides, mostly pyrite, are found as disseminations, both evenly distributed and in irregular bands. Sphalerite, chalcopyrite and pyrrhotite are subordinate. The content varies from <5% to >50% sulphides in some centimetre-thick bands.

In the central part, immediately below the massive mineralization, a quartz-talc-chlorite-carbonate schist alternates with quartz-sericite schist (talc has been identified by SEM). Carbonate occurs in up to centimetre-sized aggregates and includes both dolomite and calcite according to SEM analyses. The main sulphide is pyrite, occurring in large grains (several millimetres) as rich disseminations (20–40%), while chalcopyrite, pyrrhotite and sphalerite are subordinate. The zone is heavily mineralized and grades into the massive part of the ore.

At *Nordre Geitryggen* a zone of weak quartz-sericite alteration is present in the tuffites forming the stratigraphic footwall of the massive mineralization, followed by chloritic alteration away from the ore zone. The quartz-sericite alteration is accompanied by disseminations of pyrite, pyrrhotite and chalcopyrite and also some sphalerite, while the chlorite alteration zones only show scattered pyrite. From drill core evidence, the alteration related to this deposit has a small and variable extent (5–25 m). This is supported by Page (1963), who could not find any systematic variations in mineralogy in the wall rocks which could definitively be considered to be the result of alteration.

At *Grimsdalen* and *Grimsdalsgruva* the alteration of the tuffitic wall rocks is overall very weak, restricted to a few metres on both sides of the massive mineralization. The zones of alteration consist of up to 100% chlorite, and are usually weakly disseminated with pyrite, but occasionally also with pyrrhotite and chalcopyrite in irregular aggregates. Lenses or aggregates of quartz-albite and quartz-carbonate are often present. Several intersections show a very sharp contact between the massive mineralization and wall rock without alteration. The underlying

rhyodacite has been weakly altered to a garnet-quartz-sericite schist.

At *Nygruva* both chloritic and quartz-sericitic alterations are found in the stratigraphic footwall to the main ore lens, accompanying both heavy dissemination and intercalations or lenses of massive mineralization (Figs. 3 and 7). The alteration is restricted to some metres around the individual lenses and never exceeds 25 m from any massive mineralization. The quartz-sericite alteration is related to horizons of metarhyodacite, while chlorite seems to follow the tuffites. No alteration is found in the stratigraphic hanging wall of the deposit.

Sulphides and metal content related to alteration

In the Folldal area, quartz-sericite alteration is typically developed in felsic rocks, i.e. trondhjemitic aplites and rhyodacite, whilst chlorite-quartz alteration is most typically developed in mafic volcanic and volcanoclastic rocks. Only at *Søndre Geitryggen* are felsic volcanic rocks altered to quartz-chlorite. Pyrite is the main sulphide in the sericite zones, while pyrrhotite, often accompanied by chalcopyrite, generally dominates in chlorite zones. However, pyrite is the major sulphide in some quartz-chlorite zones, especially in the tuffite-hosted *Nordre Geitryggen* and *Grimsdalen* deposits, where it occurs in cubes up to 1 cm in size. Pyrite in the sericite zones occurs as disseminations, both evenly distributed and in irregular bands, while pyrrhotite in chlorite zones occurs mostly as irregular lenses and streaks, but occasionally also in massive bands. Pentlandite is often present as small included grains and 'flames'. Sphalerite and chalcopyrite are subordinate in both alteration types.

Data for metal content in the alteration zones of three of the deposits show that the Cu/Zn ratio for all the deposits is higher in quartz-chlorite than in quartz-sericite alteration (Table 5, Fig. 12a). The content of Pb is slightly higher in the quartz-sericite alteration. Thus the analytical results are in accordance with the mineralogical observations. Ag, Au, Bi, Co and Se are enriched in the quartz-chlorite alteration. As pointed out above, the

Table 5. Metal contents of the alteration zones of the *Nygruva*, *Søndre Geitryggen* and *Hovedgruva* deposits.

Element	Nygruva		Søndre Geitryggen			Hovedgruva	
	qz-ser	chl-qz	qz-ser	chl-qz	q-chl-c-tc	qz-ser	chl-qz
Ag	19	34	11	16	26	3	3
As	55	52	60	19	52	4	4
Au	323	1870	121	160	358	5	7
Bi	9.5	12.6	5.3	5.7	29.6	4.0	2.3
Co	77	79	18	69	44	36	102
Cr	126	373	125	114	37	205	274
Cu	5185	13980	2782	6092	11788	1868	1681
Mo	19	20	15	11	34	9	6
Pb	1729	1522	625	506	636	9	4
Sb	1.2	0.3	0.5	0.6	0.4	0.1	0.1
Se	37	48	18	25	61	3	6
Zn	10767	19689	12137	6746	23293	4781	818

qz-ser = quartz-sericite, chl-qz = chlorite-quartz, q-chl-c-tc = quartz-chlorite-carbonate-talc. Analysis techniques as listed in Table 3.

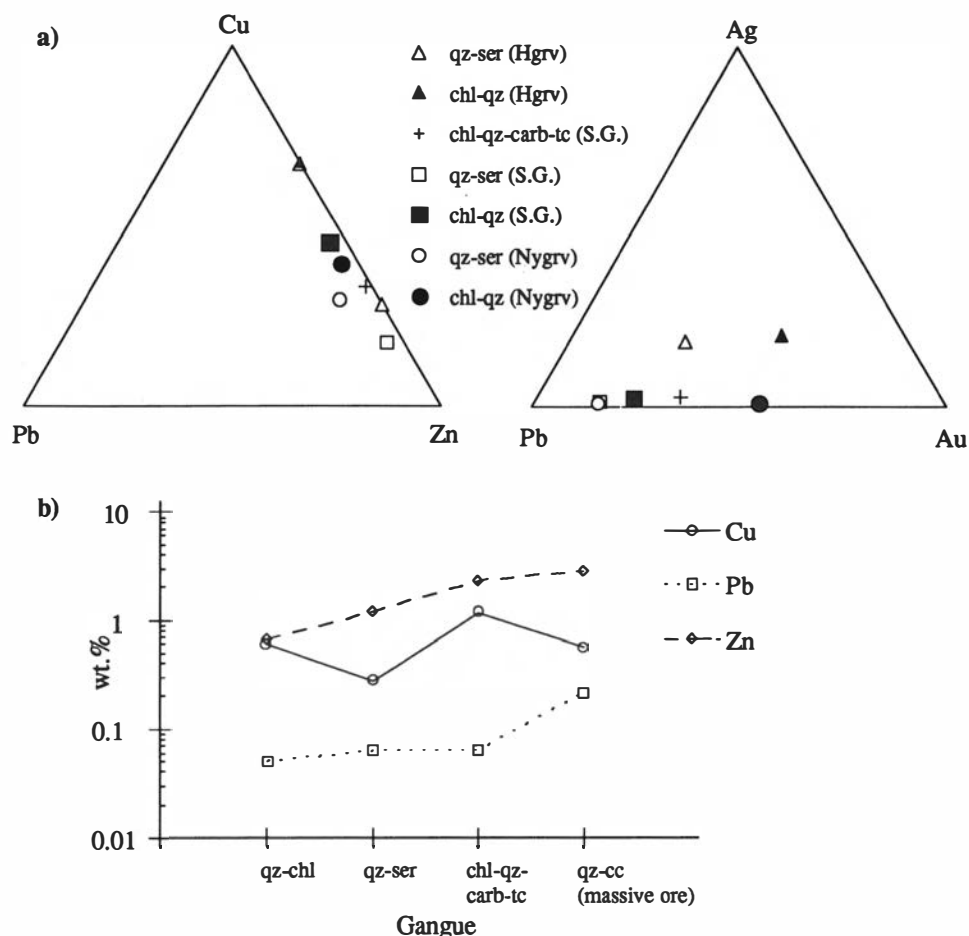


Fig. 12. (a) Metal ratios in the different alteration zones of the Nygruva, Søndre Geitryggen and Hovedgruva deposits. (b) Cu, Zn and Pb content in the alteration zones of the Søndre Geitryggen deposit. qz-ser = quartz-sericite, chl-qz = chlorite-quartz, chl-qz-carb-tc = chlorite-quartz-carbonate-talc, qz-cc = quartz-calcite.

Søndre Geitryggen deposit is the only deposit with a well-developed zoned alteration. The metal content follows this alteration, as shown in Fig. 12b. In the deposit as a whole, the content of Zn shows a systematic increase from the chlorite zone upwards into the massive ore. Cu seems to follow chlorite-rich gangue, being high in the chlorite zone and in the dolomite-talc-chlorite zone and lower in the quartz-sericite zone and in the massive ore. Pb has a quite similar pattern to Zn; it increases weakly upwards through the alteration zones and is enriched in the massive ore.

Discussion

Classification

The sulphide deposits in Folldal are situated at three different stratigraphic levels and are hosted in both felsic and mafic volcanites as well as volcanoclastic rocks or tuffites. The deposits have massive parts (>30% S or more than 50% sulphides), which are stratiform and conformable with the surrounding strata. On these grounds they are classified as volcanic-associated massive sulphide deposits (VMS) according to Franklin et al. (1981).

The deposits can further be classified with respect to content of the principal metals Cu, Zn and Pb. Accord-

ing to the classification scheme of Franklin (1986) all the deposits belong to the Cu-Zn class (Fig. 9b). The Zn/(Zn + Pb) ratio is between 0.92 (Nygruva) and 1.00 (Hovedgruva) which is also typical for Cu-Zn deposits (Lydon 1984). Dominant footwall lithologies associated with Cu-Zn deposits are mafic volcanites and volcanoclastites, which is also true for Folldal if the trondhjemitic intrusion is omitted.

Deformational vs. primary structures

Regarding the relationship between the ores and regional deformation/metamorphism of the area, the massive mineralizations have been shown to be conformable with the surrounding strata and the shape of the orebodies must then be controlled by a combination of primary features and later deformation. Despite the strong deformation, only limited remobilization seems to have occurred. Further, diffuse banding, which might be primary, is seen in the ore, especially in the tuffite-hosted deposits. Thus any zonation, on at least the scale of a deposit, might be regarded as primary. For instance, the similar stratigraphic position and similarity in ore composition allow the Grimsdalen and Grimsdalsgruva ores to be parts of one large orebody. The combined total length of the orebody is nearly 9 km while the average width is at the most 1000 m, if the Grimsdalen body is

unfolded. The thickness is only on average 3 m. Even though the ore is isoclinally folded parallel to its long axis, the deformation cannot explain this elongated shape combined with the limited thickness. Instead, the ore might have been deposited in an elongate basin or graben structure.

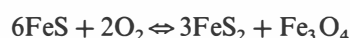
The massive part of the Søndre Geitryggen deposit makes up a steeply inclined stock situated immediately above stringer mineralization (Fig. 5). The orebody has a limited extent, even if the effect of folding is removed. This morphology is typical of proximal deposits, formed immediately above the vent (Large 1977), such as the Kuroko deposits in Japan.

Metal and mineral content

Even though all the Folldal deposits might be classified as Cu-Zn type deposits on a broad scale, there are clearly differences with respect to mineralogy, metal content and ratios, and wall-rock alteration. The deposits can be divided into three groups with respect to host rocks, and a similar division can be established on the basis of ore mineralogy or metal content. This is especially evident regarding the content of the base metals Cu, Zn and Pb and the trace metals Co, As, Bi, Ag, Au, Sb and Se (Table 3 and Fig. 9).

The content of pyrrhotite and the pyrrhotite/pyrite ratio are much lower in the volcanite-hosted deposits than in the tuffite-hosted deposits. If pyrrhotite is regarded as primary, which seems justifiable (Craig & Vokes 1992), it indicates either a higher sulphur fugacity or a lower oxygen fugacity during deposition of the massive ore in the volcanite-hosted deposits and especially in the Hovedgruva deposit (see Large 1977). One possible explanation for a high sulphur fugacity is addition of magmatic sulphur to the hydrothermal solution. Whether pyrite or pyrrhotite is formed is also dependent on temperature, and pyrrhotite is formed at higher temperature than pyrite (op. cit.).

Magnetite is mainly found in the tuffite-hosted deposits. This might be due to a higher oxygen fugacity during formation of these deposits, which seems reasonable in a more distal environment (see below). Magnetite might also have formed at the expense of pyrrhotite together with pyrite. A possible explanation is that fluids have been introduced during metamorphism, inducing the following reaction (Ramdohr 1980):



At the metamorphic grade in Folldal a log $f\text{O}_2$ of -21.5 is calculated for this reaction, showing mildly oxidizing conditions. Why this appears to happen only in the tuffite-hosted deposits might be attributable to a higher content of water in the metasediments.

The relative content of gangue minerals has also been shown to vary according to host rock, with the highest content of calcite in the tuffite-hosted deposits and the

highest content of quartz in the mafic-hosted deposits. The felsite-hosted deposit is intermediate with respect to content of both quartz and calcite. Further, the content of carbonate is higher in the upper part of ore which has a high content of sphalerite.

Calcite is also abundant in several other tuffite-hosted deposits, such as the Vingelen and Sivilvangen deposits further to the north in the Fundsjø Group (Fig. 1). In the Tverrfjellet deposit in the Støren Group (Krupp & Krupp 1985), the content of calcite increases towards the stratigraphic hanging wall together with sphalerite, while the content of quartz decreases. Calcite is also a major gangue mineral in the Skorovass deposit, which is hosted in metabasalts with a minor felsic component (Reinsbakken 1992). Otherwise, quartz is the dominant gangue mineral in most deposits, especially those which are basalt-hosted as at Høydal (Grenne & Vokes 1990), Løkken (Grenne 1989) and Killingdal (Rui 1973; Birkeland 1986).

The high abundance of calcite in the massive ores poses a problem, since the solubility of calcite decreases with temperature. Deposition should therefore not occur when the fluids come in contact with cold sea water. Franklin (1986) suggested that enrichment of carbonates could be due to boiling and phase separation of a CO_2 -rich fluid. Boiling implies shallow water depth (<1 km) and relatively high temperature of the fluids. The tuffite-hosted deposits which have the highest content of calcite are also the highest in the stratigraphy, while the Hovedgruva deposit is the lowest and has very little calcite. The absence of feeder zones related to these deposits is not in accord with this mechanism since boiling would lead to formation of an extensive feeder zone below the deposit. Another possibility is that the carbonate is a result of biogenic activity, which is known to be prominent around hydrothermal vents (e.g. Grassle 1983). The organisms are, however, not calcite-secreting and should therefore not be a source for calcite, but rather graphite.

Wall-rock alteration

The intensity of alteration is much higher in deposits hosted in volcanites than in volcanoclastites or tuffites. Similar observations have been made elsewhere in the Fundsjø Group: only very limited chloritic alteration was observed by one of the authors related to the tuffite-hosted Sivilvangen deposit and also the Vingelen deposit (Bjerkgård 1989), while a well-developed, zoned alteration underlies the Killingdal deposit hosted in basalts (Rui 1973; Birkeland 1986).

The lack of alteration associated with the tuffite-hosted deposits could be compared with the Besshi type deposits which occur in sequences of alternating sedimentary and volcanic rocks (Franklin et al. 1981), while the felsic-hosted deposits could be compared with similarly hosted Precambrian deposits in Canada with respect to alteration, such as those at Mattagami and Garon Lake

(op. cit.). Talc is interpreted to have precipitated directly on the sea floor in the case of the Mattagami Lake deposit (Costa et al. 1983). This accords with observations from the Guaymas hydrothermal field (Lonsdale et al. 1980). The mafic-hosted Hovedgruva deposit follows a general trend typical of such deposits with intense chloritic alteration, sometimes surrounded by quartz-sericite (Franklin et al. 1981; Franklin 1986).

Regarding the relationships between ore minerals and types of alteration, it has been shown that chalcopyrite and pyrrhotite are associated with chlorite-quartz alteration while sphalerite and pyrite are associated with quartz-sericite alteration. This is also reflected by the metal content. Further, the content of lead is higher in

association with quartz-sericite than with chlorite-quartz alteration. This is especially demonstrated by the Søndre Geitryggen deposit (Fig. 12b).

The degree and type of alteration related to massive sulphide deposits seem to result from an interplay between physicochemical characteristics of the ore-forming fluids and host rocks (Franklin 1986). In addition, water depth might be important in controlling the extent of alteration (op. cit), especially regarding the question of boiling. The stability of the alteration mineralogies is dependent on the ratios between activities of the cations and the activity of H^+ and temperature of the hydrothermal solutions (Fig. 13a). Thus, replacement of sericite by chlorite is largely an effect of increasing temperature, while sericite formation from feldspar is largely due to a decrease in pH as a result of sulphide deposition.

Sulphide deposition

The differences in metal content between the deposits could be due to different fluid temperatures during transport of metals and sulphide deposition. This is supported by facts that the tuffite-hosted deposits have the highest content of Zn and Pb and have only limited alteration, while the basalt-hosted Hovedgruva is high in Cu relative to Zn and has an extensive and intensive chlorite zone below the massive ore. Further, the Hovedgruva deposit is situated close to the Folldal trondhjemite. On the other hand, the content of Cu is similar in the tuffite-hosted deposits Nygruva and Nordre Geitryggen to the Hovedgruva deposit. Moreover, the felsite-hosted Søndre Geitryggen deposit shows ratios between Cu, Zn and Pb quite similar to the tuffite-hosted deposits and this is the deposit with the most well-developed alteration.

Another factor which might influence the metal contents and ratios is pH. This might be due to different degrees of mixing between hydrothermal and pristine sea water near the sea floor. Deposition of metals follows the general formula:



An increase in pH will thus promote deposition of sulphides. The solubility of Cu, Zn and Pb as chloride complexes in a temperature vs. pH-diagram and in equilibrium with a common sulphide assemblage in VMS is shown in Fig. 13b. The diagram shows that the solubility of Cu complexes is dependent on temperature to a large degree, while the solubility of Zn- and Pb complexes is less dependent on temperature, but more so on pH. Above it has been shown that the tuffite-hosted deposits had the highest content of calcite, indicating a high pH during deposition of the sulphides. This is in accord with the high content of Zn and Pb, but these deposits also have a high content of Cu.

From this the differences in metal content and ratios between the different deposits seem to have been controlled to only a limited extent by variations in pH

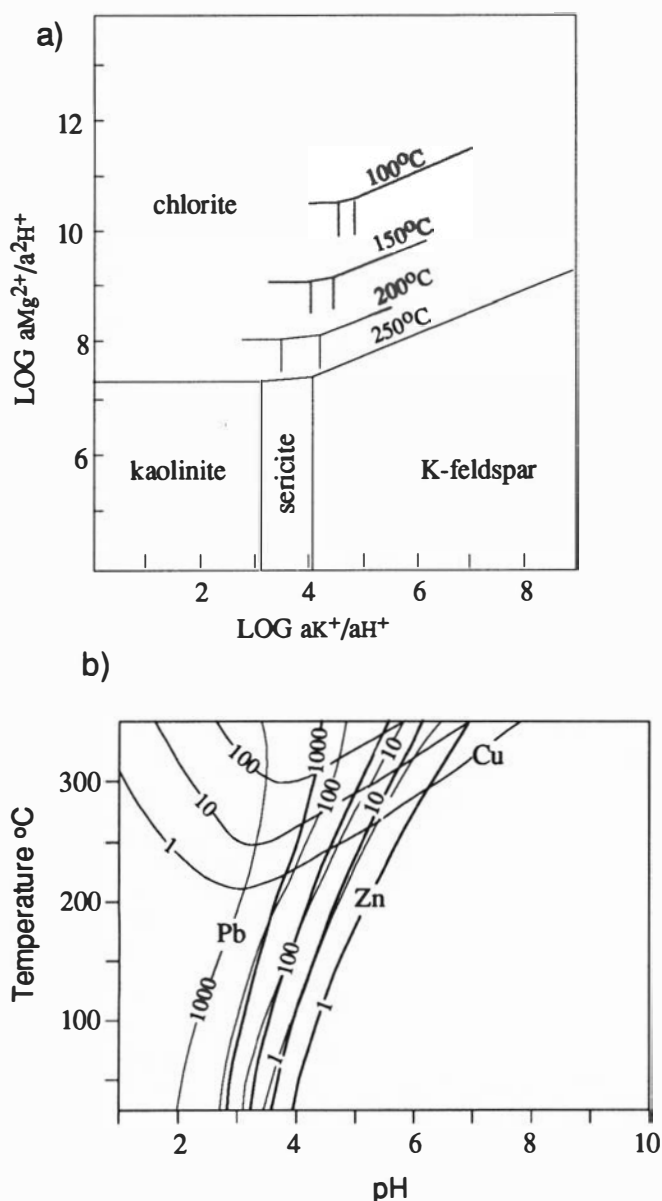


Fig. 13. (a) Stability fields of alteration minerals in relation to differences in activities of cations and H^+ and temperature of the hydrothermal solution. All minerals in equilibrium with quartz. After Riverin & Hodgson (1980). (b) Sulphide solubility patterns due to chloride complexing. Calculated total metal concentrations (in mg/kg or ppm) in a 1m NaCl-solution in equilibrium with the assemblage chalcopyrite, pyrite, pyrrhotite, magnetite, sphalerite and galena. From Lydon (1988).

or/and temperature. Temperature and pH of the fluids have, as discussed above, been more important in controlling the extent and intensity of wall-rock alteration.

Source rocks

Based on the metal data, there would seem to be a connection between host rock and metal content of the deposits. This is supported by analyses of the least altered host rocks (Table 6): the high content of Cu in the tuffite-hosted Nordre Geitryggen and Nygruva deposits and the basalt-hosted Hovedgruva compared to that in the felsite-hosted Søndre Geitryggen deposit (cf. Table 3) corresponds to a 20–40 times higher content of Cu in basalt and tuffites than in the felsic rocks. Similarly, the basalt and partly the tuffites are very high in Co, which can explain the high content of Co in the Hovedgruva deposit. The basalts, on the other hand, are very low in Pb, which is in accord with the extremely low content in the Hovedgruva deposit. Zn is twice as high in the tuffites than in the other host rocks, corresponding to a low Cu/Zn ratio in the tuffite-hosted deposits. This implies that the rocks immediately below the deposits (or corresponding rocks at deeper stratigraphic levels) would appear to be the source of the metals in the deposits.

Differences in source rocks are also important on a regional scale (Franklin et al. 1981; Sawkins 1990) and might reflect different tectonic environments. Deposits in mafic volcanites usually have a much higher Cu/Zn ratio and lower content of Pb than deposits in felsic volcanites and volcanoclastites (e.g. Franklin et al. 1981; Franklin 1986; Craig & Vokes 1992). This is also seen in the Trondheim Region Caledonides: Massive sulphide deposits in the western Støren Group have a Cu/Zn ratio close to unity and a low content of Pb, while deposits in the eastern Fundsjø Group have a Cu/Zn ratio of 2–4 and a higher content of Pb (Nilsen 1988; Craig & Vokes 1992). This might be explained by a high content of sedimentary and felsic volcanic and volcanoclastic rocks in the 'arc complex' of the Fundsjø Group compared to the basalts with MORB affinity of the Støren Group.

Heat source

The Folldal area comprises five deposits at three different stratigraphic levels. This could mean that the deposits were formed at different times. If this is true, one or

more heat sources are required for each episode of ore formation.

The stratigraphically lowermost deposit, Hovedgruva, is situated in metabasalts. The magmatic source for the basalts and associated gabbros may also have been the heat source for hydrothermal convection. Further, the metal abundances and ratios, such as the Cu/Zn-ratio and the low content of As and especially Pb, indicate that metals have been derived from a mafic source with no contribution from felsic volcanic rocks or sedimentary rocks.

The other deposits are all found in the overlying tuffites. The lowermost deposit in the tuffites, Søndre Geitryggen, and partly also the stratigraphically higher Grimsdalen deposit, are associated with extensive (length several kilometres) but thin (≤ 50 m) horizons of rhyodacite. The volume of these rocks is too small to have generated the deposits alone, but might have contributed to convection to some extent.

Regarding the tuffite-hosted deposits Nordre Geitryggen and Nygruva, there are no obvious candidates for local heat sources. This could mean that the temperature of the fluids was lower than in the volcanite-hosted deposits. Another possibility is that the deposits were formed distally to the venting sites. This could happen in two ways; either they formed in a brine pool because of the high density of the fluids (Sato 1972) or they were first deposited at the venting site but later displaced because of instabilities such as a distal slide sheet (Jenks 1971). Because no brecciation has been observed in the ores and a possible primary pyrite-sphalerite banding is observed in these deposits, the first alternative seems most viable. The presence of graphite schists in the tuffites indicates that at times the conditions must have been reducing, which is important in order to prevent the ores from oxidation and dispersion in the water column. The primary shape of the ore will, in the case of formation in a brine pool, be controlled by the shape of the depression and might be very elongated as is the case with the Grimsdalen orebody. In contrast, the elongated shapes of the Løkken orebody (in the Støren Group, Fig. 1) and Stekenjokk-Levi orebodies (in Jämtland, Sweden) are considered to have been controlled by elongated feeder zones (Grenne 1989; Zachrisson 1984, respectively).

The clustering of deposits

The area including the deposits is very restricted (about 80 km²), and there should be a reason for this concentration. Furthermore, the lateral distance between the deposits does not exceed 5–7 km and the vertical distance is < 2 km. These points and, in addition, the lack of local heat sources for some deposits, suggest that one large heat source could be responsible for formation of all the deposits in the upper tuffites. Rhyodacites have been found associated with all the deposits and are comagmatic

Table 6. Content of selected trace elements (in ppm) of host rocks to the Folldal deposits. Analysed by XRF (University of Oslo).

Rock	Mo	Co	Pb	Zn	Cu
Trondhjemitite	7–11	1–12	1–36	18–62	0–2
Rhyodacite	7–13	2–9	3–11	29–56	2
Basalt	14	56	3	69	42
Tuffite	2	37	15	132	87
Graphite sch.	7	3	31	30	18

Table 7. Size distribution of the Folldal deposits based on content of base metals and compared to the median values by Sangster (1980).

Rank	Size distribution Median valued (Sangster 1980)	Folldal				
		Deposit	Tonnage mill. t	Cu:Zn:Pb, %	Metal content (tons)	Size- (%) distribution
1	67	Grimsdalen	8.29	0.53:2.29:0.14	245380	50.8
2	13	Nordre G.	2.50	1.63:4.51:0.31	161250	33.4
3	7.8	Hovedgruva	1.15	1.94:1.21:0.00	36250	7.5
4	4.9	Nygruva	0.30	1.96:5.01:0.45	22260	4.6
5	3.1	Søndre G.	0.50	0.67:2.72:0.15	17700	3.7
6	2.5					
7	2.0	Total			482840	100.0
8	1.7					
9	1.5					
10	1.5					

with the large Folldal trondhemite (Bjerkgård & Bjørlykke 1994). This suggests that the deposits might have formed at roughly the same time and that the trondhemite might have been the major heat source. The metals seem to have been mostly derived from the tuffites at the Nordre Geitryggen and Nygruva deposits, while either the directly underlying rhyodacites or the trondhemite might have contributed in the Søndre Geitryggen and Grimsdalen deposits.

Massive sulphide deposits have a tendency to cluster around felsic volcanites and intrusives constituting volcanic centres (Sangster 1980). Examples are the Hikuroku district in Japan and the Bathurst and Noranda districts in Canada. Sangster (1980) investigated the metal content and size distribution of eight clusters of sulphide deposits from Canada and Japan and found that there was a common average total base metal content of 4.5 mill.t. ($\pm 32\%$) for each of the districts and that on average 67% of the ore was contained in only one deposit. Further, the average size of each district, including the spatially associated volcanites, was found to be on average 32 km ($\pm 29\%$) in diameter (the areas calculated as circular). The narrow range in grade and district metal content was inferred to be due to physico-chemical constraints in leaching, transport and deposition of the metals (Sangster 1980).

Similar calculations have been made for the Folldal ores and compared with Sangster's results (Table 7). The total district metal content in Folldal is far lower, only 0.48 mill.t., and the largest deposit – Grimsdalen – only contains 51% of the total metal content (proved ore). Also, the ratio between the largest and second largest deposit is only 1.5 whereas it typically should have been higher than 4. The diameter of the district, including the associated volcanic rocks, is at least 13 km (area is ≥ 140 km²), but it is difficult to be certain because of strong deformation. The Grimsdalen deposit has not been mined and if probable ore is used instead of proved, the Grimsdalen deposit will contain 62% and the district tonnage will increase to 0.62 mill.t. metal. This is still far too small compared to the average district tonnage of 4.6 mill.t by Sangster. One possibility explaining this discrepancy is that there is a yet undiscovered deposit in

the area. This was used by Sangster (1980) to explain low district values in the Snow Lake district in Canada. If this is true for Folldal, it must be the largest deposit in the area, containing 3.5–4 mill.t. of base metal. It might be smaller if there are several smaller deposits in the area. Another, and more likely possibility, is that the low metal content directly reflects and corresponds to the smaller district size of Folldal compared to the clusters of deposit analysed by Sangster (op. cit).

The trondhemitic intrusion has intruded to a shallow level in the crust, finally less than 1 km below the uppermost tuffite-hosted deposits. This shallow level may also be a reason for the small size of the deposits and the low district content of base metals. This is because a shallow heat source will tend to set up several small hydrothermal cells, compared to large cells with deeper heat sources.

Summary and Conclusions

1. Volcanic-associated massive sulphide deposits (VMS) are situated at three different stratigraphic levels in the Fundsjø Group and belong to the Cu-Zn class of deposits. The deposits are hosted in metabasalts, rhyodacites and volcanoclastic rocks.
2. The deposits are related to episodes of both felsic and mafic volcanism and intrusive activity, the felsic being the younger as seen from the stratigraphic and cross-cutting relationships. The magmatic sources/intrusives may have provided heat for hydrothermal convection cells.
3. Most deposits are thought to be generally related to the large trondhemitic intrusion at the base of the Fundsjø Group. This intrusion, acting as the major heat source for convection, is considered to be the reason for the clustering of deposits in the Folldal area.
4. The small size of the deposits might be due to the shallow level of intrusion of the trondhemite, leading to the setting up of several small convection cells.
5. The metal content of the massive part of the mineralizations is interpreted to reflect the composition of the metal sources; possible candidates are the immediately

underlying strata, perhaps with a contribution from the intrusives.

6. The variable extent and type of wall-rock alteration is a result of differences in chemistry of the host rocks, in temperature of fluids and, probably, in distance from the hydrothermal vent.

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References

- Aasgaard, G. 1935: Beskrivelse av Foldals kistfelt. In Marlow, W. (ed.): Foldal. Beskrivelse til det geologiske rektangelkart. *Norges geologiske undersøkelse* 145, 65–96.
- Birkeland, A. 1986: Mineralogisk og geokjemisk undersøkelse av Kollindal gruver, Sør-Trøndelag. Unpubl. Cand. Sci. thesis, University of Oslo, 158 pp.
- Bjerkgård, T. 1989: Regionalgeologiske undersøkelser i Vingelenfeltet, Nord-Østerdalen i det sørlige Trondheimsfeltet, med henblikk på sulfidmineraliseringene. unpubl. Cand. Sci. thesis, University of Oslo, 191 pp.
- Bjerkgård, T. & Bjørlykke, A. (1994): Geology of the Folldal area, Southern Trondheim Region Caledonides, Norway. *Norges geologiske undersøkelse bulletin*.
- Bjørlykke, K. O. 1905: Det Centrale Norges fjeldbygning. *Norges geologiske undersøkelse* 39, 595 pp.
- Bonatti, E. 1975: Metallogenesis at oceanic spreading centres. *Annual Review of Earth and Planetary Sciences* 3, 401–433.
- Boyd, R. & Nixon, F. 1985: Norwegian nickel deposits: A review. *Geological Survey of Finland, Bulletin*, 363–394.
- Bugge, J. A. W. 1978: Norway. In Bowie, S. H. U., Kvalheim, A. & Haslam, H. W. (eds.): *Mineral Deposits of Europe. Vol. 1: North-west Europe*, 199–249. Institution of Mining and Metallurgy.
- Bøe, R., Sturt, B. A. & Ramsay, D. M. 1993: The conglomerates of the Sel Group, Otta-Vågå area, Central Norway: an example of a terrane-linking succession. *Norges Geologiske undersøkelse* 425, 1–24.
- Carstens, C. W. & Engzelius, J. G. 1946: Hvorledes den forkastede Moltkegang ble funnet. *Tidsskrift for kjemi, bergvesen og metallurgi* 9, 108–110.
- Costa, U. R., Barnett, R. L. & Kerrich, R. 1983: The Mattagami Lake mine Archean Zn-Cu sulfide deposit, Quebec: Hydrothermal coprecipitation of talc and sulfides in a seafloor brine pool – evidence from geochemistry, $^{18}\text{O}/^{16}\text{O}$, and mineral chemistry. *Economic Geology* 78, 1144–1203.
- Craig, J. R. & Vokes, F. M. 1992: Ore mineralogy of the Appalachian-Caledonian stratabound sulfide deposits. *Ore Geology Reviews* 7, 77–123.
- Ellevold, K. 1976: En petrografisk og geokjemisk undersøkelse gjennom et utvalgt profil i den kambro-siluriske lagrekken i Rørosfeltet. Unpubl. Cand. Real. thesis, University of Oslo, 151 pp.
- Foslie, S. 1925: Syd-Norges gruber og malmforekomster. *Norges geologiske undersøkelse* 126, 89 pp.
- Fox, J. S., Farquhar, R., Rui, L. J. & Cook, N. 1988: Genesis of basalt-hosted massive sulphide deposits from the Trondheim and Sulitjelma districts, Norway: ore lead isotopic considerations. *Mineralium Deposita* 23, 276–285.
- Franklin, J. M. 1986: Volcanic-associated massive sulphide deposits – an update. In Andrew, C. J., Crowe, R. W. A., Finlay, S., Pennel, W. M. & Pyne, J. F. (eds.): *Geology and Genesis of Mineral Deposits in Ireland*; 49–69, Irish Association for Economic Geology, Dublin, 709.
- Franklin, J. M., Lydon, J. W. & Sangster, D. F. 1981: Volcanic associated massive sulphide deposits. In Skinner, B. J. & Sims, P. K. (eds.): *Economic Geology, 75th Anniversary Volume*, 485–627.
- Gale, G. H. & Roberts, D. 1974: Trace element geochemistry of Norwegian Lower Paleozoic basic volcanics and its tectonic implications. *Earth and Planetary Science Letters* 22, 380–390.
- Gee, D. G. 1981: The Dictyonema-bearing phyllites at Nordaunevoll, eastern Trøndelag, Norway. *Norsk Geologisk Tidsskrift* 61, 93–95.
- Grassle, J. F. 1983: Introduction to the biology of hydrothermal vents. In Rona, P. A., Boström, K., Laubier, L. & Smith, K. L. (eds.): *Hydrothermal Processes at Seafloor Spreading Centres*, 665–675. NATO Conf. Ser. IV, 12. Plenum Press, New York.
- Grenne, T. 1988: Marginal basin type metavolcanites of the Hersjø formation, eastern Trondheim district, central Norwegian Caledonides. *Norges geologiske undersøkelse* 412, 29–42.
- Grenne, T. 1989: The feeder zone to the Løkken ophiolite-hosted massive sulfide deposit and related mineralizations in the Central Norwegian Caledonides. *Economic Geology* 84, 2173–2195.
- Grenne, T. & Lagerblad, B. 1985: The Fundsjø Group, central Norway – a lower Palaeozoic island arc sequence: geochemistry and regional implications. In Gee, D. G. & Sturt, B. A. (eds.): *The Caledonide Orogen – Scandinavia and Related Areas*, 745–760. J. Wiley & Sons, Chichester.
- Grenne, T. & Vokes, F. M. 1990: Seafloor sulfides at the Høydal volcanogenic deposit, Central Norwegian Caledonides. *Economic Geology* 85, 344–359.
- Guezou, J. C. 1978: Geology and structure of the Dombås–Lesja area, Southern Trondheim Region, south-central Norway. *Norges geologiske undersøkelse* 340, 1–34.
- Heim, J. G. 1972: Zur Geologie des südlichen Trondheim-gebietes. Unpubl. Ph.D. thesis, University of Mainz, 156 pp.
- Janes, R. H. 1955: The massive sulphide deposit of Nordre Geitryggen, Norway. Unpubl. thesis, Imperial College, London, 66 pp.
- Jenks, W. F. 1971: Tectonic transport of massive sulfide deposits in submarine volcanic and sedimentary host rocks. *Economic Geology* 66, 1215–1224.
- Krupp, R. & Krupp, G. 1985: Geological setting of the Tverrfjell copper/zinc deposit, Central Norway. *Geologische Rundschau* 74, 467–482.
- Large, R. R. 1977: Chemical evolution and zonation of massive sulfide deposits in volcanic terrains. *Economic Geology* 72, 549–572.
- Lonsdale, P. F., Bischoff, J. L., Burns, V. M., Kastner, M. & Sweeney, R. E. 1980: A high temperature hydrothermal deposit on the seabed at a Gulf of California spreading centre. *Earth and Planetary Science Letters* 49, 8–20.
- Lutro, O. 1979: The geology of the Gjersvik area, Nord-Trøndelag, central Norway. *Norges Geologiske Undersøkelse* 354, 53–100.
- Lydon, J. W. 1984: Ore deposit models 8. Volcanogenic sulphide deposits. Part 1: A descriptive model. *Geoscience Canada* 11, no. 4, 195–202.
- Lydon, J. W. 1988: Ore deposit models 14. Volcanogenic sulphide deposits. Part 2: Genetic models. *Geoscience Canada* 15, no. 1, 43–65.
- Marlow, W. 1935: Foldal. Beskrivelse til det geologiske rektangelkart. *Norges geologiske undersøkelse* 145, 114 pp.
- Mørk, M. B. E., Kullerød, K. & Stabel, A. 1988: Sm-Nd dating of Seve eclogites, Norrbotten, Sweden – evidence of early Caledonian (505 Ma) high-pressure metamorphism. *Contributions to Mineralogy and Petrology* 99, 344–351.
- Nilsen, O. 1974: Mafic and ultramafic inclusions from the initial (Cambrian?) volcanism in the central Trondheim Region, Norway. *Norsk Geologisk Tidsskrift* 54, 337–359.
- Nilsen, O. 1988: The tectonostratigraphic setting of stratabound sulphide deposits in the southern Trondheim region, central Norwegian Caledonides. *Norges geologiske undersøkelse* 412, 55–66.
- Nilsen, O. & Wolff, F. C. 1989: Geologisk kart over Norge, berggrunnskart Røros & Svev – 1:250,000. *Norges geologiske undersøkelse*.
- Page, N. J. 1963: The sulfide deposit of Nordre Gjetryggen Gruve, Folldal, Norway. *Norges geologiske undersøkelse* 228, 217–269.
- Pedersen, S. A. S. 1979: Structures and ore genesis of the Grimsdalen sulphide deposits, southern Trondheim region, Norway. *Norges geologiske undersøkelse* 351, 77–98.
- Ramdohr, P. 1980: *The Ore Minerals and Their Intergrowths* (2nd ed.), 1205 pp. Pergamon Press, Oxford.
- Reinsbakken, A. 1992: The Skorovass volcanogenic massive sulphide deposit: Volcanostratigraphy, petrochemistry, hydrothermal alteration and paleotectonic setting. Unpubl. Dr. Ing. thesis, NTH, Trondheim, 363 pp.
- Renard, A. 1878: Sur la structure et la composition minéralogique du coticule et sur ses rapports avec le phyllade oligistifère. *Mémoire Curronès de l'Académie Royale Belge* 41, 42 pp.
- Riverin, G. & Hodgson, C. J. 1980: Wall-rock alteration at the Millenbach Cu-Zn mine, Noranda, Quebec. *Economic Geology* 73, 424–444.
- Rona, P. A. 1988: Hydrothermal mineralization at oceanic ridges. *Canadian Mineralogist* 26, 431–465.
- Rui, I. J. 1972: Geology of the Røros district, southeastern Trondheim region, with a special study of the Kjeliskarvene–Holtsjøen area. *Norsk Geologisk Tidsskrift* 52, 1–21.
- Rui, I. J. 1973: Structural control and wall rock alteration at Killingdal mine, Central Norwegian Caledonides. *Economic Geology* 68, 859–883.
- Rui, I. J. & Bakke, I. 1975: Stratabound sulphide mineralization in the Kjølø area, Røros district, Norwegian Caledonides. *Norsk Geologisk Tidsskrift* 55, 51–75.
- Sangster, D. F. 1980: Quantitative characteristics of volcanogenic massive sulphide deposits. 1. Metal content and size distribution of massive sulphide

- deposits in volcanic centres. *Canadian Institution of Mining & Metallurgy Bulletin* 73, 74–81.
- Sato, T. 1972: Behaviours of ore-forming solutions in seawater. *Mining Geology* 22, 31–42.
- Sawkins, F. J. 1990: Integrated tectonic-genetic model for volcanic-hosted massive sulfide deposits. *Geology* 18, 1061–1064.
- Spry, P. G. 1990: Geochemistry and origin of cotectics (spessartine-quartz rocks) associated with metamorphosed massive sulfide deposits. In Spry, P. G. & Bryndzia, T. (eds.): *Regional Metamorphism of Ore Deposits*, 49–75. VSP, Utrecht.
- Stephens, M. B. 1982: Field relationships, petrochemistry and petrogenesis of the Stekenjokk volcanites, central Swedish Caledonides. *Sveriges geologiska undersökning serie C786*, 111 pp.
- Stephens, M. B. & Gee, D. G. 1989: Terranes and polyphase accretionary history in the Scandinavian Caledonides. *Geological Society of America Special Paper* 230, 17–30.
- Stephens, M. B., Furnes, H., Robins, B. & Sturt, B. A. 1985: Igneous activity within the Scandinavian Caledonides. In Gee, D. G. & Sturt, B. A. (eds.): *The Caledonide Orogen – Scandinavia and Related Areas*, 623–656. J. Wiley & Sons, Chichester.
- Stumpfl, E. F. 1979: Manganese haloes surrounding metamorphic stratabound base metal deposits. *Mineralium Deposita* 14, 207–217.
- Sturt, B. A. & Roberts, D. 1991: Tectonostratigraphic relationships and obduction histories of Scandinavian ophiolitic terranes. In Peters, T. J., Nicolas, A. & Coleman, R. G. (eds.): *Ophiolite Genesis and Evolution of the Oceanic Lithosphere*, 745–769. Kluwer Academic Publishers, Dordrecht.
- Vogt, J. H. L. 1889: Funn av Dictyonema ved Holtsjøen, Holtålen. Vidensk. selsk. Oslo Forh. Oversikt over Videnskabs-selskabets møder i 1888.
- Waltham, A. C. 1968: The geology of the Folldal massive sulfide deposits. Unpubl. Ph.D. thesis, University of London 1968.
- Wolff, F. C. 1967: Geology of the Meråker area as a key to the eastern part of the Trondheim Region. *Norges geologiske undersøkelse* 245, 123–146.
- Wolff, F. C. 1979: Beskrivelse til de berggrunnsgeologiske kartbladene Trondheim og Østersund. *Norges geologiske undersøkelse* 353, 77 pp.
- Wonder, J. D., Spry, P. G. & Windon, K. E. 1988: Geochemistry and origin of manganese-rich rocks related to iron-formation and sulfide deposits, western Georgia. *Economic Geology* 83, 1070–1081.
- Zachrisson, E. 1984: Lateral metal zonation and stringer zone development, reflecting fissure-controlled exhalations at the Stekenjokk-Levi strata-bound sulfide deposit, Central Scandinavian Caledonides. *Economic Geology* 79, 1643–1659.
- Zachrisson, E. 1986: Scandinavian Caledonides. Stratabound sulphide deposits. *Sveriges geologiska undersökning, serie Ba* 42, scale 1:1.5 mill.