Geological setting of the Pb-Zn-Cu mineralization in the Mjønesfjell area, Nordland, northern Norway.

KENT GRIMM & HENRIK STENDAL

Grimm, K. & Stendal, H. 1991: Geological setting of the Pb-Zn-Cu mineralization in the Mjønesfjell area, Nordland, northern Norway. *Nor. geol. unders. Bull. 420*, 1-11.

The sediment-hosted Pb-Zn-Cu mineralization in the Caledonides of the Mjønesfjell area, Nordland, northern Norway has been mapped and sampled in detail as a basis for structural and geochemical studies of the mineralizations and their host rocks. The psammitic rocks of the Mjønesfjell area are interpreted as coastal marine deposits with placer accumulations.
The stratabound mineralization is divided into 'massive sphalerite ore', 'layered sphalerite ore' and 'galena-chalcopyrite ore'. The genetic interpretation is complicated by remobilization and recrystallization, mainly during fold phases F2 and F3, but the stratabound distribution of the ore is clear. The genesis of the sulphides is syngenetic with the ore elements precipitating from percolating meteoric water, which probably leached the ore-brine components from the Precambrian crystalline basement. An exhalative provenance is not favoured because of the lack of volcanic rocks in the area.

Kent Grimm, Danmarks Geologiske Undersøgelse, Thoravej 8, 2400 København NV, Danmark.
Henrik Stendal, Institut for almen Geologi, Øster Voldgade 10, 1350 København K, Danmark.

Introduction

An area with Pb-Zn-Cu mineralization has been studied in the Mjønesfjell area of the Caledonides, some 25 km east of Bodø in Nordland, northern Norway (Fig 1). The area was mapped and sampled in detail as a basis for structural and geochemical studies of the mineralizations and their host rocks.

Most of the mapping was carried out in the elevated glacially eroded valley called Mjønesskardet which is situated between two mountains, Lyngsfjellet (751m) to the south and Mjønesfjellet (1058m) to the north. The valley is characterized by many small lakes and, above 300 metres altitude, by sparse vegetation.

The occurrence of sulphides in the area has been known for many years. Several of the older local inhabitants remember the geological prospecting which took place in the 1930's. Remnants of these activities can still be observed in Mjønesskardet where holes after blasting can be found. The first to mention the occurrence of Pb-Zn sulphides in Mjønesskardet in the literature was Poulsen (1964).

The present paper is based on work carried out during field work for an M.Sc. study (Grimm 1987) in the summers of 1984 and 1985. The project was financed by the Geological Survey of Norway.

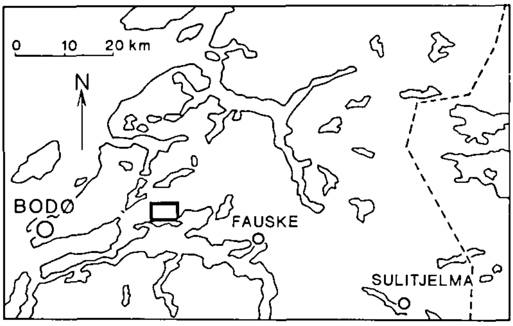


Fig. 1. Location map showing the area (box) covered by Plate 1.

Regional geology

The geology of the investigated area has only been described in publications dealing with the regional geology of this part of the Caledonides (Rutland & Nicholson 1965, Nicholson & Rutland 1969, Wilson & Nicholson 1973, Cooper & Bradshaw 1980, Stephens et al. 1985). This large-scale mapping of the western coastal areas has resulted in three published geological models for the provenance of the area:

1. Rutland & Nicholson (1965) and Wilson & Nicholson (1973) have described the Hegg-

movatn gneiss as an antiformal culmination with a core of basement rocks and an autochthonous cover of metasediments. The granitic gneisses of the western coastal massifs are considered as a westerly extension of the Baltic Shield.

2. Cooper & Bradshaw (1980) proposed a model in terms of mantled gneiss domes originating as rapakivi granites intruded during the Svecokarelian Orogeny (1900-1700 Ma), which were subsequently metamorphosed during the Caledonian Orogeny.

3. Stephens et al. (1985) proposed an alternative model in which the granitic gneisses of the western coastal massifs are considered to be an integral part of the Uppermost Allochthon completely detached from the underlying Precambrian basement. Stephens & Gee (1985) suggested that «miogeocline sequences related to a western continent (Laurentia?) are inferred for the successions in the Uppermost Allochthon».

Rutland & Nicholson (1965) and Cooper & Bradshaw (1980) described three fold phases: F1 and F2 being coaxial with westward plunging fold axes and F3 folds having a more southerly plunge. F1 folds are described as isoclinal whereas F2 are related to the development of the nappes. F3 folds are described as large open to tight folds often overturned and generally with a preference for higher structural units (Rutland & Nicholson 1965). In addition to these fold phases, Cooper & Bradshaw (1980) recognize a late phase related to gravitative tectonic adjustments.

The area mapped in this study covers 15 km^2 (Plate 1) and has hitherto received only limited attention in the literature. The lack of geological information is well reflected in the geological classification of Stephens et al. (1985) where the rocks from the Bodø/Heggmovatn area are referred to as «sedimentary cover/Precambrian basement of uncertain tectonostratigraphic status».

Lithological units

The lithologies in the area comprise metasediments, granitic gneisses and amphibolites.

Metasediments

Psammitic rocks are the dominating rock types in the Mjønesfjellet area. They are a heterogeneous suite of garnet-bearing fine- to medium-grained psammites. Due to variations in textures and mineralogical compositions the psammitic rocks comprise a wide range of types, e.g. quartzite, biotite quartzite, arkosic sandstone, biotite gneiss, and biotite-muscovite gneiss. The mineralogical composition is typically: quartz (58%), feldspar (7%), biotite (12%), muscovite (2%), garnet (5%), accessory minerals (zoisite, sphene, zircon) and opaque minerals (sulphides). Within the rock succession a considerable variation in the actual content of each mineral is recognized.

Calc-silicate rocks within the psammites rocks occur as up to 15 cm thick competent layers. These calc-silicate rocks possess a characteristic mineral zonation: the middle layer (2-4 cm thick) is fine-grained and generally composed of garnet and quartz in equal amounts. An approximately 1 cm-thick, fine-to medium-grained, quartz rim encloses the middle layer, the quartz grains being oriented perpendicular to the bedding. Surrounding these two layers there is a 1-4 cm thick layer of fine grained quartzitic sandstone, the contact to the host rock being gradual whereas the contact to the quartz rim is well defined. The calc-silicate rocks are composed mainly of quartz and garnet, but diopside and epidote are observed in some places.

Biotite-amphibole-garnet schist appears as dark, 0.2-2.0 m-thick concordant layers in the psammitic rocks. Mineralogically, the rock is composed of garnet (35%), amphibole (25%), biotite (20%), quartz (15%), sphene, zoisite and apatite (‹5%). The garnets can reach sizes of about 2 cm in diameter, and poikiloblastic inclusions of quartz and sphene are common. The occurrence in the garnets of rotated helicitic inclusions of sphene and the presence of rotated quartz-filled pressure shadows indicate a weak rotation of the rock.

Intrusive rocks

Medium-grained muscovite-garnet granitic gneiss, interpreted as an intrusive rock, is composed of quartz (35%), plagioclase (25%), potash feldspar (25%), muscovite (10%), garnet (5%) and apatite (‹1%). It occurs both as irregular bodies from 20 m^2 up to 1 km^2 in area as well as smaller pegmatitic veins 0.1 m to several metres thick and up to 700 metres in length. The garnets reach up to 2 cm in diameter; they are euhedral and commonly exhibit poikilitic inclusions of quartz.

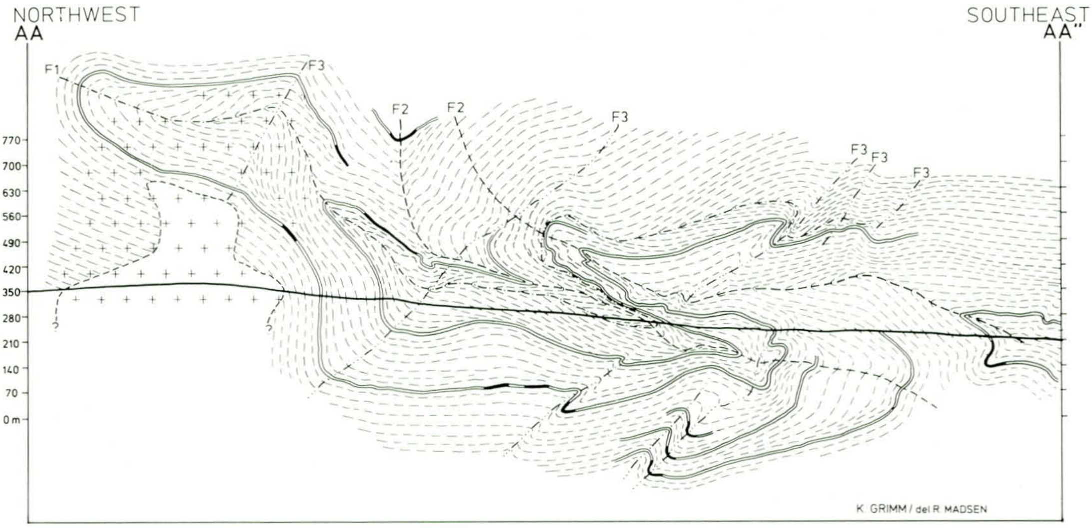


Fig. 2. NW-SE profile (AA-AA") across the Mjønesfjell area. Surface level approx. 350 m. Cf. Plate 1.

Amphibolite occurs as up to 1m-thick discordant dykes which can normally be traced over about 20 metres. The main minerals are hornblende (75%), biotite (15%), plagioclase (5%) and pyroxene (5%); some garnet is present locally.

Two-mica aplite has been observed on the northern side of Lyngsfjellet as a large-scale joint filling. It is a grey, fine-grained, weakly foliated, muscovite-biotite aplite. Garnet is present as very small grains (‹0.5 mm) in amounts less than 0.5 vol .%.

Structural setting

The mapping was complicated by the lack of distinct marker horizons in the area. However, careful correlation of discontinuous rusty horizons in the metasediments provided a reasonable basis for the mapping of the structural pattern of the area. It was not possible to map out calc-silicate layers, or the biotite-amphibole-garnet schist. These lithologies occur concordantly within the psammites and probably represent original stratigraphic units. It was also impossible to map out the discordant amphibolite bodies.

The geological sections (Figs. 2 and 3) and the map (Plate 1) show the intensely deformed central part of the mapped area. The geological sections are constructed from projections, along local fold axes and true dips of layers, on to the planes of the sections.

Structures ascribed to three periods of folding, here abbreviated as F1, F2 and F3, occur within the area. Structures of the F1 generation are difficult to observe in the field. The F1 fold closures are based upon interpretations rather than direct observation. Keeping this in mind, the F1 structures can be descri-

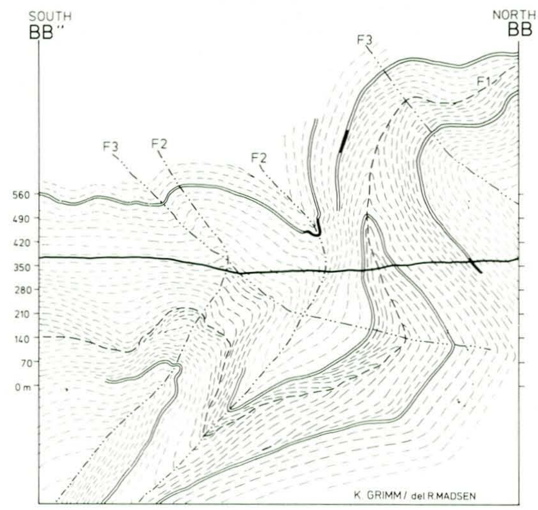


Fig. 3. N-S profile across the Mjønesfjell area. Surface level approx. 370 m. Cf. Plate 1.

bed as north-verging isoclinal folds with westerly plunging fold axes.

The F2 generation is well illustrated in Fig.2 which shows a geological section approximately parallel to the structures of the F3 fold phase. The F2 folds are isoclinal to tight and coaxial with the F1 structures. Fig.3 shows a geological section approximately perpendicular to the general trend of the F3 fold axes. The F3 structures consist of gentle to open east-verging folds with SW-plunging fold axes. A plot of 62 fold axes (Fig.4) contoured after the Kalsbeek (1963) counting net, reveals two clusters at 263°/26° and 242°/19°, with a density of 16 vol%. The most westerly plunging axes are considered to represent the coaxial F1 and F2 folds. The SW-plunging axis represents the general axial orientation of the F3 folds.

The intrusive muscovite-garnet granitic gneiss occurs in three structural settings. A homogeneous, medium-grained intrusive body, approximately 1 km^2 in size is present in the central part of the map area Mjønesskardet (Plate 1). The granitic gneiss has a well developed muscovite foliation. Parallel with this foliation there are 20-30 cm-thick garnet-bearing (ca. 5 vol.%) horizons. There is only a slight grain-size variation towards the contact with the host rock, the contact itself being abrupt and discordant. Within the granitic gneiss body, indistinct late magmatic granite veins are present.

To the west and southwest of the area, the homogeneous intrusive body grades into an area of intense mixing of metasediment and granitic gneiss. The metasediment in this area exhibits a biotite foliation whereas the granitic gneiss shows no sign of foliation. The granite occurs as irregular veins varying in size (thickness: 0.1-0.5 m, length: 0.5-2.0 m) and degree of mixing with the metasediment.

The granitic gneiss also occurs as pegmatitic veins of several generations. The veins show no decrease in grain size towards their discordant contacts with the host rocks. One generation of veins shows a preferred N-S orientation (Plate 1). The N-S trending veins are concentrated to the south of the homogeneous granitic gneiss body. Smaller veins of random orientation (not shown on the map) have locally been boudinaged.

The amphibolite is commonly discordantly intruded into the metasedimentary rocks and

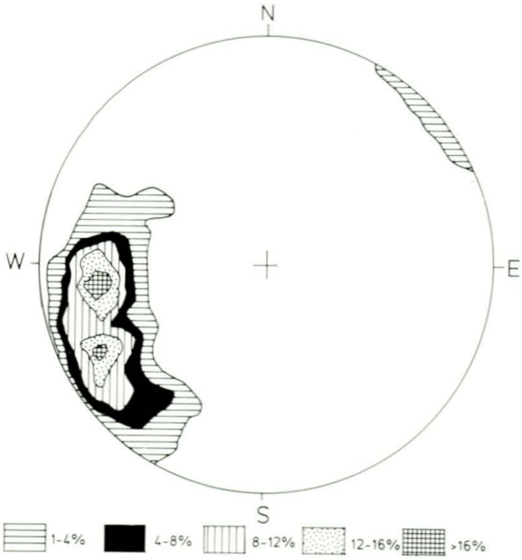


Fig. 4. A contoured plot of fold axes (N=62) in a Lambert equal area stereographic net.

is itself clearly transected by at least one generation of granite veins.

Within the metasandstones, indisputable sedimentary structures (cross bedding and wavy bedding) are observed. This observation, and the occurrence of an ilmenite-sphene-zircon placer east of Mjønestinden (located just outside the eastern limit of the geological map), suggest a coastal marine environment of deposition.

As well as affecting of pegmatites, boudinage is also a common structure within the ore-bearing horizons. In many places, boudinaged and thinned fold limbs are depleted in sulphides relative to the thickened hinge zones where sulphides are concentrated. The 'massive sphalerite ore' (see below) is most common in F2 and F3 hinge zones while the 'layered sphalerite ore' commonly occurs on fold limbs. The 'galena-chalcopyrite ore' occurs in fold limbs and often in boudinaged layers (0.2 - 1m thick).

Mineralization

The concordant Zn-Pb-Cu mineralizations in Mjønesskardet are widespread (Plate 1), but the largest accumulations of sulphides are more common in the western part of the valley. The mineralized horizons are generally 0.5

- 1.0 m in thickness (a few layers are up to 12 m) and occur in more or less rusty layers, but with the greatest concentration of sulphides in the fold cores which represent low-pressure regions. Along the limbs of the folds the ore may be boudinaged. The ore-bearing rusty layers are discontinuous, but can be followed over distances of up to 2 km. The layers were clearly affected by folds of all three deformation phases but the high concentrations of ore occur only in the F2 and F3 folds. No mineralization has been observed in the magmatic rocks.

The stratabound mineralization is divided into 'massive sphalerite ore', 'layered spalerite ore' and 'galena-chalcopyrite ore'. The spatial relationships between the different ore types seem to be associated with structural features. If one can speak about 'zonation', it is related to position in the larger fold structures and is the result of the folding itself and the induced mobilization of the sulphides.

'Massive sphalerite ore' is the richest ore type with approximately 20 vol% of ore minerals, especially sphalerite (70-90 vol%) which is accompanied by pyrrhotite (2-20 vol%), chalco-pyrite (1-5 vol%) and galena (1-5 vol%). The mineralization occurs mainly in strongly deformed layers (4-12 m thick) with the highest concentration of ore minerals in the hinge zones of large folds.

The host rock is typically composed of fine-grained quartz-garnet aggregates (diameter <2 cm) and epidotized megacrysts consisting of epidote, diopside, amphibole and garnet. Another characteristic feature of the host rock is the occurrence of quartz vugs (diameter <2 cm) with quartz crystals up to 2 mm in length orientated perpendicular to the wall of the vug. The sulphides are concentrated between these aggregates and vugs, giving the impression of a para-conglomerate with a matrix of ore minerals.

Rare, thin, quartz-rich layers (< 3 cm thick) have been affected by disharmonic folding, due to plastic deformation in a matrix of almost massive sulphide. Quartz-filled microcracks (width around 25 µm) coated with limonite penetrate the sulphides. Marcasite alterations occur in the pyrrhotite along microcracks (approximately 1 µm thick). The sphalerite grains contain inclusions of chalcopyrite up to 40 µm in size (type locality UTM: VQ 977 681).

'Layered sphalerite ore' has a sulphide content that does not exceed 2 vol %. The distribution of ore minerals is similar to that of the 'massive sphalerite ore': sphalerite (50-70 vol%), pyrrhotite (15-25 vol%), chalcopyrite and galena (< 5 vol%). The mineralization occurs as concordant, mm thick, layers of sulphides with a spacing of a few centimetres, with a marked affinity for layers with the highest garnet content. The mineralized layers may be slightly folded. Galena normally occurs as individual grains rather than in aggregates with the other sulphides. The host rocks are fine-grained, weakly biotite-foliated, garnet-bearing psammites and gneisses which have been subject to extension especially on fold limbs.

Generally, the garnets associated with the mineralization have poikiloblastic inclusions of quartz and sphalerite indicating post-mineralization growth. In addition, angular fragments of garnets, with virtually no inclusions, are present, indicating a pre-mineralization and pre-deformation generation of garnet growth (type locality UTM: VQ 979 686).

'Chalcopyrite-galena ore' comprises a disseminated ore type with an opaque fraction totalling less than 3 vol %. The proportions of ore minerals are: chalcopyrite (10-35 vol%), galena (10-35 vol%), sphalerite (30-50 vol%) and pyrrhotite (10-30 vol%). The host rocks are composed of weakly to strongly biotite-foliated, fine-grained gneisses with heterogeneous banding. They are commonly boudinaged and are generally not rusty.

A few grains of bravoite are found in aggregates with pyrrhotite and chalcopyrite. The sphalerite contains small blebs of chalcopyrite (about 5 µm in size). Galena and sphalerite occur as microcrack fillings in quartz and garnet, and/or as individual grains. Pyrrhotite often contains lamellar intergrowths of monoclinic pyrrhotite in hexagonal phases (Nilsson 1988) and has been altered to marcasite along many grain boundaries.

Graphite is a common constituent in all three kinds of sulphide mineralization and is normally concentrated as inclusions in garnet (less than 1 vol % graphite).

A different kind of mineralization is a placer type, consisting of mm-thick layers of sphene and zircon grains in a fine-grained psammite on the east side of the valley (located just outside the map-area of Plate 1). The sphene grains commonly contain a relict core of ilmenite. The layers of sphene/zircon are in many

	Muscovite garnet granitic gneiss (6 samples)			Mineralized metasediments (30 samples)			Metasedimentary rocks (30 samples)		
wt %	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD
SiO_2	73.19	70.93 - 75.48	1.48	65.40	25.57 - 84.02	13.15	74.14	63.99 - 83.07	5.76
Al_2O_3	14.82	14.28 - 15.40	0.48	9.30	1.90 - 14.87	2.92	11.05	7.64 - 15.77	2.42
Fe_2O_3	1.38	0.80 - 3.27	0.94	9.75	3.32 - 40.34	7.28	4.60	1.23 - 10.53	2.54
TiO_2	0.08	0.01 - 0.30	0.11	0.63	0.07 - 1.92	0.37	0.70	0.15 - 1.75	0.44
MgO	0.15	0.01 - 0.52	0.20	0.98	0.01 - 2.66	0.54	0.84	0.15 - 1.74	0.45
CaO	0.56	0.28 - 1.03	0.27	4.79	0.93 - 15.61	4.14	2.66	0.53 - 11.48	2.30
Na_2O	3.37	0.60 - 4.90	1.48	0.31	0.04 - 1.90	0.40	1.08	0.10 - 3.30	0.89
K_2O	3.99	3.09 - 5.05	0.69	1.88	0.01 - 6.76	2.03	2.76	0.01 - 5.40	1.56
MnO	0.16	0.01 - 0.41	0.16	0.54	0.10 - 1.49	0.39	0.24	0.02 - 1.84	0.37
P_2O_5	0.25	0.08 - 0.48	0.13	0.07	0.01 - 0.24	0.06	0.06	0.01 - 0.17	0.04
ppm									
Sr	22	5 - 72	27	208	23 - 599	168	169	40 - 383	92
Rb	251	153 - 419	93	78	5 - 231	62	104	5 - 192	56
Pb	45	10 - 138	48	8591	49 - 47600	11858	110	12 - 635	141
Zn	73	19 - 182	64	16044	148 - 152400	33544	105	24 - 530	101
Cu				1548	29 - 12800	2637	18	5 - 81	19
Cd				29	10 - 191	39	10	10 - 12	1
V	9	5 - 31	11	44	5 - 143	36	41	5 - 116	33
Ba	63	10 - 172	70	436	10 - 2400	538	515	21 - 1500	483
Sn	17	10 - 36	11	1) 154	10 - 1300	332	2) 171	10 - 914	301
Co				48	5 - 339	89	10	10 - 12	1
Zr	37	19 - 103	33	203	10 - 453	106	323	81 - 907	243

	Mean	Range	SD
1) 24 samples:	Sn 24	10 - 51	13.12
2) 23 samples:	Sn 13	10 - 59	10.56

Table 1. Major and trace element geochemical data from the metasediments and granitic gneiss.

places isoclinally folded with the axial surfaces parallel to the bedding of the host rock.

Geochemistry

Geochemical data for the most common rock type from Mjønesfjellet are given in Table 1, together with simple statistics (mean, range and standard deviation). The analyses were carried out using XRF by the Geological Survey of Norway, Trondheim.

The granitic gneiss has a typical granite composition (Table 1) with 71-75% SiO_2 and 15% Al_2O_3, but with varying contents of the alkalis especially in the sodium content (0.6-4.9% Na_2O). The trace elements are characterized by high Rb compared to Sr, high Sn and low Ba and Zr contents.

The mineralized metasediments differ from the metasedimentary rocks mainly in the contents of base metals and iron but also in CaO and MnO, probably because these elements are constituents of garnet which is associated with the mineralized rocks. Variations in major element geochemistry show a very wide range in the mineralized metasediments mainly due to the erratic variation of contents of the base metals. The base metal content averages up to 20% of combined metals. The Sn content has erratic values in a few samples. If these particular values are excluded from the calculations of the means (Table 1), the Sn content is then comparable with that of other sedimentary rocks. The samples with erratic Sn values coincide with high garnet and/or biotite contents, suggesting Sn enrichment in these phases.

Factor analysis

The purpose of the factor analysis is to reveal characteristics in the sample material which might illustrate the co-variation of elements as well as their relation to different minerals. The analysis was carried out using IBM SAS software (Allen 1985). Minor elements were log-transformed during processing. Only factors with eigenvalues greater than 1.5 were retained. In order to facilitate interpretation, the factors were rotated using the Varimax procedure. The retained factors with the corresponding factor loadings are compiled in Tab-

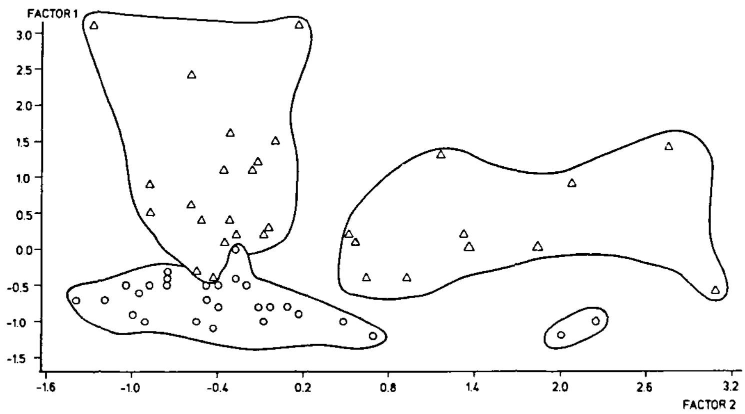


Fig. 5. The factor scores on factor 1 against factor 2. The symbols represent mineralized (triangles) and non-mineralized (circles) metasedimentary rocks.

le 2. Data from 60 samples were processed. The factors are characterized by the following associations of elements in order of decreasing importance:

Factor 1:	Zn, Cd, Co, Pb, Cu	versus SiO_2
Factor 2:	CaO, MnO	versus Na_2O, K_2O, Rb
Factor 3:	MgO, Al_2O_3, TiO_2, P_2O_5	versus SiO_2
Factor 4:	V, Ba	versus Sn

Factor 1 heavily weighs the chalcophile elements and expresses 26.7% of the total variance. The element association of factor 2 indicates that high contents of CaO and MnO are weighed; 22.4% of the total variance is expressed by factor 2. Factor 3 bears high factor loadings on lithophile elements and expresses 19.4% of the total variance. Factor 4 expresses 13.8% of the total variance and weighs high contents of the trace elements V, Ba and Sn.

Factor 1 characterizes an important feature in the sample material, in that it distinguishes mineralized samples from non-mineralized. High contents of ore-material can only occur at the expense of the rock-forming minerals. It is therefore understandable that factor 1 weighs low SiO_2 contents. Considering that garnet is a common mineral in the samples, it is inferred that factor 2 measures high contents of garnet and at the same time reflects the composition of the garnet. Factor 3 bears high factor loadings of MgO and Al_2O_3 which might reflect the fact that muscovite is a common mineral in Mjønesfjellet. Since muscovite shows no systematic variation in its occurrence in Mjønesfjellet, and since no clear interrelationship between the variables describing the factor exist, this factor is considered to be of minor importance. V and Ba commonly occur as trace elements in mica, and are sometimes useful pathfinders for sulphides. Barium might also be common in K-feldspar. Thus, there are a number of possible interpretations of factor 4.

Fig. 5 is a plot of factor scores for factors 1 and 2. It separates the mineralized from the

ROTATED FACTOR PATTERN

	Factor 1	*Factor 2*	*Factor 3*	*Factor 4*
Zn	0.92333	0.13247	-0.05240	0.07034
Cd	0.84259	0.12848	-0.23492	-0.08498
Co	0.83386	0.22591	0.05692	-0.13327
Pb	0.81205	0.17023	-0.01141	0.10554
Cu	0.80307	0.23598	-0.16110	0.01292
CaO	0.06058	0.87582	0.18648	-0.18512
MnO	0.12985	0.84066	0.28296	-0.07281
Fe_2O_3	0.50919	0.54817	0.34312	-0.02765
Zr	-0.33473	-0.45922	0.34614	0.18464
Na_2O	-0.18868	-0.51398	0.11837	-0.32817
K_2O	-0.23568	-0.64476	0.48420	0.28461
Rb	-0.10621	-0.82594	0.34990	0.31747
MgO	-0.02225	0.14439	0.79501	0.10344
Al_2O_3	-0.42551	-0.16474	0.74313	0.05177
TiO_2	-0.18589	-0.02838	0.67792	0.09444
P_2O_5	0.17562	-0.02271	0.65592	-0.16967
SiO_2	-0.55734	-0.43770	-0.56486	0.07263
V	-0.15606	-0.25246	0.23922	0.81921
Ba	-0.20683	-0.30436	0.23703	0.79275
Sn	0.00471	-0.04434	0.28658	-0.80790
Variance explained by each factor:	4.681175	3.916185	3.399222	2.413763
Cumulated variance:	4.681175	8.597360	11.996582	14.410345
Percent of total variance:	26.7	22.4	19.4	13.8
Cumulated percent of total variance:	26.7	49.1	68.5	82.3
Total variance:	17.5028			

Table 2. The Varimex rotated factor loadings.

non-mineralized samples and divides the former into two populations with different garnet contents.

Discussion

Regional geology

According to maps and geological sections produced by earlier authors, the rocks exposed in the Mjønesfjellet area consist mainly of basement gneisses with a thin cover of metasediments. The work carried out by the present authors shows that the rocks on Mjønesfjellet consist mainly of metasediments and that the thickness of the metasedimentary cover is considerably greater than hitherto assumed. The general structural pattern in the region as described by earlier workers is in good geometrical accordance (with regard to fold phases, fold styles and orientation of fold axes) with the data obtained from Mjønesfjellet where two early co-axial, eastward plunging, generations of folds are succeeded by a later south-westward plunging fold generation.

There are several indications that the metamorphic grade has reached amphibolite facies: (a) the occurrence of amphibole, zoisite and garnet, (b) the occurrence of amphibolite, and (c) the mobilization of sulphides during the F2 and F3 phases. This is consistent with the work of Rutland & Nicholson (1965) who, based on regional studies, recognized three fold phases and two major events of amphibolite-facies metamorphism overlapping in time with the two latest phases of folding.

The psammitic rocks of the Mjønesfjell area are interpreted as coastal marine deposits, in accordance with the occurrence of sedimentary structures (cross bedding and wavy bedding) and heavy mineral layers (sphene and zircon). The passive Baltoscandian continental margin, which existed during the Late Precambrian and Cambrian (Stephens & Gee 1985) forms a possible miogeoclinal geological setting for the development of the psammitic rocks.

The amphibolite dykes appear discontinuous (boudinaged ?). Their degree of metamorphism, their disturbed and irregular appearance and the fact that they are locally cut by at least one generation of granite veins suggest a comparatively early age of intrusion of basic dykes.

Since the homogeneous granitic gneiss body is only weakly deformed, it is believed that the intrusion took place during F3. However, there were several phases of minor intrusions (pegmatitic veins and aplite) before and after F3. Because of their undisturbed character, intrusion of the N-S trending granite and aplite veins is considered to have occurred after the main phases of folding, boudinage and amphibolite-facies metamorphism. Their intrusion overlaps in time with the development of conjugate joints resulting from tectonic adjustments after the folding.

The interpretation of the Heggmovatn gneiss, including the rocks in Mjønesfjellet, as representing a window of Precambrian rocks comparable to Nasafjell, Rishaugfjell and Tysfjord, is inconsistent with residual gravity anomaly data which show gravity lows over the Precambrian windows, but only small mass deficiencies over the western coastal granite-gneiss massifs (Gabrielsen et al. 1981).

Based upon the recent work in Mjønesfjellet and on the results of earlier workers in the region, an alternative model is proposed correlating the rocks in Mjønesfjellet with sequences in the Middle Allochthon of Stephens et al. (1985). The metasedimentary rocks from Mjønesfjellet show many similarities with the lithologies of the Middle Allochthon, which consists of crystalline Precambrian rocks and thick units of unfossiliferous feldspathic sandstones containing garnet and epidote-group minerals. Higher structural levels contain Late Proterozoic pretectonic intrusions of dolerite dykes.

The amphibolite bodies of Mjønesfjellet could represent metamorphic equivalents of the dolerites of the Middle Allochthon, an interpretation which is consistent with the increase in metamorphic grade from east to west. As noted earlier, the Middle Allochthon is interpreted as consisting mainly of Baltoscandian, passive continental margin, miogeoclinal sediments. This geological setting forms a probable basis for the geological model of sulphide mineralization in Mjønesfjellet.

Stephens & Gee (1985) and Stephens et al. (1985) have described the Uppermost Allochthon (which they suggest represents the granitic gneisses of the western coastal massifs) as consisting of miogeoclinal sediments originating from a western continent (Laurentia?).

It is believed that either this model or the proposed alternative provides a possible explanation for the provenance of psammitic rocks of the Mjønesfjellet area. Rutland & Nicholson (1965), Wilson & Nicholson (1973) and Cooper & Bradshaw (1980) all consider the western coastal massifs as being composed of a basement/cover complex of Baltoscandian origin. This interpretation can be applied to the Mjønesfjellet area if the psammitic and intrusive rocks are considered to represent the cover. However, the basement has not been observed in the area; and intrusive rocks do not occur in the cover sequences related to the Precambrian windows elsewhere in the region. The contact to the Heggmovatn massif, if it exists, must be found further north than hitherto assumed.

Ore geology

The sulphides in the Mjønesfjellet area are stratabound, dominated by sphalerite, and are generally associated with garnet-bearing layers. The psammitic rocks hosting the mineralization were deposited in a coastal environment, possibly along a passive continental margin. No signs of volcanic activity have been observed.

Mobilization of sulphides is a well established concept (Vokes 1968, Ramdohr 1969, Pedersen 1980). The tendency towards a concentration of ore in hinge zones is a strong indication that the sulphides of the Mjønesfjell area have been mobilized. Partial melting of sulphides involving transport in a molten state is not likely to have been the mechanism in the Mjønesfjell area, since this probably requires temperatures above 700°C (Pedersen 1980). Rather, a mechanism involving mechanical mobilization on a micro-scale may have been operational since micro-crack fillings with galena and sphalerite occur in garnet and quartz grains. These micro-crack fillings were probably formed at relatively low temperatures. However, the main mechanism of mobilization in the Mjønesfjell area was probably fluid-phase mobilization where metal-bearing fluids migrated from areas of high pressure to low pressure sites (e.g. the hinge zones of folds) where the sulphides were reprecipitated.

Factor analysis divides the samples into mineralized and non-mineralized populations and separates the elements into characteristic associations such as chalcophile and lithophile elements. It also reflects the mineralogical composition, e.g. the high contents of Ca and Mn in garnets. The ability of factor 2 to separate the mineralized samples into two populations suggests either a primary genetic difference (i.e., two periods of mineralization) or, more likely, that an originally homogeneous deposit has suffered metamorphic modifications involving fluidphase mobilization of the sulphides. The factor analysis indicates that the mineralized samples can be divided into only two populations, one of which has an affinity to layers rich in garnet. The 'massive sphalerite ore' and the 'layered sphalerite ore' both have an affinity to garnet-rich layers whereas the' galena-chalcopyrite ore' has only a weak affinity to garnet-rich layers. This may indicate that the 'galena-chalcopyrite ore' is only weakly affected by mobilization whereas the other two consist almost entirely of reprecipitated mobilized sulphides in areas susceptible to sulphide precipitation, e.g. low-pressure regions and layers with calc-silicates (originally carbonate-rich sediments).

The genetic interpretation is complicated by remobilization and recrystallization, mainly during fold phases F2 and F3, but the stratabound distribution of the mineralization is clear. The Mjønesfjell mineralization belongs to the clastic-hosted Pb-Zn deposits. In general, these types of deposits are found in shales e.g. Sullivan, Canada (Ethier et al. 1976) and McArthur River, Australia (Lambert 1976, 1982) although the Laisvall type is hosted in sandstone. The shale-hosted deposits are commonly associated with fault zones, but this is not the case in Mjønesfjellet. The clastic sediments resemble more the Laisvall type (Bjørlykke & Sangster 1981) which has been genetically interpreted in two models: (a) matching a Mississippi Valley-type, epigenetic deposit from a saline brine at 150°C (Rickard et al. 1979), and (b) a groundwater model presented by Bjørlykke & Sangster (1981) for Laisvall, and by Samama (1976) for the Largentire Pb-Zn-Cu mineralization. The present study has not provided any data supporting a basinal brine model which involves hydrothermal (possibly magmatic) solutions rising along faultzones in the basement. The models of Samama (1976) and Bjørlykke & Sangster (1981) are more likely. They both involve descending meteoric waters leaching the adjacent crystalline basement for base metals with subsequent, syngenetic precipitation of sulphides during contact between relatively fresh, well oxidized, cratonic groundwater and more saline, and basic, marine waters.

In Mjønesfjellet some calc-silicate-rich layers are present. Stanton (1987) has described skarn formation with syngenetic exhalative Zn-Cu-Fe-Mn-Al mineralization in carbonate-rich layers in Australia. However, the carbonate content is much lower in Mjønesfjellet and no visible signs of volcanic activity responsible for exhalative elements have been observed.

Conclusions

Structural studies in the Mjønesfjell area have shown that the concordant Pb-Zn-Cu mineralizations are concentrated in F2 and F3 folds which were the preferred sites of precipitation for mobilized sulphides. The mineralized horizons are generally 0.5 -1.0 m in thickness (rarely up to 12 m) and occur in more or less rusty layers. The stratabound mineralization is divided into massive sphalerite ore, layered spalerite ore and galena-chalcopyrite ore.

'Massive sphalerite ore' is the richest ore type with approximately 20 vol% of ore minerals. The mineralization occurs mainly in strongly deformed layers. The host rock is typically composed of fine-grained quartz-garnet aggregates, epidotized megacrysts and quartz vugs. The sulphides are concentrated between these aggregates and vugs.

'Layered sphalerite ore' has a sulphide content which does not exceed 2 vol %. The mineralization occurs as concordant, mm-thick layers of sulphides with the greatest affinity for layers with the highest garnet content. The host rocks are fine-grained, weakly biotite foliated, garnet-bearing psammites and gneisses which have been affected by moderate extension.

'Chalcopyrite-galena ore' is a disseminated ore type with an opaque fraction less than 3 vol %. The host rocks are composed of weakly to strongly biotite-foliated, fine-grained gneisses with a heterogeneous banding. They are commonly boudinaged and are generally not rusty.

The metasediments are shallow-water marine sediments with placer accumulations of sphene, ilmenite and zircon. The genesis of the sulphides is syngenetic with the ore elements precipitating from percolating meteoric water, which probably leached the ore-brine components from the Precambrian crystalline basement.

Acknowledgements

The authors wish to express their gratitude to Dr. F. M. Vokes, NTH and A. Korneliussen, NGU, for constructive comments on the manuscript; to NGU for financial support for the field work in the area; to L. Skjernaa, University of Copenhagen, for help and comments on the geological map; and to A. Pratt and J. Bailey, University of Copenhagen, for improving the English manuscript.

References

Allen,A. 1985: *SAS user's guide: Statistics, version 5.* Cary N-C: SAS Institute Inc., 1985, 923 pp.

Bjørlykke,A. & Sangster,D.F. 1981: An overview of lead deposits and their relation to red-bed copper and carbonate-hosted lead-zinc deposits. *Econ.Geol.75th Anniv. Vol.,* 179-213.

Cooper,M.A. & Bradshaw,R.1980: The significance of basement gneiss domes in the tectonic evolution of the Salta region, Norway. *J.Geol.Soc.London 137,* 231-240.

Ethier,V.G., Campell,F.A. , Both,R.A. & Krause,H.R. 1976: Geological setting of the Sullivan orebody and estimates of temperatures and pressure of metamorphism. *Econ. Geol. 71,* 1570-1588.

Gabrielsen, R. H, Ramberg, I. B, Mørk, M. B. E & Tveiten, B.1981: Regional geological, tectonic and geophysical features of Nordland, Norway. *Earth Evol. Sci. 1,* 14-26.

Grimm,K. 1987: *En strukturel og geokemisk malmgeologisk undersøgelse af Bly-Zink-Kobber mineraliseringer i sparagmit serien, Mjønesdalen i Valnesfjord området, Nordland, Norge.* Unpubl. M.Sc thesis Univ. Copenhagen, 143 pp.

Kalsbeek,F. 1963: A hexagonal net for the counting out and testing of fabric diagrams. *Neues Jahr. Min. V,* 173-176.

Lambert,I.B. 1976: The McArthur zinc-lead-silver deposit: features, metallogenesis and comparisons with some other stratiform ores. *In* Wolf (ed.), *Handbook of Stratabound and Stratiform Ore Deposits, Vol. 6.* Elsevier, Amsterdam, 535-585.

Lambert,I.B. 1982: Constraints on the genesis of major Australian lead-zinc-silver deposits: from Ramdohr to present. *In* Amstutz, G.C., El Goresy, A., Frenzel, G., Kluth, C., Moh, G., Wauschkuhn, A. & Zimmermann, R.A. (eds.) *Ore Genesis: The State of the Art.* Springer Verlag, 625-636.

Nicholson, R & Rutland,R.W.R. 1969: A section across the Norwegian Caledonides; Bodø to Sulitjelma. *Nor. geol. unders. 260,* 86 pp.

Nilsson, B. 1988: *En metamorf og malmgeologisk undersøgelse af Zn-Pb-Cu-mineraliserede bjergarter Mjønesfjellet, N.Norge.*Unpubl. M.Sc thesis Univ. Copenhagen, Denmark, 140 pp.

Pedersen,F.D. 1980: Remobilization of the massive sulfide ore of the Black Angel mine, Central West Greenland. *Econ.Geol. 75,* 1022-1041.

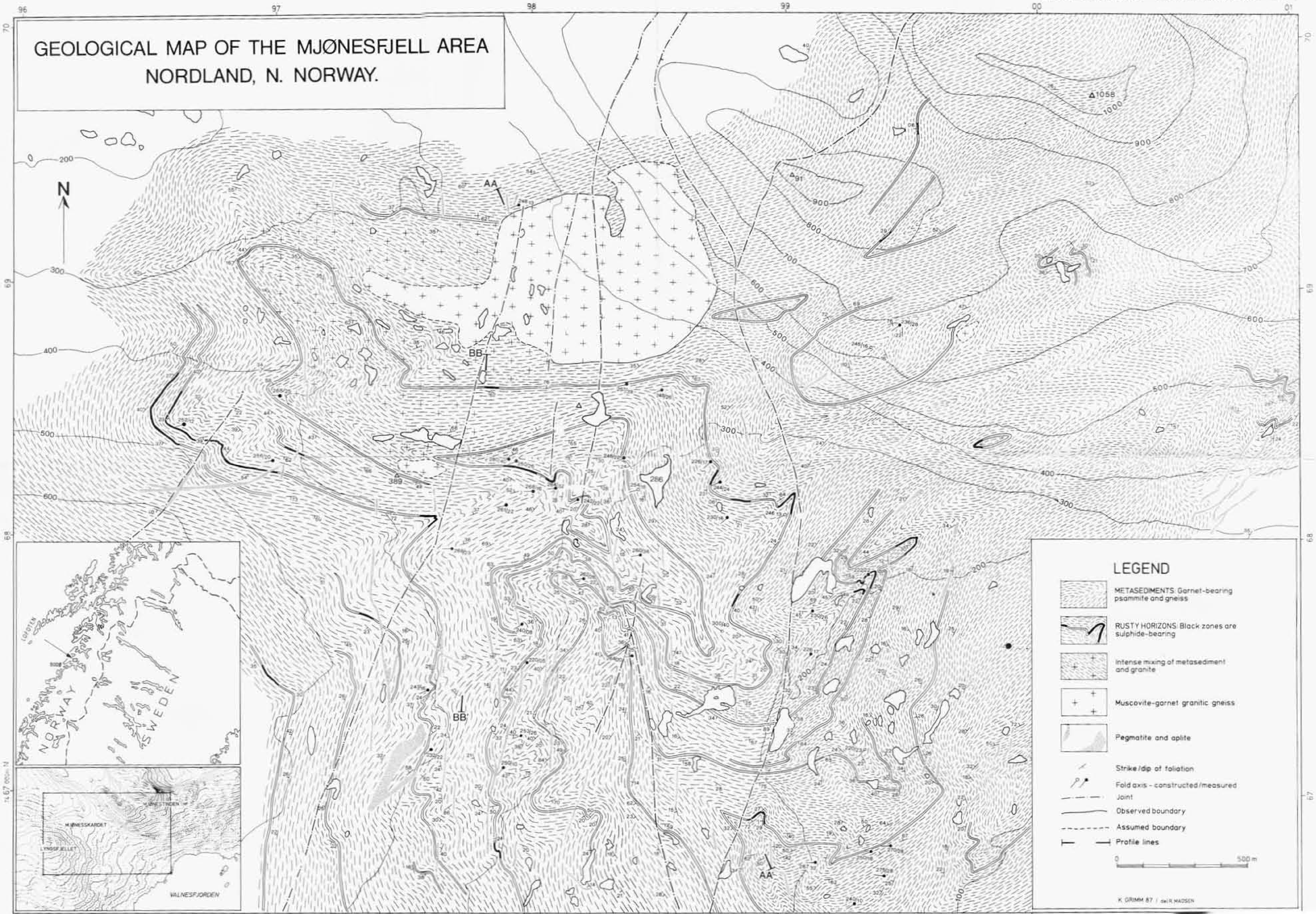
Poulsen,A.O. 1964: Norges gruver og malmforekomster. II Nord Norge. *Nor. Geol. Unders. 204,* 101 pp.

Ramdohr,P.1969. The ore minerals and their intergrowths. Pergamon Press Ltd., 1174 pp.

Rickard,D.T., Willdń,M.Y., Marinder,N-E. & Donelly,T.H. 1979: Studies on the genesis of the Laisvall Sandstone Lead-Zinc Deposit, Sweden. *Econ.Geol. 74,* 1255-1285.

Roberts,D & Gee,D.G.1985: An introduction to the structure of the Scandinavian Caledonides. *In* Gee,D.G.& Sturt, B.A. (eds.) The Caledonide orogen - Scandinavia and related areas. John Wiley & Sons Ltd, Chichester, 55-68.
Rutland,R.W & Nicholson,R. 1965: Tectonics of the Caledonides of part of Nordland, Norway. *Q.J.Geol.Soc.Lond. 121,* 73-109.
Samama,J.C. 1976: Comparative review of the copper-lead sand-stone-type deposits. *In* Wolf (ed.) *Handbook of stratabound and stratiform ore deposits, Vol. 6.* Elsevier, Amsterdam, 1-20.
Stanton,R.L 1987: Constitutional features, and some exploration skarns of eastern Australia. *Trans. Instn. Min. Metall. (Sect.B:Appl.earth sci) 96,* 37-57.
Stephens,M.B. & Gee,D.G.1985: A tectonic model for the evolution of the eugeoclinal terranes in the central Scandinavian Caledonides. *In* Gee,D.G.& Sturt,B.A (eds.) *The Caledonide orogen Scandinavia and related areas.* John Wiley & Sons Ltd, Chichester, 953-978.
Stephens,M. Gustavson,M. Ramberg,I.B & Zachrisson,E. 1985: The Caledonides of central-north Scandinavia a tectono-stratigraphic overview. *In* Gee,D.G.& Sturt,B.A (eds.) *The Caledonide orogen Scandinavia and related areas.* John Wiley & Sons Ltd, Chichester, 138-168.
Vokes,F.M.1968: Regional metamorphism of the Palaeozoic geo-synclinal sulfide ore deposit of Norway. *Inst. Min. Metal. Trans. 77,* B53-B59.
Wilson,R. & Nicholson,R.1973: The structural setting and geochronology of basal gneisses in the Caledonides of part of Nordland, Norway. *J.Geol.Soc.Lond. 129,* 365-387.

Manuscript received September 1989; revised typescript May 1990; accepted November 1990.


GEOLOGICAL MAP OF THE MJØNESFJELL AREA
NORDLAND, N. NORWAY.
N
LEGEND
METASEDIMENTS: Garnet-bearing psammite and gneiss
RUSTY HORIZONS: Black zones are sulphide-bearing
Intense mixing of metasediment and granite
Muscovite-garnet granitic gneiss
Pegmatite and aplite
Strike/dip of foliation
Fold axis - constructed/measured
Joint
Observed boundary
Assumed boundary
Profile lines
0
500 m
K. GRIMM 87 / del R. MADSEN
LOFOTEN
NORWAY
SWEDEN
MJØNESTINDEN
MJØNESSKARDET
LYNGSFJELLET
VALNESFJORDEN
AA
AA'
BB
BB'
Δ1058
Δ91
389
286
96
97
98
99
00
01
70
69
68
67
67 000m N
97 000m E