Deformation and metamorphism of massive sulphides at Sulitjelma, Norway

NIGEL J. COOK

Mineralogisches Institut der Universität Würzburg, Am Hubland, 8700 Würzburg, Germany

CHRISTOPHER HALLS

Mining Geology, Department of Geology, Imperial College of Science and Technology, London SW7 2BP, U.K.

AND

ALAN P. BOYLE

Department of Earth Sciences, University of Liverpool, Brownlow Street, Liverpool L69 3BX, U.K.

Abstract

The copper-bearing stratabound pyritic massive sulphide bodies contained in metamorphosed basic eruptives of Ordovician age at Sulitjelma in Nordland County, Norway, form one of the important fields of sulphide mineralisation within the Köli Nappe Complex. The sulphide bodies and their enclosing rocks were subject to successive stages of penetrative deformation and recrystallisation during the cycle of metamorphism and tectonic transport caused by the Scandian Orogeny. Textures within the ores and the immediate envelope of schists show that strain was focused along the mineralised horizons. The marked contrast in competence between the massive pyritic sulphides and their envelopes of alteration composed dominantly of phyllosilicates, and the metasediments of the overlying Furulund Group, led to the formation of macroscale fold and shear structures. On the meso- to microscale, a variety of textures have been formed within the pyrite–pyrrhotite–chalcopyrite–sphalerite sulphide rocks as a result of strain and recrystallisation. Variations in pyrite : pyrrhotite ratios and in the texture and proportions of associated gangue minerals evidently governed the strength and ductility of the sulphide rocks so that the same sulphide mineral can behave differently, displaying different textures in different matrices. In massive pyritic samples there is evidence of evolution towards textural equilibrium by recrystallisation, grain growth and annealment during the prograde part of the metamorphic cycle. Later, brittle deformation was superimposed on these early fabrics and the textural evidence is clearly preserved. By comparing published data on the brittle-ductile transformation boundaries of sulphide minerals with the conditions governing metamorphism at Sulitjelma, it is concluded that most of the brittle deformation in the sulphides took place during or after D_3 under retrograde greenschist conditions. Grain growth of pyrite in matrices of more ductile sulphides during the prograde and early retrograde stages of metamorphism produced the coarse metablastic textures for which Sulitjelma is well-known. In some zones of high resolved shear stress, pyrite shows ductile behaviour which could be explained by a dislocation flow mechanism operating at conditions close to the metamorphic peak. In those horizons in which pyrrhotite is the dominant iron sulphide, the contrast in ductility between silicates, pyrite and pyrrhotite has led to the development of spectacular tectonoclastic textures in which fragments of wall rock have been broken, deformed, rolled and rotated within the ductile pyrrhotite matrix.

KEYWORDS: deformation, metamorphism, sulphides, Sulitjelma, Norway.

Introduction

AS a result of many geological and mineralogical investigations of pyritic massive sulphide deposits undertaken during the past 50 years, it has been recognised that the assemblages of sulphide minerals which form these deposits have undergone the same history of deformation and meta-

Mineralogical Magazine, March 1993, Vol. 57, pp. 67–81

morphism as the host rocks which enclose them (McDonald, 1967; Vokes, 1969; Mookherjee, 1976, and references therein). In spite of this, the mechanisms governing the deformation, metamorphism and texture, until recently, have received relatively little attention, whereas there is a wealth of published information on deformation and metamorphism of silicate minerals and rocks (see, for example, the review by Brodie and Rutter, 1985). Nevertheless, most massive sulphide deposits preserved in orogenic belts display post-genetic features clearly attributable to mechanical and chemical effects caused by later metamorphism and deformation. Cataclasis, plasticity and diffusive processes of mass transfer have all been recognised as playing a part in the deformation, recrystallisation and remobilisation of sulphide minerals subjected to tectonic stress and metamorphism (e.g. Kalliokoski, 1965; McClay, 1982; Craig, 1983; Marshall and Gilligan, 1987).

The massive pyritic Cu–(Zn) sulphide deposits of Sulitjelma, northern Norway, are regarded as a classic example of stratabound volcanogenic exhalative mineralisation contained within the regionally metamorphosed allochthon of the Scandinavian Caledonides (Vokes, 1976; Frietsch *et al.*, 1979; Stephens *et al.*, 1984). Numerous textural features within the sulphide deposits have been ascribed by earlier investigators to the effects of metamorphism (e.g. Berg, 1927; Carstens, 1944; Krause, 1956). The Sulitjelma deposits show a range of macroscopic and microscopic textures which are also observed in metamorphosed sulphide deposits elsewhere. Many of these textures were partly described in the earlier works by Berg, Carstens and others, however we believe it is useful to supplement and bring these observations up to date in the context of recently completed studies of the history of deformation and metamorphism in the Sulitjelma region. These studies provide a well-defined P-T framework within which the evolution of the spectacular textures of metamorphic recrystallisation and deformation observed in the Sulitjelma sulphides can be discussed. The geological setting of the sulphide deposits within the sequence of rocks forming the Sulitjelma area will be summarised first.

Geological setting

Host rocks. Current views on the geological setting and tectonic evolution of the Sulitjelma region can be found in Boyle *et al.*(1985), Boyle (1980, 1987, 1989), Stephens (1986), Burton *et al.* (1989), and Pedersen *et al.* (1991). A map of the region compiled by Kollung (1989, 1990) at a scale of 1:100000 has recently been published. Earlier studies of the geological evolution of the Sulitjelma area are those by Vogt (1927), Kautsky (1953), Nicholson and Rutland (1969) and Wilson (1973). The Sulitjelma region contains three major rock associations lying within the Köli Nappe Complex of the Upper Allochthon of the Central Scandinavian Caledonides (Stephens *et al.*, 1985). These include a major metabasic igneous complex, the Sulitjelma ophiolite (Boyle, 1980), the plutonic parts of which intrude an older unit of predominantly metasedimentary rocks, the Skaiti Supergroup (Boyle *et al.*, 1985; Kollung, 1989, 1990). This association is stratigraphically overlain by a sequence of metasediments and calc-alkaline volcanic rocks, the Furulund and Sjønstå Groups (Boyle, 1989). The bodies of sulphide mineralisation are concentrated at the junction between the Sulitjelma Ophiolite and the cover rocks of the Furulund Group. The sediments of the upper part of the Furulund Group contain fossils of Ordovician–Silurian age near the contact with the Sjønstå Group (Vogt, 1927; Wilson, 1971), while a gabbro pegmatite within the ophiolite has recently been dated at 437 ± 2 Ma using U/Pb zircon/titanite methods (Pedersen *et al.*, 1991). The three rock associations are interpreted as having formed in an ensialic marginal basin during the Ordovician. In this setting, the Skaiti Supergroup represents part of the rifted continental crust and the Sulitjelma Ophiolite the floor of the oceanic basin. The Furulund and Sjønstå Groups form part of the sedimentary infill of the marginal basin (Boyle, 1989; Pedersen *et al.*, 1991). Earlier workers (e.g. Kautsky, 1953; Stephens *et al.*, 1985; Stephens, 1986) have preferred a thrust-stack model in which the lithotectonic components of the Sulitjelma sequence are genetically unrelated, having been transported tectonically from separate environments and superimposed.

The cycle of events during the Scandian collision led to compression and closure of the marginal basin (D_1) and emplacement of the basin sequence onto the Baltic Shield in the form of a large-scale fold nappe, the Sulitjelma Fold-Nappe (D_2). During this process, inversion of the stratigraphy in the lower limb of the nappe took place so that the sedimentary cover sequence now underlies the ophiolite at the present level of exposure (Boyle, 1987). The deformation (D_2) which accompanied nappe emplacement caused strong simple-shear resulting in the development of sheath folds, rotation of porphyroblasts in matrix, and overturning of the metamorphic zones which range from biotite to kyanite grade in a broadly Barrovian sequence (Boyle *et al.*, 1985; Boyle, 1987; Burton *et al.*, 1989). All of the significant orebodies lie within the garnet isograd or rocks of higher grade. At the garnet isograd, which lies within the Furulund Group to the east of the orebodies, *PT* conditions have been determined as 480 °C and 5 kbar. Temperature and pressure rise westwards within the Furulund Group reaching about 620 °C and 9–10 kbar to the west of the orebodies in Sjønstådalen (Burton *et al.*, 1989; Boyle and Westhead, 1992). 'Peak' metamorphic conditions were attained during or just after D_2. Burton and O'Nions (1992) have determined and radiometrically dated part of the *PTt* path for the Skaiti Supergroup. Using garnets from graphite-bearing and graphite-free layers in a single hand specimen, they have determined the pressures and temperatures prevailing during successive stages of garnet growth. Initial growth under conditions of low a_{H2O} in the graphite-bearing layers took place at 540 ± 18 °C and 5.2 ± 0.5 kbar. In the graphite-free layers, initial growth took place at 540 ± 16 °C and 8.0 ± 1.0 kbar, while later growth of inclusion-free garnet rims in equilibrium with the graphite-free matrix took place at 544 ± 16 °C and 7 ± 1.0 kbar. Ages of the garnets from the graphite-bearing layers determined using the $^{147}Sm–^{143}Nd$ method and the $^{238}U–^{206}Pb$ method are indistinguishable. For the garnets in the graphitic layers, the ages obtained were 434.1 ± 1.2 Ma and 433.9 ± 1.0 Ma respectively, while ages for inclusion-free garnet rims from the graphite-free layers gave 424.6 ± 1.2 Ma and 423.4 ± 1.7 Ma. Subsequently, Burton and O'Nions (1992) have determined *PTt* data for a garnet-bearing assemblage at the garnet isograd in the Furulund Group. The $^{147}Sm–^{143}Nd$ and $^{238}U–^{206}Pb$ ages obtained are 434.1 ± 1.2 Ma and 433.9 ± 1.0 Ma respectively, with a corresponding temperature of 458 ± 20 °C and a pressure of 6.5 ± 1.0 kbar. These dates enable the time of emplacement of the Sulitjelma Fold Nappe to be constrained and the thermobarometric data indicate that heating took place at a rate of 8 °C Ma^{-1} and burial at a rate of about 0.8 km Ma^{-1}.

Uplift and exhumation of the Sulitjelma Fold Nappe was accompanied by the widespread formation of stacked crenulation folds and kink bands, as well as by the formation of large-scale upright folds, often with cores of Precambrian basement gneiss. Available Rb–Sr data suggest an average rate of cooling in the order of 4 °C Ma^{-1} for some 37 Ma after 'peak' metamorphic conditions (Burton and O'Nions, 1991). These studies show that the sulphide bodies were subject to relatively rapid burial and heating during D_1, followed by further heating and partial exhumation during D_2 when strong penetrative simple shear accompanied the formation and emplacement of the Sulitjelma Fold Nappe. It was at this stage that 'peak' conditions of metamorphism at temperatures of 480 °C and pressures of 5–10 kbar were reached. Following this, the Sulitjelma sequence was subject to slow uplift, exhumation and cooling which was accompanied by the non-penetrative deformation of D_3.

Sulphide bodies. The geology of the Sulitjelma orefield has recently been described by Cook *et al.* (1990) who have classified the Sulitjelma sulphide deposits as belonging to the Cyprus type. Geological evidence shows that they were formed at or near the top of the Sulitjelma Ophiolite by volcanic-exhalative processes. The orefield contains more than 20 individual sulphide deposits (Fig. 1) which together formed a resource of some 35 million tonnes with an average grade of 1.82% Cu and 0.40% Zn. Mining of the deposits ceased in 1991 after more than 100 years of continuous production because of the exhaustion of economic reserves. The deposits are tabular in shape, reaching 1200 m in length and 300 m in width, and are from 0.5 to several metres thick. All of the deposits show an axis of elongation. The deposits to the north of Langvatn in the northern field (Fig. 1) show elongation in a NW–SE direction which is parallel to the D_2 stretching lineation in the host rocks (Vogt, 1952; Kautsky, 1953; Wilson, 1973; Boyle, 1987). Cook (1987) has suggested that this elongation may also reflect the primary morphology of the sulphide bodies which could have been formed in parallel trough-like features on the sea floor related to the fracture systems which fed the hydrothermal system.

Each orebody has an associated zone of intense hydrothermal alteration along its lower stratigraphic contact. This alteration predates the later effects of dynamothermal metamorphism but the changes which took place at this early stage are reflected in the subsequent metamorphic assemblages and patterns of deformation which characterise these zones. As a result of folding and shearing within the Sulitjelma Fold Nappe, the alteration zones are now found both subjacent and superjacent to the sulphide bodies. These zones are marked by a distinctly retrograde greenschist mineral assemblage in which chlorite, biotite and albite are the chief silicate minerals. Cook (1987) and Cook *et al.* (1990) attribute this mineralogy, in part, to the modification of the original chemistry of the footwall rocks by hydrothermal metasomatism which accompanied the exhalative process on the Ordovician sea floor. Minerals more typical of the garnet grade in

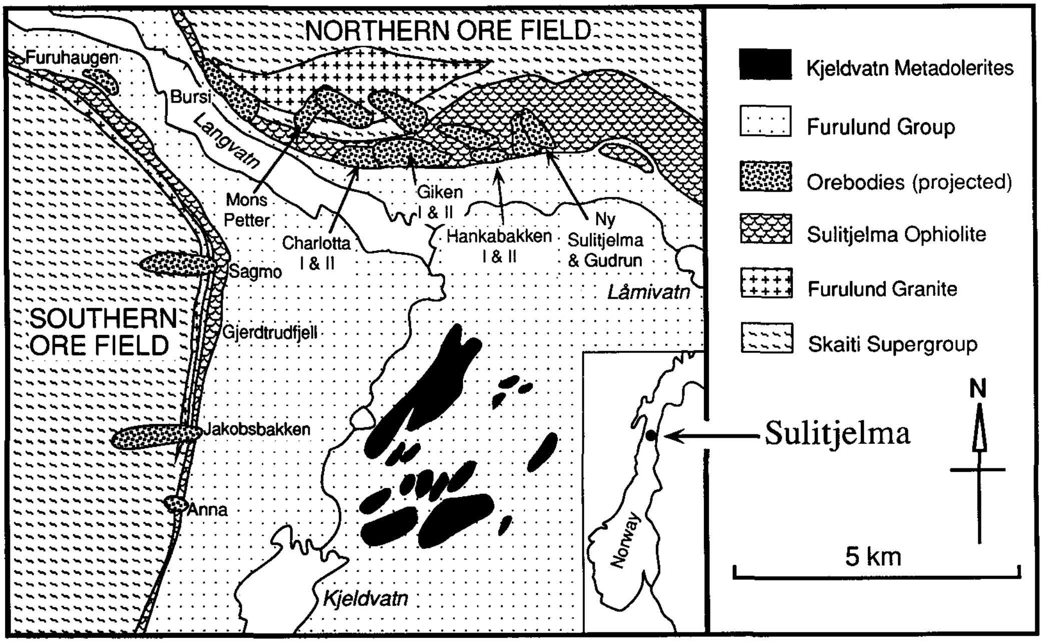

FIG. 1. Simplified geological map of the Sulitjelma area showing the location of the principal massive sulphide deposits.

amphibolite facies are largely absent from these zones. The hydrous mineralogy of the metamorphosed alteration zones suggests that they were particularly receptive to fluids during the retrograde stages of metamorphic evolution. The temperatures at which this metamorphism occurred were probably comparable with those at which the original sulphide deposition and hydrothermal alteration took place so it is reasonable to expect that similar mineralogies would be produced, though the later metamorphic assemblage shows foliated and schistose textures because of the tectonic stresses.

The structual evolution of the field enclosing the deposits has been largely determined by the response of these zones of alteration to metamorphism and to the successive stages of penetrative deformation which have affected the Sulitjelma sequence. In comparison to the metapelites of the Furulund Group, the alteration zones show incompetent behaviour during deformation. Strain has been focussed within the mineralised and altered zones because of the ductile behaviour of the phyllosilicates and some sulphides. Thus, the mineralised and altered zones take on the character of thrust horizons and where contrasts in rheology occur, tectonoclastic breccias have formed. These are a widespread and characteristic feature of the mineralised sequence at Sulitjelma. Structural and textural evidence shows that during the early prograde and later retrograde stages of the metamorphic cycle, the massive pyritic rocks within the deposits behaved more competently than the silicate alteration zones composed dominantly of chlorite, biotite and sericite and the associated foliated sulphide-phyllosilicate rocks. The progressive deformation, recrystallisation and ordering of the phyllosilicate minerals in the alteration zones during early retrograde metamorphism evidently led to increased permeability and fluid flow during later stages of retrograde metamorphism. The alteration zones then appear to have behaved as conduits for metamorphic fluids, as well as important horizons of shearing and disjunction within the sequence.

Macroscopic features of deformation

The distinct contrast in competence between the sulphide rocks and their phyllosilicate alteration envelopes, and also between the metabasic rocks of the Sulitjelma Ophiolite and the metasediments of the Furulund Group, has given rise to a range of macroscopic features which reflect the different behaviour of these rocks during deformation. Field and underground mapping of the sulphide bodies shows that the mineralised horizon within the Sulitjelma Ophiolite has behaved as a weak zone marked by enhanced shear strain at all stages in the history of deformation. The original morphology of the sulphide bodies has been strongly modified by folding, shearing, flattening and extension which have resulted in tectonic thickening, attenuation and boudinage, features which are observed in all parts of the Sulitjelma orefield.

Fold-controlled features. Folding of the sulphide bodies has given rise to changes in thickness reflecting the bulk strain involved, and also to variations in ore grades which reflect the contrast in ductility between pyrite and the associated copper and zinc sulphides and also the repetition of sulphide stratigraphy in fold hinges. The thickest of the mined sulphide bodies is Mons Petter II which lies in the hinge of a recumbent fold, the geometry of which is consistent with the cap of a D_2 sheath fold. Tight D_1 and D_2 folds within the sulphide lenses have contributed significantly to the tenor of the orebodies locally. Chalcopyrite and other ductile sulphides are significantly enriched in fold hinges. Late D_3 folding also has an effect on the shape of the sulphide bodies, producing large-scale open folds and some development of pinch and swell features.

Shear-controlled features. Shearing at and along the contacts of the sulphide bodies has led to repetition, stacking and excision of the stratigraphy in the mineralised horizon. Evidence for repetition and interruption of the stratigraphy of the mineralised zone in various parts of the Giken II deposit has been given by Cook (1987) and explained as a result of detachment and differential displacement along shear planes. Laznicka (1985) has described similar features from a number of pyritic sulphide deposits in metamorphic terranes worldwide. The effects of shearing on the feeder zone underlying the Giken II deposit has also been described by Cook *et al.* (1990). Coarse-grained segregations of ductile sulphides, chiefly chalcopyrite and pyrrhotite, sometimes described as 'ore pegmatites', are also common within the Giken II deposit and in the other bodies at Sulitjelma (Fig. 2*a*). These have formed as a result of mechanical and chemical remobilisation under differeltial stress. They are of economic significanae because they contain higher concentrations of precious metals which are often associated with Sb minerals (Cook *et al.*, 1990; Cook, 1992). 'Ore pegmatites' are a feature common to many of the massive sulphide deposits in the Norwegian Caledonides, including Bleikvassli (Vokes, 1963) and Joma (Olsen, 1980).

Where contrasts in ductility between sulphides, cherty keratophyre and phyllosilicates coincide with large-scale shearing along the contacts of the sulphide bodies and within the metamorphosed alteration envelopes, spectacular zones of tectonoclastic breccia have formed. Boulders and blocks of cherty keratophyre reaching 25 m in diameter have been tectonically incorporated in the hanging wall of the intensely sheared Sagmo deposit (Fig. 2*b*). Elsewhere, tectonic reworking of keratophyre and wallrocks leads to a variety of breccia textures in the phyllosilicate matrix of the alteration envelope (Fig. 2*c*).

The most graphic example of the effects of shearing and tectonoclastic behaviour within a sulphide horizon is that shown by the zone which crops out in the Gjertrudfell area and extends for several km southwards to Anna mine and beyond. The sulphide zone is between 0.5 and 5 m thick (Fig. 2*d*) and consists of a matrix of pyrrhotite and some chalcopyrite in which are set rounded and rotated fragments of cherty wallrock, quartz and reworked sulphides. The rock has evidently formed as a result of the extreme contrast in ductility between the pyrrhotite-rich sulphide assemblage and the surrounding silicates which have been torn away from the contacts by shearing and incorporated in the sulphide matrix. The texture shows that some tectonic transport has taken place along this horizon and it ranks with other horizons of tectonic breccia elsewhere within the Sulitjelma sequence (cf. Wilson, 1973), though the scale of movement involved is difficult to determine.

In the Sulitjelma orefield a series of late faults cuts through the massive sulphide bodies. Associated with these are quartz-carbonate veins which carry quantities of sulphide, chiefly pyrrhotite and chalcopyrite together with sulphosalt minerals which have probably been remobilised from the adjacent pyritic masses. Masses of anhydrite with subordinate amounts of barite and celestite are also found in veins, segregations and vugs within the phyllosilicate-rich metamorphosed alteration zones beneath the sulphide bodies where they are often intergrown with actinolite, biotite, chlorite, calcite and quartz. These are believed to have crystallised from retrograde fluids concentrated at a late stage within fractures and vugs in the permeable alteration zones. Studies of footwall alteration in massive sulphides from other regions have led to suggestions that silicification plays an important role in decreasing the permeability of the underlying feeder zone. At Sulitjelma, footwall alteration did not lead to silicification and the abundance of sulphate minerals shows that the alteration zone

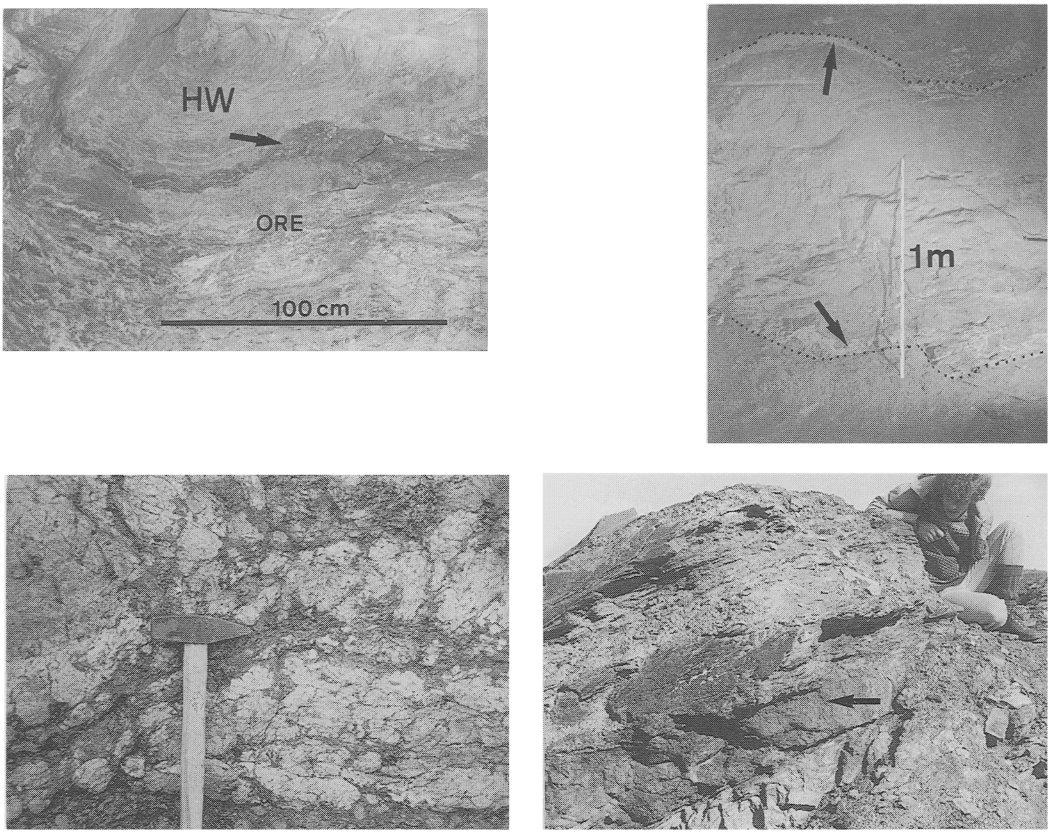

FIG. 2. (A, *top left*). Segregation of ductile sulphides (arrowed) emplaced in the roof of the Giken II deposit, adjacent to the hanging wall (HW). (B, *top right*). Large block of keratophyric material emplaced in the hanging wall of the Sagmo deposit. Note concentrations of chalcopyrite (arrowed) at rims of block. (C, *bottom left*). Breccia of felsic fragments in a chloritic matrix, Surface outcrop, Mons Petter. (D, *bottom right*). Surface outcrop of tectonoclastic sulphides, Anna mine. Horizon of rolled sulphides is 30 cm thick.

behaved as a channel of enhanced permeability during the later stages of metamorphic and structural evolution.

Mineralogy and microscopic features of deformation

The mineralogy of the massive sulphides is dominated by pyrite with which are associated lesser amounts of pyrrhotite, chalcopyrite and sphalerite. Galena and arsenopyrite are minor phases and a wide variety of sulphosalts, antimonides, tellurides and native metals occur in trace quantities (Ramdohr, 1938; Cook, 1987). Pyrrhotite is the main sulphide locally in some areas of footwall dissemination and is the major component of the coarse sulphide segregations produced as a result of tectonic remobilisation. Associated gangue minerals are chiefly chlorite, biotite, albite, titanite, quartz and sericite, with lesser amounts of actinolite, hornblende, spessartine-rich garnet and clinozoisite (Cook *et al.*, 1990). A typical example of chloritic alteration is shown in Fig. 3*a*. Abundant evidence is found in the textures of the alteration envelopes to demonstrate that the retrograde assemblages have formed at the expense of earlier high-grade assemblages showing clear signs of deformation. Differences in sulphide and silicate proportions and mineralogy have resulted in wide variations in the tectonic behaviour of the different rocks within the mineralised horizon. This has also meant that the same sulphide mineral can show different patterns of growth and deformation in different matrices. This is the case with pyrite at Sulitjelma. However, the refractory behaviour of pyrite during metamorphism distinguishes it from the associated sulphides, chalcopyrite, pyrrho-

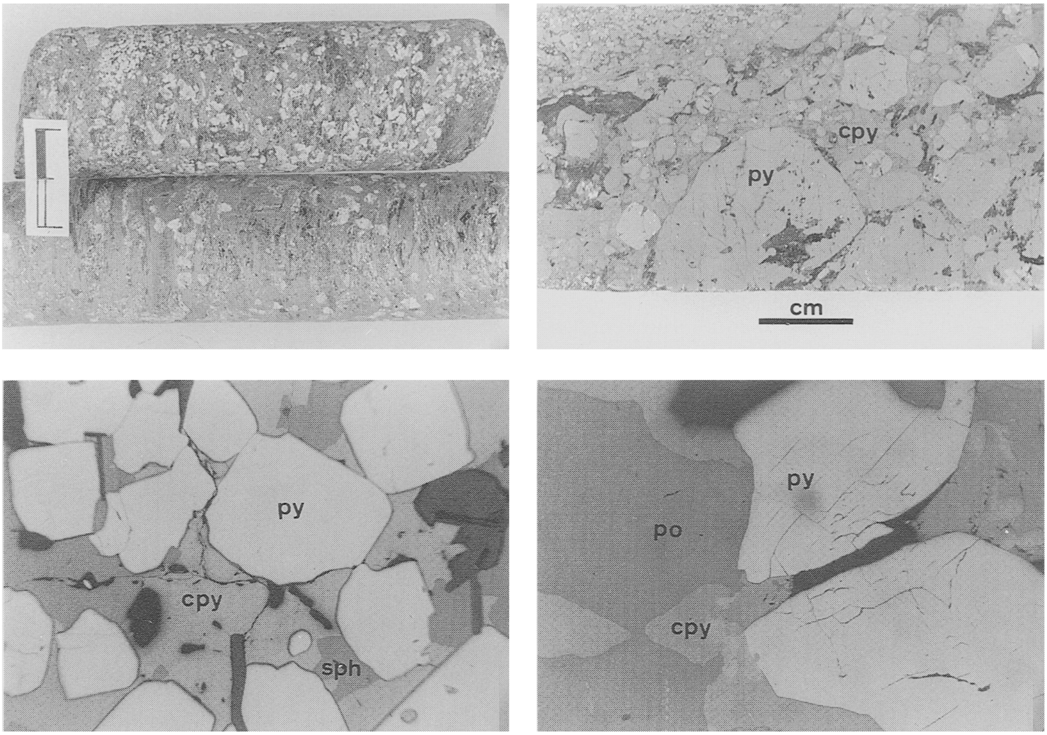

FIG. 3. (A, *top left*). Typical appearance of chloritic alteration; chlorite (light grey)—biotite (dark) and albite (white) porphyroblasts, from drillcore intersection of Giken II horizon, west of main deposit. (B, *top right*). Coarse-grained sulphide rock, with large porphyroblasts of pyrite (py) set in a matrix of chalcopyrite (cpy). Dark gangue is biotite. Note the rounded form of the pyrite porphyroblasts. (C, *bottom left*). Similar fabric to Fig. 3*b* in finer-grained rock, shown in reflected light. py: pyrite, cpy: chalcopyrite, sph: sphalerite. Width of field 0.2 cm. (D, *bottom right*). Curved grain boundary between pyrite porphyroblast (py) and chalcopyrite (cpy)–pyrrhotite (po) matrix.

tite, sphalerite and galena which readily recrystallise. A much wider range of textures is preserved in pyrite which can therefore provide valuable evidence concerning the stages by which the final textural configuration of sulphides has been reached. Because pyrite is the most abundant sulphide and provides the most complete record of the evolution of metamorphic and tectonic textures in the Sulitjelma orebodies, the following account of microscopic textures is chiefly concerned with features observed in pyrite. For purposes of description the textures are classified in several categories. These are primary/early growth textures, equilibrium textures, textures produced by ductile deformation, textures produced by brittle deformation and sulphide–silicate intergrowth textures. It must be emphasised that pyrite from a given sample often shows more than one textural feature. For instance, late cataclastic features are often superimposed on early metablastic aggregates.

Primary/early textures. Because the pyritic ores have been metamorphosed to amphibolite grade and recrystallisation evidently took place under dynamic conditions near the peak of the metamorphic cycle, primary hydrothermal growth textures are not generally preserved. However, some of the larger pyrite porphyroblasts have grown around corroded cores which are similar to those described by Craig and Vokes (1993). These probably formed during the prograde part of the metamorphic cycle. The superimposition of a later retrograde generation of fine-grained pyrite around these is interpreted by Craig and Vokes as the result of sulphur release from pyrrhotite in a buffered pyrite–pyrrhotite assemblage. The effects of these phenomena on textures in the Sulitjelma sulphide deposits require further investigation.

Equilibrium textures. Within many of the massive sulphide rocks, metablastic growth of pyrite has taken place in a matrix of the more ductile sulphides, chalcopyrite, pyrrhotite and sphalerite (Figs. 3*b* and *c*). In the more pyritic massive sulphides, recrystallisation and grain growth during metamorphism has led to impingement of pyrite grain boundaries and the development of annealed mosaic textures with 120° triple junctions, sometimes with grains of chalcopyrite, pyrrhotite or galena confined in the interstices at the triple point. Pyrite–chalcopyrite grain boundaries are often curved (Fig. 3*d*). This is a consequence of the geometrical constraints imposed on heterogeneous polycrystalline aggregates as they recrystallise to equilibrium configurations, minimising the free energy associated with the phase and grain boundaries (Smith, 1948). Under such circumstances, pyrite morphology is clearly dependent on the extent to which grain growth can proceed uninterrupted in ductile matrices. Euhedral pyrite porphyroblasts are common within the metamorphosed chloritic alteration envelopes, though growth habits are frequently tabular, reflecting anisotropy in the stress field and the diffusion rates in the directions parallel to and normal to the foliation.

Textures produced by ductile deformation. The spectacular rounded and distorted pyrite porphyroblasts found within the sulphide rocks and the metamorphosed chloritic alteration envelope of the Sulitjelma orebodies were described by Berg (1927) and by Carstens (1944). These pyrites can reach up to 10 cm in diameter (Fig. 4*a*) and are distinguished by their curved crystal faces (Fig. 4*b*). In the sulphide rocks they are surrounded by matrices of ductile pyrrhotite and/or chalcopyrite. Almost spherical pyrite porphyroblasts of similar size are also found in the sulphide bodies at Sulitjelma. These have not been seen *in situ* by the present authors but are preserved in various collections. In these cases, the matrix is also one of the ductile sulphides (usually chalcopyrite) and the porphyroblasts have polished surfaces which appear to have been produced by some mechanism associated with rotation of the porphyroblast within the matrix during the

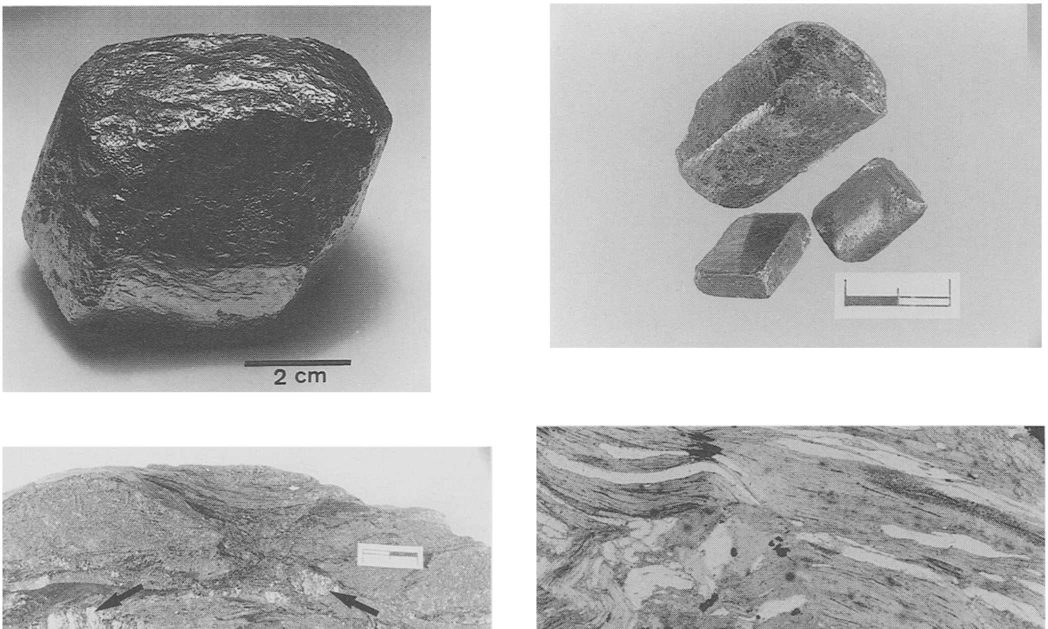

FIG. 4. (A, *top left*). Large rounded pyrite porphyroblast, Giken II deposit. (B, *top right*). Rounded pyrite porphyroblasts, Giken II deposit, showing rounded crystal faces. Scale 2 cm. (C, *bottom left*). Pyrite crystals (arrowed) elongated by (probable) pressure solution within a chlorite–biotite schist, Giken II deposit. (D, *bottom right*). Detail of deformed fragment from the above tectonoclastic sulphide, transmitted light. Width of field 1.0 cm.

'durchbewegung' which accompanied heterogeneous simple shear of the mineralised horizons during D_2. Ramdohr (1960, p. 70) ascribed the rounding of the faces on such equant porphyroblasts to 'inhibited growth', noting that the degree of rounding was related to the dominant crystal forms, those with (210) being most susceptible. In further discussion of porphyroblastic phenomena, Ramdohr (1960, p. 735) concludes that the growth of the large pyrite porphyroblasts at Sulitjelma must have taken place after deformation because evidence of cataclasis is lacking. It has since been demonstrated that large pyrite porphyroblasts, like idioblastic silicates, can grow under metamorphic conditions while deformation is occurring. Curved trails of actinolite and other silicate inclusions record the rotation of these porphyroblasts during deformation (Carstens, 1944), a phenomenon since described from localities outside Norway by Brooker *et al.* (1987), Craig (1990), Craig and Vokes (1993). Craig *et al.* (1991) have described spectacular sigmoid inclusion trails in pyrites from Ducktown, Tennessee, and recognise this as evidence of growth simultaneous with rotation in a sheared matrix of pyrrhotite and silicates. At Sulitjelma, the growth of porphyroblasts was accommodated both by phyllosilicates and the ductile sulphide phases.

In addition to 'rounding', many of the large pyrite porphyroblasts at Sulitjelma show distortion of interfacial relationships which can only be ascribed to strain under the influence of simple shear (Figs. 4*a* and *b*). This has been achieved without fracturing or cataclasis and therefore some mechanism of crystal plasticity must be reponsible for the deformation observed. Mookherjee (1971), no doubt prompted by the comments of Buerger (1928), suggested that plastic deformation of pyrite should be possible under some geological conditions because there were many examples of deformed pyrites, the occurrence of which would be hard to explain in any other way. The distorted porphyroblasts at Sulitjelma support this contention. Brittle fracturing and cataclasis was long considered the only mechanism by which pyrite would deform under geological conditions (Adams, 1910; Veit, 1922; Buerger, 1928; Graf and Skinner, 1970; Atkinson, 1975). However, Graf *et al.* (1981) recognised that it was possible for plastic strain to occur in pyrite prior to brittle failure, and Cox *et al.* (1981) showed that thermally activated dislocation flow mechanisms (dislocation creep, dislocation glide) would allow plastic deformation in pyrite to take place at temperatures of 500–700 °C under a range of stress conditions feasible in a metamorphic environment (see also McClay and Ellis, 1983; Cox, 1987; Siemes *et al.*, 1991). Couderc *et al.* (1980) and Graf *et al.* (1981) have confirmed the occurrence of dislocation flow mechanisms in natural pyrites using transmission electron microscopy.

At temperatures below 450 °C dislocation flow plays little part in deformation and McClay and Ellis (1983) have confirmed that in rocks of lower metamorphic grade, pressure solution and cataclasis are the dominant processes by which pyrite is deformed. Pressure solution and new growth take place by a diffusive process of mass transfer in the fluid phase surrounding the pyrite in response to stress gradients around the grains (see Rutter, 1976; Beach, 1979). During the retrograde stages of metamorphism in the Sulitjelma sulphide bodies, there is evidence that pressure solution was important. Elongation of pyrite by pressure solution along the surfaces parallel to foliation is common, particularly in banded samples dominated by chlorite and biotite (Fig. 4*c*). Aspects ratios of 1.5 : 1, or rarely 2 : 1, are produced by this process.

The sulphide horizon in the Gjertrudfjell area of the southern orefield, described by Cook *et al.* (1990), provides an example of the spectacular tectonoclastic textures produced as a result of contrasts in rheology between ductile sulphide and more competent silicates. In this horizon, rounded and rotated fragments of cherty keratophyric schist and quartz ranging in size from less than 1 mm to several cm are supported in a matrix of hexagonal pyrrhotite with lesser amounts of chalcopyrite. The sulphide matrix has evidently flowed during shearing, so that the less ductile schist and quartz was disrupted and reduced to small rounded fragments, isolated and rotated in the sulphide matrix. Such heterogeneous behaviour during shear deformation of mixed sulphide-silicate rocks gives rise to the typical 'durchbewegung' textures seen here in Sulitjelma and illustrated by Ramdohr (1960, p. 49) in specimens from Saxberget in Sweden. These textures have been described from other sulphide deposits elsewhere in Norway by Vokes (1968, 1973) and their development is largely due to the ductile behaviour of pyrrhotite. Experimental work has shown that, whereas pyrrhotite is relatively strong at room temperature, it will behave plastically under stress, becoming rapidly more ductile at temperatures above 100 °C (Kelly and Clark, 1975), recrystallising and annealing in a short time. The effects of 'durchbewegung' in the pyrrhotite-rich horizon on Gjertrudfell are mirrored in the relationship between phyllosilicate matrices and clasts in other tectonoclastic breccia

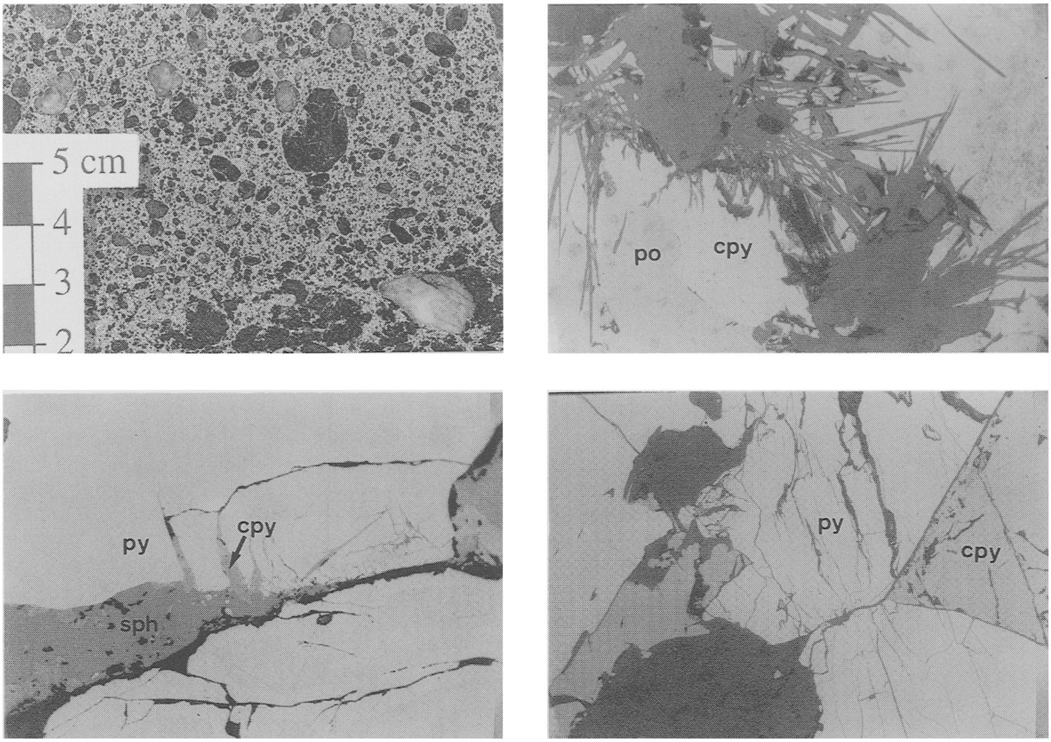

FIG. 5. (A, *top left*). Tectonoclastic rolled fabric incorporating wall rock fragments in a pyrrhotite matrix. Collected from surface outcrop, Gjertrudfjellet. (B, *top right*). Intergrowth of chlorite and biotite laths (dark grey) in a pyrrhotite (po)–chalcopyrite (cpy) matrix. Sagmo deposit. Width of field 0.2 cm. (C, *bottom left*). Cracks and microfractures in a pyrite porphyroblast (py) filled with chalcopyrite (cpy). sph: sphalerite. Giken II deposit. Width of field 0.2 cm. (D, *bottom right*). Late retrograde cataclasis of recrystallised and annealed pyrite (py). Note 120° triple junction between pyrites and chalcopyrite (cpy). Giken II deposit. Width of field 0.2 cm.

horizons at Sulitjelma, in which rounded fragments are encased in chlorite or chlorite–biotite–sericite matrices (cf. Cook *et al.*, 1990, Fig. 17*d*).

Pyrrhotite, chalcopyrite, sphalerite and galena in the sulphide bodies at Sulitjelma generally show evidence of ductile deformation, as would be predicted from experimental studies (Clark and Kelly, 1973; Kelly and Clark, 1975). The cases in which brittle fracturing of chalcopyrite and sphalerite has been observed are probably the result of post-D_3 deformation under conditions below the brittle–ductile transition boundaries for these minerals. For chalcopyrite this requires temperatures below 200 °C at pressures less than 500 bars with strain rates in the order of 7.2×10^{-5} sec^{-1} (Kelly and Clark, 1975). The continued mobility of pyrrhotite and chalcopyrite until late in the structural and metamorphic evolution is shown by their intergrowth with hydrous silicates of the retrograde assemblage (Fig. 5*b*).

Textures produced by brittle deformation. Brittle cataclastic deformation of pyrite porphyroblasts (Fig. 5*c*) accompanied by remobilisation of the more ductile sulphides and other minerals, including Au- and Ag-bearing phases, into cracks and microfractures (Fig. 5*d*) is a characteristic feature of the Sulitjelma sulphide rocks. The extent to which plastic flow and/or mass transfer in a fluid phase can account for the mobilisation of the minerals filling cataclastic fractures has been the subject of much discussion (see Marshall and Gilligan, 1987). Vokes and Craig (1993) have presented evidence from the Gressli deposit, central Norway, demonstrating that mobilisation can play a major role. During metamorphic events when a hydrous intergranular phase is present, mobilisation of sulphides by this process, as well as by ductile mechanisms, would be predicted (Etheridge *et al.*, 1983).

Some recrystallised pyrites have grown in zones of low strain and are undeformed except for a late D_3 brittle fracturing. Single pyrite crystals growing isolated in silicate host rock have created shadows of reduced stress in which gangue minerals and the softer sulphides have grown. Selkman (1983) has used similar features as markers to study stress and displacement distributions around pyrite grains. Chalcopyrite often occurs in the pressure shadows of pyrite porphyroblasts. Elsewhere, chalcopyrite displays deformation lamellae, kink-banding, and exsolution of cubanite is widespread. Sphalerite displays some cataclastic fracturing, with infilling by chalcopyrite. This shows that chalcopyrite entered the brittle field after sphalerite during retrograde cooling (cf. Vokes and Craig, 1993). The ductility of chalcopyrite is more temperature dependent than that of sphalerite. Sphalerite is also riddled with 'chalcopyrite disease' and chalcopyrite shows a tendency to segregate around the grain margins during cooling. Similar patterns of inclusion/exsolution and segregation of pyrrhotite in pyrite, bismuthinite in galena and magnetite in ilmenite are also observed. The coarse-grained pyrrhotite also displays deformation lamellae and twinning.

Sulphide–silicate textures and intergrowths. Where pyrite has behaved cataclastically in the phyllosilicate-rich rocks, ribbons of pyrite fragments are spread out along cleavage. Directly analogous textures are also seen where fractured and elongate albite porphyroblasts occur in similar matrices (cf. Cook *et al.*, 1990, Fig. 17*a*). Pressure solution and extreme cataclastic reduction of pyrite has led to the formation of bands composed entirely of pyrite microclasts. Pyrite also often grows along the cleavage of chlorite laths, demonstrating that both minerals were forming and recrystallising together during retrograde metamorphism. The low strength of the phyllosilicate-rich schists with banded and disseminated sulphides suggests that pressure solution became an important process towards the end of the retrograde cycle of metamorphism, under lower grade conditions than in the more competent massive sulphide rocks.

Metamorphic history of the ores

Using the published *PTt* data summarised above, an attempt can be made to relate the metamorphic and structural features observed in the sulphide-bearing rocks at Sulitjelma to the *PTt*-deformation history of the Sulitjelma Fold Nappe. The *P–T–t* pathways for the Furuland Group established by Burton *et al.* (1989) and Boyle and Westhead (1992) are used. These are shown in Fig. 6 onto which are also superimposed the brittle–ductile transformation boundaries for the main sulphide minerals based on experimental data from Clark and Kelly (1973), Salmon *et al.* (1974), Atkinson (1975), Kelly and Clark (1975) and Cox *et al.* (1981), together with the fields of greenschist and amphibolite grade metamorphism. The brittle–ductile boundaries for the sulphides are maximum values due to the disparity between experimental strain rates and geologically realistic strain rates which are several orders of magnitude lower. The experiments were also carried out under dry conditions. Most natural deformation processes take place in the presence of hydrous fluids which enable diffusive mass transfer, and also permit these processes to continue under lower grade conditions than would be required to produce the same effects in dry rocks.

The approximate conditions under which the three main stages of deformation took place at Sulitjelma are shown on Fig. 6 and all lie above the brittle–ductile transformation boundary for pyrite. This implies that most of the brittle deformation and related recrystallisation seen in the massive sulphides occurred under retrograde conditions at the end of D_3 or even after, well within the greenschist facies. This is consistent with the evidence of simultaneous intergrowth of chlorite and sulphides in the metamorphosed alteration zones.

During D_1–D_2 the mechanical contrast between silicate and massive sulphides, particularly those rich in pyrrhotite, led to partition of strain so that thrusting and shearing tended to be focused within and adjacent to the sulphide bodies. The similarity in *PT* conditions during prograde (D_1–D_2) and retrograde (D_3) metamorphism may have led to the development of similar textures in the sulphides at both stages but the features produced during D_3 are those dominantly preserved. The only textural record of the high-grade conditions prevailing at the time of D_2 is found in the ductile deformation of the large pyrite porphyroblasts.

Throughout most of the metamorphic cycle, pyrrhotite and chalcopyrite were within their fields of ductile behaviour and would have responded to stress by plastic deformation and recrystallisation. This implies that dynamic remobilisation of these sulphides could have continued throughout the retrograde stages of metamorphism in Sulitjelma, long after the peak conditions of metamorphism were reached. During the late stages of metamorphism and deformation the sulphides would remain ductile after the silicates had entered their field of brittle behaviour (see Marshall and Gilligan, 1987). Of the major sulphides, only pyrite was in the field of

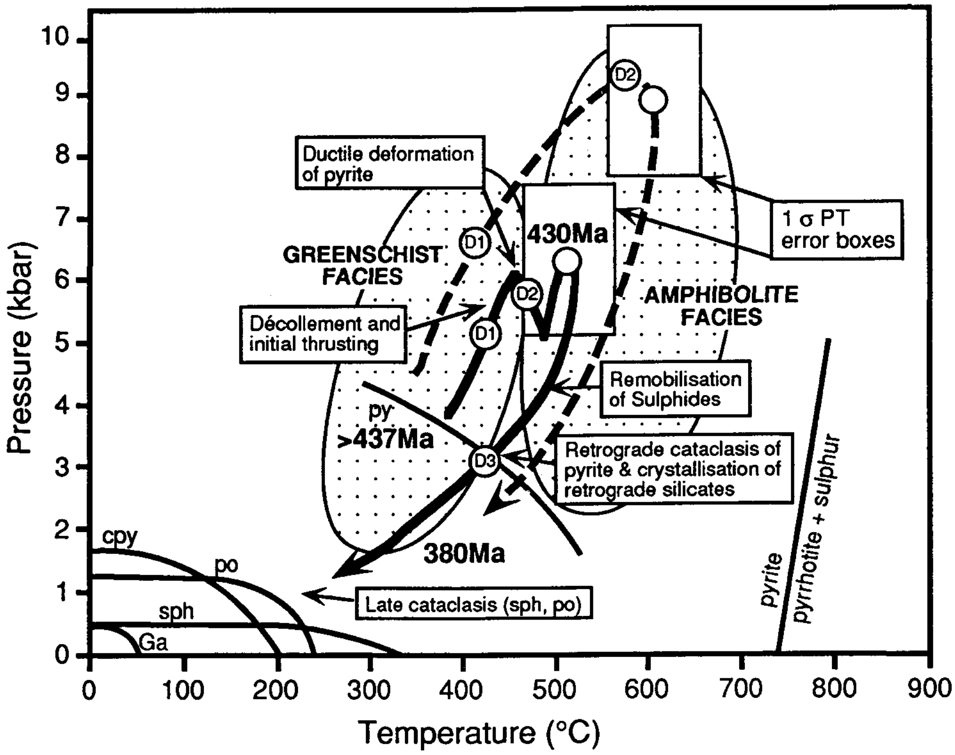

FIG. 6. Diagram illustrating the metamorphic development of sulphides at Sulitjelma, modified after Fig. 4 in Marshall and Gilligan (1987). Sources of sulphide data (5% ductile strain before failure at a strain rate of 7.2 × 10^{-5} sec^{-1}) are cited in the text. *P–T–t* paths for the Furulund Group, eastern samples as a solid line (Burton *et al.*, 1989) and western samples as a dashed line (Boyle and Westhead, 1992). Error box refers to metamorphic peaks determined by these authors. Circles with numbers relate to deformation episodes, open circles to peak conditions. Sources of data are as follows, >437 Ma (Pedersen *et al.*, 1991), garnet isograd peak (Burton and O'Nions, 1992). Pyrite stability curve from Kullerud and Yoder (1959). sph: sphalerite; po: pyrrhotite.

brittle deformation for a significant part of the metamorphic cycle.

Although quartz, albite, sphene and related framework silicates would have entered the brittle deformation field early during retrograde metamorphism, the characteristically ductile behaviour of the phyllosilicates would have led to increasing partition of strain in the alteration zones surrounding the pyritic sulphide bodies as temperatures fell during the retrograde stages. These zones would also have become the conduits for hydrous fluids which would have had an important influence on the mechanical and chemical response of sulphides and silicates at the local scale during deformation, as well as generally helping to reduce the frictional resistance of these zones to shear movements (Carpenter, 1968; Etheridge *et al.*, 1983; Lister and Williams, 1983; Thompson and Connolly, 1992). The low-grade mineral assemblages in the vugs and cavities and the dynamic brittle–ductile textures associated with tectonoclastic horizons provide evidence of the conditions prevailing during D_3.

Conclusions

In the sulphide rocks at Sulitjelma, mosaic textures with 120° triple junctions between large pyrite porphyroblasts show that textural equilibrium was achieved in the massive sulphides near the peak of the metamorphic cycle coinciding with D_2. These are preserved where the sulphide rocks were protected from later deformation. Plastic deformation of pyrite porphyroblasts is one of the special features observed in the orebodies at Sulitjelma and is believed to be due to high resolved shear stress acting in certain zones at temperatures of 450–500 °C near the peak of the metamorphic cycle. The most widespread textures are those in which cataclasis of the pyrite is accompanied by plastic deformation of the more ductile sulphides. These provide a record of deformation and recrystallisation which took place during the retrograde stages of the metamorphic cycle when the rocks returned to greenschist facies. During the waning stages of retrograde metamorphism, textures in fine-grained pyrite were governed by pressure solution and cataclasis.

The most thoroughly deformed rocks are the tectonoclastic breccias. The Gjertrudfjell horizon provides an excellent example of the 'durchbewegung' textures produced because of the contrast in rheological behaviour between sulphide and silicate when subjected to shearing under greenschist conditions. High fluid pressures may have played an important part in the formation of the tectonoclastic horizons in which phyllosilicates form an intrinsically weak and potentially permeable matrix.

Acknowledgements

The comments of Martin Okrusch on an earlier version of this paper and those of an anonymous reviewer led to significant improvements in the text and are greatly appreciated by the authors.

References

Adams, F. D. (1910) Differential pressure on minerals and rocks. *J. Geol.*, **18**, 489–525.

Atkinson, B. K. (1975) Experimental deformation of polycrystalline pyrite: Effects of temperature, confining pressure, strain rate and porosity. *Econ. Geol.*, **70**, 473–87.

Beach, A. (1979) Pressure solution as a metamorphic process in deformed terrigenous sedimentary rocks. *Lithos,* vol. **12**, 51–8.

Berg, G. (1927) Über das Vorkommen sog. porphyrischer Kieskristalle in den Lagerstätten der intrusiven Kiesgruppe: Gesteins Untersuch. *Preuss. Geol. Landesanst. Mitt. Abt.*, **3**, no. 3, 8–11.

Boyle, A. P. (1980) The Sulitjelma amphibolites, Norway: Part of a lower Palaeozoic Ophiolite complex? In *Ophiolites, Proc. Int. Ophiolite Symposium, Cyprus 1979* (A. Panayioutou, ed.), Cyprus Geol. Surv. Dept., 567–75.

—— (1987) A model for the stratigraphic and metamorphic inversions at Sulitjelma, central Scandes. *Geol. Mag.*, **124**, 451–66.

—— (1989) The geochemistry of the Sulitjelma ophiolite and associated basic volcanics: tectonic implications. In: *The Caledonide Geology of Scandinavia* R. A. Gayer, ed.), Graham and Trottman, London, 153–63.

—— and Westhead, K. (1992) Metamorphic peak geothermobarometry in the Furulund Group, Sulitjelma, Scandinavian Caledonides: Implications for uplift. *J. Met. Geol.* (in press).

—— Mason, R., and Hansen, T. S. (1985) A new tectonic perspective of the Sulitjelma region: In *The Caledonide Orogen, Scandinavia and related areas* (D. G. Gee and B. A. Sturt, eds.), John Wiley and Sons, London, 529–42.

Brodie, K. H. and Rutter, E. H. (1985) On the relationhip between deformation and metamorphism with special reference to the behaviour of basic rocks. In *Metamorphic Reactions, Kinetics, Textures, Deformation* (A. B. Thompson and D. C. Rubie, eds.), Advances in Physical Geochemistry, Volume 4; Springer Verlag, New York, 138–79.

Brooker, D. D., Craig, J. R., and Rimstidt, J. D. (1987) Ore metamorphism and pyrite porphyroblast development at the Cherokee Mine, Ducktown, Tennessee. *Econ. Geol.*, **82**, 72–86.

Buerger, J. J. (1928) The plastic deformation of ore minerals (Parts 1 and 2). *Am. Mineral.*, **13**, 1–17, 35–51.

Burton, K. W., Boyle, A. P., Kirk, W. L., and Mason, R. (1989) Pressure, temperature and structural evolution of the Sulitjelma fold-nappe, central Scandinavian Caledonides. In: *Evolution of Metamorphic belts* (J. S. Daly *et al.*, eds.) Geol. Soc. (London) Spec. Pub. 43, p. 391–11.

Burton, K. B. and O'Nions, R. K. (1991) High-resolution garnet chronometry and the rates of metamorphic processes. *Earth Planet. Sci. Letters*, **107**, 649–71.

Burton, K. W. and O'Nions, R. K. (1992) The timing of mineral growth across a regional metamorphic sequence. *Nature*, **357**, 235–8.

Carpenter, J. R. (1968) Apparent retrograde metamorphism: Another example of the influence of structural deformation on metamorphic differentiation. *Contrib. Mineral. Petrol.*, **17**, 173–86.

Carstens, C. W. (1944) Om dannelsen av de norske svovelkisforekomster. *K. Nor. Vidensk. Selsk. Forh.*, **17**, 27–54.

Clark, B. R. and Kelly, W. C. (1973) Sulfide deformation studies: I. Experimental deformation of pyrrhotite and sphalerite to 2000 Bars and 500°C. *Econ. Geol.*, **68**, 332–52.

Cook, N. J. (1987) *The Sulitjelma orebodies, Northern Norway: A geochemical and mineralogical investigation.* Unpublished Ph.D. thesis, University of London, 545 p.

—— (1992) Antimony-rich mineral parageneses and their association with Au minerals within massive sulphide deposits at Sulitjelma, Norway. *Neues Jahrb. Miner., Mh.*, 97–106.

—— Halls, C., and Kaspersen, P. O. (1990) The geology of the Sulitjelma ore field, northern Norway—some new interpretations. *Econ. Geol.*, **85**, 1720–37.

Couderc, J-J., Bras, J., Fago, M., and Levade, C. (1980) Étude par microscopie électronique en transmission de l'état de déformation de pyrites de différentes provenances. *Bull. Minéral.*, **103**, 547–57.

Cox, S. F. (1987) Flow mechanisms in sulfide minerals. *Ore Geology Reviews*, **2**, 133–71.

—— Etheridge, M. A., and Hobbs, B. E. (1981) The experimental ductile deformation of polycrystalline and single crystal pyrite. *Econ. Geol.*, **76**, 2105–18.

Craig, J. R. (1983) Metamorphic features in Appalachian massive sulphides. *Mineral. Mag.*, **47**, 515–25.

——(1990) Ore textures and paragenetic studies—some modern case histories and sources of comparative data. In *Advanced Microscopic Studies of Ore Minerals* (J. L. Jambor and D. J. Vaughan, eds.), Min. Assoc. Canada Short Course Notes, **17**, 263–317.

——and Vokes, F. M. (1993) The metamorphism of pyrite and pyritic ores. *Mineral. Mag.* **57**, 3–18.

————and Simpson, C. (1991) Rotational fabrics in pyrite from Ducktown, Tennessee. *Econ. Geol.*, **86**, 1737–46.

Etheridge, M. A., Wall, V. J., Cox, S. F., and Vernon, R. H. (1983) The role of the fluid phase during regional metamorphism and deformation. *J. Metam. Geol.*, **1**, 205–226.

Frietsch, R., Papunen, H., and Vokes, F. M. (1979) The ore deposits in Finland, Norway, and Sweden—a Review. Econ. Geol., **74**, 975–1001.

Graf, J. L. and Skinner, B. J. (1970) Strength and deformation of pyrite and pyrrhotite. Ibid., **65**, 206–15.

——Bras, J., Fago, M., and Couderc, J.-J. (1981) Transmission electron microscopic observation of plastic deformation in experimentally deformed pyrite. Ibid., **76**, 738–42.

Kalliokoski, J. (1965) Metamorphic features in North American massive sulfide deposits. Ibid., **60**, 485–505.

Kautsky, G. A. (1953) Der geologische Bau des Sulitjelma-Salojauregebeites in den nordskandinavischen Kaledoniden. *Sveriges Geol. Undersökning*, **528C**, 232 pp.

Kelly, W. C. and Clark, B. R. (1975) Sulfide deformation studies: III. Experimental deformation of chalcopyrite to 2000 bars and 500 °C. *Econ. Geol.*, **70**, 431–53.

Kollung, S. (1989) Bedrock geological map of the Sulitjelma region, northern Norway, scale 1 : 100 000, with description. *Norges Geol. Unders. Skrifter*, **93**, p. 1–47.

——(1990) Berggrunnskart over Sulitelmafeltet. Målestokk 1 : 100 000. *Norges Geologiske Unders., Bilag til NGU Skrifter*, **93**, Trondheim.

Krause, H. (1956) Zur Kenntnis der metamorphen Kieslagerstätte von Sulitjelma (Norwegen). *Neues Jahrb. Mineral., Abh.*, **89**, 137–48.

Kullerud, G. and Yoder, H. S. (1959) Pyrite stability in the Fe–S system. *Econ. Geol.*, **54**, 533–72.

Laznicka, P. (1985) Concordant versus discordant ore deposits and ore transformations. In: *Handbook of strata-bound and stratiform ore deposits* (K. H. Wolf, ed.), Vol. 11, Elsevier, Amsterdam, 119–316.

Lister, G. S. and Williams, P. F. (1983) The partitioning of deformation in flowing rock masses. *Tectonophys.*, **92**, 1–34.

Marshall, B. and Gilligan, L. B. (1987) An introduction to remobilisation: information from ore-body geometry and experimental considerations. *Ore Geology Reviews*, **2**, 87–131.

McClay, K. R. (1982) Tectonic and sedimentary structure in the sulphide orebodies of Mt. Isa (Australia) and Sullivan (Canada). *Inst. Min. Metall. Trans.*, **91**, section B, 146–52.

——and Ellis, P. G. (1983) Deformation and recrystallisation of pyrite. *Mineral. Mag.*, **47**, 527–38.

McDonald, J. A. (1967) Metamorphism and its effects of sulfide assemblages. *Mineralium Deposita*, **2**, 200–20.

Mookherjee, A. (1971) Deformation of Pyrite (discussion). *Econ. Geol.*, **66**, 200.

——(1976) Ores and metamorphism: temporal and genetic relationships. In *Handbook of stratabound and stratiform ore deposits* (Wolf, K. H., ed.), vol. 4. Elsevier, Amsterdam, p.203–60.

Nicholson, R. and Rutland, R. W. R. (1966) A section across the Norwegian Caledonides: Bodø to Sulitjelma. *Norges Geol. Unders.*, **260**, 1–86.

Olsen, J. (1980) Genesis of the Joma stratiform sulfide deposit, central Norwegian Caledonides. In: *Proceedings of the 5th Quadrennial IAGOD Symposium, Utah* (J. D. Ridge, ed.), E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 745–57.

Pedersen, R-B., Furnes, H., and Dunning, G. (1991) A U/Pb age for the Sulitjelma Gabbro, Northern Norway: further evidence for the development of a Caledonide marginal basin in Ashgill-Llandovery time. *Geol. Mag.*, **128**, 141–53.

Ramdohr, P. (1938) Antimonreiche Paragenesen von Jakobsbakken bei Sulitjelma. *Norges Geol. Tidsskr.*, **18**, 275–89.

——(1960) *Die Erzmineralien und Ihre Verwachsungen*, Akademie-Verlag, Berlin, 1089 p.

Rutter, E. H. (1976) The kinetics of rock deformation by pressure solution. *Phil. Trans. Roy. Soc.*, **A238**, 203–19.

Salmon, B. C., Clark, B. R., and Kelly, W. C. (1974) Sulphide deformation studies. II. Experimental deformation of galena to 2000 Bars and 400 °C. *Econ. Geol.*, **69**, 1–16.

Selkman, S. O. (1983) Stress and displacement distributions around pyrite grains. *J. Struct. Geol.*, **5**, 47–52.

Siemes, H., Hennig-Michaeli, C., and Martens, L. (1991) The importance of deformation experiments on minerals for the interpretation of metamorphic ore textures. *Ore Geology Reviews*, **6**, 475–83.

Smith, C. S. (1948) Grains, phases and interfaces: an interpretation of microstructure. *Trans. Amer. Inst. Mining Metall. Engin.*, **175**, 15–51.

Stephens, M. B. (1986) Terrane analysis of Sulitjelma, Upper Allochthon, Scandinavian Caledonides. *Geol. Fören. Stockh. Förh.*, **108**, 303:4.

——Swinden, H. S., and Slack, J. F. (1984) Correlation of massive sulfide deposits in the Appalachian–Caledonian Orogen on the basis of paleotectonic setting. *Econ. Geol.*, **79**, 1442–78.

——Gustavson, M., Ramberg, I. B., and Zachrisson, E. (1985) The Caledonides of central-north Scandinavia—a tectonostratigraphic overview. In: *The Caledonide Orogen, Scandinavia and related areas* (D. G. Gee and B. A. Sturt, eds.), John Wiley and Sons, London, 135–62.

Thompson, A. B. and Connolly, J. A. D. (1992) Migration of metamorphic fluid: some aspects of mass and heat transfer. *Earth Science Reviews,* **32**, 107–21.

Veit, K. (1922) Schiebungen und Translationen in Mineralien. *Neues Jahrb. f. Min. Geol. u. Pal., Bl.Bd.*, **45**, 125–8.

Vogt, T. (1927) Sulitelmafeltets Geologi og Petrografi. *Norges Geol. Unders.*, **121** 560 pp.

——(1952) Flowage structures and ore deposits of the Caledonides of Norway. *Int. Geol. Congress XVIII Session,* Great Britain 1948, Procs. Pt. 33, 240–4.

Vokes, F. M. (1963) Geological studies on the Caledonian pyritic zinc lead orebody at Bleikvassli, Nordland, Norway. *Norges Geol. Unders.*, **22**, 126.

——(1968) Regional metamorphism of the Palaeozoic geosynclinical sulphide ore deposits of Norway. *Trans. Inst. Min. Metall.*, Sect. B (*Appl. Earth Sci.*), **77**, B53–B59.

——(1969) A review of the metamorphism of sulphide deposits. *Earth Sci. Rev.*, **5**, 99–143.

——(1973) 'Ball textures' in sulfide ores. *Geol. Fören. Stockholm Forh.,* **95**, 403–6.

——(1976) Caledonian massive sulphide deposit in Scandinavia: A comparative Review. In *Handbook of strata-bound and stratiform ore deposits* (K. H. Wolf, ed.), Vol. 6, Elsevier, Amsterdam, 79–127.

——and Craig, J. R. (1993) Post-recrystallisation phenomena in metamorphosed strata-bound sulphide ores. *Mineral. Mag.* **57**, 19–28.

Wilson, M. R. (1971) The timing of orogenic activity in the Bodø–Sulitjelma tract. *Norges Geol. Unders.*, **269**, 184–9.

——(1973) The geological setting of the Sulitjelma ore bodies, central Norwegian Caledonides. *Econ. Geol.*, **68**, 307–16.

[*Manuscript received 4 February 1992:
revised 18 May 1992*]