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Tittel

The Gressli deposit, Tydal, central Norwegian Caledonides (preliminary title)

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Råstoffgruppe	**Råstofftype**	
Malm/metall	Cu, Zn, Pb. Ag, Au	

Sammendrag, innholdsfortegnelse eller innholdsbeskrivelse

Er utkast til publikasjon; usikkert hvem som er co-forfattere,men Vokes er hovedforfatter.
Tar for seg i oversikt geologien i søndre del av Trheimsfeltet føe en går detaljert inn i geologien i Tydalsområdet og videre inn i gressliområdet. Mineraliserte nivåer i disse områdene blir nevnt.
Gressliforekomsten bli historisk gjennomgått fram til boringene i 1975, samt BP minerals sine boringer i 1984-85 langsstrøket. Disse boringene gå Zn-mineralsering av subøkonomisk type. Gressliforekomsten er i seg selv en liten forekomst beregnet etter boringer til ca. 0,90 % Cu og 5,52 % Zn.
Gruvegeologien beskrives, sammen med detaljert malmpetrografi. og mineralkjemi knyttet til ZnS og Py.
Avslutningsvis diskuteres utviklingen av malmteksturen i Gressli-forkomsten.

The Gressli deposit, Tydal, central Norwegian Caledonides

(Preliminary title)

Introduction

The Trondheim District of the Central Norwegian Caledonides is one of the most important of the sub-provinces of the Scandinavian Caledonian metallogenic belt ( ) for the occurrence of stratabound, often stratiform, base-metal bearing iron sulphide deposits; historically, it was the largest producer of this type of ore in the whole belt ( ).

The present contribution describes the geology and mineralogy of one of the minor deposits of the Trondheim District, a deposit which did not in the least contribute to the production statistics, but which exhibits interesting features as regards geological environment and ore-mineral textures.

The Gressli deposit in Tydal, some 65 km SE of Trondheim (Fig. 1) is one of many which are hosted by a more or less continuous "greenstone" belt, some 300 km long, forming the eastern flank of the District from the Dombås area in the south to the Snåsa area in the north. This ore-bearing belt of bimodal metavolcanites and lesser intercalated metasediment, termed variously the Fundsjø Group or the Hersjø Formation (see discussion in Grenne 1987), has been often correlated with the ore-bearing Storen Group greenstones on the western flank of the Trondheim district. The reality of this correlation is in doubt at the present time (Grenne & Lagerblad 1985).

In the existing literature the shift of nomenclature of the eastern greenstone belt seems to occur at or about the area in question (Grenne 1987). To the north, in the Meråker-Verdal area, the term Fundsjø Group has been applied (Wolff 1967), while to the south, in the Killingdal - Røros - Folldal area, the rocks are usually referred to as the Hersjø Formation (Rui 1972).

The stratabound sulphide deposits in the Hersjø-Fundsjø greenstones were mainly very limited in size, only five of the more than 20 ore bodies which were worked containing more than one million tonnes. The last to be worked (Killingdal, Rui 1973) was closed down in 1986.

The main iron sulphide mineral present in the often massive ores is pyrite; pyrrhotite contents are minor, although the monosulphide dominates occasionally in certain zones. Although, historically, production was based on the copper present as chalcopyrite (range 1-3% Cu), the eastern Trondheim District ores are characterized by a predominance of sphalerite over chalcopyrite; Zn values typically ranging from 3 to 15%. The high Zn:Cu ratios, coupled with the presence of some few tenths of a percent of lead (0.2-0.4% Pb) serve to distinguish the Fundsjø-Hersjø ores geochemically from, e.g., the ophiolitic, metabasalt-hosted, ores of the western part of the Trondheim District, such as Løkken (Grenne et al. 1980, Grenne 1989).

Tectonostratigraphy

The main tectonostratigraphic units of the east-central part of the Trondheim District are shown in Figure 1 (mainly after Gee et al. 1985). These are from west to east (structurally higher to lower) the Støren, Gula and Meråker nappes (Köli nappes of the Upper Allochthon). Some authors, e.g., Guezou et al. 1980; Krill 1980, distinguish a separate tectonic unit, the Tronget unit, between the Støren and Gula nappes. The Meråker nappe is underlain by a lower (Seve) unit of the Upper Allochthon, the Essandsjø nappe.

The Fundsjø greenstones, hosting the Gressli and other sulphide deposits, together with stratigraphically overlying (structurally underlying), mainly sedimentary units, constitute the stratigraphic units of the Meråker nappe in the area under consideration (see below).

Paleotectonic Setting

On the basis of the geochemistry of the Fundsjø-Hersjø volcanites, Grenne (1987) has suggested that the unit originated in early Tremadoc times during the early stages of a marginal basin opening by rifting of a magmatic arc, with magma being trapped from a heterogeneous mantle above an active or previously active, west-dipping subduction zone. Grenne (op. cit.) considers that basin extension took place under a continental margin or a microcontinent, with contemporaneous deposition of sediments of platform affinity, probably on the Laurentian side of Iapetus, and that these Tremadoc events were followed by continued basin spreading to the west in the Tremadoc-Arenig interval giving rise to the predominantly MORB-type ophiolites of the present western Trondheim District which host the important massive pyritic Cu-Zn ores of the Løkken area.

An alternative interpretation by Mandeville (1988) based on work in the Ålen area, some 25 km south of Tydal, is that the Fundsjø Group represents a rifted continental margin setting during the continued opening of the Iapetus Ocean, a phase which probably came to a close by mid-Arenig time due to mature arc/marginal basin collision with the outermost portion of the Baltoscandian margin. Mandeville's interpretation has much in common with the hitherto-held interpretation of the paleotectonic depositional setting for the Bleikvassli and Mofjellet stratiform Zn-Pb-Cu deposits in the Rana area of Nordland. Stephens et al. (1984) and Vokes (1988) have advocated an early, rifting, paleotectonic environment of deposition for the Rana ores, but on the Laurentian side of the developing Iapetus.

More recently, Skauli et al. (----) and Bjørlykke et al. (1992), have discussed the probable age of the Bleikvassli ore on the basis of recent Pb/Pb and Rb/Sr isotope determinations. Their conclusion is that while the slope of the lead isotope data indicate a maximum age of 1000 yr. from the age of deposition, the geological setting and isotopic compositions favour a Cambrian age. These conclusions are in accord with the earlier views cited above.

Bjørlykke et al. (1992) point to considerable enrichment in $^{206}Pb/^{204}Pb$ for the Gressli ore compared with other deposits in the Upper Allochthon and interpret this as being caused by the addition of metamorphically mobilized radiogenic lead.

Geology of the Tydal Area

The main features of the geology of the Tydal area are shown on Figure 2. The rocks of the Meråker nappe are separated from those of the structurally overlying Gula nappe or complex to the WNW by a steeply-dipping tectonic contact. The predominantly metasedimentary Gula rocks are of pre-Ordovician age (Roberts & Sturt 1980) and may also include Precambrian elements (Wolff & Roberts 1980). They comprise migmatites, calc-silicate gneisses, biotite-hornblende schists with thin amphibolites, graphite schist, marble, quartzite and quartzite conglomerate.

The Fundsjø Group rocks, hosting the Gressli deposit, structurally highest in the Meråker nappe, are here composed mainly of bimodal submarine volcanites, mixed biotitic metapelites and graphite schists. They are overlain by the basal conglomerate of the succeeding Sulåmo Group, with locally-derived clasts including greenstones, metagabbros and quartz keratophyres, which are in turn overlain by mainly gray and calcareous phyllites, with subordinate greenstones and greenschists. Highest, structurally, of the Meråker nappe units, is the Kjølhaugen Group of Lower Silurian age (Getz 1980; Wolff 1967) which in Tydal is composed almost entirely of meta-marls represented by biotite-porphyroblastic sericite-carbonate schists (the Stuedal schists of Reusch (1890)). The contacts between these units, which are often coincident with steeply dipping fractures, have been interpreted as folded thrusts (Wolff 1967, Rui & Bakke 1975, Roberts 1978). The Kjølhaug group is separated from the underlying Hummelfjell formation of possible Silurian age (Rui 1972) by the proposed sole of the Trondheim nappe (Wolff 1967). The Gula and Fundsjø groups have been subjected to tight post-schistosity folding on N-S axes resulting in deep fold structures and steep dips to east and west. The Kjølhaug group has suffered only relatively gentle post-schistosity folding resulting in shallow dips and folding on a dome- and basin pattern (Fig. 2).

The Fundsjø group has been intruded by a large mafic body, the Fongen-Hyllingen complex of late Silurian age, which includes a layered cumulate facies in its extreme northern and north-western part, considered to represent the stratigraphic base (Wilson & Olesen 1975, Wilson 1981, 1985). Mapping has shown that the Fundsjø Group rocks to the east of the mafic complex are predominantly sedimentary in character while to the west they are mainly volcanic. Thus thin metavolcanites, including pyroclastites, equivalent to those around Gressli to the west of the gabbro, occur east of the gabbro within thick biotite and biotite-amphibole schists, while the latter thin out westwards to interfinger with the thick metavolcanites around Gressli.

A volumetrically important component of the Fundsjø Group west of the gabbro complex consists of conformable swarms of basic feldspar-porphyry intrusive sheets (see below). Thin gabbro-diorite bodies have been intruded into the Fundsjø and particularly the Kjølhaug Group at numerous levels. The largest of these occurs to the southwest of Gammelvollsjøen (Fig. 2) where a contact aureole consisting of chlorite-epidote-garnet schist is developed. The Fundsjø Group has also been intruded by numerous trondhjemite-monzonite bodies, particularly to the east of the gabbro complex.

Mineralization in the district is almost exclusively confined to the Fundsjø Group. By far the most common type within this unit consists of sulphide impregnations in graphite schists, generally concentrated in those levels of the sequence containing the most abundant felsic extrusives.
Sphalerite-pyrite-(chalcopyrite-galena) mineralization in felsic pyroclastites occurs at several localities along a discontinuous belt west of the gabbro complex. Apart from the deposits at Gressli and Gammelsætergruve the occurrences are of very restricted strike length and thickness although base-metal contents, particularly with respect to Zn and Pb, may be high in certain cases.

In the Kjølhaug Group of Tydal where graphitic schists have not been recorded, the Våraviken prospect, a rich, but subeconomic, concentration of sphalerite-pyrrhotite-pyrite- (galena-chalcopyrite) mineralization occurs on the east flank of the Gammelvollsjøen metagabbro.

Geology of the Gressli Area

The Gressli deposit lies at a level within the dominantly intermediate to basic extrusives of the Fundsjø Group which contains abundant felsic extrusives, graphite schists and biotite-staurolite-sillimanite schists. This level, which dips steeply westward, can be traced continuously southward from the deposit for at least 5 km and discontinuously northward for at least 12 km, and has been termed the Gressli belt (Fig. 2). This belt is probably stratigraphically equivalent to that hosting the Rødhammeren deposit 15 km to the south (Nilsen 1971). The belt contains several types of felsic volcanites at a number of sub-levels, forming piles which are probably the result of deposition during a restricted timespan around several extrusive centres.

A similar belt, termed the Hynna belt, occurs on the opposing limb of a deep post-schistosity synformal structure to the west of the Gressli belt. This belt, however, contains no major felsic extrusive accumulations and only thin, though numerous, base metal-poor sulphide occurrences in Fe-rich or dominantly iron sulphide-bearing chlorite schists. The core of the synform consists almost entirely of mafic extrusives devoid of mineralization.

Mafic to intermediate extrusives.

The mafic to intermediate extrusives of the Gressli belt are mainly dark, fine to medium-grained massive amphibolites, though traces of pillow textures can be observed in the vicinity of the Gressli deposit and well-developed pillows occur near the Gula Group contact north of the river Nea. The development of amygdales is similarly uncommon, suggesting that eruption took place under a considerable depth of seawater (Moore 1965, Jones 1968). Mineralogically the Gressli metabasites comprise oligoclase- and cummingtonite- amphibolites and oligoclase-quartz-cummingtonite-hornblende rocks (Kisch 1962).

To the south of the Gressli deposit, for at least 1 km along strike, the mafic to felsic extrusives lying in the lower structural and stratigraphic levels of the felsic belt contain sections which are altered to chlorite, chlorite- actinolite or sericite-chlorite schist. The mafic volcanites lying immediately above the felsic pyroclastites contain abundant biotite together with carbonate or epidote, locally grading to biotite schist. This alteration decreases away from the felsic pile. In this area there has also been recorded what appears to be the deformed remains of a small stockwork system consisting of 9 m of coarse-grained garnet-chlorite-(dravite) schist with chalcopyrite veins. Although such alteration is not visible in the immediate vicinity of the Gressli deposit, the easterly footwall amphibolites containing fine chalcopyrite veinlets are greatly enriched in K_2O and Rb.

Table 2, columns 1 and 2, show, respectively, the means of 10 analyses of the Gressli belt metabasic extrusives and that of seven analyses of their equivalents to the east of the gabbro complex. Compared with their interpreted distal equivalents, the Gressli belt metabasites contain increased silica due to the presence of andesites and are relatively enriched in Pb. The Tydal Fundsjø group metabasites do not appear to differ geochemically from those of the adjoining Meråker area to the north as reported by Grenne & Lagerblad (1985) and Grenne (1987). The Gressli belt volcanites range from ocean-floor basalts to island-arc generated, low-K tholeiites on plots of Ti-Zr, Ti-Cr and Ti-Cr-Y using the method of Pearce & Cann (1973) and Pearce & Gale (1977). However it should be noted that Cr is enriched locally around the Gressli deposit and near mineralization east of the gabbro, as shown by the presence of Cr-muscovite as large flakes (also reflected by a Cr-anomalous area in shallow overbuden). Such Cr anomalies have also been recorded from the Heath-Steele stratiform volcanogenic orebody in Canada (Wahl 1978) and from the Kuroko deposits of Japan (Ishikawa et al. 1962). Evidence from the Skorovas (Grong district) and Gressli deposits also suggests that Ti and Zr may be enriched in the hosts to mineralization, and that the steep gradient of this enrichment excludes such a fundamental change as that of the site of basalt generation as being the cause. Zirconium can be accomodated in both sphene and apatite, which may occur in metamorphosed alteration zones. In the Gressli area, coarse-grained sphene is clearly visible in altered felsic extrusives while in the wallrocks of the Gressli deposit P2O5 is enriched together with Zr. Elsewhere, Ti enrichments have been reported around massive sulphides at Boliden (Nilsson 1968) and Broken Hill (Plimer 1979); and P_2O_5 enrichments at Heath Steele (Wahl 1978). The method should therefore be used with care, especially where analyses of extrusives from the vicinity of mineralization may have been included in the data set, if plate tectonic interpretations are to be made. However, the abrupt occurrence of "ocean-floor" basalts (having high Ti, Cr, Zr) in the area otherwise dominated by low-K or calc-alkaline basalts, especially where felsic extrusives also occur, could indicate alteration related to mineralization such that these elements could be used as additional exploration tools.

Felsic extrusives

Three main concentrations of felsic extrusive rocks occur in the Gressli belt-at Måltoppfjell, along the river Nea, and south of the Gressli deposit (Fig. 2). These probably represent the products of individual submarine centres, each having their own textural and mineralogical characteristics.

In the Måltoppfjell area, 9 km north of the Gressli deposit, there occur three relatively thin horizons of pyrite and pyrite-sphalerite-impregnated, commonly silicified and sericitized, pyroclastites. The westernmost of these, near the Gula contact, is associated with the old Selbu copper mines (Aasgaard 1927) which contain massive pyrite and massive magnetite mineralization. These occur in a chloritic alteration zone, containing Fe-rich chlorite, garnet and actinolite/?grunerite, similar to that occurring at the Kongens deposit of the Meråker district, 20 km to the north. (?Reference?)

Straddling the river Nea 3 km NNW of the Gressli deposit there occurs the greatest pile of felsic extrusive material in the district. The bulk of this consists of fine to medium grained felsic pyroclastites and flows having conspicuous networks of conformable and cross-cutting veins composed of coarse-grained gedrite-anthophyllite, garnet, sphene and staurolite. This phenomenon is interpreted as representing a metamorphosed hydrothermal alteration assemblage similar to those occurring at the Rødhammeren deposit (Nilsen 1971). Associated with these are blocky agglomerates which also contain similar alteration, primarily in the matrix but also occasionally cross-cutting the clasts. The most advanced alteration occurs towards the southern end of the acid pile near Hillmo bridge (Fig. 2) where sphene and staurolite are especially abundant and where massive, pure, garnet-amphibole assemblages have been blasted out during the driving of a local hydroelectric tunnel. Further south, and into the area structurally overlying the felsic pile at Gressli, sphene and staurolite contents and grain sizes decrease until near the southernmost extremity there occur only thin amphibole-(garnet)-bearing felsic horizons. The third occurrence of felsic lithology in the Nea area comprises subordinate massive to schistose quartz-porphyries commonly having clear blue quartz "eyes" and locally having a completely sericitized matrix. These may represent either extrusives or sills, occurring most profusely in the vicinity of the blocky agglomerates and of the area of advanced alteration around Hillmo bridge. In strong contrast to the felsic extrusives of Måltoppfjell and Gressli, the Nea felsic pile contains but rare sulphide impregnations.

The felsic extrusives hosting the Gressli ore body differ from the other felsic accumulations, primarily by the common occurrence of very fine grained (cherty) members. In part at least these are the results of silicification; they contain fine to coarse-grained disseminations of pyrite. At the Gressli deposit this lithology was termed "mine quartzite" by the early workers and was reported to contain up to 30 wt.% sillimanite (?Reference?). It occurs, with a thickness of up to 1-2 m, in the footwall of the massive pyritic sulphides. Along strike to the south the felsic pyroclastites contain sphalerite impregnations at several localities and are altered to quartz-sericite or sericite-chlorite schist. Similar degrees of alteration also occur in the nearby amphibolites. Fuchsite occurs in these lithologies, locally also very fine-grained disseminations of magnetite, which is otherwise practically absent from the parageneses of mineralizations around Gressli. Coarse two- amphibole meta-alteration assemblages of the type found in the Nea felsic pile do not occur in the vicinity of Gressli. Apart from these lithologies, the Gressli felsic pile is composed of abundant pyroclastites having flattened cherty, chloritic or biotite-rich lapilli of centimetre dimensions, minor agglomerates and fine- to medium-grained biotite- quartz-feldspar-garnet schist. Quartz-porphyries are rare. According to the Streckeisen classification the felsic extrusives of Gressli range from rhyolites to quartz- andesites. Table 2, column 3, shows the mean of 37 analyses of Gressli belt felsic extrusives.

<u>Graphite schists</u>

Schistose to cherty carbonaceous horizons, varying in thickness from dm-scale to 5 m, and often containing abundant banded pyrrhotite - (pyrite - chalcopyrite - arsenopyrite) impregnations of probable sedimentary origin, occur at several levels in the Gressli belt, apparently being restricted in extent to the Nea and Gressli acid piles (Fig. 2). North of Måltoppfjell however they increase in abundance into the Meråker district where they also occur at several levels. Such horizons represent the most abundant type of sulphide mineralization in the Tydal district, but, although lying at numerous levels around the Gressli deposit, they appear to be stratigraphically distinct from rich base-metal mineralization. Table 2, column 6, shows the mean of 51 analyses from the Gressli belt. Due to their elevated contents of base metals (and of As, Ni, Co, Mo, V, Cr, Fe, S, and U) and high conductivity/magnetic susceptibility, these horizons have complicated massive sulphide exploration in the districts of Meråker, Tydal and Tynset, in the eastern Trondheim Region. They can, however, be of use as stratigraphical markers in the volcanic pile.

It is interesting to compare the Tydal and Meråker districts with the Gjersvik nappe of the Grong District, 150 km to the north, containing the Skorovas and Gjersvik deposits, regarding the occurrence of Fe-rich marker horizons. In the latter district graphite schists are virtually absent, while horizons of sulphide-magnetite, silicate (garnet-epidote-amphibole) and siliceous (magnetite/hematite chert) facies exhalites extend, for example, for 10-15 km from the Skorovas deposit, occurring at levels equivalent to and stratigraphically above the mine mineralization (Halls et al. 1977, Ferriday et al. 1981). Such horizons are almost absent from the Tydal and Meråker districts, massive magnetite occurring only in the Måltoppfjell area where the graphite schists appear to wane. There would therefore seem to be a general antipathetic relationship between the occurrences of carbonaceous horizons where Fe is present primarily as pyrrhotite, and exhalite horizons where Fe is primarily present as magnetite or hematite. Such a relationship may be explained by local palaeogeographic/environmental differences between these districts, both of which otherwise have sequences of mainly island arc character and are of approximately the same age. The fundamental difference between these districts is the presence of abundant organic matter in the Tydal-Meråker area which led to the widespread development of the sulphide facies. Such an abundance would occur for example at pelagic depths on the submarine slope, where organisms would flourish due to maximum upwelling of nutrients and where oxidation would be at a minimum (Doyle & Pilkey 1979). Any later tendencies towards increasing pH, largely via increasing pCO_2, would be counteracted by organic material such that, with sufficient supply of sulphate, the sulphate-reducing bacteria could increase pS_2 to levels permitting sulphide deposition (Dimroth 1979). In the Gjersvik nappe however, shallower depths on, for example, a shelf/shelf edge led to the dependence of sulphide preservation on seafloor troughs near the site of emission where the circulation of oxidizing currents was restricted, and to the formation of chemical sediments representing a broad and rapidly varying span of Eh/pH conditions.

Such environmental differences, possibly combined with less explosive volcanism which might be expected at increased depths, may also have been responsible for the spread along strike of small base metal (primarily Zn-(Pb) rich occurrences in the Gressli belt rather than their concentration in fewer, larger bodies. With "blanket" reducing conditions, and with the absence of a particular funnelling channelway and trap, it would be possible for less vigorously exhaled base-metal-rich brines, especially those of high density (Sato 1972) to survive and be distributed over a much greater radius compared with those which were emitted more violently into a largely oxidizing environment with steep Eh/pH gradients defining vent-proximal reducing traps. These palaeogeographic differences may therefore have important consequences regarding the economics and priorities of ore exploration in different districts. In districts with abundant graphite schists representing widespread reducing conditions, successful exploration may therefore depend more on the detection of large traps, which could lie within a considerable radius from eruptive centres. On the other hand, in the case of districts having largely oxidic representatives e.g. hematite cherts, this may depend more on the concentration of exploration around large centres and their commonly associated piles of blocky pyroclastics since the conditions for base-metal-rich sulphide deposition/preservation are unlikely to have existed for great distances beyond these.

It has always been a daunting prospect to approach the practicalities of exploration in graphite schist environments, not only because of the geochemical/geophysical "red-herring" role of these schists, but also because of our inadequate present state of knowledge concerning palaeo-environmental analysis of submarine volcanic piles, for example the identification of areas likely to contain sizeable sulphide traps or that of other manifestations of these. Certainly more practical research is required in this field, since large volumes of such sequences having economic potential occur worldwide, in which simple mapping and standard geochemical/geophysical methods alone have often proved to be insufficient for detection of blind or subcropping massive sulphides.

Biotite-staurolite-sillimanite schists

Biotite schists commonly containing abundant staurolite, sillimanite and garnet (also kyanite, Kisch 1962) occur as horizons extending between and structurally beneath the three acid extrusive piles in the Gressli belt. Similar schists have also been reported from within the Fundsjø Group biotite schists east of the gabbro complex (Kisch 1962). These have previously considered to be in-folded Gula Group lithologies (Rui 1972, Nilsen 1971) but are here interpreted as being contemporaneous with the Fundsjø volcanites, representing pelites deposited during brief pauses in extrusive activity, possibly also containing components derived by alteration of the predominantly basic volcanic pile. These components may now be represented by the locally rich concentrations of highly aluminous mineral assemblages that occur. Table 2, column 4, shows the mean of 22 analyses of the Gressli belt schists, while column 5 gives that of 11 analyses of biotite-sericite-amphibole schists lying east of the gabbro complex. The Gressli belt schists show slight relative enrichments in K_2O and Rb due to increased biotite content, also local enrichments in Cr (to 760 ppm). No visible concentrations of sulphides occur in these lithologies, which appear to be stratigraphically distinct from the Gressli mineralization, having been observed only once in drill core.

Feldspar porphyry sheets

Swarms of largely conformable basic intrusives, commonly having chilled margins and with interiors densely packed with euhedral to rounded or flattened feldspar phenocrysts, occur at all levels throughout the Gressli belt. The sheets vary in thickness from dm-scale to over 20 m, being locally enlarged by multiple injection up to thicknesses of __ m where it is often difficult to distinguish the individual sheets from the trapped screens of the host metabasic extrusives. In the Gressli belt these intrusives constitute up to about 30% of the total thickness of the sequence. The basic porphyries have been studied by other workers in the Tydal district and in the adjoining districts to north and south where they also occur (Kisch 1962, Nilsen 1971). They are interpreted as having been intruded during a tensional event following the earliest deformation of the Gula and Fundsjø groups in Lower Ordovician time, and predating late Silurian thrusting in the Meråker-Færen district (Grenne & Lagerblad 1985). In the Tydal district they have been observed cutting the gabbro complex. These intrusives would therefore appear to have no genetic affinities with the Fundsjø volcanics, being more related to development of the basin in which the Kjølhaug group sediments were deposited following early Caledonian uplift and erosion of the Gula and Fundsjø groups. Analyses given in Table II.

Minor gabbroic to monzonitic intrusives

Although uncommon around the Gressli deposit, trondhjemitic to monzonitic sheets occur throughout the Fundsjø group. These appear to have been intruded in at least two episodes, the earliest being related to Fundsjø group volcanism and the latest being related to cross-fracturing on a NE-SW/NW-SE pattern.

A crosscutting body of metagabbro occurs structurally beneath the Gressli horizon. Isolated bodies of the same type can be followed northward in a line running roughly parallel to the contact of the gabbro complex.

The Gressli Deposit

Historical, grade and tonnage.

The massive sulphide mineralization at Gressli outcrops intermittently over a strike length of approximately 130 m and varies in thickness between 2 and 3.5 m. The deposit was discovered in 1792, and was worked during three periods totalling 24 years until 1868. During this time the mineralization, which was then considered to be a low quality copper ore because of its high Zn content, was mined to a depth of 30 m down dip. There are no representative records of the grades or tonnages extracted during this period.

In 1916 three diamond drill holes were sunk into the deposit, but these were set back down dip only sufficiently enough to intersect the mineralization at the depth to which it had been previously worked. Reported results of this drilling included intersections of 2.3 m at 1.12 % Cu, 7.48 % Zn and 40 % S; and 3.4 m at 0.89 % Cu and 25 % S (no Zn analysis). In 1926, the Geological Survey of Norway (NGU) channel-sampled the surface workings, reportedly obtaining an average Zn content of 15.42 % (Aasgaard 1927). The results of these investigations appeared to show that the deposit consisted of several closely clustered massive sulphide lenses having a marked collective plunge to the south-west and also an unclear tendency to extend at depth in a south-easterly direction.

The first indications of the possible tonnage of ore at Gressli are given by Foslie (1926) who estimated, on the basis of the earlier drilling, proven and probable tonnages at 10,000 and 30,000, respectively. Possible ore was given as 425 tonnes per metre depth below these tonnages.

During 1946-49 NGU carried out a TURAM electromagnetic survey and geological mapping of the Gressli belt in the vicinity of the deposit, which revealed the problems posed by the presence of the numerous graphite schist horizons mentioned above (Singsaas & Brekken 1947, Bjørlykke 1949). Further work, including drilling, was carried out at various periods in the '60s, '70s and '80s by a number of prospecting companies. In 196- Sulfidmalm A/S (Falconbridge) drilled x holes and

Additional drill holes, totalling 930 m, were drilled by A/S Sydvaranger (Killingdal Grubeselskab) in 1974 and 1975. A CP (mise à la masse) geophysical survey preceeded the 1975 drill-programme (Gvein 1976).

The latest activity took place in 1984-85 (B.P. Minerals International Ltd./Norsk Hydro A/S JV) and included detailed geophysical, geochemical and geological surveys over the Gressli belt following an airborne geophysical survey using the INPUT system over the Tydal district. This resulted in the drilling of seven holes in the Gressli belt, mainly away, but along strike, from the deposit itself, which intersected sphalerite mineralization of subeconomic grade and thickness (Ferriday 1985).

As a result of the drilling in 1974 and 1975, as well as of the earlier holes, Gvein (1976) estimated a 'probable' ore tonnage of 78,000 à 0.90 % Cu and 5.52 % Zn. (Silver contents of up to 15 g/t were also mentioned, but see later.)

<u>Mine geology.</u>

The Gressli deposit is sited at the northern tip of the Gressli felsic pile (Fig. 3), being bounded to the north-west by a SSE-trending fault (which also displaces the western contact of the gabbro complex), and thinning out to the southeast along a strike which swings from being roughly east-west into a more north-south orientation (which is most typical of the district) within 100 m.

The outcropping mineralization consists of an upper (HW) zone of massive, crudely-banded, sphalerite-pyrite- (chalcopyrite) ore, underlain by massive pyrite which grades downward into pyrite-impregnated sericitic quartz schist. The hanging-wall rocks of the deposit, dipping 40-50° to the south-west, consist of thin schistose acid pyroclastites which locally contain sparse veinlets and impregnations of galena. The footwall rocks consists of massive basic extrusives which locally contain chalcopyrite veinlets. In addition to these host rocks there occur feldspar-porphyry sheets which disrupt the stratigraphy considerably. A diagrammatic vertical lithological column through the deposit is shown in Fig. 4, which also shows a column through the southerly equivalents of the mine package for comparison, both having been constructed from mapping and borehole data.

Few details are known of the internal geometry of the Gressli deposit. It was interpreted in earlier reports as consisting of several closely stacked lenses, though there is little available information to support this interpretation.

To judge by the results of the diamond drilling and the geophysical surveys the deposit is a southeasterly-dipping "plate" of sulphides of varying "massiveness", having a maximum east-west extension of about 200 metres and a north-south horizontal projection not exceeding 100 metres (Fig. 5). It is thickest (about 4 m) in upper, northerly, part, thinning-out to, apparently, nothing down dip.

The sulphide plate also appears to thin out along strike to the southeast and northwest. However the exact nature of the northwestern boundary is not clear. No extension of the sulphides appears to have been found beyond the SSE striking fault already mentioned (see Fig. 3) though there is no evidence that this structure actually displaces the sulphides. In fact, some of the older reports make a point of the apparent thinning-out of the "ore plate" before the fault plane is reached (see interpretation in Fig. 5). At depth in this area, the sulphide plate is split into two parallel levels (horizons) apparently by an intrusive feldspar porphyry sheet.

Both the old reports and the present investigation agree that the sulphide plate shows a distinct and consistent stratigraphical (?) or structural layering, with massive, often banded, sphalerite-rich pyrite ore towards the HW, underlain by Zn-poor massive pyrite ore which becomes increasingly quartz-rich towards the FW where it has the appearance of a pyrite-disseminated variably micaceous, quartzite. Such layering would be usually taken to indicate that the exposed part of the deposit at least is correct way up.

However, due to the poor exposure around the mine, the lack of geological information from the drillcores, coupled with the disruptive effects of the late feldspar-porphyry intrusives, it has not been possible to delineate ore-body structures in any detail. Along strike to the south, the distribution of altered lithologies suggests that the felsic pile has not been inverted.

ORE PETROGRAPHY - MINERAL TEXTURES

The mineralised zone at Gressli varies in composition from a massive sulphide ore with over 90 percent sulphides to a low-sulphide quartz-(muscovite) rock. The following section will deal with the mineralogy and textures mainly of the sulphide-rich portions of the deposit. These are dominated by the abundance of the main sulphide, pyrite and the forms it exhibits; other sulphides occur mainly as matrix to; and as fracture-controlled veins in, the individual pyrite grains. A gangue phase, consisting dominantly of quartz, is also a prominent component of the ore at the macro- and microscales.

Pyrite.

Pyrite textures are dominated bu sub- to anhedral grains, closely- to moderately-packed, and having grain sizes varying widely between fractions of a mm and several mm - up to an occasional maximum of 10 mm.

Grain forms shown by the pyrite may be described under two classes; i) growth textures and ii) deformational/replacement textures. The latter dominate the pyrite morphology, especially at the microscopical scale.

Growth textures shown by the pyrite comprise both porphyroblasts and foam (triple junction) textures.

The porphyroblasts, quantitatively minor in amount, show perfect to imperfect cubic outlines, best developed in a sphalerite-rich matrix. Most of them exhibit limited number of relatively large, rounded to elongated inclusions and embayments (chadacrysts) of dominantly sphalerite, but locally also of chalcopyrite and pyrrhotite (Figs.). Locally, small numbers of silicate grains, especially mica flakes, are present within the pyrite grains or straddle their grain boundaries with the matrix.

The proportion of this type of grain-form in the ore is rather lower than normally met with in comparable metamorphosed sulphide ores. This is no doubt partly due to later deformation and replacement, but also due to high density of pyrite growth centres during prograde metamorphism.

The latter factor no doubt also accounts for the fairly high proportion (relative to porphyroblasts) of foam-textured pyrite at Gressli. Patches showing well-developed examples of this texture are abundant in the massive parts of the ore but, again, have been partly modified by subsequent deformation, leading, i.a., to disruption and 'opening-up' along the triple junction boundaries, often followed by veining and replacement by matrix sulphides and/or quartz. Se later (Figs.).

Deformational/replacement textures dominate the pyrite morphology and relatively few grains are totally unaffected by these subsequent effects. Cataclastic (brittle deformational) textures are ubiquitous and affect an estimated 90 % of all the pyrite in the specimens examined microscopically. The effects vary from the merest accentuation of cleavages, to networks of open fractures, to in places, completely crushed, brecciated grains. The fracture openings seem often to be controlled by one set of dominant cubic cleavages, but are frequently very irregular and only roughly controlled by cleavage.

The fractures, of all dimensions, have been infilled with one, or all of the matrix sulphides, to a lesser extent by quartz (see later) (Figs.). Thus infilling of deformational openings (veining) in the pyrite grains by the matrix sulphides gas apparently taken place both with and without detectable corrosion or replacement of the vein walls or clasts. Often the 'matching walls' criterion may be applied, in many cases the replacement of the pyrite has been substantial (Figs.). Both chalcopyrite and sphalerite have obviously been very mobile and active in these processes, their relative proportions apparently depending on their relative abundances in the immediate adjacent matrix. On the other hand the two matrix sulphides show a clear succession or paragenesis of veining and replacement (see below).

Quartz behaves in a similar, but much less pronounced, manner as the matrix sulphides. The general sulphide-rich textures of the massive parts of the ore are frequently interrupted by the presence of quartz and other non-sulphide minerals in the form of irregular to rounded bodies of verying dimensions; mm to cm scale. These are described later but it may be noted here that pyrite grain morphology in these gangue bodies (? pods) is completely different from that in the massive sulphide ore (see above). Firstly, grains of pyrite (and other sulphides) are much more sparsely distributed in the quartz-dominated bodies; their forms are never euhedral but dominantly irregular, elongated or lenticular to lozenge-shaped in outline and of markedly smaller grain size than in the adjacent massive sulphide ore. In places larger grain aggregates showing foam texture can be observed as isolated "fragments" in the quartz matrix (Figs.).

The pyrite grains and aggregates are aligned within each quartz-rich area in a directed texture (Fig.) which is noticeably lacking in the adjacent massive sulphides. Such texture is more or less constant in attitude in any one particular quartz-rich body; conformity of attitude between adjacent quartz-rich areas is difficult to determine.

The shapes and orientation of the pyrite grains in the quartz-rich gangue, the partly disrupted and infilled remnants of foam texture, as well as the infilling by quartz of enlarged cleavages and fractures in individual grains are taken as evidence of pyrite replacement (grain reduction) by introduced quartz which crystallised under stress to give the directed texture of the pyrite remnants and their enclosing quartz.

Examination of a limited number of polished sections of the massive ore reveals that it is occasionally cut by structures (zones) of very limited widths (mm to cm) in which the usual medium to coarse grain size of the pyrite is reduced by at least two orders of magnitude (X mm to 0.0X mm) apparently by local cataclasis or crushing. These features can be isolated single zones of varying thickness, up to a mm or two, or anastomosing systems of such zones over a width of up to 2 or 3 cm. Apparently also of the same age and provenance are zones or bands of the order of 2 to 3 cm in width where crushing of the 'normal' pyrite is quite intense, though size reduction is less - maybe only by one order of size.

The matrices to these zones of comminution or crushing consists of the normal matrix sulphides of the ore; in order of abundance, sphalerite, pyrrhotite and chalcopyrite. These, especially the pyrrhotite exhibit a completely annealed triple junction texture. In place a minor gangue phase (? quartz) can be observed cementing the pyrite clasts.

A prominent feature of the narrower, more sharply defined crush zones is the presence, at times dominance, of perfectly euhedral (cubic) pyrite cubes, together with the irregular clasts, and of the same order of size as these. These euhedrons show all the features of metablasts, especially a fine poikilitic texture involving matrix sulphides as chadacrysts.

In addition to the small euhedral pyrite crystals within the zones of movement, the selvedges or rims of may of the larger clasts of 'old' pyrite adjacent to the zones show apparent recrystallisation with the formation of euhedral crystals outermost, of the same order of sizes as the apparently newly (re)crystallised cubes. These recrystallised selvedges, of the order of some few tenths of a mm in width, show a "filigree-like" (? dendritic?) intergrowth of pyrite and matrix sulphides (see Fig.).

Examination of the larger, 'older' pyrite grains and clasts adjacent to the narrower crush zones indicates that they are not noticeably more affected cataclastically than is the general case with pyrite in the massive portions of the ore. In other words the textural effects of the late movements producing these features did not extend beyond the immediate, recrystallised, selvedges of the bordering clasts or grains.

In some of the broader, less intense, crush zones it can be seen that a gangue component (mainly quartz) has been involved in the general comminution along with the pyrite. These gangue clasts) mm) include anhedral to euhedral grains and aggregates of pyrite. A careful search of the pyrite-quartz contacts reveals limited evidence (see Fig.), that the quartz infills deformational fractures in the pyrite, suggesting that the gangue clasts originate in the late quartz bodies emplaced in the massive sulphides as described above and below under "Gangue".

The quartz clasts (as well as the independent pyrite clasts present) are surrounded and veined by chalcopyrite, to a lesser extent by pyrrhotite and sphalerite. This would imply a renewed mobilization of these sulphides during the movements which produced the crush zones.

The formation of the narrow crush zones at least and the recrystallisation of the pyrite is accompanied by distinct changes in minor-trace element contents. These will be described and discussed in a later section on mineral chemistry.

<u>Sphalerite.</u>

In keeping with the general base-metal chemistry of the Gressli ore, noted above, sphalerite is the dominant base-metal sulphide present, especially in the more zinc-rich zones nearer the structural HW of the ore body.

It is the dominant matrix sulphide to the pyrite metablasts and porphyroclasts, either forming an almost monomineralic groundmass or being intergrown with varying proportions (up to may be 20 percent) of chalcopyrite and pyrrhotite. Due to its isotropic optical nature, grain size and shape are not always obvious, but where observed, and especially when in intergrowth with other sulphides, it shows a poygonal, foam-textured mosaic with a grain size between 0.05 and 0.3 mm.

Sphalerite is also widely distributed as grains and grain aggregates in the quartz-rich portions of the ore and itself includes abundant grains (? clasts) of silicate minerals.

As well as forming the matrix to pyrite, sphalerite is also prominent as rounded to elongate chadacrysts (inclusions and embayments) in the larger pyrite metablasts (Grain sizes vary with pyrite grain sizes - of order of 0.1 - 0.3 mm or more). The chadacrysts occur both peripherally and centrally within the pyrite metablasts. Sphalerite is also prominent as an infilling- and, interpreted, replacing component in the fractured and brecciated pyrite grains. It fills in between matching walls, but also has obviously replaced considerable amounts of pyrite in areas of more intense pyrite fragmentation (Figs.   ).

Vokes & Craig (1992) presented evidence to show that the sphalerite 'followed' the chalcopyrite into the pyrite fractures; in other words that it was mobilized later than the chalcopyrite (see Figs. 9 + 10 in V & C, 1992, and Fig. here).

The sphalerite in these fractures and cracks appears to originate from the general matrix surrounding the pyrite grains, though often it would seem that it has also orginated from the sphalerite chadacrysts within the pyrite grains themselves (see Fig.). The textural evidence here is also that sphalerite moved into the pyrite fractures subsequently to thge chalcopyrite (Fig.).

However evidence is also present indicating that chalcopyrite has 'invaded' and partly replaced sphalerite chadacrysts in pyrite subsequent to the latter's brittle deformation.
(Discussion later - refer to V & C Fig. 11).

The matrix sphalerite is irregularly, often sparsely, intergrown in foam-textured, polygonal mosaics with the other matrix sulphides; chalcopyrite and, less commonly, pyrrhotite. In addition to these intergrowths, sphalerite in both the matrix and in the chadacrysts in the pyrite metablasts, is frequently, but erratically, 'peppered' with finely to extremely finely-divided chalcopyrite and/or pyrrhotite bodies. These take on various forms, from anhedral or rounded, subhedral, to elongated or lath-like (Figs. ?). These iclusions are occasionally aligned along apparent crystallographic directions in the host sphalerite, as shown by the alignment of chalcopyrite bodies in the III directions shown in Fig. .

No apparent systematics have been observed in the distribution of this type of texture in the Gressli sphalerite. It occurs irregularly in the matrix sphalerite, while any one pyrite porphyroblast may show chadacrysts with and without the texture in close proximity to each other. Peripheral "embayments" of sphalerite with the inclusions along the edges of pyrite grains often show sharp boundaries with adjacent inclusion-free sphalerite of the matrix surrounding the pyrite.

In transmitted light in doubly polished thin sections the Gressli sphalerite shows an even yellow-brown colour (reddish in thicker sections) which reflects the mineral's rather homogeneous Fe content (see below).

Under crossed polars the sphalerite can be seen to exhibit a fine lamellar to reticulate texture (etc. etc.)

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Chalcopyrite.

The copper-iron sulphide occurs in the matrix to the pyrite porphyroblasts and clasts in subordinate amounts compared to those sphalerite; relative proportions vary from about 1:100 to 20:100 from section to section. Chalcopyrite is present as single grains and as grain aggregates, intergrown with dominant sphalerite (in places also with pyrrhotite) in a typical polygonal annealed or 'foam' texture. Grain size in these intergrowths is similar to that in the more or less monomineralic sphalerite, of the order of 0.05 to 0.3 mm.

However, the most characteristic and quantitatively most important mode of occurrence of the chalcopyrite is as infilling and veining of cataclastically deformed pyrite grains and breccias of pyrite clasts.

It characteristically occurs filling fracture openings towards the centres of the deformed pyrite grains, whereas sphalerite tends to occupy those parts of the same fractures which are nearest to the edges of the grains or to sphalerite chadacrysts within the grains (see Figs.).

As mentioned above under **Pyrite**, these relationships would seem to indicate a sequence of filling of the fractures in pyrite by the two matrix sulphides, chalcopyrite-pyrite preceding sphalerite (see below under Discussion).

Similarly, chalcopyrite is by far more common of the two sulphides occupying openings along the grain boundaries of disrupted foam-textured pyrite (see Fig.).

As in the case of sphalerite, the chalcopyrite has often extensively and irregularly replaced the walls of the fractures or the outer zones of pyrite clasts. Both minerals seem to show the same degrees of effect in this respect (see Figs.).

Pyrrhotite.

Pyrrhotite is the least abundant of the sulphide minerals observed in the Gressli ore and appears to have a very erratic distribution. (Aasgaard (1927) asserted that pyrrhotite was absent, both in the mine and as the tips.) The present writers have not observed the iron monisulphide in situ in any of the accessible ore outcrops, but it is present as a major component of a small number of blocks on the mine tips and has been observed microscopically in a number of the polished sections examined.

The pyrrhotite-rich specimens examined consorted of irregular to rounded pyrite grains, clasts and replacement residuals up to several mm in size, sparsely distributed in a matrix of dominant pyrrhotite, together with lesser sphalerite and chalcopyrite. The sphalerite is concentrated in thin, irregular, lens- to wisp-like "schlieren" or streaks, defining a roughly parallel, curving, directed texture in the matrix. The matrix fabric is otherwise the typical polygoned, foam-textured mosaic that characterises the Gressli matrix sulphides generally. Grain size varies between the monomineralic pyrrhotite zones (0.05 mm to 0.2 mm) and the po-sl-(cp) intergrowths (may be 1/10 of this ??).

In spite of the directed texture defined by the sphalerite-rich streaks, the individual grains of the sulphides do not show any form-orientation and are free from any sizes of strain (e.g. strain extination in pyrrhotite). The whole matrix to the pyrite grains and clasts is completely annealed.

The pyrite grains and clasts within thin matrix vary from subrounded poikilitic grains, 5 mm across and showing few cataclastic effects, to completely shaffered grains and individual clasts of the same order of size as the matrix sulphides. All the matrix sulphides, in varying proportions, have infilled the fractures in the deformed pyrite grains and replaced their walls to varying degrees (Figs.). Chalcopyrite is preferably concentrated in pressure-shadow zones at the ends of, or between pyrite grains, but especially in fractures within the brittlely deformed iron disulphide.

Pyrrhotite is also prominent as matrix sulphide in some of the late crush or shear zones affecting the ore (see above). In these, it forms, together with chalcopyrite and sphalerite the annealed, foam-textured mosaic hosting the anhedral clasts and recrystallised euhedral grains of pyrite which characterise the late features.

Other sulphides are present only in trace amounts in the Gressli massive ore.

Galena has been observed microscopically in a couple of polished sections as rare subhedral grains irregularly intergrowth with chalcopyrite, often at its grain contacts with sphalerite. Grain size is of the order of --- mm. Even rarer are occasional, smaller inclusions in metablastic pyrite.

Arsenopyrite was observed in one polished section as two clasts in one of the broader crush zones described above. One comprised a group of fractured, anhedral grains of the order of 0.5 x 0.25 mm in cross-section; the other an eu-sub-hedral grain about 0.25 mm across. The derivation of these grain was not apparent, they appeared to belong to the same stage in the paragenesis as the "older" cataclastically deformed pyrite of the ore.

Gangue (Non-sulphide).

The non-sulphide or gangue component of the Gressli ore is composed dominently of quartz, with lesser amounts of white mica (muscovite) and minor to trace amounts of epidote, clinozoisite, feldspar, amphibole and apatite.

The silicates occur in the more massive sulphidic portions of the ore in the form of irregular to generally rounded bodies of very varying sizes (mm to cms) which show interpretable replacive contacts to the surrounding sulphides (see below) and which contain large numbers of sulphide grains of all shapes and sizes (Figs.).

There are no obvious structural controls on the shapes of these quartz-rich bodies; forms such as veins or breccias are lacking, though in one or two cases they occur as strainshadow "tails" with respect to large pyrite porphyroblasts.

Polished section observations provide good evidence that these irregular bodies of gangue, or at least portions of them, have been 'mobile' subsequent to the period of pyrite cataclasis and the subsequent periods of matrix sulphide veining and replacement. Quartz of the gangue bodies penetrates into even the finest cleavage cracks and other openings in the adjacent pyrite grains; it surrounds clasts of pyrite obviously broken off larger metablasts and it penetrates along the grain boundaries of disrupted foam-textured pyrite aggregates, often isolating fragments displaying such textures as clasts or replacement residuals (Figs.).

As mentioned previously, pyrite grain morphology and quartz-pyrite fabrics within these gangue bodies are very characteristic and very different compared with the massive sulphide fabrics.

Textural relations between the quartz and the matrix sulphides, especially sphalerite and chalcopyrite, are also indicative of widespread replacement of the latter by the former. The main forms of evidence comprise 'overprinting' or destruction of earlier sulphide-sulphide infilling or replacement textures by volumes of later quartz. Examples include fractured poikiloblastic grains of pyrite, veined and heavily replaced by sphalerite and chalcopyrite, surrounded by quartz which can be seen to penetrate the fractures in the quartz and to replace the sulphides already there (Figs.). In the case of foam-textured pyrite, remnants of chalcopyrite, earlier introduced along disrupted grain boundaries, can be seen isolated within the subsequently-introduced quartz (Fig.).

In thin section the dominant (95+ percent) quartz of the gangue bodies shows a fine to medium grained (mm to mm) allotriomorphic mosaic which approximates to a metamorphic foam-type texture with mainly triple junction contacts between grains. However, in contrast to the similar textures in the matrix sulphides, this quartz texture shows only a low proportion of strain-free, clear, annealed grains. The vast majority (90-95 percent) are moderately to highly strained, as shown by their extinction patterns, while still retaining their outer polygonal shapes (Figs.).

True strain twins are rare, but a considerable proportion of the grains exhibit other textures which may be attributable to deformation. These are in the form of closely spaced, sub-parallel, often curved, microfractures and lines of dust-like opaque or high refractive index minerals and minute fluid inclusions, intersecting individual grains but seldom extending into adjacent ores.

These features do not appear to show any form of preferred orientation within the bodies of quartz-rich gangue; their orientations shown divergences of up to 90° in any one field of view. Generally but not universally they are oriented at rather high angles to the strain extruction domains in the individual quartz grains.

As already noted, a small proportion of quartz grains are clear and non-strained, apparently due to partial annealing of larger, strained grains. Their distribution is apparently erratic. The quartz filling narrow cleavage and other fractures in adjacent deformed pyrite grains often shows a parallel, fibre-type (antitaxial) texture at right angles to the walls of the fractures (Fig.). Such texture is often interpreted to imply filling of the fractures under a state of tension (during opening of the cracks). See Ramsey & Huber, 1983.

Of the other non-sulphides in the Gressli ore, the most abundant is a white muscovitic mica. It occurs rather erratically in the specimens examined, from more or less trace azmounts to several percent, making it difficult to give any meaningful modal analyses.

Where mica is most abundant, the gangue component of the ore is best described as a quartz-muscovite-(sulphide) schist. The mica is typically present as individual flakes or layers of flakes (grain size to) with a more or less parallel orientation - at least on the scale of individual handspecimens or thin sections. Less commonly the muscovite occurs as felts of randomly oriented flakes some tenths of a mm in length, usually parallel to the general mica foliation. Bending and strain extinction is not uncommon in some of the larger flakes.

Individual muscovite flakes with random orientation can also be observed as inclusions in undeformed metablastic pyrite grains, often straddling the contact to enclosing matrix sulphide or quartz. Such observations could be taken to imply that muscovite was present prior to, or crystallised during, pyrite metablastesis. (Alternatively these relations could be due to the strong crystallising force of later formed muscovite.)

Epidote/clinozoisite is present in the Gressli ore as individual grains or grain fragments, rarely as aggregates, sparsely and irregularly distributed in the gangue-rich portions of the ore. In a few sections it can be present as a minor mineral, but on the whole must be classed as a trace component. its mode of occurrence suggests that it is rather a relic from an initial (?metavolcanic) mineralogy than a late-crystallising phase.

Apatite is present in quartz in varying, generally trace, amounts. It has been tentatively identified by its high relief over the surrounding quartz, colourless nature; low birefringence and characteristic subhedral grain cross-sections.

Feldspar: Present in the quartz of some of the thin sections examined are vague, "dirty", patches which can be resolved at higher magnefication into highly sericitized and/or epidotised remnants ("ghosts") of feldspar. (Dimensions) Occasionaly these patches show one or two twin lamellae of the polysynthetic type, but they are generally untwinned. They have been varyingly overgrown along their boundaries, often also internally, by clear, unstrained grains of quartz (Figs.).

The altered, partly overgrown, appearance of these feldspar grains and aggregates indicates that they are relicts from an earlier mineralogy and fabric.

MINERAL CHEMISTRY

Sphalerite geochemistry

The sphalerite of the gressli ores, like that of many metamorphosed massive sulfides, occurs as homogeneous dark reddish brown grains interstitial to and as inclusions within the other ore minerals. Seventy-three electron microprobe analyses representing all observed types of sphalerite occurrences have been carried out. The data are presented in figure and representative analyses are given in table.

The iron contents of the sphalerites are relatively constant within each grain varying only over a range of one to one and one-half mol percent FeS. The total range of iron (6.2-8.35 wt.%) content is from 10.52 to 14.18 mol percent FeS with a slight bimodality in distribution (Fig.). Manganese contents range from 0.09 to 0.71 weight percent with very distinct bimodal distribution that correlates with the iron content. With few exceptions, grains with iron contents less than about 12.3 mol percent FeS contain Mn contents in the range 0.1 to 0.2 wt.%. On the other hand, if iron contents are greater than about 12.3 mol percent FeS, Mn contents are generally in the range of 0.55 to 0.70 wt.%.

Cadmium contents of the sphalerite range from 0.05 to 0.46 but about 90 % of analyses are $\pm$ 0.1 wt.percent. There is no discernible correlation or trend in the cadmium contents. Copper contents range from zero to 3.2 wt.% but most values are below 0.25 wt.%. The higher values may well represent contamination of the analytical volume by small inclusions of chalcopyrite that are relatively common in the sphalerite. There are no discernible trends in copper contents relative to any of any of the other metals and the compositional range of "chalcopyrite-disease" - containing sphalerite is the same as that of sphalerite grains which contain no visible chalcopyrite inclusions. This suggests that the metamorphism either had little effect on the chalcopyrite within the sphalerite or that re-equilibration after peak metamorphism had a rather random pattern relative to iron and manganese contents.

The 3.7 percent spread of FeS contents in the sphaøerites of the Gressli deposit is less than that reported for some other similar Caledonian-Appalachian deposits (e.g. Tjåter, Ankarvattnet, Stekenjokk, Ducktown; Hutchison and Scott 1980) but still complicates the application of the sphalerite geobarometer. It is generally assumed that the pyrite, pyrrhotite and sphalerite equilibrated at peak metamorphic conditions and that the observed variations in FeS contents of the sphalerites reflect differential re-equilibration during cooling. The presence of chalcopyrite and pyrrhotite in contact with some of the sphalerite could easily be responsible for the re-equilibration. This would be consistent with the interpretation of Hutchison and Scott (1980), Brocker, et al. (1986) and others in accounting for FeS compositional variations. Sphalerite retrograde re-equilibration influenced by iron loss to chalcopyrite and pyrrhotite decreases the iron (and hence FeS) content of the sphalerite shifting the apparent pressure of formation to higher than original values. Accordingly, it is presumed that the least affected (or unaffected) sphalerite would retain the highest FeS content and most accurately indicate the peak metamorphic pressure. The highest iron contents (FeS = 14.2 mol percent) would indicate a pressure of about 5.2 kb, a value consistent with the general geology of the area. The lowest iron contents (FeS = 10.5 mol percent), if original, would indicate metamorphic pressures of greater than 9 kilobars, values much higher than would appear reasonable.

The reason for the bimodal distribution of manganese contents is not clear. It may represent original differences; but, if peak metamorphism equilibrated the distribution of all other elements, why not manganese ? In this case, the Mn-FeS correlation would also be consistent with Mn retarding the loss of FeS and and re-equilibration of the sphalerites. On the other hand, if Mn contents were uniformly distributed (along with copper, cadmium and iron) during the peak of metamorphism, the presently observed values may reflect simultaneous loss of iron and manganese during retrograde re-equilibration. Where the manganese would go is not known as it has not been found during analysis of other phases. ^Regardless of the cause of the manganese contents, it appears that it would not have affected the interpretation of the sphalerite as a geobarometer (Scott 1976; Kissin et al., 1986).

Table Representative Sphalerite Analyse

	Zn	Fe	S	Mn	Cd	Cu	Σ	FeS mol %
1492.2h	60.15	8.34	33.87	0.65	0.27	0.01	103.29	13.95
1489.1jb	60.51	6.58	33.38	0.09	0.26	0.75	101.57	11.22
1481.1e	61.41	6.17	33.08	0.17	0.27	0.05	101.15	10.58
1488.2cr	59.71	7.53	33.78	0.61	0.26	0.02	101.91	12.75

Pyrite Geochemistry.

Standard electron microprobe analysis of pyrite, the dominant sulfide mineral of the Gressli deposit does not reveal the presence of any elements above background levels. However, detailed elemental mapping of a few samples using high beam currents and long count times followed by image processing (Craig, et al., 1994) reveals that the distributions of arsenic, cobalt, and nickel are not uniform. Application of this technique permits recognition of irregular distributions of elements at concentration levels at or below normal detection levels. It does not give reliable quantitative analysis but does accurately reveal differences in concentrations. In isolated typical recrystallized grains the arsenic contents were found to be irregular and patchy without any clear relationship to grain boundaries.

Similar analysis of pyrite through which there has been a micro-shear (Fig.) reveals that arsenic, originally relatively high in the primary pyrite, has beenremoved in recrystallized pyrite grains in and along the recrystallized margins of the fracture. Cobalt follows a similar but more subdued pattern. Nickel, in contrast, is very low in the primary pyrite and in disseminated recrystallized grains in the shear. However, nickel is clearly enriched in the pyrite that has recrystallized along the margins of the fracture.

The recrystallized nature of the pyrite clearly indicates that the shearing must have occurred while temperatures were still significantly elevated. The distribution of the elements indicates that solutions passing through the fracture were removing arsenic and cobalt but carried some nickel, at least during the early period of recrystallization of the pyrite along the margins.

DISCUSSION - THE DEVELOPMENT OF THE GRESSLI ORE FABRIC

The Gressli ore body shows no recognisable fabric elements resulting from original depositional processes. Present day fabric is the result of through-going mechanical (deformational) mixing, metamorphic recrystallisation, late cataclasis and mixed chemical and mechanical remobilization (Marshall & Gilligan 1987).

It is even doubtful whether zoning of the ore has any relation to original depositional zonation. It thus cannot be cited as evidence for younging directions (way up criteria).

The gross zonation into a generally massive sulphidic (often sphalerite-dominated) hangingwall zone and a sulphide-poor, siliceous (quartz-dominated) footwall zone, which is often cited as evidence for original stratigraphic layering, could conceivably be the result of post-depositional influx of SiO_2-rich fluids along a structurally controlled zone of permeability following the contact to the massive sulphides.

Textural evidence from the massive sulphide ore is indicative of a considerable influx of silica and other related elements (Al_2O_3 etc.) during a period which succeeded the main metamorphic recrystallisation, but while deformational stress was still high. Such a mechanism could reconcile the evidence for quartz influx and replacement of the pyrite and the earlier remobilized matrix sulphides with that of a metamorphically recrystallised and deformed quartq fabric.

In view of the above-mentioned evidence for complete destruction of depositional fabric, it is well-high impossible to reconstruct a complete history of the development of the Gressli sulphide body.

The sparse and erratically-distributed evidence of possible pre-metamorphic mineralogy and fabrik, such as the highly altered and partly overprinted feldspar relics, the occasional possible clast of "balled-up" mica schist and various other mineral fragments, is litte on which to base a pre-metamorphic/deformational picture.

The earliest decipherable event in the ore would appear to be the metablastic, occasionally porphyroblastic, development of pyrite to a variably-packed fabric in a groundmass (matrix) dominated by sphalerite, but with variable amounts of chalcopyrite and, in certain restricted zones, abundant pyrrhotite. The relative amounts of non-sulphides present during this period is not easy to estimate in view of later modifications of the ore fabric.

The metamorphically recrystallised pyrite fabric appears to have been none-directional and to have comprised a mixture of euhedral and subhedral individuals, together with a high proportion of polygonal grains exhibiting the so-called "foam- or triple-junction texture (Stanton, 1964, 1972).

The more well-developed (porphyroblastic) pyrite individuals are characterised by relatively large and sparsely distributed chadacrysts of the matrix sulphides, dominantly sphalerite. These comprise both true(?) inclusions and embayments along the matrix-pyrite contacts. Another, minor, type of inclusion in pyrite pobbibly referrable to this period of metablastic growth comprises isolated, tabular crystals (books) of muscovite, entirely enclosed by pyrite or straddling the pyrite - matrix contacts. In contrast to the more abundant muscovite which charcterises parts of the quartz-rich gangue, these early (?) mica crystals show no preferred orientation.

The sphalerite of the matrix and that forming the chadacrysts shows very irregular, erratic, emulsion-type intergrowths ("disease") with small drops, rods and grains of both chalcopyrite and pyrrhotite. The timing of the development of these intergrowths is uncertain.

The first decipherable deformational event recorded by the Gressli ore fabric was the brittle, cataclastic disruption of the metablastic pyrite fabric. Individual metablasts were variably fractured along generally cleavage-controlled networks or thoroughly disrupted (brecciated). Areas of foam-textured pyrite were variably disrupted along grain boundaries and to a lesser extent by the fracturing of individual grains.

Concomittantly with the deformational movements, chalcopyrite of the matrix appears to have moved into the developing fractures in the pyrite, eventually filling them completely and variably replacing their walls. Chalcopyrite is thus to be found typically in the interior parts of the fractured pyrite grains or groups of clasts. it is also the dominant mineral filling the grain-boundary and other fractures in disrupted foam-textured pyrite.

Sphalerite is also frequently present as the sole or dominant matrix sulphide filling fractures in deformed pyrite or cementing groups of pyrite clasts; it also replaces the iron sulphide to the same extent as the chalcopyrite.

Sphalerite has, however, demonstrably been mobile at a later stage than has the chalcopyrite (see Figs. , above and Vokes & Craig, 1992). It has moved from the matrix into the outer reaches of previously chalcopyrite-filled cracks, in pyrite grains apparently displacing (replacing) the chalcopyrite, similarly the sphalerite from some of the larger chadacrysts within the pyrite grains has moved into chalcopyrite filled cracks in their vicinity (Fig.).

Sphalerite also appears as irregular veinlets along the central portions of the chalcopyrite veins, implying that these were reopened and refilled subsequent to the initial chalcopyrite deposition (see Vokes & Craig 1992, Fig. 10).

Pyrrhotite has also participated in these mobilization - infilling - replacing processes togehter with the other matrix sulphides when present; textural evidence indicates it was mobilized together with the chalcopyrite.

Both the high degree of mobility of the matrix sulphides and the clear evidence of a sequence of mobilization (as between chalcopyrite and sphalerite) are unusual in the writers' experience in the metamorphosed stratabound sulphide ores of the Caledonian-Appalachian metallogenic belt. However, the relative order og mobility shown by the matrix sulphides at Gressli agrees with the general orders of metamorphic mobility displayed by sulphide minerals (see, i.a., Vokes 1971, Marshall and Gilligan 1987, Gilligan and Marshall 1987).

The type of mobilization involved was briefly discussed by Vokes & Craig (1992), who, while leaning towards fluid state (chemical) remobilization on textural grounds, were not able to rule out a contribution from solid state (Creep, flow) mobilization. These writers considered that these processes occurred entirely within the sulphide (ore) mass and that no components of the veining and replacing sulphides had been introduced from outside this.

Textural evidence has already been presented that at some stage following the termination of the above-described events, a second mobilization event took place, this time involving mainly the gangue elements of the ore; in particular SiO_2. Polished section observations provide good evidence that considerable quantities of quartz-rich gangue were deposited irregularly throughout the more massive sulphide portions of the deposit, either through a process of replacement of the pre-existing minerals or by deposition in pore-spaces formed by their penecontemporaneous leaching and removal (see above, pp.   ).

Thin section evidence (also reviewed above, pp.   ) shows that the non-sulphide minerals in these interpreted late mobilization bodies were subjected to continuing directed pressure during and after their emplacement and crystallisation, i.e. that this period of high-SiO_2 mobilization was syn- or at least late-(metamorphic-deformational) orogenic ?

The other, often minor to trace, non-sulphide minerals in the quartz-rich mobilisate bodies present certain problems. The greater part of the muscovite present is intergrown with the quartz in a directed texture that in places can be designated a quartz-muscovite schist, though the occurrence of true mica-dominated folioe is rather rare. The mica also shows deformational effects, though to which it is intergrown.

On the present interpretation this muscovite would have crystallised, under stress, together with the dominant quartz, from fluids of most probably metamorphic origin (see below).

A small proportion of the muscovite present in the ore, that enclosed or partly enclosed by the metablastic pyrite, is arguably of an earlier stage of formation.

Other relict, earlier, mineralogy includes the altered, partly overprinted feldspars; matted, deformed fragments (?clasts) of mica schist and possibly isolated crystals or fragments of epidote/clinozoisite and amphibole.

It is an open question if any of the abundant quartz in the gangue bodies is in any way a remnant of an earlier SiO_2-rich deposition. (E.g. a cherty exhalite.) It has not been possible to 'deduce' any textural evidence (e.g. clast-like remnants) that could define such relict early deposition. On the other hand, the origin of the large amounts of quartz present in the interpreted mobilizate bodies of gangue minerals in the Gressli massive sulphides is not immediately obvious.

The problem seems to be related to the nature of the zone of high-SiO_2-(py) rock forming the footwall portion of the Gressli deposit and which attains a thickness of several metres in places. Two possible interpretations of this FW zone were hinted at in the beginning of this discussion; either an original, stratigraphical layer of SiO_2-rich rock, e.g. a chert, or, a silicified shear - or other structural zone. In the first case the SiO_2rich bodies in the massive sulphidic parts of the ore could be the results of metamorphic remobilization from this layer; in the latter the bodies could be formed directly from the SiO_2-rich fluids circulating along the shear (?) zone.

The last endogenic modifications of the Gressli ore fabric appear to be the results of very local, restricted internal movements of possibly shear type. These gave rise to zones, measured on the scale of mm to cm of intense cataclasis of the pyrite, accompanied by ductile deformation of the matrix sulphides. These restricted zones cut through, disrupt and destroy the fabric resulting from the previously discussed deformation, mobilization and replacement processes.

The orientation of these zones with respect to gross ore-body morphology is not known due to the difficulty of observing them megascopically in outcrops.

The movements involved led to the production of narrow, but perhaps extensive, zones of finely granulated pyrite in an intensely sheared matrix of sphalerite, pyrrhotite and lesser chalcopyrite.

There then followed a period of annealing of the base-metal sulphides and pyrrhotite with a possibly concomitant growth of fine-grained, idiomorphic pyrite as individual euhedral crystals within the zones and as 'fringes' (selvedges) at the edges of some of the larger, 'older' pyrite grains and clasts adjacent to the zones. This may have taken place by complete recrystallisation of the fine cataclastic pyrite or by the growth of euhedral outer zones on the fragments and broken surfaces. The former mechanism is ptobably favoured by the evidence of ubiquitous chadacrysts of matrix sulphides in the 'new' idiomorphs and in a filigree-type of intergrowth along the recrystallised selvedges. (See Figs. above.)

Some of the broader (1-2 cm wide) crush zones show what appears to be an influence of the type of matrix sulphide on the size and euhedralism of the 'view' pyrite crystals. Those in a matrix of pyrrhotite are clearly larger and more idiomorphic than those in a purely sphalerite matrix (Fig.).

This would appear to indicate that the new pyrite growth was at least facilitated by the transfer of S from the matrix pyrrhotite as it cooled, a mechanism proposed for general pyrite idioblastesis by Craig & Vokes (l993a,b).

Textural evidence has been presented above that the quartz-rich gangue mobilisates of the ore were also involved in the cataclasis produced by these crush zones. The rounded quartz clasts occur often in a matrix of chalcopyrite, which also veins and partly replaces them. This implies that a second remobilization of the chalcopyrite had taken place in the late crush zones, which was probably also responsible for the rstricted numbers of hair-like chalcopyrite-filled cracks observed in sphalerite and gangue.

As has been shown above (section on Mineral Chemistry) the changes taking place in these narrow crush zone were not only in respect of texture. There occurred a considerable readjustm,ent of trace element contents between the 'old' pyrite and the new fine-grained recrystallised variety.

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axial plunge aligned almost parallel to the dip direction, which is typical of deposits in this part of eastern Trondheimsfelt (Vogt 1945). It is more than likely that early deformation events have strongly influenced the morphology and orientation of the ore lenses. However the poor exposure around the mine, combined with the destructive effects of later feldspar-porphyry sheets do not allow detailed mapping of these structures. From the sulphide stratigraphy of the exposed mineralization it is apparent that at least this part of the deposit is the correct way up. Along strike to the south, the distribution of altered lithologies similarly suggests that the acid pile has not inverted.

Ore mineralogy and petrography.

Samples of the Gressli sulphide ore, taken from available surface workings and mine openings, as well as from dump material, have been investigated macroscopically and microscopically to determine mineral composition and textures. In addition to standard light microscopy in reflected aand transmitted light, SEM/Microprobe techniques were used to determine chemical compositions of the more important sulphides.

The ore consists of, in varying proportions, pyrite, sphalerite, chalcopyrite and pyrrhotite as main minerals in descending order of abundance. Sparce, small grains of galena were found in one of the speciments investigated microscopically, though it is macroscopically visible in a thin, foliated, zone close to the footwall of the western part of the ore.

The main gangue mineral is quartz, while variable, lesser amounts of muscovite etc. etc. occur through the material examined.

Due to the irregular, restricted outcrops available for sampling, it has not been possible to arrive at any meaningful modal composition of the Gressli ore. However, the majority of samples investigated can be designated as massive ore, with typically over 80 percent sulphides. Textures are normally granoblastic, coarse-grained (0.5-3 mm, occasionally coarser). Foliated or schistose textures are not obvious macroscopically except near the infrequently exposed opre-wall rock contacts. Modal banding, sulphide-sulphide and sulphide-gangue, is present especially in the upper (HW-near) sphalerite-rich ore zone, though it is not possible to relate this to depositional layering.

Figures (so far)

1. Smallish map of the east-central Trondheim District, showing Trondheim and Tydal with the nappes and F-H marked (cf. Wilson 1985, Fig. 1).

2. Geology of the Tydal area. Based on map provided by IF, but needs modifying and improving.

3. Need a larger-scale map of the surroundings of the Gressli deposit. Can Ian supply this?

4. Diagrammatic sections through the Gressli sequence.

Tables (so far)

Table 1. The stratigraphy of the Meråker nappe in the east- central Trondheim District (from Gee et al. 1985).

Table 2. Major and trace-element chemistry of Fundsjø Group rocks, Tydal area.(need one-or more-analysis of the porphyry sheets)

Table 3. (needed)-mentioned in text Analyses of the mineralization. Does Ian have this?

Table 2. Major and trace-element chemistry of Fundsjø Group rocks, Tydal area.

	1	2	3	4	5	6
SiO_2 %	56.35	36.96	66.01	54.57	56.74	51.29
Al_2O_3	10.20	13.95	11.78	18.01	13.94	12.94
TiO_2	0.75	1.02	0.38	1.10	1.11	0.60
Fe_2O	10.95	10.79	4.80	9.09	7.85	13.15
MgO	4.27	5.22	1.45	3.51	5.39	2.76
CaO	7.62	8.67	2.37	1.26	3.40	3.80
Na_2O_2	2.79	2.91	3.60	1.31	2.79	1.13
K_2O	0.13	0.67	1.51	4.51	2.11	2.55
MnO	0.21	0.15	0.06	0.11	0.12	0.18
P_2O_5	0.12	0.27	0.11	0.18	0.20	0.51
Cu ppm	47	42	50	32	26	219
Pb	12	2		19	7	63
Zn	94	92	99	100	66	317
S	8435	2714	9817	2276	1287	80560
As	4	3	5	3	4	51
Mo	2	0	3	1	1	32
W	1	18	6	36	6	14
Cr	145	239	36	131	1230	183
Ni	55	69	9	47	99	193
Co	29	29	9	25	18	43
Sb	0	3	0	0	1	2
Sn	2	4	1	4	1	2
V	215	272	45	158	152	511
Th	1	1	2	8	6	7
U	2	0	1	1	1	12
Rb	8	21	27	118	68	66
Sr	144	218	142	87	238	153
Y	28	26	32	29	27	43

Zr	67	80	125	171	184	106
Cl	17	83	6	23	31	17
Ba	57	130	148	414	362	276

(1) Metabasic extrusives, Gressli belt (10); (2) Metabasic extrusives, east of gabbro complex (7); (3) Felsic extrusives, Gressli belt (37); (4) Biotite-staurolite schist, Gressli belt (22); (5) Biotite-sericite-amphibole schist, east of gabbro complex (11); (6) Graphite schist, Gressli belt (51).

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