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Deformation and recrystallization microstructures in deformed ores from the CSA mine, Cobar, N.S.W., Australia

B. A. BRILL*

Department of Geology, University of Newcastle, NSW 2308, Australia

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Abstract—Semi-massive and vein Cu–Pb–Zn mineralization occurs at the CSA mine in the Cobar mineral province in western New South Wales, Australia. In these ore bodies the sulphides show textures which are characteristic for deformation by brittle failure, dislocation glide, dislocation creep and precipitation creep. The textures are similar to those that have been produced in experimental studies and those observed in many naturally deformed ores. Several textures indicate that recrystallization and deformation of the ore minerals occurred simultaneously. Together with the mesoscale vein structures they support a syn-tectonic origin for the mineralization.

INTRODUCTION

EARLY studies on naturally deformed ores have recognized that sulphide minerals respond to deformation and metamorphism (Stanton 1964, McDonald 1967, Ramdohr 1969, Vokes 1969, 1971). Knowledge of the deformation mechanisms of ore minerals have largely been derived from studies on metals and ceramics (Stanton 1964) and were reproduced in laboratory experiments on sulphides or observed in naturally deformed geological materials.

Early experimental deformation of ore minerals by Buerger (1928) had already recognized deformation by slip and deformation twinning. In more recent years experimental deformation on sulphides has produced slip, twinning, dislocation climb and recrystallization textures. The dominant deformation mechanisms observed in sulphide minerals (Cox 1987) are as follows:

(1) brittle failure, which leads to the development of inter- and intragranular fracturing;

(2) low-temperature plasticity: this includes deformation by dislocation glide (slip bands, kinks) and mechanical twinning;

(3) dislocation creep: this is an important flow mechanism that leads to the development of a lattice preferred orientation, dynamic recovery (i.e. subgrains) and dynamic recrystallization;

(4) solution–precipitation creep: this results in pressure-solution effects on mineral grain boundaries;

(5) solid-state diffusion creep, including Coble creep and Nabarro–Herring creep (Atkinson 1977);

(6) grain-boundary sliding: this mechanism operates in fine-grained materials at elevated temperatures.

Which mechanism operates is dependent on the material and on parameters such as temperature, stress, strain rate and grainsize.

* Present address: Department of Geology, University of Melbourne, Parkville, Victoria 3052, Australia.

Brittle failure has been described as the major deformation mechanism for experimentally deformed pyrite (Graf & Skinner 1970, Atkinson 1975) and for many naturally deformed pyrite ores (Vokes 1969, Mookherjee 1971, Craig 1983). Recent work has shown that pyrite can undergo dislocation-glide processes at elevated temperatures (400–700°C Cox *et al.* 1981) at laboratory strain rates. Sandecki (1984) recognized ductile behaviour in naturally deformed pyrite.

Low-temperature plasticity. Deformation by slip has been achieved in low-temperature experiments in pyrrhotite (Graf & Skinner 1970, Clark & Kelly 1973, Atkinson 1974), in chalcopyrite (Buerger 1928, Atkinson 1974, Kelly & Clark 1975, Roscoe 1975), in sphalerite (Buerger 1928, Clark & Kelly 1973) and galena (Buerger 1928, Lyall 1966, Lyall & Paterson 1966, Salmon *et al.* 1974, Atkinson 1976, 1977, Clark *et al.* 1977, McClay 1980). Evidence for deformation by slip is very common in naturally deformed pyrrhotite (Larson 1973), chalcopyrite (Richards 1966) and sphalerite (Richards 1966, Frater 1985). Deformation twins occur at more elevated temperatures in experimentally deformed pyrrhotite (Graf & Skinner 1970, Clark & Kelly 1973, Atkinson 1974), in chalcopyrite (Buerger 1928, Atkinson 1974, Kelly & Clark 1975, Roscoe 1975), in sphalerite (Buerger 1928, Clark & Kelly 1973) and galena (Lyall & Paterson 1966), and have been observed in naturally deformed chalcopyrite (Richards 1966) and sphalerite (Richards 1966, Frater 1985, Sandecki 1984). Kink bands have been produced experimentally in deformed sulphide minerals such as pyrrhotite (Clark & Kelly 1973, Atkinson 1974) and galena (Lyall 1966, Lyall & Paterson 1966, Salmon *et al.* 1974, Clark *et al.* 1977, McClay 1980).

Dislocation creep is an important flow process at elevated temperatures and gives rise to the development of subgrains. Subgrains during the recovery of chalcopyrite (Roscoe 1975) and galena (Atkinson 1976, Clark *et al.* 1977) were observed after experimental deformation of these minerals. Many naturally deformed pyrrhotite (Richards 1966, Lawrence 1973), chalcopyrite (Cox & Etheridge 1984), sphalerite (Sandecki 1984, Frater 1985) and galena ores (Richards 1966, Sandecki 1984) have been described as having deformed by dislocation creep. Knowledge about recrystallization behaviour of sulphides has largely been derived from experimentally annealed galena (Siemes 1964, 1976, Stanton & Willey 1971, 1972, Salmon *et al.* 1974, Atkinson 1977, Clark *et al.* 1977, McClay 1980) and indicates that recrystallization in galena commences at temperatures as low as 200°C (Stanton & Gorman 1968) and at even lower temperatures for low strain rates (Atkinson 1977).

Solution–precipitation creep (pressure solution) is a common deformation process in many silicates and carbonates under lower-greenschist facies metamorphic conditions (Ramsay & Huber 1983) and appears to be the major deformation mechanism for pyrite at low metamorphic grades (McClay & Ellis 1983, 1984).

Solid-state diffusion creep involves two processes, grain-boundary controlled diffusion (Coble creep) and lattice controlled diffusion (Nabarro–Herring creep); at low stresses and small grainsizes Coble creep is predominant over Nabarro–Herring creep. Coble creep was observed in fine-grained polycrystalline galena from low-grade metamorphic environments by McClay (1980, 1983). Lattice diffusion creep has not yet been recognized in geological materials but may be important in low fluid-pressure, high-grade metamorphic terrains at low stresses (Cox 1987).

Grain-boundary sliding (or superplasticity) occurs at elevated temperatures without loss of cohesion along the grain boundaries and is usually accompanied by diffusive mass transfer (Marshall & Gilligan 1987). This process may have been important in some highly deformed fine-grained sulphide ores (Cox 1987).

The microstructures of ore minerals from the CSA mine have been studied in detail in order to determine the deformation mechanisms that have operated during the regional metamorphism of the ore bodies. It will be shown that sphalerite and chalcopyrite have deformed by dislocation glide and dislocation creep, whereas pyrite mainly deformed in a brittle manner. Galena and pyrrhotite recrystallized to a large extent.

REGIONAL GEOLOGY

Mineralization in the Cobar area is hosted principally by metasediments of the Lower Devonian Cobar Supergroup, a sedimentary and volcanic sequence (Pogson & Glen 1985) (Fig. 1). Most mineral deposits in the Cobar area are confined to a deep water, turbiditic sedimentary sequence and have no association with volcanic or intrusive rocks. The sediments were deposited within the Cobar basin, which formed by rifting during the early Devonian (Scheibner 1973, 1974). Subsequent metamorphism of lower-greenschist grade affected the sequence possibly during the early Carboniferous (Glen

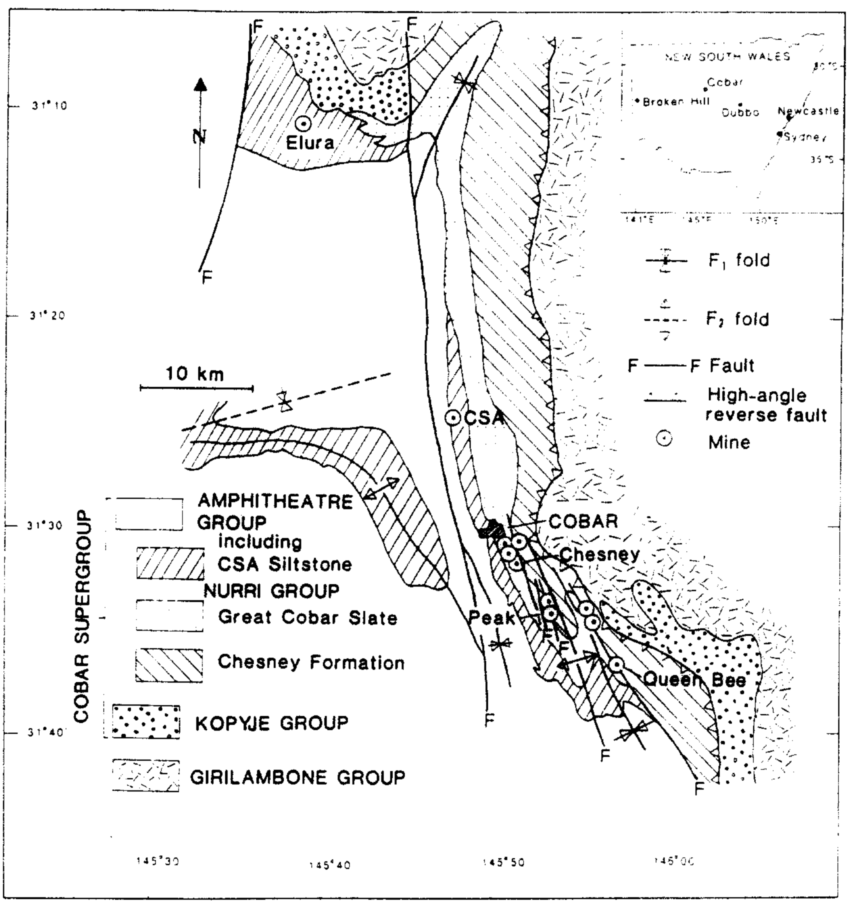

Fig 1. Simplified geology at Cobar. Map modified from Glen (1985).

1982, Brill 1988). Basement underlying the early Devonian trough fill of the Cobar basin is not known with certainty but is likely to comprise rocks similar to the deep marine sedimentary and volcanic Girilambone Group of Cambrian to Ordovician age (Pogson *et al.* 1976, Pogson & Felton 1978) which is exposed east of the Cobar trough.

Structure and metamorphism

According to Glen (1985) the Cobar area can be divided into two major strain zones, a high D_1 strain zone at the eastern margin of the basin and a low D_2 strain zone further west. A progressive deformation resulted in development of NW-trending F_1 folds, followed by rotation of the stress field and NE-trending F_2 folds. An intense NW-trending axial-planar cleavage S_1 is developed in the high D_1 strain zone in the eastern part of the area. The D_2 strain zone is characterized by F_1 folds folded by F_2 folds and only a poorly developed S_1 cleavage (Glen 1982). The study area is located within the D_1 zone of intense strain and cleavage development. A weak effect of the D_2 deformation is evident in the CSA mine in the form of refolded S_1 cleavage planes. Metamorphism reached lower-greenschist grade with temperatures of approximately 350°C, as indicated by chlorite compositions and fluid inclusion studies (Brill in preparation). Si contents and b_0 values of studies on white micas (Brill 1988) show that lithostatic pressures during metamorphism reached 3 kb.

MINERALIZATION

The ore minerals discussed in this study occur within steeply N-plunging elongate ore lenses which are subparallel to the regional cleavage S_1 and are transgressive to bedding (Fig. 2). The mineralization is surrounded by a broad alteration halo showing intense silicification and chloritization of the metasiltstone host rock. The main ore types are Cu-rich lenses with varying amounts of chalcopyrite, pyrrhotite, pyrite, quartz and calcite, which are discordant to bedding and subparallel to cleavage; Cu–Zn lenses, which are pyrite-rich and massive or layered subparallel to S_1; siliceous granular chalcopyrite lenses, which are linked along strike by massive chalcopyrite veins (Glen 1987), and a banded Pb–Zn ore type. The mineral banding in the last ore type is transgressive to bedding and is non-sedimentary in origin. Shear zones dissect the ore bodies and contain a late sphalerite–galena phase. All mineralized veins occur transgressive to bedding and show a range in time relationships with schistosity (see Fig. 4 and later discussion).

Different ideas on ore genesis have been expressed in the last 50 years, ranging from epigenetic (Rayner 1969) to syn-genetic (Sangster 1979) and remobilized syngenetic (Brooke 1964, 1975, Gilligan & Suppel 1978, Marshall & Sangameshwar 1982). Glen (1985, 1987) has recently proposed a metamorphic origin for mineralization. This paper presents details of ore mineral paragenesis and textures to further support a metamorphic origin for the mineralization at the CSA mine.

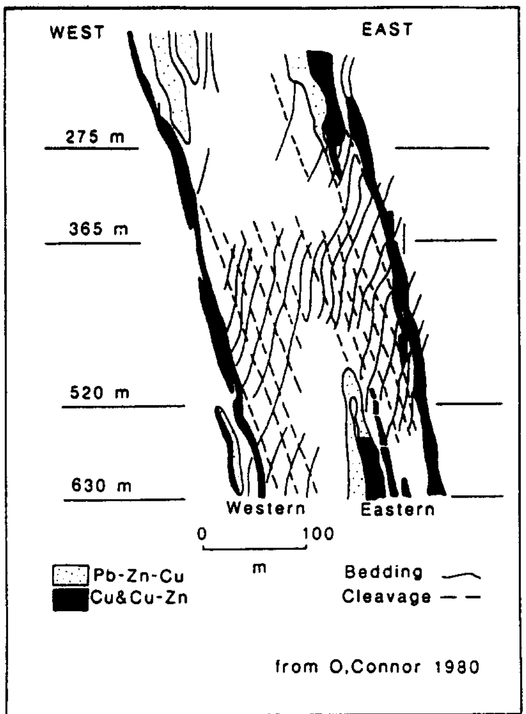

Fig. 2. Cross-section through the CSA ore body.

ORE PETROLOGY

The main ore minerals in the CSA ore lenses are pyrite, chalcopyrite, pyrrhotite, sphalerite and galena with quartz, calcite, chlorite and white mica as the major gangue minerals. In addition, small amounts of sulfosalts (bismuthinite, galenobismuthite, boulangerite, stromeyerite), arsenopyrite, clausthalite, tetrahedrite, bismuth, stannite, cubanite (orthorhombic) and mackinawite are widespread and have been described by earlier workers (Gow 1965, Robertson 1968, 1974, Rayner 1969). The paragenetic sequence is shown in Fig. 3. Replacement textures of pyrite by later sulphides show that a major part of the pyrite is earlier than the main mineralization. Late metamorphic pyrite forms porphyroblasts and overgrowths on earlier pyrite aggregates. Replacement of pyrrhotite resulted in the formation of secondary pyrite and marcasite (Fig. 5a). Most of the pyrrhotite growth is contemporaneous with chalcopyrite, sphalerite and galena. Some pyrrhotite is postkinematic and is associated with post-kinematic chlorite and white mica which overprint the foliation. Sphalerite from the CSA mine shows 'chalcopyrite disease' (Barton 1978) a texture considered to be a product of epitaxial growth or replacement of sphalerite by later chalcopyrite (Craig & Vaughan 1981, Eldridge *et al.* 1983, Kojima & Sugaki 1985, Sugaki *et al.* 1987).

Sphalerite and galena are also associated with chlorite-filled shears which cut earlier copper minerali-

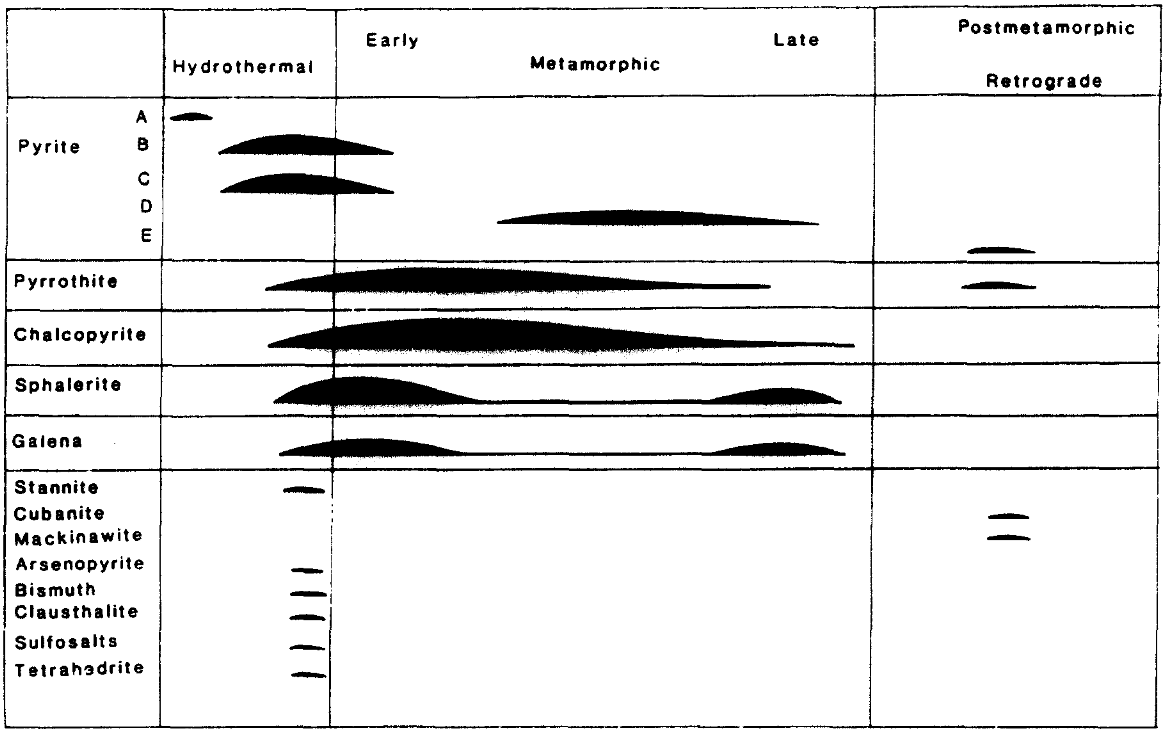

Fig. 3. Paragenetic diagram of the ore minerals at the CSA mine.

zation. The banding of the Pb–Zn ore consists of alternate layers of sphalerite–galena–pyrrhotite. Preferred orientation of the mineral aggregates in the S_1 direction is not very common because of extensive recrystallization, especially of galena. The weak foliation and the layering may be results of oriented recrystallization, as has been described by Stanton & Wiley (1972) for galena ore from Coeur d'Alene and for galena–sphalerite–garnet schist from Broken Hill (Stanton & Wiley 1971, fig 1), especially considering that a substantial amount of the Pb–Zn ore in the CSA mine occurs within shear zones. A review on layering of sulphide assemblages has been compiled on similar terms by McDonald (1967). All minor minerals listed in Fig. 3 are contemporaneous with the main ore minerals, with only marcasite, cubanite and mackinawite having formed as secondary low-temperature phases.

DEFORMATION AND METAMORPHISM OF THE SULPHIDES

On a mesoscale chaotic textures are common both in Cu ore and Pb–Zn ore, which show similarities to 'Durchbewegungs textures' described from many deformed Scandinavian ore deposits (Vokes 1969). Different vein types appear to have formed at different stages during deformation (Fig. 4). The earliest are slightly oblique to the cleavage and have been folded; those at high angle to cleavage are ptygmatically folded. Most veins are of syn-kinematic origin and are near-parallel to cleavage planes. They show no folding and are often boudinaged. Subhorizontal tension veins are common and show fibres of quartz. Non-folded veins, slightly oblique to cleavage, have formed late in the deformation history. Post-dating the schistosity are shear veins, which have displaced cleavage planes. Similar sets of veins have been described from other ore deposits in the Cobar area (Glen 1985, 1987).

Deformation textures in pyrite

Deformation of pyrite from the CSA mine has occurred by brittle fracturing, especially in the case of porphyroblastic pyrite. The fractures are filled with later sulphide phases like chalcopyrite and pyrrhotite. Overgrowth textures on fine-grained pyrite are common and

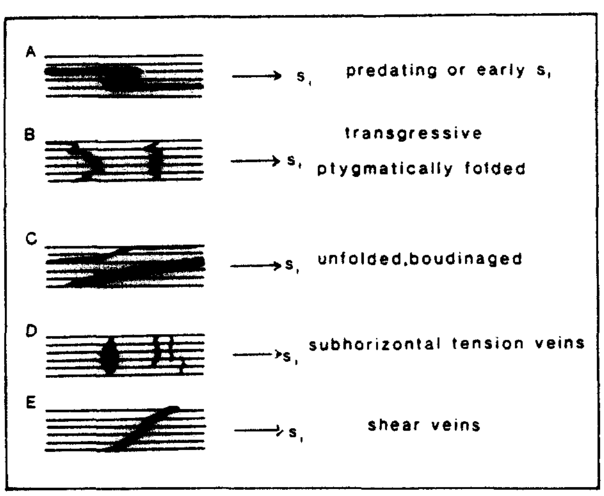

Fig. 4. A schematic diagram showing the time relationships and differing orientations of the principal vein sets at the CSA mine.

are possibly attributable to deformation by pressure solution, since it has been shown that naturally deformed fine-grained pyrite deforms largely by pressure solution whereas brittle failure was favoured by coarse grainsizes (McClay & Ellis 1983, 1984).

Deformation, recovery and recrystallization textures in sphalerite

Sphalerite from the CSA mine shows textures which indicate deformation by twinning, dislocation climb (subgrains) and of dynamic recrystallization.

Grainsize and grain boundaries. A characteristic of sphalerite from the CSA mine is its strong variation in grainsize. Grains vary from only a few microns to 0.5 mm in size. Most of the small grains occur at triple junctions of larger sphalerite grains and have been consumed by expanding neighbouring grains, similar to 'run-away grains' as described by Nielsen (1966). Some of them could also be due to cut-effects. The recrystallized sphalerite fabric is characterized by grainsizes of 0.05 mm and straight grain boundaries with dihedral angles of 120° suggesting equilibrium has been obtained. Adjustment of grain boundaries has taken place especially in the coarser aggregates which show frequently cuspate grain boundaries as a result of grain-boundary bulging (Fig. 5b). Within the bulges recrystallized grains have often nucleated.

Twinning. Several types of twins are present. In deciding whether they are of growth, deformation or annealing origin the criteria given in Richards (1966), Frater (1985) and Cox (1987) have been used. If a twin is straight and broad in nature and cannot be related to a deformation event, it is regarded as a growth twin (Frater 1985). Deformation twins are narrow within a single grain (Richards 1966) and can be distinguished from broad parallel-sided and bluntly terminated growth twins by their fine and discontinuous habit (Cox 1987). In contrast to growth twins, Frater (1985) regarded twins which have reduced the surface free energy of grains at triple junctions and grain margins as annealing twins. In this study the broad, straight twins will be referred to as recrystallization or annealing twins.

Polysynthetic deformation twins in sphalerite occur preferentially in coarse sphalerite (Fig. 5d) and intersection and bending of twins is common. The formation of these twins appears to have been dependent on the orientation of the host grain and growth twins have often served as hosts for polysynthetic deformation twins (twins in sphalerite were etched with HI). At the grain boundary of sphalerite and pyrrhotite feather twins can be developed in response to stress by two different neighbouring mineral phases (Fig. 5d). According to Richards (1966) these twins are of recrystallization origin. Straight annealing twins are common in sphalerite (Figs. 5b & e). Grain growth in sphalerite has taken place according to the Fullman–Fisher concept of grain growth in order to lower the interfacial free energy (Fullman & Fisher 1951). This is shown by grain growth at the expense of neighbouring grains by incorporating them into a twin orientation rather than the orientation of the growing grain (Fig. 5e).

Subgrains. Subgrains in sphalerite commonly have incomplete subgrain boundaries; only rarely crystallographic alignment of subgrains and resulting rectangular grain shapes can be observed. The free-ending subgrain boundaries have probably only low misorientations (Cox 1987); such boundaries are known to migrate easily and coalesce with other subgrain boundaries (Poirier 1985). The coalescence of subgrains has been observed by Cox & Etheridge (1984) in chalcopyrite from Tasmania. The abundance and distribution of subgrains within sphalerite is highly variable and generally more pronounced in coarser aggregates. Higher abundance of subgrains is developed where curvature of growth or annealing twins has occurred in order to respond to inhomogeneous local stress (Fig. 5f).

Recrystallization. Metallurgical studies have shown that the initial development of recrystallized grains begins in regions with the highest local degree of deformation (Cahn 1966). In sphalerite new grains can be observed along grain and twin boundaries. Nucleation of new free grains appears to form by grain-boundary bulging of coarser grains (Figs. 5b and 6a), and has been reported from experimentally deformed galena (McClay & Atkinson 1977) and pyrite (Cox *et al.* 1981) and from naturally deformed chalcopyrite (Cox & Etheridge 1984). Some of the new grains and subgrains are similar in size (Figs. 5c & f) suggesting that low-angle subgrain boundaries may have turned into high-angle grain boundaries during recrystallization. Subgrain rotation is a major nucleation process in many minerals (Poirier & Nicolas 1975) and occurs preferentially near grain boundaries of deforming grains (Cox 1987). This type of recrystallization process is similar to the subgrain nucleation which has been described as a common process in metals (Cahn 1966) and silicates (1977). Following nucleation substantial grain growth has taken place either by grain-boundary migration or twin coalescence (Fullman–Fisher concept).

Recrystallization of sphalerite along grain boundaries of coarser more strongly deformed grains, nucleation from subgrains and a subgrain structure in recrystallized grains are similar to textures described in quartz (White 1977) and chalcopyrite (Cox & Etheridge 1984) and can be attributed to dynamic recrystallization.

Development of straight, unstrained annealing twins indicates that some post-tectonic recrystallization occurred as well. Secondary recrystallization resulted in 'run-away grains' and free-ending twins.

Deformation, recovery and recrystallization textures in chalcopyrite, galena and pyrrhotite

Chalcopyrite. As for sphalerite a strong variation in grainsize is typical for chalcopyrite. Many of the strongly deformed grains are 0.5–1 mm in size and are elongated in the direction of the foliation. Small grains occur at triple junctions and have been partially consumed by larger grains during grain growth. Grain boundaries are often serrated, especially in the larger, strongly deformed grains (Fig. 6b). Modification of deformed grain shapes due to grain-boundary migration has been intense, resulting in bulging of grain boundaries.

Deformation of chalcopyrite appears to have occurred mainly by dislocation glide. Evidence for the deformation mechanism is shown by the development of polysynthetic deformation twins (Fig. 6c). Even though slip planes have not been observed, curvature of twins is an indirect indication that dislocation glide (slip) has taken place (Atkinson 1974) (Fig. 6c).

An excellent electrolytic etch has been developed by Cox & Etheridge (1984) to detect subgrain structures in chalcopyrite. However, no subgrain structure was visible in chalcopyrite from the CSA mine after application of the electrolytic etch. It appears that nucleation of strain-free grains has occurred from larger strongly deformed grains along grain boundaries by grain-boundary bulging (Fig. 6d). Recrystallized grains are equant, some with annealing twins and equilibrium triple junction angles approaching 120°. As in sphalerite, recrystallization in chalcopyrite was probably dynamic, even though no subgrain structure was detected. It seems, however, that the recrystallized grains have suffered some degree of deformation, as some triple junctions do not show equilibrium and some grain shapes are elongated. Recrystallized grains often cluster around grain boundaries of relict, strongly deformed grains, a texture that has been observed in syn-tectonic recrystallized quartz (White 1977). This texture is due to boundary migration processes which are important in the development of dynamically recrystallized microstructures (Cox 1987). During secondary recrystallization abnormal grain growth led to grainsizes up to 1.5 mm.

Galena. Grainsizes in galena vary between 0.2 and 0.8 mm with some coarse aggregates containing grains up to a few mm. Elongation of recrystallized grains is common as a result of recrystallization and growth during deformation. Slip has probably been operative to produce elongate grain shapes even though the slip planes have not been directly observed. The textures observed in galena are due to recovery and recrystallization. This is indicated by the formation of subgrains with irregular shapes and free-ending subboundaries (Fig. 6e). Nucleation of recrystallized grains possibly took place from subgrains.

Pyrrhotite. Deformation textures such as twins, kinks, slip bands and subgrains which have been described for pyrrhotite (Graf & Skinner 1970, Clark & Kelly 1973, Atkinson 1974) have not been developed by pyrrhotite from the CSA mine. Instead the pyrrhotite fabric is characterized by equant polygonal grainshapes and triple junction angles approaching equilibrium; textures that are due to extended annealing processes. The only indications of deformation are intergranular fractures of the type that have been observed from pressure release in the experimental deformation of pyrrhotite by Atkinson (1974), and which are possibly due to unloading at the CSA mine.

DISCUSSION

The deformation textures observed in the sulphides from the CSA mine are similar to those achieved in experimental deformation of ore minerals. However, it has to be taken into account that the experiments were carried out on dry sulphides and at strain rates which are up to 10 orders of magnitude faster than geological strain rates, and as Etheridge *et al.* (1984) pointed out, water can influence the chemical and mechanical behaviour of sulphides. Therefore deformation and recrystallization of sulphides under natural conditions may occur at lower temperatures than those indicated by the experiments. This temperature difference has been implied for chalcopyrite by Roscoe (1975).

Deformation of pyrite from the CSA mine has been in a brittle manner by brecciation and fracturing. Even though ductile behaviour of pyrite is possible and has been achieved in experiments, this has only been observed for temperatures greater than 450°C at 300 MPa confining pressure and strain rates of 10^{-4}–10^{-5} s^{-1}. Below this temperature pyrite is expected to behave cataclastically. The often elongate nature of overgrowth textures on CSA pyrite indicate that deformation by pressure solution might have taken place, a process very common in low-grade metamorphic terrains (McClay & Ellis 1983, 1984, Ramsay & Huber 1983). However, there is no doubt that some of the overgrowth textures observed in CSA pyrite are due to overgrowth by pyrite phases which were deposited later in the paragenesis.

Sphalerite, chalcopyrite, galena and pyrrhotite show textures of ductile deformation similar to those achieved in the experimental deformation of common sulphides. Twinning, slip and microfracturing have been observed during the experimental deformation of sphalerite at temperatures up to 500°C, 200 MPa and strain rates of $7.2 \times 10^{-5}\,s^{-1}$ (Clark & Kelly 1973). Sphalerite is one of the stronger sulphide minerals but nevertheless is ductile over most conditions of regional metamorphism. Galena is the most ductile of the common sulphides. The microstructures observed in galena from the CSA mine are due to extensive recovery and recrystallization processes. Structures indicative of intracrystalline strain, such as subgrains (Fig. 6e), are present but subgrain coalescence has taken place during continued recovery and recrystallization. Recrystallization in pyrrhotite has been more intense than in the other sulphides resulting in a purely recrystallized, polygonal fabric. This is in contrast with the observations from the experimental deformation of pyrrhotite which showed recovery and recrystallization to be important at temperatures greater than 450°C (Clark & Kelly 1973, Atkinson 1974, McClay 1983). However, annealing recrystallization of natural

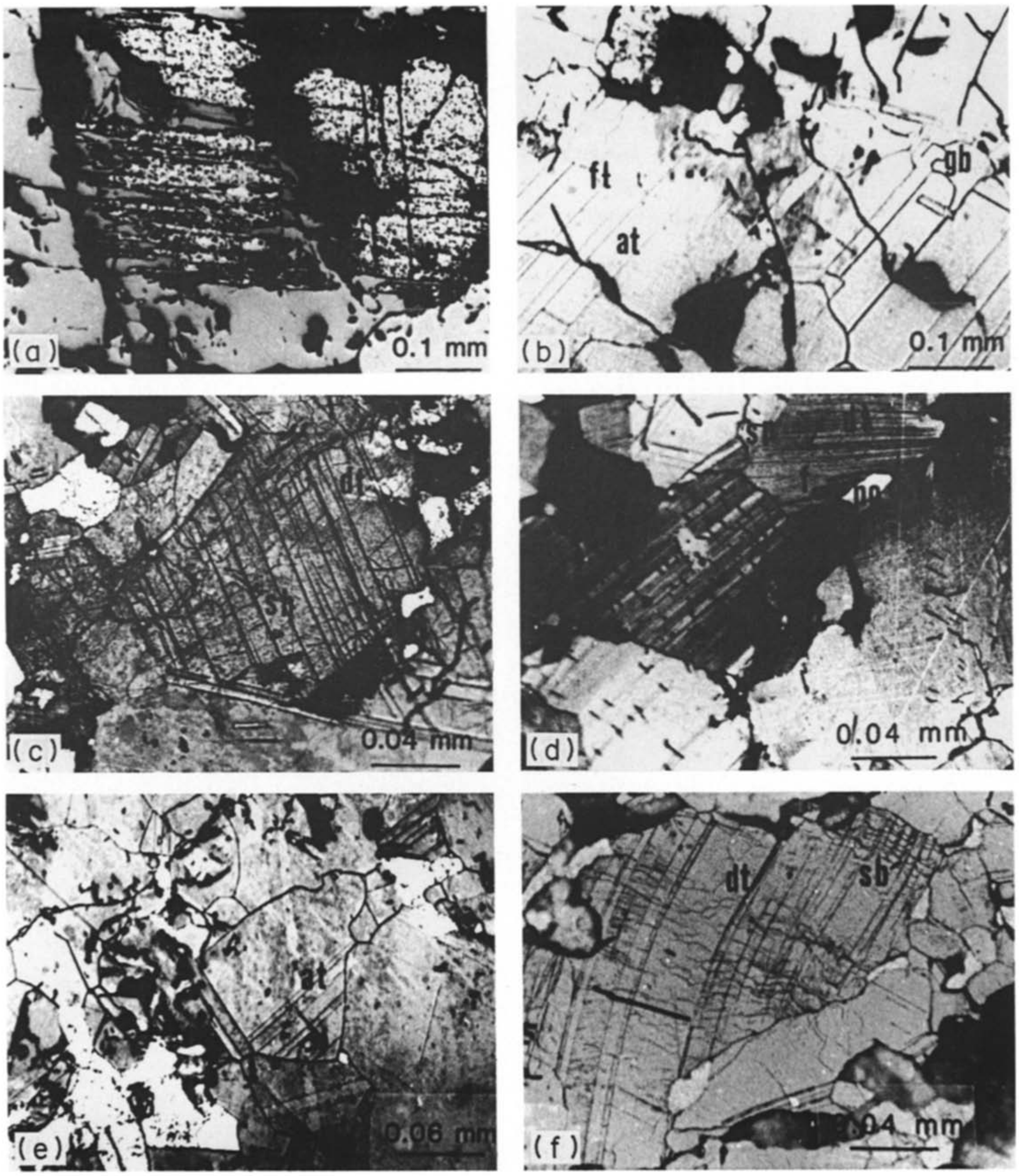

Fig. 5. (a) Secondary pyrite and marcasite from replacement of pyrrhotite along (0001) basal planes. (b) Adjustment of grain boundaries through grain-boundary bulging (gb) of sphalerite. Note also straight annealing twins (at) and free-standing twins (ft) (H_2O_2 etch). (c) Polysynthetic deformation twins in coarse sphalerite (dt). A weak developed subgrain structure (sb) overprints the deformation twins (H_2O_2 etch). (d) Feather twins (f) in sphalerite at the contact of sphalerite (sp) and Pyrrhotite (po) as response to local stress. Note also deformation twinning (dt) in neighbouring sphalerite grains (HI etch). (e) Straight annealing twins (at) at sphalerite grow at the expense of neighbouring grains. Arrows indicate growth direction (H_2O_2 etch). Subgrains (sb) in sphalerite show a higher density where deformation twins (dt) have been bent (H_2O_2 etch).

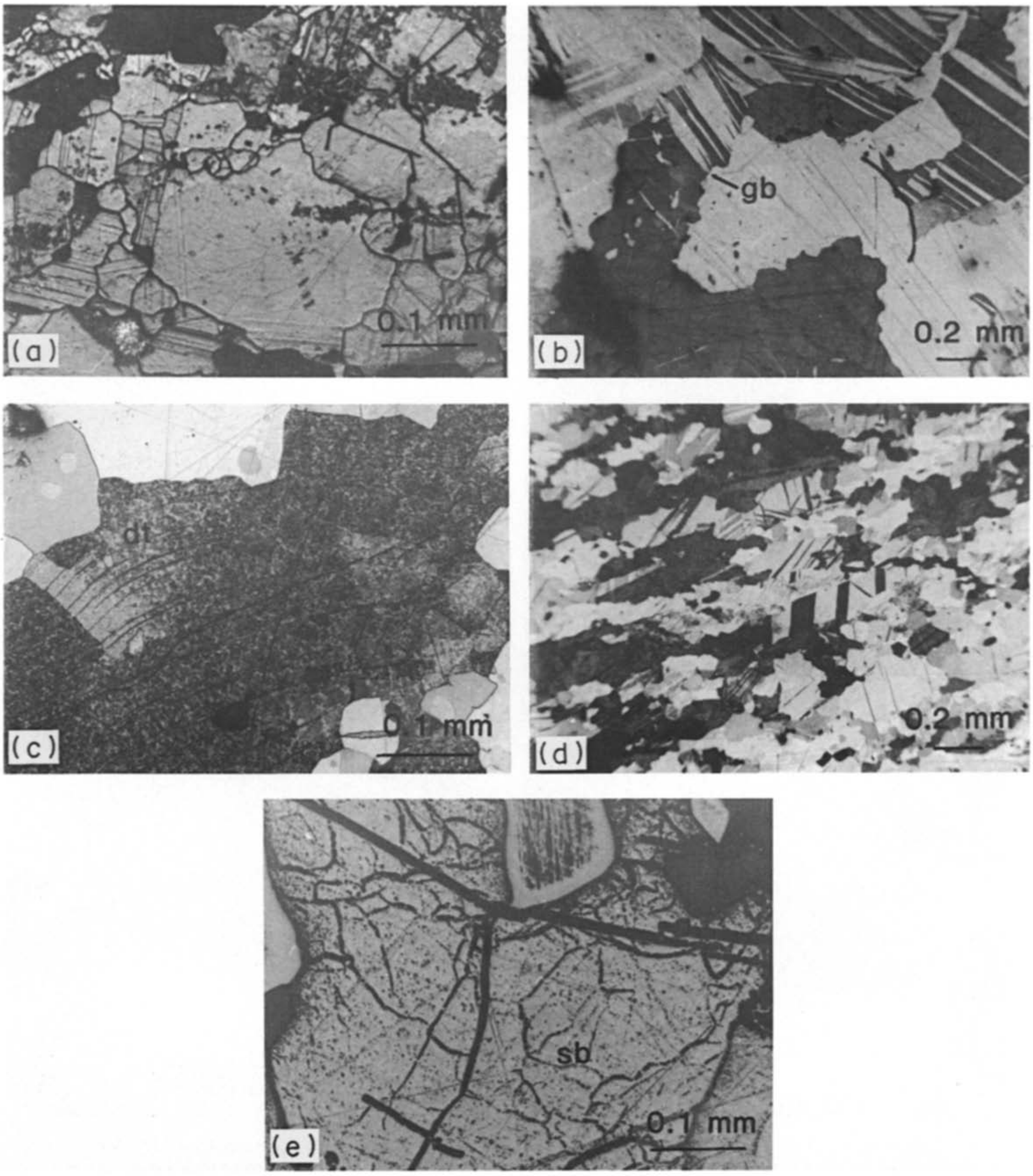

Fig. 6. (a) Recrystallization fabric in sphalerite. Note the clustering of new recrystallized grains along the grain boundary of a coarser sphalerite grain (H_2O_2 etch). (b) Cuspate grain boundaries in chalcopyrite as a result of grain-boundary bulging (gb) (NH_4OH+ H_2O_2 etch). (c) Polysynthetic deformation twins (dt) in chalcopyrite. Curvature of twins is an indirect indication of slip (NH_4OH + H_2O_2 etch). (d) Recrystallization fabric in chalcopyrite. Note elongate grains and clustering of new recrystallized grains around larger elongate grains (NH_4OH H_2O_2 etch). (e) Subgrain structure (sb) in galena. Subgrain boundaries are incomplete and free ending (HCl + Thiourea etch).

pyrrhotite is common in some low-grade ores (Marshall & Gilligan 1987).

The fabric both in sphalerite and chalcopyrite is typical of dynamic syn-tectonic recrystallization (Figs. 6a & d). The development of strongly differing grainsizes and differing degrees of deformation within polycrystalline sphalerite and chalcopyrite is similar to that observed in syntectonically recrystallized quartz (White 1973, 1977), and similar to the dynamic recovery and recrystallization processes that occur during steady-state deformation in metals and ceramics (Hardwick *et al.* 1961/1962, Honeycombe 1984) and in experimentally deformed ice (Burg *et al.* 1986, Wilson 1986).

In a dynamically recrystallized fabric the newest recrystallized grains are undeformed or only slightly deformed, whereas the oldest grains are subjected to a greater degree of deformation (White 1977). Both sphalerite and chalcopyrite from the CSA mine show clearly different degrees of deformation in different grains within one sample. In both sulphides the coarser grains show a greater degree of deformation with the development of deformation twins, serrate grain boundaries, grain elongation and in sphalerite, subgrain formation, which indicate that they are older than the smaller recrystallized grains (Figs. 5c & f and 6c). However, the newly recrystallized grains are not strain-free as would be expected during post-tectonic static recrystallization. Instead they show signs of intracrystalline strain such as curvature of annealing twins and in the case of sphalerite, development of a subgrain structure. The annealing twins have often been affected themselves and show a well developed subgrain structure. Well developed subgrain deformation textures in some grains and their absence in others are noted in sulphides from other deposits, such as dynamically recrystallized chalcopyrite from Tasmania (Cox & Etheridge 1984). Nucleation of recrystallized grains can take place by two major mechanisms—the rotation of subgrains or the bulging of high-angle grain boundaries. Both mechanisms have been observed in quartz (White 1977) and experimentally deformed ice (Wilson 1986). Microstructures in sphalerite, chalcopyrite and galena suggest that both mechanisms could have been operative for new grain nucleation during dynamic recrystallization.

Following dynamic recrystallization, secondary growth appears to have taken place both in sphalerite and chalcopyrite and this is shown by abnormal grainsize, free ending twins and 'migration recrystallization' (Guillope & Poirier 1979) (Figs. 5b & e).

The microstructures observed in the sulphides from the CSA mine are similar to those in the associated silicates. In quartz the abundant undulose extinction and trails of fluid inclusions along subgrain boundaries indicate that formation of subgrains has been intense (White 1973). Kinking is also a common texture found in quartz and the fabric is typical of dynamic recrystallization with recrystallized grains clustering along grain boundaries of elongated, strained grains from which they have formed, similar to the fabric observed in sphalerite and chalcopyrite, suggesting that both sulphides and silicates have been deformed by similar processes. However, solution transfer (pressure fringes around pyrite) has been important in quartz and this is consistent with the observation by Etheridge *et al.* (1983) that solution transfer is an important deformation process in silicates whereas dislocation glide is the dominant mechanism in sulphides. In the silicates from the CSA mine, especially quartz, both solution transfer and dislocation glide have been operative.

CONCLUSION

Ore minerals and silicates from the CSA mine all show the effect of deformation and metamorphism. The major deformation mechanisms observed include brittle failure, mechanical twinning, dislocation climb (subgrains) and possibly solution–precipitation creep (pressure solution). Dynamic recrystallization of chalcopyrite and sphalerite led to textures similar to those observed in quartz mylonites (White 1977) and in experimentally deformed ice (Burg *et al.* 1986, Wilson 1986).

Processes which led to the observed microstructures are not unlike those operating during the dynamic recovery and recrystallization in metals and ceramics (Hardwick *et al.* 1961/1962, Honeycombe 1984). Nucleation of strain-free grains took place along grain boundaries and from subgrains within coarser, more strongly deformed grains. The resulting structure consists of polycrystalline aggregates with different grains showing different degrees of deformation. The attempt to relate the microstructures of different sulphide assemblages to different stages in genesis proved to be difficult, most likely due to the mild effect that the D_2 deformation event had on the mineral assemblages. However, deviatoric stress regimes have been operative in the mine area and have led to a more strongly deformed chalcopyrite fabric in shear zones.

Minor post-tectonic recrystallization has led to the development of straight annealing twins and secondary recrystallization, resulting in abnormal grainsizes.

This study indicates that the ore zones at the CSA mine have formed early in the deformation history. Continuous syn-tectonic grain growth, deformation and recrystallization microstructures complement sulphide structures found on a mesoscale, especially the relationships between vein orientation and the cleavage. They show that mineralization commenced early in the deformation history and continued into a late-kinematic stage (i.e. minor occurrence of late shear veins). They are consistent with an early syn-tectonic origin for the main mineralization at the CSA mine and argue against a model of a deformed syn-genetic body.

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