Post-recrystallisation mobilisation phenomena in metamorphosed stratabound sulphide ores

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Abstract

Metamorphosed stratabound iron- and base-metal sulphide deposits often exhibit microtextures in which fractures in cataclastically-deformed pyrite porphyroblasts are filled with matrix sulphides; chalcopyrite, sphalerite, pyrrhotite or galena. Discussions of such textures have mostly centred on whether solid-phase or fluid-phase mechanisms were responsible for the movement of the matrix sulphides.

The small Zn–Cu sulphide body at Gressli, in the central Norwegian Caledonides, shows these textural features to an extreme degree. Both chalcopyrite and sphalerite show heavy replacive relations to the cataclastically deformed metablastic pyrite, along fracture walls and grain boundaries. They also occur injected along the opened-up triple junctions of foam-textured pyrite. In addition, parts of the ore show patchy quartz with clear replacive relationship to all three sulphides, a feature not often reported from such ores. Such textures can be interpreted to support a mobilisation sequence chalcopyrite–sphalerite–quartz within the Gressli ore. Their extent and degree of development indicate that fluid-phase mobilisation of the three minerals must have played a dominant role. Chalcopyrite and sphalerite are most likely derived from within the ore-mass itself; an external source for the SiO_2 seems most probable, in the form of metahydrothermal solutions moving along retrograde shear zones at or near ore-walls.

KEYWORDS: metamorphism, sulphide ores, microtextures, Gressli, Norway.

Introduction

THE purpose of this presentation is to draw attention to and to discuss textures present in one of the metamorphosed stratabound sulphide ores of the Norwegian Caledonides which are indicative of fluid-state mobilisation and replacement during or after post-metamorphic peak conditions. This mobilisation has involved components of minerals presumably present in the ores prior to and during the metamorphism (mainly chalcopyrite and sphalerite) as well as components which could also have been introduced from outside the actual ore-volume (mainly quartz).

Although these textural phenomena are by no means unknown to sulphide petrographers, and have indeed been illustrated and described in numerous papers, they have often constituted a minor part of the total textural appearance of the ores concerned. Recent investigations by the present authors have brought to light examples where these types of textures assume a much more dominant role. They would seem to indicate that fluids, of presumably metamorphic origin, can play a greater role than hithertofore recognised, in modifying the textures of metamorphosed sulphide ores.

This recognition would seem to be of significance as a general contribution to the on-going assessment of the role of metamorphic fluids in ore genesis and ore modification.

Microtextures indicative of internal mobilisation

Matrix sulphides. Most students of metamorphosed sulphides are well-acquainted with microtextures which are taken as indicating movement (mobilisation) of softer, more ductile sulphides such as chalcopyrite, pyrrhotite, sphalerite and galena into microfractures in harder, more brittle sulphides (pyrite, arsenopyrite), oxides (magnetite, chromite) or silicates. Examples which come easily to mind involve chalcopyrite filling partly cleavage-controlled fractures in pyrite porphyroblasts (Fig. 1) or tensional pull-apart fractures in deformed pyrite grains (Fig. 2). Other aspects of the same process would include the migration of the 'softer' sulphides into 'pressure shadows' outside the stronger, harder minerals (Fig. 3). (See also Amstutz, 1969; Craig and Vokes, 1992; Cox, 1987; McQueen, 1987; Natale, 1969; Vokes, 1963, 1969; Gilligan and Marshall, 1987).

The relations between the fractured brittle sulphides and the softer in-filling sulphides vary from pure 'filling' relationships as evidenced by so-called 'matching walls', through corrosion of the fracture walls, to considerable replacement of the brittlely-deformed mineral. In the latter case replacement may proceed so far that only residuals remain as evidence of the process.

The fact that the fracture-infillings and eventual replacement have occurred in metablastic, often porphyroblastic, pyrite and other strong minerals means that the mobilisation processes must have taken place during or subsequent to the prograde phase of metamorphism in which the metablasts formed. Fracturing is often considered to have occurred during continuing movements affecting the whole sulphide mass, which, at the temperatures prevailing, must have deformed in a ductile or plastic manner. Movement of this type, often involving rotation of the more brittle components of the ores (silicate fragments, pyrite and other porphyroblasts) in a matrix of the more ductile components, has been referred to by the German term Durchbewegung (Vokes, 1969, 1973; Marshall and Gilligan, 1989). Evidence is often present that fracturing of pyrite metablasts was initiated where two or more of these impinged on each other during these rotational movements (See Fig. 1).

Non-sulphide minerals. As far as the present writers are aware, little has been published regarding possible mobilisation/replacement features of non-sulphide minerals in metamorphosed stratabound sulphide ores. Most earlier petrological studies of such ores (including those of the present authors) seem to have assigned a passive role to the 'gangue components' during and after the recrystallisation of the ores. However, more recently, evidence has been accumulating that under conditions of low-grade metamorphism, where little recrystallisation has taken place, non-sulphide, as well as sulphide, components can be very mobile. McClay (1991), for example, has documented pressure–solution mobilisation of pyrite, barite, carbonate and quartz in stratiform Zn–Pb–barite deposits in the northern Canadian cordillera. However, the mobilised components in this case seem to have been mainly removed from the system, though McClay (1991) does mention 'common' quartz and carbonate veining. No mention of replacement by the mobilised components in made.

Possible late-metamorphic (retrograde) fluid-induced mobilisation leading to deposition of anhydrite with subordinate barite and celestite is mentioned by Cook *et al.* (this volume) from the footwall alteration zone of some of the Sulitjelma ore bodies.
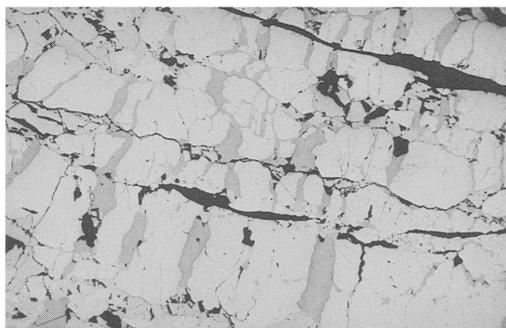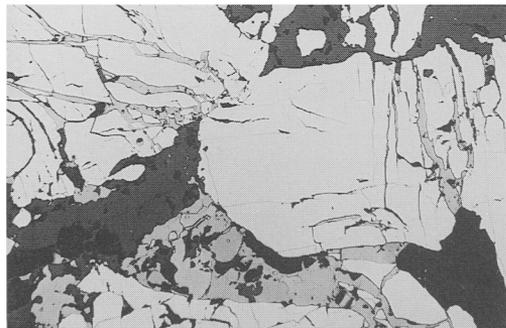
FIGS. 1. and 2. FIG. 1 (*left*). Chalcopyrite (light grey) filling fractures in pyrite metacrysts. Amphibolite grade. Bleikvassli, Norway. Ord. refl. light. Width of field: 2 mm. FIG. 2 (*right*). Chalcopyrite (light grey) filling tension ('pullapart') fractures in pyrite (white) at high angle to foliation defined by silicate laths. Kambalda, W.A. Ord. refl. light. Width of field: 1.25 mm.
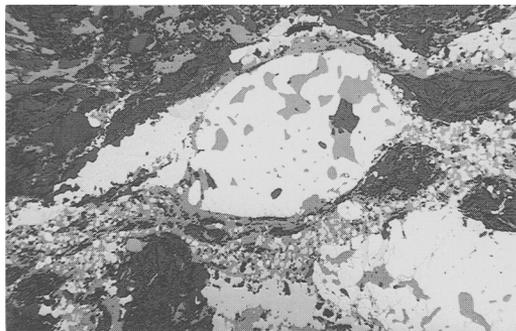
FIG. 3. Chalcopyrite and pyrrhotite (light grey) forming pressure shadow 'tail' at one side of deformed pyrite metablast (white). Lergruvebakken, Røros, Norway. Ord. refl. light. Width of field: 3 mm.

Evidence will be presented below that, in at least one metamorphically recrystallised stratabound sulphide deposit in the Norwegian Caledonides, quartz appears to have been mobile at a stage subsequent to the main amphibolite facies recrystallisation and to have heavily replaced the main sulphide minerals present. However, preliminary reinterpretation of the sulphide–quartz relations in other highly metamorphosed Caledonian sulphide ores indicates that the phenomena to be described are perhaps not unique to the deposit that will be used as an example.

Mobilization mechanisms

Discussions of the nature and conditions of the mobile phase which was responsible for the filling of fractures of the types under consideration have usually formed part of the general discussion of problems of metamorphic mobilisation or remobilisation (see, among many others, Ramdohr, 1953; Amstutz, 1969; Vokes, 1971; Mookherjee, 1976; Marshall and Gilligan, 1987).

Earlier discussions of the mechanism involved centred on two main types: solid state and fluid state mobilisation. One of the latest treatments of the subject (Marshall and Gilligan 1987) arrived at the following scheme based on the earlier proposals.

'Chemical'	—	all liquid-state transport, including solutions, melts and wet diffusion.
'Mechanical'	—	all solid-state ductile transfer including plastic and cataclastic flowage.
'Mixed'	—	concurrent chemical and mechanical transfer.

The authors concluded that 'in reality, most mobilisation and remobilisation is mixed', though one or other of the first two mechanisms may dominate in specific cases.

There seem to have been relatively few discussions of the types of mobilisates which have been active on the scale indicated by the observations outlined earlier in this paper. Earlier literature cited above (e.g. Amstutz, 1969; Natale, 1969) was not too specific regarding the nature of the mobilisates responsible for the healing of fractures in cataclastic pyrite and arsenopyrite by matrix sulphides. The consensus seems to have been that mechanical mobilisation was mainly responsible, i.e. the ductile or plastic 'inflowing' of the softer sulphides and that the involvement of solutions was less likely (see also McDonald, 1967).

In a more recent discussion of the microtextural evidence for (re)mobilisation in metamorphic environments, Cox (1987) noted that pyrite is often deformed by pull-apart across intragranular extension microfractures which can then be filled by silicates, carbonates, or sulphides, by deposition from solution during fracturing or by solid state intrusion of ductile sulphides.

Gilligan and Marshall (1987) also mention that 'chalcopyrite is commonly seen healing fractures in pyrite' and that this is 'usually interpreted as fluid state (re)mobilisation, and therefore pressure–solution segregation of chalcopyrite away from the mixed sulphide matrix'. This brief statement of Gilligan and Marshall (1987) is the first suggestion the present authors are aware of that pressure–solution segregation could be responsible for a differential mobilisation of matrix sulphides in metamorphosed ores. It would accord with the common observation that chalcopyrite is the dominant sulphide filling fractures in pyrite in such ores. Evidence will be presented below that in an example where both chalcopyrite and sphalerite are moved into fractures in pyrite, the copper sulphide has preceded the zinc sulphide.

The question of the presence or absence of replacement features has received relatively little attention when instances of the textures were mentioned. It might reasonably be suggested that in cases where the 'invaded', brittlely deformed, metablasts (e.g. pyrite) had been extensively corroded or replaced, that fluid-assisted processes had more likely been active (either direct solution transfer or fluid-assisted diffusion).

Metahydrothermally-generated quartz on the other hand has been the subject of a vast literature over the years, mainly as a general petrological problem (see Fyfe et al., 1978), but also in

connection with the transport and deposition of metals of economic interest. In the latter field, the interest has undoubtedly been mainly centred on the role of metamorphic fluids in the formation of gold-bearing quartz veins and other bodies (see e.g. Cox *et al.*, 1987, 1991; Hobbs, 1987). Little if anything seems to have been written on the subject of metahydrothermal quartz deposition in massive sulphide deposits, though there is no reason to assume that they are any form of special case. Considering the amount of metahydrothermal quartz present within metamorphic terrains, it should not be surprising that sulphide deposits in the same terrains have at times been affected by it.

Observations from the Gressli deposit, central Norwegian Caledonides

Recent microscopical investigations of the small metamorphosed Zn–Cu deposit at Gressli in the Tydal area of the eastern Trondheim District of the central Norwegian Caledonides have shown a proliferation of textures of the type discussed above, involving metablastic pyrite and the softer matrix sulphides, chalcopyrite and sphalerite, as well as quartz. The textures indicate a considerably greater degree of mobilisation of the latter minerals and replacement of the pyrite than has so far been recognised in Scandinavian Caledonian ores and would indicate that meta-

morphic fluids have been especially active in the case of Gressli.

The deposit, situated some 65 km southeast of Trondheim (Fig. 4), is one of many which are hosted by a more or less continuous, bimodal Ordovician volcanite belt, some 300 km long, forming part of the eastern flank of the Trondheim Distict (Grenne and Lagerblad, 1985; Grenne, 1988).

The deposit is situated in interlayered basic and felsic metavolcanites and metasediments, here at amphibolite facies metamorphic grade, some few hundred metres from the western contact of a large, layered mafic intrusive body, the Fongen–Hyllingen Complex (Wilson and Olesen, 1975; Wilson, 1985) of late Silurian age (426 Ma, Wilson *et al.*, 1983).

Contact-metamorphic minerals (andalusite, sillimanite, cordierite) in the aureole of this mafic massif have been overprinted by the later regional metamorphism (end-Silurian), producing kyanite, white mica and staurolite-bearing assemblages (Olesen *et al.*, 1973; Wilson and Olesen, 1975).

The possibility is present, therefore, that the Gressli ore body and its host-rocks have been subjected to both contact- and regional-metamorphic episodes, though there is no conclusive evidence of two phases of metamorphism in the ore itself.

Gressli is a small Fe–Zn–Cu–S deposit. An
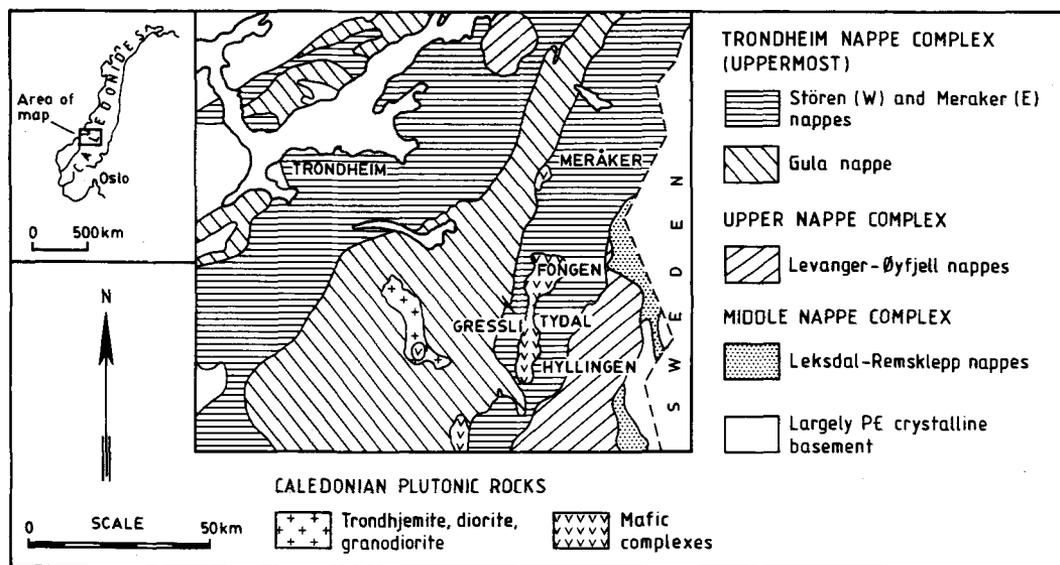
FIG. 4. Simplified geological map of the region southeast of Trondheim showing the main tectonostratigraphic units and the location of the Gressli deposit, Tydal.

unpublished company report based on the results of diamond drilling in 1974–1976, gives 'probable ore' at Gressli as 78000 t at 0.90% Cu and 5.52% Zn. Its ore mineralogy is dominantly pyrite and sphalerite with less chalcopyrite and, in some specimens, pyrrhotite. The main gangue mineral is quartz, while variable, minor amounts of muscovite occur throughout the material examined.

Due to the irregular, restricted outcrops available for sampling, it is not possible to arrive at any meaningful modal composition of the Gressli ore. However, the majority of samples investigated can be designated as massive ore, commonly containing over 80% sulphides. Textures are typically granoblastic, coarse-grained (0.5–2 mm but occasionally coarser). Foliated or schistose textures are not macroscopically obvious, though modal banding, both sulphide–sulphide and sulphide–silicate, is present, especially in a sphalerite-rich zone close to the present hanging wall. Galena, while only sparsely present in the mas-

sive ore, is macroscopically visible in a thin zone close to the hanging wall of the western part of the area.

Restricted zones along parts of the wall rock–ore contacts are best described as sulphide–quartz–(muscovite) schist.

Ore textures seen at low magnifications are dominated by anhedral to subhedral pyrite granules, often showing a weak, directed texture, between which the softer, matrix, sulphides occur in varying amounts. In parts of the ore where the matrix minerals are sparse or lacking, the pyrite exhibits a characteristic, somewhat irregular, form of triple-junction or 'foam' texture (Stanton, 1964, 1972). This type of pyrite intergrowth (Fig. 5) dominates other forms of the mineral usually regarded as indicative of metamorphic growth. In fact, the relative absence of sub- to euhedral pyrite porphyroblasts, which are so characteristic of many Caledonian metamorphosed sulphide ores, is one of the noticable features of the Gressli ore textures.
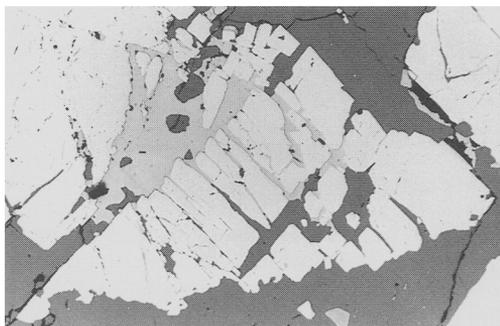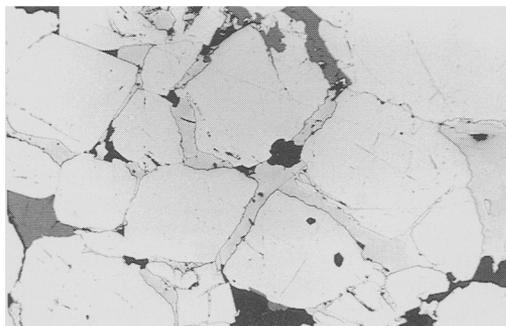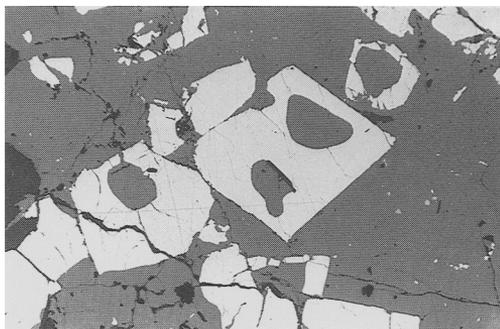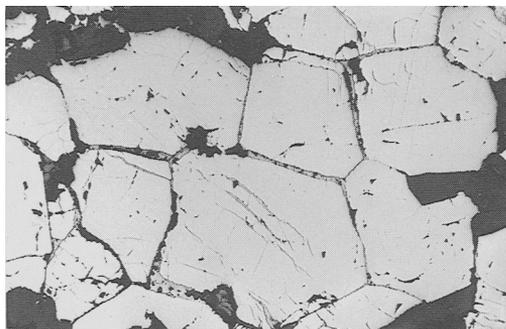
FIGS. 5–8.— FIG. 5 (*upper left*). Metablastic pyrite (white) showing triple junction ('foam') texture. Interstitial sphalerite and chalcopyrite. Gressli. Ord. refl. light. Width of field: 2 mm. FIG. 6 (*upper right*). Subhedral pyrite metablasts (white) with rounded inclusions (chadacrysts) of sphalerite (grey) in sphalerite matrix, Gressli. Ord. refl. light. Width of field: 1.25 mm. FIG. 7 (*lower left*). Foam-textured pyrite (white) partly replaced along triple junctions by chalcopyrite (light grey). Gressli. Ord. refl. light. Width of field: 1.25 mm. FIG. 8 (*lower right*). Heavily fractured pyrite (white) infilled and replaced by chalcopyrite (light grey) and sphalerite (dark grey). Gressli. Ord. refl. light. Width of field: 0.5 mm.

Other features indicative of metablastic growth of the pyrite granules, observable in areas with higher matrix to pyrite ratios, include rounded inclusions (chadacrysts) of matrix minerals, dominantly sphalerite (Fig. 6) as well as caries-like 'growth embayments' along their peripheries.

Both the poikilitic inclusions and the embayments show, to varying degrees, the fine-grained, emulsion-like texture between sphalerite and copper- and iron sulphides usually referred to as 'chalcopyrite disease' (Barton, 1978; Barton and Bethke, 1987).

The above-mentioned textural evidence implies that the Gressli pyrite underwent a metamorphic recrystallisation, probably under prograde conditions. Arguably it did so in a matrix of varying abundance of sphalerite, lesser chalcopyrite and in some restricted zones, pyrrhotite. It is not easy to assess how much non-sulphide matrix was present during the recrystallisation of the ore.

The prograde metamorphic textures of the ore have been overprinted to a considerable extent by textures due to deformation, but especially, to later (possibly retrograde) mobilisation and replacement phenomena. These seemingly involved both the matrix sulphides and the quartz gangue. It is the predominance of these latter mobilisation–replacement textures that makes the economically-insignificant pod of sulphides at Gressli so interesting to an ore petrographer.

Mobilisation and replacement features — matrix sulphides. The matrix sulphides, chalcopyrite and sphalerite have moved, in considerable proportions with respect to the metablastic pyrite grains. This is indicated by two main textural features, involving both the foam-textured pyrite and individual subhedral pyrite grains.

In the case of the former, the triple junction grain boundaries appear to have opened up, either by tectonic deformation or by fluid-pressure, allowing the components of chalcopyrite to move in between the pyrite grains and often replace them to varying degrees (Fig. 7).

However the more striking textural evidence of matrix sulphide mobilisation is seen in many of the highly fractured individual pyrite metablasts, where both chalcopyrite and sphalerite, or their components, have moved from the matrix into the fractures and have replaced to varying degrees, not only the fracture walls, but the outer edges of the pyrite grains.

These effects are more numerous and striking than seems to be the general case with metamorphosed Scandinavian Caledonian sulphides. Furthermore there seems to be a systematic relative behaviour as between chalcopyrite and sphalerite, i.e. and order of mobilisation with respect to the pyrite.

The often highly fragmented pyrite grains may be 'invaded' and partly replaced by either of the two matrix sulphides, depending, it seems, on their relative preponderance in a particular microvolume of the ore (e.g. Fig. 8) But quite frequently both matrix sulphides have moved into the pyrite fractures, always, it seems, such that chalcopyrite preceded sphalerite (Fig. 9). This apparent relative order of mobilisation—or mobility—would seem to agree with general orders of metamorphic mobility of sulphide minerals given by several workers in this field (Vokes, 1971; Marshall and Gilligan, 1987; Gilligan and Marshall; 1987—see above).

Not only does sphalerite appear to have 'followed' chalcopyrite into fractures in pyrite as shown in Fig. 9, but it often appears in the centres of composite fracture-fillings (Fig. 10), implying that these may have been reopened after the formation of the initial chalcopyrite filling.

In many instances, the chalcopyrite components, moving along fractures—or incipient fractures—in the pyrite, have come into contact with the rounded, poikilitic inclusions of sphalerite which were enclosed in the iron disulphide during its prograde growth. As seen in Fig. 11, the invading chalcopyrite has replaced, or at least corroded the outer rims or edges of the sphalerite inclusions. This process *may* have led to the formation of the 'chalcopyrite disease' texture observed in several of the inclusions, though, since this texture also occurs in grains of matrix sphalerite, the evidence is not conclusive. So far we have not been able to identify mobilised sphalerite in contact with the 'older' sphalerite of the poikilitic inclusions.

The above presented evidence of unusual matrix sulphide mobility at a late metamorphic stage is, as mentioned, one feature that makes the Gressli textures of especial interest in the context of metamorphosed Caledonian ores. However, this does not seem to be the whole story of mobilisation and replacement shown by the ore. Relations between all the major sulphides and much of the predominantly quartz gangue seem also to be interpretable in terms of mobilisation and replacement.

Quartz-sulphide textural relations Quartz occurs throughout the massive ore at Gressli in the form of irregular patches of variable size (mm to cm) and frequency (Fig. 12), though none has been observed in the form of veins or other structurally-controlled forms. Normally the amount of such quartz observed is of the order of 10% by volume. However in narrow zones near
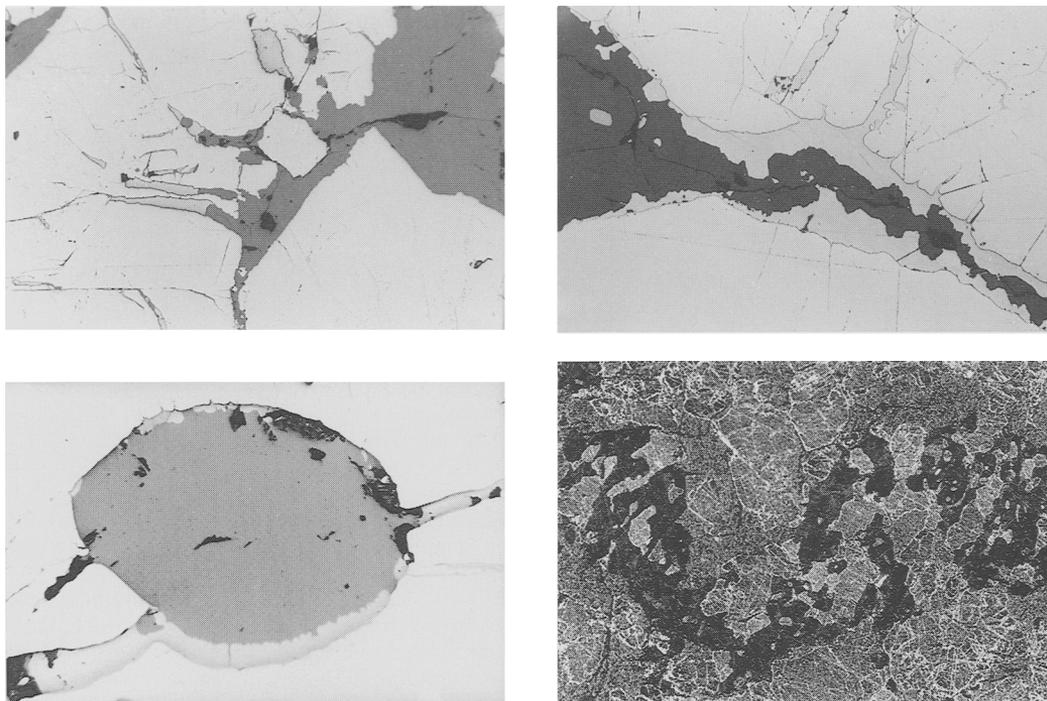
FIGS 9–12. FIG. 9 (*upper left*). Openings in heavily fractured pyrite infilled with matrix sulphides; sphalerite (dark grey) apparently following chalcopyrite (light grey). Gressli. Ord. refl. light. Width of field: 1.25 mm. FIG. 10 (*upper right*) Sphalerite (dark grey) and chalcopyrite (light grey) as composite filling of fractures in pyrite (white). Sphalerite appears to be emplaced later than the chalcopyrite. Gressli. Ord. refl. light. Oil immersion. Width of field: 0.5 mm. FIG. 11 (*lower left*). Chadacryst of sphalerite (dark grey) in pyrite oikocryst (white) invaded and partly replaced by mobilised chalcopyrite (light grey). Gressli. Ord. refl. light. Width of field: 0.625 mm. FIG. 12 (*lower right*). Patch of replacive quartz (dark) in pyrite-sphalerite ore. Polished slab of Gressli ore. Oblique incident light. Width of field: 9 mm.

the ore walls, and occasionally within the ore body, quartz is the dominant mineral and the rock may be described as a quartz–pyrite–mica schist.

Of particular interest in the present context is abundant microscopical evidence that the quartz has actively replaced all three of the major sulphides in the ore, pyrite, chalcopyrite and sphalerite. The introduction, or mobilisation, of quartz must therefore have taken place at a later stage than the veining and replacement of the pyrite by the matrix sulphides already described. Some of the various forms of quartz replacement textures are illustrated in Figs. 13 to 15.

In Fig. 13, a replacement residual of sphalerite, which itself includes a residual of pyrite, lies at the centre of a patch of quartz which has replaced the same sulphides around its borders.

In Fig. 14 an originally poikiloblastic pyrite grain has been veined and replaced by both chalcopyrite and sphalerite. All three sulphides have been later surrounded and replaced by

quartz, parts of which still retain numerous, irregular replacement residuals of the sulphides.

Fig. 15 illustrates the effect of quartz replacement in an area of foam-textured pyrite. Most of the earlier surrounding sulphides have been replaced, but small residuals of chalcopyrite are still visible at places between the pryrite grains.

Discussion

The textural evidence presented in this paper indicates considerable mobility of the components of chalcopyrite, sphalerite and quartz within the metamorphosed pyritic sulphide body at Gressli at periods subsequent to the main prograde recrystallisation of the ore. (Whether these periods could be said to include truly retrograde conditions or not, will not be taken up here.)

The matrix sulphides first veined and replaced pyrite grains that had been fractured either by
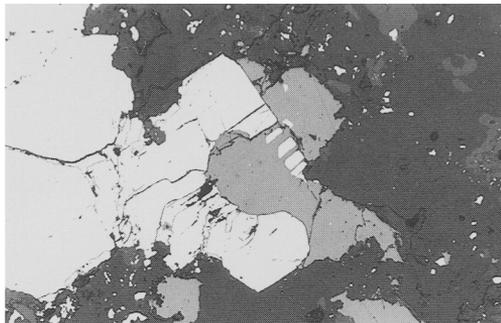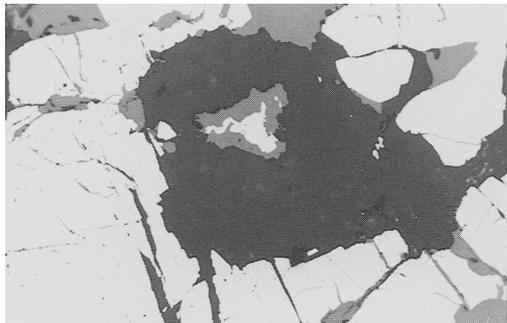
FIGS 13 and 14. FIG. 13 (*left*). Quartz (dark) replacing sphalerite (grey) and invading pyrite (white). Sphalerite residual in the quartz encloses residual of pyrite. Gressli. Ord. refl. light. Width of field: 1.2 mm. FIG. 14 (*right*). Poikiloblastic pyrite grain (white) partly surrounded and replaced by sphalerite (grey) and chalcopyrite (light grey). Late quartz (dark) replacing sulphides. Gressli. Ord. refl. light. Width of field: 1.25 mm.
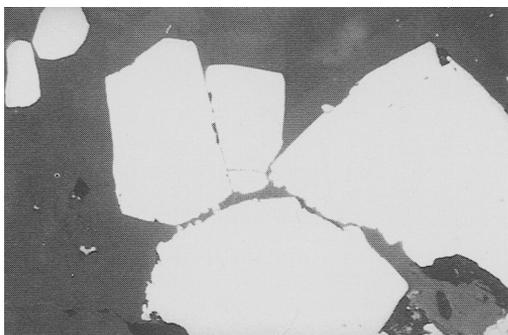
FIG. 15. Four pyrite grains (white) forming part of a foam-textured aggregate, which has been mostly destroyed (replaced) by quartz (dark). Gressli. Ord. refl. light. Width of field: 0.5 mm.

tectonic deformation (cataclasis) or by pore fluid pressure, or a combination of both. The heavy replacement of the pyrite indicated by the textures would seem to favour the mobilisation of the matrix sulphides in a fluid phase, though solid-state (creep, flow) mobilization cannot be entirely ruled out. This mobilisation is considered to have occurred entirely within the sulphide mass; nothing suggests that the chalcopyrite and sphalerite (or their components) have been introduced from outside.

As regards the quartz, the case for fluid-phase mobilisation is much more convincing; quartz is not a mineral normally considered amenable to solid-state mobilisation under metamorphic conditions. The SiO_2-bearing fluids responsible appear to have permeated the massive ore without recourse to obvious structural permeability, though this may have been obliterated by later metamorphism. Using the terminology of Hobbs (1987) we may be dealing here with a case

of chemically-enhanced permeability, the fluids enlarging the porosity of the massive ore by the replacement processes so well indicated by the ore textures.

In the case of the quartz, an origin totally within the original ore mass is more debatable than in the case of the matrix sulphides. It is possible that it represents metahydrothermally transported SiO_2 from outside the acutual ore-mass that has permeated the metamorphosed sulphides.

The origin and transport path(s) of the postulated metahydrothemal solutions responsible for the mobilisation of sulphides and quartz in the Gressli, and similar ores (see below) are somewhat conjectural at the present state of research on the area. Cox *et al.* (1987) and Marshall and Gilligan (1987) emphasise the role of stress-controlled dissolution (pressure solution) of sulphides and other minerals and the transport of the dissolved species over varying distances. Such mobilised material may be deposited in grain-scale microfractures or as large vein systems and may replace already existing phases. Depositional sites may be close to, or distantly removed from, source sites. In the Gressli example, the chalcopyrite and sphalerite occurring in fractures in pyrite and along triple junction boundaries, have obviously been deposited close to the site of their original dissolution. It does not seem possible to be so categorical about the source of the quartz-bearing solutions or about the distances between this and the replacement-depositional sites in the Gressli sulphides.

Directions of future research

Some of the most important questions yet to be answered concern the nature of the fluids which

have effected the above-described mobilisation and replacement in the Gressli ore. We have as yet no fluid inclusion or isotopic data with which to determine their chemistry, pressure and temperature, or provenance. We are postulating that they are metahydrothermal in origin since we have no evidence to support fluids of any other type. However, the timing of the events is difficult as the deposition of SiO_2, for example, had to be such that it replaced metamorphically recrystallised pyrite, yet itself shows the effects of deformation, e.g. in the form of strain extinction.

Attention will also have to be paid to the metamorphic history of the host-rocks, in particular to try to assess the significance of the early contact-metamorphic event.

It is also necesary to investigate (or re-investigate) the textures of other metamorphosed Caledonian stratabound sulphides to see if mobilisation/replacement textures similar to those at Gressli are present. Obvious candidates for such investigations are highly recrystallised and deformed deposits such as Bleikvassli (Vokes, 1963) and Mofjell (Saager, 1966) and others in the northern Caledonides.

Of potentially greater Caledonian ore-genetical significance, however, is the great similarity between the replacement textures in the Gressli ore and those in apparently unmetamorphosed sea-floor sulphides at the Høydal deposit, in the Løkken ophiolite, southwest of Trondheim.

Textures at Høydal, described by Grenne and Vokes (1990) seem to be almost indentical with those discussed in the present paper. Both deposits show strong evidence of replacement of pyrite by both chalcopyrite and sphalerite, followed by the dissolution of sulphides and the concomitant or subsequent deposition of quartz, by circulating fluids. One of the deposits is highly metamporphosed; the other still retains sea-floor textures very little modified by later events. However, it may be that the fluids involved in both cases could have belonged to the general realm of metamorphism, though at distinctly different stages. Grenne and Vokes (1990) assigned the deposition of quartz at Høydal (and Løkken) to the latest stage of sea-floor deposition, and to what they termed the post-seafloor stage following or accompanying tensional ('pull-apart') and other fracturing of brittle sulphides. This last stage could in effect have been the stage of early generation of metamorphic fluids in this low-metamorphic part of the central Caledonides. However, the replacement of the Høydal pyrite by chalcopyrite and sphalerite is difficult, at the present state of knowledge, to assign to metahydrothermal solutions. Further research is necessary in order to determine the true nature of the fluids involved at both Høydal and Gressli, as well as in other relevant Caledonian sulphide ores.

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