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Polyphase Deformation of the Massive Sulphide Ore of the Black Angel Mine, Central West Greenland

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The massive Fe-Zn-Pb sulphide sheets constituting the Angel Zone ore body of the Black Angel Mine, show evidence of three phases of deformation at greenschist facies metamorphic grade. During an early phase an originally layered sulphide ore type was isoclinally folded. Subsequent thrusting parallel to the ore body transformed the layered ore into massive and porphyroclastic ore tectonites. Late, open folds refolded the earlier structures and caused localized differential mobilization of the sulphides. The microstructures of the layered ore tectonite indicate a period with static grain growth, interpreted as the result of prograde metamorphism, followed by a dynamic recrystallization under low stress and at low strain rates, which is correlated with the early isoclinal folding. The microstructures of the massive and the porphyroclastic ore tectonites indicate syntectonic recrystallization under high stress and at high strain rates, corresponding to the thrusting of the ore bodies. The microstructures of the mobilized sulphides show evidence of repeated plastic/cataclastic deformation and recrystallization, corresponding to highly variable strain and strain rate conditions during the mobilization. Post-deformational annealing took place at elevated temperature and was largely controlled by inhibition-dependent grain growth and to a minor extent by orientation-dependent grain growth.

INTRODUCTION

The Black Angel Mine, central West Greenland, is developed in two massive Fe-Zn-Pb sulphide ore bodies, the Cover Zone in the east and the Angel Zone in the west. The ore bodies occur in the lower Proterozoic Marmorilik Formation (Fig. 1) which comprises a sequence (up to 1200 m thick) of carbonates with minor, intercalated fine grained clastics and which overlies older basement gneisses with an erosional discordance. The nearly flat-lying, sheet-like ore bodies are up to 600 m wide and 1000 m long, and vary in thickness between 0.5 m and 35 m. They contain a total of 7 million metric tons of ore with an average grade of 5.5% Pb, 15% Zn and 30 ppm Ag. The sulphide sheets occur in the upper part of the Marmorilik Formation at an elevation of 600 m to 700 m above sea-level, 1 km east of the mining town of Marmorilik. They are intercalated in a sequence of graphite-bearing dolomite laminites, evaporite-bearing

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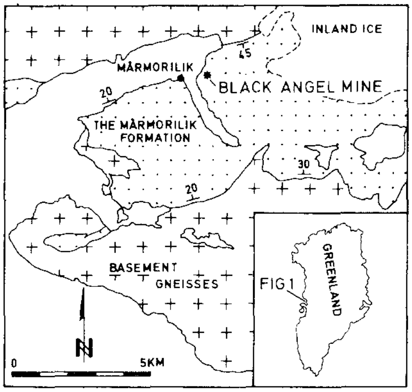


Fig. 1 Generalized geological map of the Marmorilik district

marble and minor semipelite, and are interpreted as having formed by interaction between metal-carrying sabkha brines and H_2S formed by bacteriological or abiological degradation of the sulphates (Pedersen, 1980). Subsequent to the formation of the ore bodies, the rocks of the Marmorilik district were deformed and metamorphosed during the evolution of the Rinkian mobile belt which has been radiometrically dated at 1790-1650 m.y. (Henderson and Pulvertaft, 1967). An early phase of deformation (D_1) involved south-directed wedging in the basement gneisses with accomodating folding of the overlying metasediments into south-facing, tight- to isoclinal synclines. During the final stage of the emplacement of the basement wedges, the synclines were transected by southward-directed thrusting (D_2). A late deformation episode (D_3) was associated with the appearance of megascopic dome structures in the ductile basement gneisses. The metasediments slid off the rising domes and were deformed into open- to tight folds, overturned to the north and overprinting the earlier formed structures. During and after deformation the rocks of the Marmorilik district were subject to a regional metamorphic event which produced recrystallization under conditions corresponding to middle- to lower greenschist facies (Garde, 1978).

The three phases ($D_{1, 2, 3}$) are reflected in the mesoscopic structures of the Black Angel Mine area, though within the sulphide ores the effects of individual phases are more localized and have been accompanied by the development of distinctive ore tectonites. Consequently the microstructures of the tectonites can be related to respective phases and, as metamorphic conditions and the effects of confining pressure can be shown to have been relatively constant throughout the deformation, they can be used to illustrate the responses of massive sulphides to variations in stress, strain and strain rate.

In the present study, the microstructures within the more westerly of the ore bodies, The Angel Zone, are described and interpreted. Details of the tectonic events within this ore body and of the P-T conditions which prevailed during the deformation are given elsewhere (Pedersen, 1980a) but have been summarized below as a background to the present investigation.

TECTONIC EVENTS WITHIN THE ORE BODY

By a comparison with the easternmost Cover Zone ore body, the pre-deformational shape of the Angel Zone ore body is thought to have been an elongate, saucer shaped sheet, with a thickness of 0.5 - 8 m (Fig. 2. 1). The least deformed parts of the ore bodies consist of up to 1 m thick pyrite-rich layers that alternate with weakly- to distinctly-layered (mineralogically) sulphides composed of mm- to cm-thick laminae of pyrite and sphalerite + galena (Fig. 3). The layering in general parallels the layering in the enclosing marbles and suggests that the ore was widespread prior to deformation.

The first deformation phase (D_1) is represented in the Angel Zone ore body by a number of recumbent, isoclinical

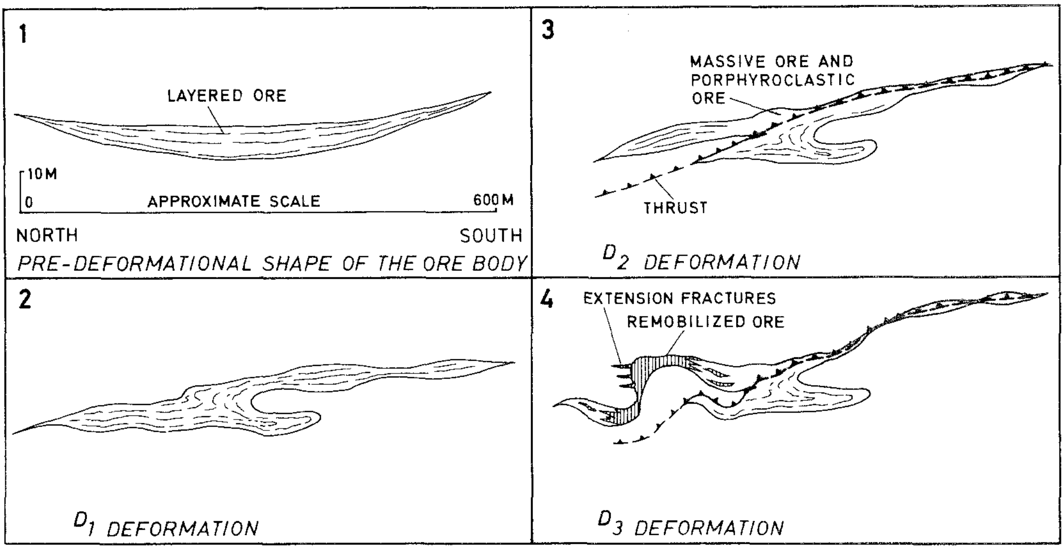
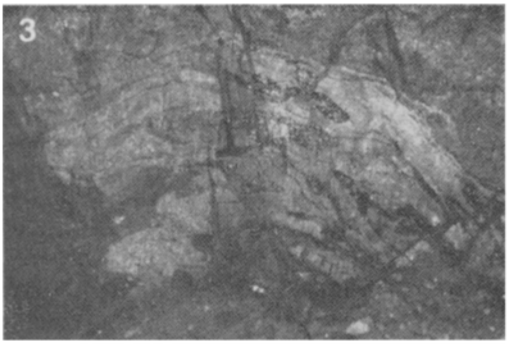


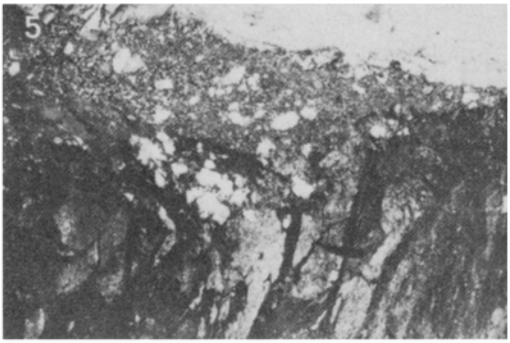
Fig. 2. Schematic representation of the tectonic development of the Angel Zone ore body. For explanation, see text

folds occurring along the lower boundary in the central part of the sulphide sheet and by pinch and swell structures in the south (Fig. 2.2). The layered ore deformed by small scale folding and plastic flow parallel to the layering (Fig. 3). The more mobile minerals (galena, chalcopyrite, sphalerite) were mobilized towards local, low stress areas such as the hinge zones of small folds, extension fractures in folded, pyrite-rich ore and necked zones in the sulphide sheet.

The D_2 deformation is defined by a number of low angle thrusts that have displaced the upper parts of the ore body towards the south. The thrust planes were mainly confined to the sulphide sheet (Fig. 2.3) and caused intense shearing of the layered ore to produce massive and porphyroclastic ore tectonites. A transition in ore types can be traced from the lower, isoclinally folded areas towards the thrusts: The layering of the ore first becomes wispy and irregular, but closer to the thrust planes the ore has recrystallized to a finer grain size and is more massive in appearance. Milled-out fragments of pyrite ore and rounded marble inclusions (derived from fragments of carbonate layers in the sulphide sheet) are indicators of the intense D_2 shearing of the ore body. The thrust planes are marked by layers of porphyroclastic ore (Fig. 4), composed of "large" (up to 5 mm), rounded pyrite grains (reflecting the relict grain size of the layered ore) in a matrix of extremely fine grained sphalerite and galena.

The final phase (D_3) is most pronounced in the northern region of the ore body, where open- to tight D_3 folds, overturned to the north, caused widespread differential mobilization of mobile elements in the ore body (Fig. 2.4), producing a coarse grained, mobilized ore tectonite. The hinge zones of the larger folds typically contain a zoned, coarse grained ore layer composed of a lower sphalerite-pyrite-carbonate layer and a galena-fahlore-quartz layer along the fold crests (Fig. 5). During the later stages of the mobilization, an increase in pore fluid pressure led to hydraulic fracturing of the host marbles along the steep limbs of the folds with the coarse grained sulphides being subjected to further plastic deformation and fluid





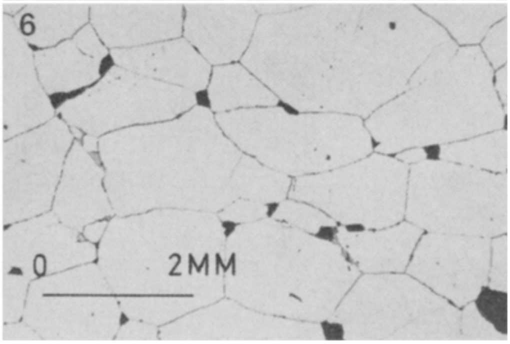


Fig. 3. Isoclinally folded layered ore from the lower part of the Angel Zone ore body, deformed during D_1. Pyrite layers (grey and light grey) alternate with sphalerite-galena layers (dark grey and black)

Fig. 4. Porphyroclastic ore (grey, above hammer) along D_2 thrust plane which separates white marble (uppermost) from grey, laminated marble (lowermost). Lenses of white, coarse grained calcite have precipitated along the base of the thrust plane. Note the lenticular and subrounded quartz bodies (dark grey to black, above hammer) which represent tectonized and recrystallized chert inclusions

Fig. 5. Mobilized sulphides (D3) from the upper, northern region of the ore body. A layer of massive, coarse grained sphalerite (dark grey, behind hammer) is overlain by a galena-fahlore-quartz layer (grey). The enclosing marbles (white) are at the top. Note the patches of coarse grained quartz (white, light grey) in the galena-rich layer

Fig. 6. Aggregate of elongate pyrite grains from a pyrite-rich layer in the lower, isoclinically folded part of the ore body, annealed during D_1. Black areas represent dissolved carbonate. Note the intergranular films of chalcopyrite (light grey). Etched (pyrite etching: conc. HNO_3, 1 minute)

state remobilization as they cemented the fractures. The effects of D_3 in the southern part of the ore body appear to have been limited to gentle folding with some thickening of the hinge zones of upright folds and concomittant thinning along the limbs.

P-T CONDITIONS DURING THE DEFORMATION

In a recent study of the deformation and differential mobilization of the Angel Zone ore body, Pedersen (1980a) concludes that the maximum metamorphic conditions indicated for the mine area are 500°C at a fluid pressure of up to 1.5 kb. A metamorphic peak in the mine area is mirrored by the scattered occurrence of tremolite. Within the sulphide ore, the tremolite occurs in an assemblage with phlogopite, chlorite, calcite, dolomite and quartz. It shows equilibrium grain boundaries with each, except for the chlorite and dolomite which are present in too small quantities to permit relations to be determined with certainty. Tremolite rarely shows any microscopically visible signs of plastic deformation where it is associated with sulphides showing typical D_1 microstructures (see below), but deformed phlogopite is ubiquitous. In several places tremolite occurs in contact with intensily deformed phlogopite, suggesting that the growth of the tremolite took place after the cessation of the movements which deformed the mica. In contrast to this, the tremolite, phlogopite, quartz and, to some extent, the carbonates which occur in association with sulphides showing D_2 and D_3 microstructures (see below) have evidently been fractured, bent and kinked. However, the tremolite, though clearly pre-D_2 and D_3, shows no signs of retrogression to lower temperature assemblages and hence supports the suggestion that the three phases of deformation took place at approximately equivalent temperatures.

MICROSTRUCTURES OF THE ORE MINERALS

As the three phases of deformation affected different parts of the Angel Zone ore body with varying intensity (Pedersen, 1980a), it is possible to define domains in which the mesoscopic effects of any one phase are dominant. Further, as distinctive types of ore tectonites are associated with each phase, it may be reasonably assumed that where a particular ore tectonite is predominant, the microstructures of the ore can be considered to have developed as a result of one phase of deformation. Generally, where early phases are predominant, overprinting by later phases is either weak, consisting of minor microstructural adjustments, or is absent. Where later phases are dominant, the effects of earlier phases are largely obliterated.

For the purposes of the present investigation, three domains have been selected, each exemplifying the effects of a different deformation phase: i) the Central Domain, where D_1 is well-developed in the lower, central area of the ore bdoy and is characterized by isoclinically folded, layered ore (Fig. 3); ii) the Southern Domain, where the massive and porphyroclastic ore tectonites produced by intense shearing (Fig. 4) are associated with D_2 thrusting in the south of the ore body; and iii) the Northern Domain, where coarse grained, mobilized and remobilized ore tectonites (Fig. 5) are associated with the open, D_3 folds in the north of the ore body. Locally, D_2 ore tectonites have undergone microstructural modifications during D_3 and consequently, these are described seperately and in addition to the accounts of the microstructures of each of the domainal ore tectonites. The terminology adopted in the accounts below follows Stanton (1972) with the exception that recrystallization is defined as the process of formation and/or the migration of a high angle grain boundary.

THE CENTRAL DOMAIN: D_1 MICROSTRUCTURES OF THE LAYERED ORE TECTONITE

This ore tectonite is composed of alternating layers of nearly monomineralic pyrite and layers composed of sphalerite + galena in varying amounts (Fig. 3). As the two types of layers respond quite differently to deformation due to a large ductility contrast they will be treated seperately.

The pyrite layers are up to 1 m thick and comprise up to 70% (weight) pyrite. The remainder is mainly interstitial carbonate with sphalerite, chalcopyrite and quartz occurring in minor, varying amounts. The grain size of the pyrite

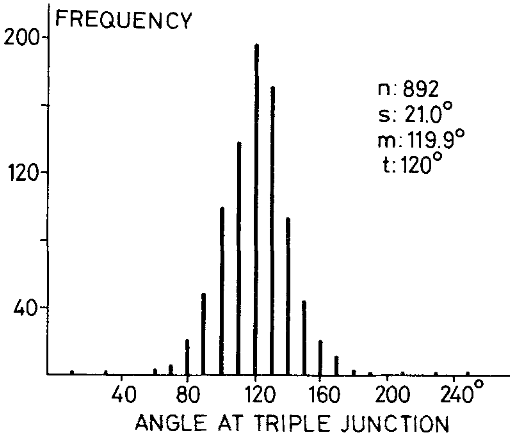


Fig. 7. Frequency distribution of triple junction angles in monomineralic, elongate pyrite grain aggregates, annealed during D_1. n: number of measurements; s: standard deviation; m: mean value; t: theoretical value of angle

is between 0.2 and 4 mm, but locally, secondary recrystallization (coarsening) has produced porphyroblasts up to 3 cm in diameter. The grains define a granoblastic microstructure ("foam-structure") with smooth or curved grain boundaries. Minor chalcopyrite and galena are frequently present, forming intergranular "films". Sphalerite in general occurs as elongate or rounded bodies along the grain boundaries, and as cuspate to subrounded bodies at triple junctions. Although some individual pyrite grains are equidimensional, aggregates are generally characterized by elongate grain shapes (Fig. 6). Measurements of triple junction angles in monomineralic pyrite aggregates show an unimodal distribution with a mean value close to the theoretical value of 120° (Fig. 7). Although not statistically significant in itself, the relatively large standard deviation of the distribution may indicate considerable heterogenity of the degree of annealing in the sample material as compared to calculated distributions and with distributions from naturally and experimentally annealed materials (Smith, 1964; Stanton, 1972 p. 237).

The sphalerite-galena layers of the layered ore are characterized by their relatively coarse grain size (5-6 mm). The microstructures show evidence of an early grain growth period, interpreted as D_1 in age, followed by minor plastic deformation, and differential recrystallization of galena. This later deformation is interpreted as the combined effects of D_2 and D_3 deformation. The D_1 microstructures of the sphalerite and the galena consist of well developed foam structures with the minor phase, galena, occurring as an intergranular film or as cuspate bodies which fill the interstices between the sphalerite grains (Fig. 8). The sphalerite shows abundant twins which, although generally slightly deformed, are interpreted as annealing twins by analogy with similar twins described by Richards (1966) and Stanton and Gorman (1968). Measurements of the dihedral angles at sphalerite/sphalerite/galena triple junctions show that the aggregates have annealed. However, a blunting of the frequency distribution and a relatively large standard deviation (17.4° on 392 measurements with a mean value of 127.8° and a theoretical value of 134°) suggests the presence of D_2 and D_3 deformation effects, subsequent to which the aggregates did not anneal completely. Microstructural equilibrium has been attained in the Pb-Zn-rich layers between sphalerite-galena and scattered pyrite grains and aggregates. The grain shape of the pyrite closely reflects the matrix in which it grew. Subhedral to euhedral crystals or anhedral grains with smooth grain boundaries are developed where pyrite is in contact with pyrite, galena or non-opaque minerals. Anhedral grains with seriate to interlobate grain boundaries are frequently developed where pyrite occurs in contact with sphalerite. Both of these microstructural types indicate the attainment of equilibrium between pyrite and the neighbouring minerals during the early grain growth. The caries-like corrosion of pyrite in contact with sphalerite occurs preferentially along crystal faces other than (100) and, as pointed out by Stanton (1964), this corrosion is probably an orientation effect or the result of the presence of an iron poor sphalerite along the contact. Poikiloblastic pyrite is important as it provides evidence for the nature of the subsequent deformation. The inclusions are typically composed of one large sulphide grain which, in the case of sphalerite, often shows annealing twins and small exsolution bodies of chalcopyrite. The inclusions and the matrix frequently show a close lattice orientational relationship which suggests that the poikiloblastic pyrite at least in part grew under near-static conditions (Fig. 9).

Quartz and carbonates have annealed with the sulphides (Fig. 10) while phlogopite is deformed by kinking, bending and locally by fracturing. Chlorite is deformed in some samples, but usually it is developed as fan-shaped crystal aggregates (Fig. 10). Tremolite appears to be microscopically undeformed. It occurs as columnar crystals which are frequently associated with intensily deformed phlogopite.

A number of mineral phases of minor importance have annealed with the main ore minerals during this early annealing period. Chalcopyrite is the most widespread, being closely related to sphalerite in which it occurs exsolution bodies along annealing twins (Fig. 11) and along grain boundaries. Stannite occurs as single grains or simple aggregates, in most cases closely related to sphalerite, and a few scattered grains of arsenopyrite, electrum, polybasite, rutile, hematite, magnetite, and graphite have been noted.

Interpretation of the D_1 microstructures. Nonequilibrium microstructures in pyrite grains described by Pedersen (1980a) include framboids, euhedral and fibrous growth cortices, nucleation centers of euhedral pyrite and quartz grains and colloform microstructures. They suggest that the starting material for the later-formed granoblastic microstructure was no different from other stratabound sulphide deposits, which in general consist of extremely fine grained sulphides.

The D_1 microstructures of the pyrite layers show many similarities with aggregates formed by static grain growth or annealing (Smith, 1964; Stanton, 1964, 1972; Lawrence, 1972). However, the well-annealed elongate pyrite grains, which characterize the isoclinally folded ore, cannot solely be interpreted as a result of static grain growth. Massive sulphide ores in which elongate pyrite grains define a foliation have been described by several authors (Kanehira, 1959; Vokes, 1969; Mookherjee, 1971; Rickard and Zweifel, 1975), but as pyrite deforms almost exclusively by cataclasis under nearly all geologically feasible experimental conditions (Graf and Skinner, 1970; Atkinson, 1975), the interpretation of elongate pyrite grains in deformed rocks is problematic. Atkinson (1975) suggests that plastic deformation of pyrite may take place at very high sulphur vapour partial pressures, but as this situation is envisaged to be rare in nature, this type of deformation is probably subordinate. An alternative possibility is that deformation is accomplished by "pressure solution" (or Coble creep), involving diffusion along the grain boundaries (possibly with the participation of a chemically active fluid) at levels of stress which are too low for significant amounts of cataclastic or plastic deformation to take place (Atkinson, 1975). In the case of the Black Angel ores, the occurrende of elongate pyrite grains is tentatively interpreted as an indication of a period during which the deformation of the pyrite took place at low stress and at very low strain rates by diffusion creep. Although not possible to demonstrate microscopically, it is yet difficult to imagine a situation where a temperature of 500°C has been attained during the deformation, without any prior static grain growth in the sulphides. It is therefore suggested that the development of the D_1 microstructures observed in the pyrite took place by a combination of the two processes.

The D_1 microstructures of the sphalerite-galena layers are characterized by a number of features which, by anal-

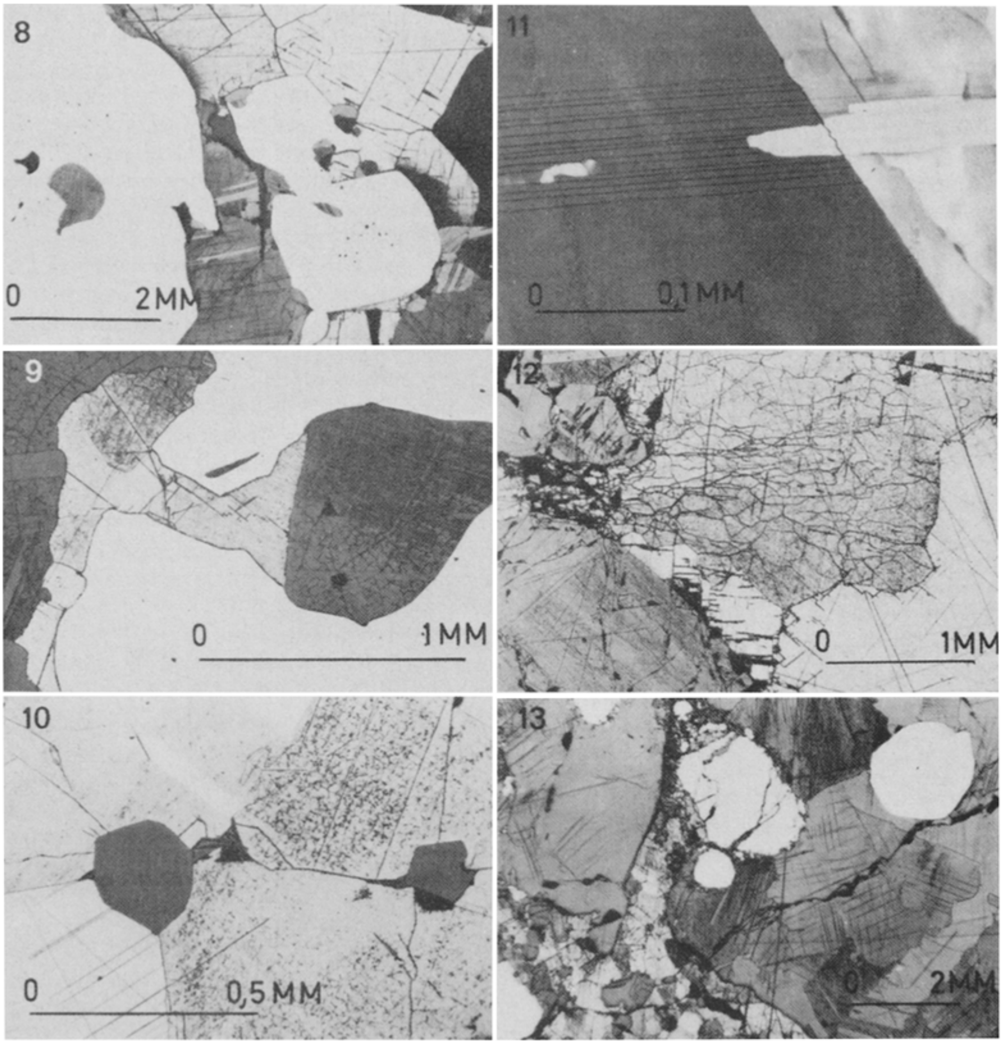


Fig.8-13

ogy with some of the microstructures of the pyrite layers, indicate a static annealing resulting in aggregates composed of equidimensional grains. However, the interpretation of the elongate pyrite grains as having been formed by diffusion creep suggests that the equidimensional sphalerite and galena grains to some extent formed by dynamic recrystallization and grain growth, although this is very difficult to demonstrate microscopically. This type of deformation is nevertheless a feasible process at the temperatures that are indicated to have prevailed during the D_1 deformation.

Syntectonic recovery and recrystallization of experimentally deformed galena has been reported by several authors (Gill, 1969; Salmon et al., 1974; Atkinson, 1974, 1976, 1977, 1978; Clark and Kelly, 1976; Clark et al., 1977; McClay and Atkinson, 1977). Atkinson (1976, 1977) suggests that coarse grained galena ores may undergo recrystallization and normal grain growth during de-

Fig. 8. Annealed D_1-aggregate composed of pyrite (white), galena (light grey, with cleavage traces) and sphalerite (dark grey and black). Annealing twins in sphalerite indicates slight deformation (bending), which is also shown by the subparallel deformation twins (thin, curved lines, lower center). Etched (galena and sphalerite etching: thiourea solution, 80°C, 1.5 minutes; for details, see Rickard and Zweifel, 1975)

Fig. 9. Partly incorporated inclusion of sphalerite (dark grey) and galena (light grey) along the rim of a large pyrite grain (white). Note the close orientational relationship between the galena inside the pyrite grain and on the surface of this grain, indicated by the slightly deflected cleavage traces. D_1 annealing; etched

Fig. 10. D_1 annealing between sphalerite (light grey) and quartz (grey). Aggregates of chlorite are associated with the quartz (grey and black, left center). Etched

Fig. 11. Chalcopyrite exsolution bodies (light grey) in D_1 annealed sphalerite (dark grey and grey; grain boundary in right hand side of figure). Note the complete agreement between annealing twins in the two minerals. Etched, 2 nicols partly crossed

Fig. 12. Weakly deformed sphalerite (grey, left hand side)-galena (light grey and nearly white) D_1 aggregate. A flattening (D_2) has caused formation of elongate subgrains in the galena between the two sphalerite aggregates. Etched

Fig. 13. D_2 shear-zone in small galena-rich layer (various shades of light grey, fine grained) between sphalerite aggregates (grey). The sphalerite shows abundant deformation twins and patchy (primary) recrystallization. A pyrite grain (white) in the shear-zone has deformed cataclastically. Etched

formation at temperatures above 300°C and at low strain rates. In view of the low strain rates indicated for D_1 by the elongate pyrite grains, and the ability of ready recovery and annealing shown by galena at 400°C to 600°C (Siemes, 1964, 1976, 1977; Stanton and Gorman, 1968; Stanton and Gorman Willey, 1970, 1971, 1972; Stanton, 1970), it is not to be expected that the microstructures developed in galena by syntectonic recovery and recrystallization under the given tectonic conditions will be any different from those formed by static annealing.

Due to its more complex crystal structure, sphalerite tends to differ from galena in its response to deformation. As opposed to galena, sphalerite deformed and annealed experimentally over a wide range of temperatures shows no microscopically visible signs of recovery, the most commonly observed annealing feature being recrystallization to a new, fine grain generation in the old strained crystals. According to Clark et al. (1977), this difference in behaviour is caused by the nature of the dislocations in the two minerals. In galena the dislocations formed during deformation tend to be complete dislocations, i.e. the Burgess vector is equal to an identity period of the lattice. This allows the dislocations to move through the lattice withouth disturbing the structure, thereby enhancing recovery processes. In sphalerite the dislocations tend to separate into partial dislocations which are unable to migrate through the lattice without disturbing the crystal structure. This results in dislocation pile-ups and the appearance of stacking faults in the lattice. In this case, recrystallization tends to be the more economic annealing process. The sphalerite aggregates of the layered ore are characterized by a fairly coarse grain size, and show evidence of normal grain growth, and disposition of "foreign" mineral phases during this growth. Accordingly, these aggregates show many similarities with experimentally deformed sphalerite aggregates which in turn have been statically annealed at temperatures of 400°C to 600°C (Stanton and Gorman, 1968; Stanton and Gorman Willey, 1971; Stanton, 1972). By analogy with the interpretation of the pyrite aggregates, the sphalerite-galena aggregates thus could have formed by a static grain growth followed by a dynamic recrystallization and grain growth during D_1.

THE SOUTHERN DOMAIN: D_2 MICROSTRUCTURES OF THE MASSIVE AND THE PORPHYROCLASTIC ORE TECTONITES

The microstructures of the massive and the porphyroclastic ore tectonites show evidence that they formed from the layered ore tectonite during at least one major episode with plastic deformation and recrystallization of the ductile minerals and cataclastic deformation and partial recrystallization of the brittle aggregates. The massive ore occupies an intermediate position between the layered ore tectonite and the porphyroclastic ore tectonite with regard to microstructure. It contains relicts of strained ductile-, and fragments of brittle mineral aggregates originating from the layered ore tectonite, set in a matrix of new, recrystallized small grains. The massive ore tectonite shows a gradational relationship to the porphyroclastic ore tectonite which represents the final product of D_2 deformation. This is composed of rounded pyrite grains or aggregates which reflect the original grain size of the layered ore tectonite ("porphyroclasts", Spry, 1969, p. 228), occurring in a matrix of fine grained sphalerite and galena formed by complete recrystallization of the medium grained ductile minerals originally present in the layered ore tectonite.

Sphalerite and Galena

The first indications of plastic deformation (D_2) of the layered ore tectonite is observed in Pb-Zn-rich regions as a weak straining of sphalerite and galena. At elevated temperatures galena responds to deformation by subgrain formation (Salmon et al., 1974) and this is observed in several samples of weakly deformed layered ore. With deformation of either pyrite or sphalerite aggregates, interstitial galena forms subgrains, either equidimensional or elongate at right angles to the axis of maximum shortening (Fig. 12). Where deformation is more intense, these subgrains grade into a new generation of grains sensu stricto[1], characterized by smaller grain size than the parent material. Coexisting sphalerite shows few signs of deformation at this stage. The early formed annealing twins are slightly bent

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[1] The distinction between subgrains and grains in galena is somewhat arbitrary because of the gradational relationship that exists between the two types of grains Dynamic recrystallization of galena is probably performed by nucleation of new grains from unstrained subgrains (Clark et al., 1977). By this process a relatively high degree of uniformity in lattice orientation will be preserved during the early stages of recrystallization until grain boundary migration results in a larger variation in lattice orientations. The angle of lattice misfit across subgrain boundaries is generally less than approximately 10°, and the subgrain boundaries stop at, and etch less easily than grain boundaries. The subgrains in most cases show a fairly uniform surface etching while grains in many instances etch differently due to a larger difference in lattice orientation between adjacent grains. The degree of lattice fit between adjacent grains and subgrains are in many instances indicated by the later formed cleavage traces which cut across several of these grains/subgrains, being deflected from grain to grain.

and under high-power magnification the grain boundaries are irregular, especially where the sphalerite is in close contact with brittle minerals. Further deformation is marked by the appearance of slip-bands(?) and several generations of deformation twins. At this stage, which corresponds with the intitial development of the massive ore tectonite, the first evidence of primary (patchy) recrystallization is observed in the sphalerite. Pyrite begins to show microscopically visible signs of deformation in areas of more intense strain, i.e. notably in areas where small shear-zones are developed in galena-rich layers. Pyrite crystals in the shear-zones have deformed cataclastically or show signs of abrasion ("polishing"). Where sphalerite is affected by these zones it is highly strained and partly or completely recrystallized whereas the galena has usually recrystallized completely (Fig. 13). However, the galena frequently shows preserved elongate subgrains and grains characterized by sutured grain boundaries which locally grade into small, equidimensional grains (Fig. 14). Where more intense deformation has occurred, for instance along the mesoscopic thrust planes, the D_1 aggregates of sphalerite- and pyrite have been fractured and have recrystallized completely. Pyrite grains have been rotated, frequently with a rim of early annealed sphalerite acting as a protective shield. Upon further rotation this shield recrystallizes, leaving the pyrite grains open to abrasion by the matrix minerals or to fracturing upon collision with other pyrite grains, thus producing a new pyrite grain size class (Fig. 15). At this stage in the deformation only scattered, rounded fragments of the early annealed sphalerite remain in the matrix; these are highly strained and show evidence of primary recrystallization. However, the original grain size of the matrix minerals can still be inferred from the grain size of the sphalerite and/or galena inclusions in the pyrite porphyroclasts, formed during D_1 and shielded against the effects of the subsequent deformation (Fig. 15). These latter microstructures are characteristic of the porphyroclastic ore tectonite which consists of 1-5 mm large, rounded or ellipsoidal pyrite grains, occurring in a matrix of sphalerite and galena with a grain size of 0.04-0.2 mm. The porphyroclastic ore tectonite is further characterized by a random distribution of the major ore minerals, i.e. no evidence of layering remains. Galena together with minor chalcopyrite occasionally shows a preferred positioning in pressure fringes and fractures associated with pyrite or quartz aggregates.

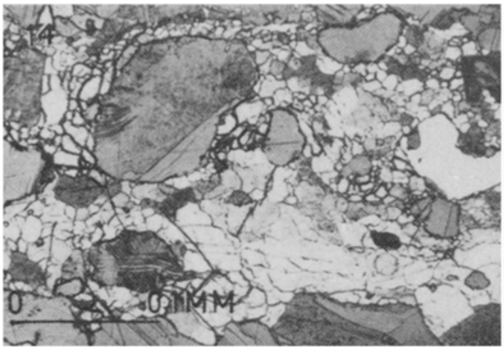
Pyrite

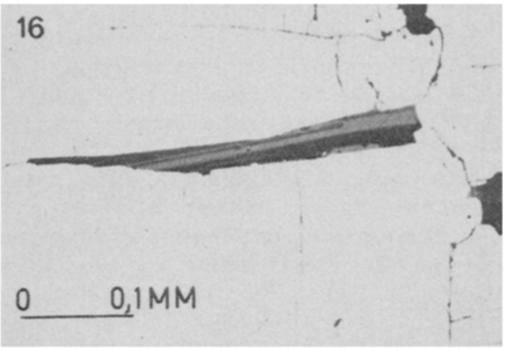
Thick pyrite-rich layers in the upper part of the isoclinally folded central domain and in the southern domain (Fig. 2, 3) show the effects of the D_2 deformation to various degrees, depending upon the amount of interstitial, ductile minerals present. In monomineralic pyrite aggregates recrystallization with very minor fracturing takes place along the grain boundaries. Where sphalerite and galena equilibrated with the elongate pyrite as intergranular films during D_1, fracturing of the pyrite has occurred. Sphalerite, chalcopyrite and to a lesser degree galena have subsequently filled the fractures and have then annealed after the cessation of the D_2 (and D_3?) deformation of the ore body (Fig. 16).

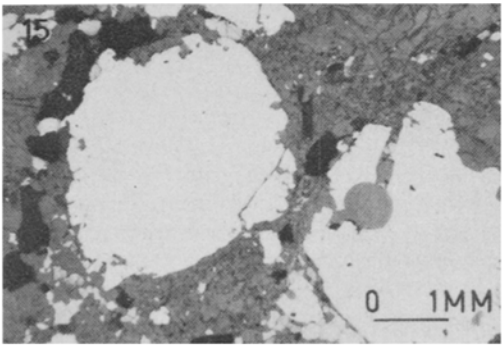
The non-opaque minerals have all been fractured and plastically deformed during D_2. Quartz shows cataclastic deformation, in general in collision with other brittle minerals (Fig. 17). Phlogopite, chlorite and tremolite are bent and fractured and frequently show signs of having been rotated in the ductile matrix.

Interpretation of the D_2 Microstructures

The D_2 microstructures differ from the coarse grained, well-annealed D_1 aggregates, and are clearly the result of different physical conditions during the deformation.







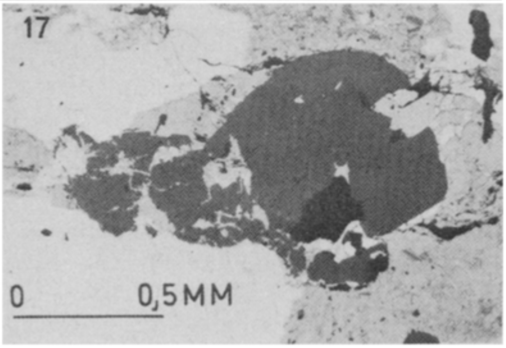


Fig. 14. Detail of galena-rich area in a small D_2 shear-zone. Elongate subgrains with sutured grain boundaries, grading into equidimensional subgrains and grains are seen in the galena (light grey). The sphalerite is highly strained and shows minor primary recrystallization (uppermost). Etched

Fig. 15. Porphyroclastic ore (D_2). Two pyrite porphyroclasts (D_1, white) have been rounded in the sphalerite-galena matrix which is characterized by a small grain size. Note the large round D_1 sphalerite inclusion in the right pyrite grain, and the new generation of small inclusions (D_2 and D_3) incorporated along the rim of the porphyroclasts. These show fracturing in the area of closest contact. Etched

Fig. 16. Fractured D_1 pyrite aggregate which has been cemented by sphalerite (grey and black) that subsequently has annealed during or after D_2 (and D_3?). Etched

Fig. 17. D_1 quartz aggregate (dark grey) deformed cataclastically during D_2 upon collision with pyrite porphyroclasts (white). Matrix minerals dominated by sphalerite (grey). Etched

The D_2 deformation of the D_1 pyrite grains takes place either by cataclasis, or by recrystallization along the grain boundaries according to the amount of interstitial ductile minerals present. According to Atkinson (1975), the breaking strength of pyrite aggregates increases with a decrease in porosity and an increase in confining pressure. As the confining pressure can be considered to have been relatively constant over the ore body during D_2, the development of the D_2 microstructures in the pyrite may have depended to a large degree upon the porosity of the aggregates. The term "porosity" is not used here in the normal sense of meaning intergranular voids, but instead refers to the amount of ductile sulphides, quartz and carbonates present in the pyrite ore in the form of intergranular films or small inclusions along the grain boundaries. These impurities, particularly the ductile sulphides, can be envisaged to have an influence on the strength of the pyrite aggregates similar to porosity sensu stricto. In samples with a very low "porosity", recrystallization without cataclasis along the grain boundaries is frequently observed. Following Read (1968), quoted by Atkinson (1975), this feature is ascribed to stress-induced recrystallization. This is a transformation that takes place in pyrite when a stress close to the stress for macroscopic fracture is applied at high temperature.

The elevated temperature which prevailed during the D_2 deformation is reflected by characteristic deformation features in the galena. Experimental studies by Stanton and Willey (1972), Salmon et al. (1974) and Clark et al. (1977) have shown, that elongate galena grains of the type shown in Figure 14 can be produced by two processes: A static annealing at elevated temperature of a sample deformed by kinking at low temperature, or by syntectonic recovery and recrystallization in samples deformed at elevated temperatures. In both cases it is the kinking introduced in the crystal which determines the outline of the elongate grains, but the exact shape of these depends on the temperature at which they are produced. Elongate grains in samples deformed below 200°C tend to have straight grain boundaries, while those formed above 200°C tend to have sutured grain boundaries. The sutured grain boundaries in the Black Angel galena thus indicate that the D_2 deformation took place above 200°C which is in accordance with the temperature estimated from calc-silicate parageneses.

The overall reduction in grain size associated with the D_2 deformation of the ductile minerals can be estimated from the size of the sphalerite and galena inclusions incorporated in pyrite during the early stages of the grain growth which accompanied or followed cessation of D_2 movements. The size of these inclusions diminishes towards the centre of pyrite grains. The average size of the innermost inclusions is 0.01 mm, which is comparable with the grain size of the parent material of the D_1 aggregates, which in general is 0.2-6 mm. This reduction in grain size is the result of the observed cyclically alternating deformation and annealing recrystallization in the sphalerite and galena from the porphyroclastic ore tectonite. The cyclic recrystallization kept the grain size in these areas at a constant level (i.e. at a certain lattice strain) by recycling the new grains as they attained a certain size. The grain size attained during dynamic recrystallization may be related to the imposed stress as suggested by Kohlstedt et al. (1976) for olivine and White (1977) for quartz. The microstructures of the D_2 aggregates, especially in the porphyroclastic ore, are thus very similar to the microstructures of (blasto-) mylonites formed by hot-working (Bell and Etheridge, 1973). Dynamic recovery and recrystallization may lead to grain refinement and an associated strain softening in quartz-mylonites (White, 1975, 1977), a process which is proposed to have been active in the ore body during the D_2 thrust movements.

The D_2 microstructures are thus interpreted as having formed largely as a result of plastic deformation, syntectonic recovery and recrystallization at a temperature close to 500°C and at significantly higher stress and strain rates than the conditions indicated for the D_1 deformation.

THE NORTHERN DOMAIN: D_3 MICROSTRUCTURES OF THE MOBILIZED SULPHIDES

The mobilized sulphides occurring in the open folds of the northern part of the ore body are characterized by a macroscopic zoning and a wide range of grain size. These features reflect the repeated grain growth, plastic deformation, and recrystallization in response to the continous deformation that took place during the mobilization of the minerals. Coarse grained aggregates occur in some veinlets, sulphide protuberances into the host rock, and where concentrations of less ductile minerals (chiefly pyrite and quartz) partly shielded the sulphide mass against later deformation. Where later movements have occurred, coarse grains have recrystallized into smaller grains.

In the lower sphalerite-pyrite-carbonate layer large pyrite porphyroblasts (up to 0.3 m) may represent a product of near-static grain growth. Inclusions of sphalerite, quartz and carbonate define euhedral growth layers, thus probably reflecting the media in which the pyrite grew. In most instances the porphyroblasts show evidence of having been rotated in the sphalerite-rich matrix subsequent to their formation. This is suggested by fracturing upon collision with other pyrite grains or by polishing of the surface of the grains. The sphalerite matrix usually consists of an "early formed", coarse grained generation (5 mm to several cm), which has been partly or completely transformed by plastic deformation and recrystallization into a finer grain size (less than 2 mm). A similar feature is observed in many of the sphalerite-infilled extension fractures in the host marble. Here an initially coarse grained sphalerite has been transformed into an extremely fine grained matrix (less than 0.2 mm) with subrounded, elongate sphalerite porphyroclasts which define a foliation parallel to the walls of the fracture. The annealing twins in the recrystallized sphalerite grains show a preferred orientation subparallel to, and at right angles to this foliation (Fig. 18). The sphalerite is usually free of inclusions, but locally it may contain exsolution bodies of chalcopyrite. These are scattered or are localized to annealing twins in the sphalerite, where the coincidence of twin planes in the two minerals demonstrates that they originated by exsolution (Stanton, 1972, p. 260). Where sphalerite shows evidence of later deformation, the chalcopyrite inclusions have migrated to recrystallized zones, deformation twins, and grain boundaries.

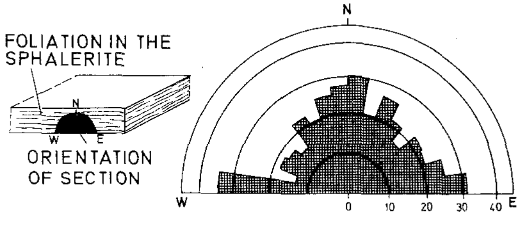


Fig. 18. Preferred orientation of annealing twins in sphalerite from an extension fracture, deformed and annealed during D_3. In the left hand side of the figure the orientation of the sample is shown in relation to the walls of the fracture and the parallel foliation in the sphalerite. In the right hand side is shown the distribution according to the orientation of 403 measurements

In the overlying galena-fahlore-quartz layer, evidence of repeated plastic deformation, polygonization, and recrystallization occurs in the galena aggregates. In "sheltered regions", i.e. where abundant quartz or pyrite have strengthened the sulphide mass, an extremely coarse grained galena (1-6 cm grain size) has been partly preserved against later deformation. It characteristically shows development of both equidimensional and elongate subgrains. The equidimensional subgrains are 1-4 mm across and form a well-developed polygonal structure. They grade into a mosaic of grains sensu stricto, which in turn show evidence of renewed plastic deformation and polygonization. The elongate subgrains are in particular observed in the extension fractures outside the main ore zone. They have sutured grain boundaries, are up to a few cm long, and have a length:width ratio of 2:1.5 to 2:1. In most samples they grade into an annealed mosaic of sutured elongate grains sensu stricto.

Interpretation of the D_3 Microstructures of the Mobilized Sulphides

The presence of extremely coarse grained as well as fine grained sulphides, the evidence of repeated polygonization in galena, and repeated recrystallization in sphalerite are typical of mobilized and remobilized ores. In a quantitative study of folded galena-rich layers in the Mount Isa ore body, McDonald (1970) concluded that an anomalous grain size of the galena was restricted to the hinge zones of folds. McDonald (op. cit.) interpreted this as a result of the low stress in these zones. Stephansson (1974) similarly concluded in a thermodynamic study of stress-induced diffusion during folding that the distribution of mean stress controls the growth of new grains, resulting in the development of larger grains in the low stress areas. The coarse grained sulphides in the Black Angel Mine occur in settings in which low stress conditions were established during the deformation, and the observed exaggerated grain growth is thus interpreted as a result of this feature. However, it is possible that the refinement of the sulphides that followed the differential mobilization played a major role in the formation of the coarse grain size. In general one mineral dominates in the two zones in the mobilized area, i.e. sphalerite or galena. The relatively small amount of other minerals present in these layers occur in large, well defined aggregates, indicating that a high degree of "sammelkristallisation" ("collection crystallization", Ramdohr, 1969, p. 105) has taken place in response to the high diffusion rates that are envisaged to have been established in this region. This has resulted in aggregates of the major minerals that are relatively free from foreign minerals along the grain boundaries. Neither this nor the isotropic stress which in general prevails in the hings zone of a fold would impede the grain growth, as it is improbable that the latter would give rise to strong preferred orientations in the aggregates.

The deformation of the mobilized ore resembles the development of the porphyroclastic ore, thus indicating highly varying stress, strain and strain rate conditions during the mobilization. Repeated polygonization, recrystallization, and renewed plastic deformation characterize the microstructures of the galena. In the extension fractures, the galena developed a foliation by wrapping around harder minerals. The foliation is defined by elongate grains with sutured grain boundaries, equivalent to the elongate grains and subgrains formed during D_2 from the layered ore. Pyrite deformed exclusively by cataclasis, induced by rotation in the ductile matrix. Sphalerite deformed by repeated recrystallization in a manner similar to the sphalerite of the layered ore during D_2 deformation, with the difference that the mobilized ore parent material was more than ten times larger than the sphalerite of the layered ore. As the pyrite porphyroblasts are scattered, it is not possible to monitor the reduction in grain size as closely as in the case of the layered ore. The samples which have been examined indicate that the size of the sphalerite inclusions incorporated in the pyrite during(?) D_3 deformation is of the same magnitude as in the porphyroclastic ore tectonite, although the variation in size is much larger.

Following D_3 deformation, the aggregates probably underwent some grain growth and grain boundary adjustment. The exsolutions of chalcopyrite along sphalerite grain boundaries have formed intergranular films in adjacent galena recrystallized during D_3, and suggest that adjustment of the sphalerite-galena grain boundaries has occurred. Fahlore occurs as subrounded aggregates which locally are deformed, fractured, and healed by galena or chalcopyrite. Reactions between fahlore and pyrite and sphalerite have produced arsenopyrite, enargite, bornite, and loellingite. In the sphalerite-infilled extension fractures the sheared sphalerite has retained a small grain size. Only very small amounts of impurities occur in these fractures, mainly in the form of chalcopyrite, and the small grain size can hardly be ascribed to inhibition-dependent grain growth on the basis of these scattered inclusions. A strongly preferred lattice orientation of recrystallized grains in monomineralic aggregates will impede the grain growth (Stanton and Gorman, 1968; Lawrence, 1973; Clark et al., 1977), so that the preferred lattice orientation in the sheared sphalerite from the extension fractures (Fig. 18) may account for the retention of a small grain size within the fractures.

THE SOUTHERN DOMAIN: D_3 MICROSTRUCTURES OF THE PORPHYROCLASTIC ORE TECTONITE

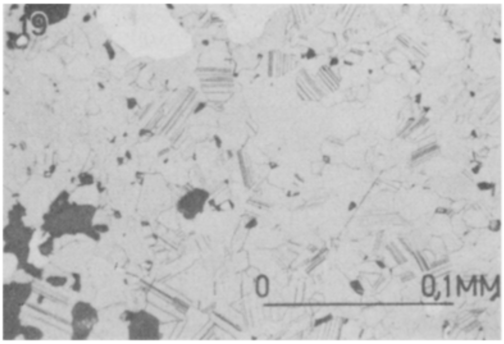
Following cessation of the D_2 deformation, the porphyroclastic ore tectonite underwent a period characterized by weak, renewed plastic deformation and annealing during and after D_3. The effects are local, but are particularly well-seen in the southern part of the ore body. Pyrite shows evidence of renewed grain growth and grain boundary adjustment along the rim of the porphyroclasts. Consequently, a new generation of sphalerite and galena inclusions, which reflect the new, small grain size of the matrix minerals, was included in the porphyroclasts (Fig. 15). The small pyrite grains, formed by the collision of larger grains during D_2, show widespread annealing with the sphalerite and the galena in the matrix, resulting in equilibrium microstructures such as caries structure and straight or curved grain boundaries with dihedral angles against sphalerite and galena approaching 180° (Fig. 19). The effects of grain boundary adjustment and normal grain growth are widespread in aggregates of sphalerite and galena which in general are completely annealed. Where sphalerite occurs as a minor phase in galena, spheroidization (Lawrence, 1973) has occurred. In several samples secondary recrystallization is observed in the sphalerite but this feature is not widespread (Fig. 19).

Careful examination of the sphalerite aggregates reveals that they show deformation features. D_2-annealing twins are slightly bent and locally differential recrystallization has occurred adjacent to pyrite porphyroclasts (Fig. 20). This (D_3?) deformation is believed to be the primary reason for the blunting of the frequency distribution and for the relatively large standard deviation (18° on 726 measurements with a mean value of 120.2° and a theoretical value of 120°) shown by dihedral angles in the sphalerite aggregates.

Interpretation of the D_3 Microstructures of the Porphyroclastic Ore Tectonite

D_3 deformation was characterized by gentle folding with an associated thinning of the ore layer along the limbs, and a concomittant thickening along the fold crests. Microstructures indicative of plastic deformation of the fine grained D_3 aggregates are exclusively observed in sphalerite. This straining of the sphalerite could have been induced during a much later deformation episode occurring under retrogressive metamorphic conditions, but it could equally reflect any strain hardening that accompanied syntectonic recrystallization of the sphalerite. During a later static annealing period following cessation of deformation, the galena would then anneal completely. Pyrite would probably not be deformed to any large extent in the ductile matrix during a syntectonic recrystallization accompanying folding (see later), but the grain boundaries would no doubt be subject to minor adjustment. Although it is not possible to differentiate between the two possible modes of formation of the D_3 aggregates, an origin by syntectonic recrystallization is favoured. This is due to the relatively high temperature which is indicated to have prevailed during this period by the extensive mobilization that took place in the northern region of the ore body.

A characteristic feature of the porphyroclastic ore tectonite is the retention of a fine grain size. If the tempera-



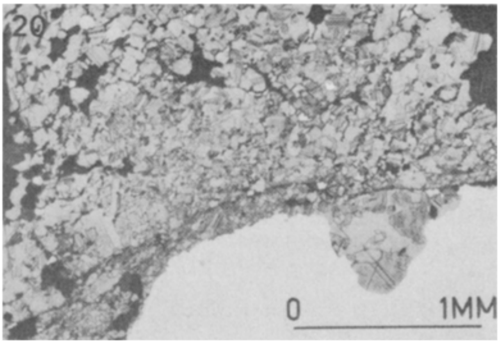


Fig. 19. Well-annealed D_2-aggregate of sphalerite (grey) and pyrite (white). The sphalerite shows secondary recrystallization (coarsening). Normal grain growth has been inhibited by minute grains of carbonates, quartz and galena (black, dark grey and grey, respectively) which occur along the grain boundaries and at the triple junctions. Note the weak D_3 deformation which has caused bending of the annealing twins in the sphalerite. Etched

Fig. 20. D_3 deformation and differential recrystallization of the sphalerite matrix (D_2) which occurs adjacent to a D_1 pyrite porphyroclast (white). Etched

ture had decreased rapidly after cessation of D_3 movement, a fine grain size would probably have resulted, although the experimentally produced rates of recrystallization are so fast at 400°C in the minerals under consideration (Stanton and Gorman, 1968) that a rapid fall in temperature is unlikely to account for the small grain size of the sphalerite and the galena. Careful examination of the fine grained aggregates reveals that the grain size is dependent on the degree of "purity" of the individual samples, and that the largest amount of grain growth has occurred in the monomineralic aggregates. In areas where the D_2 and D_3 deformations have affected an average ore (mainly composed of sphalerite and pyrite but with significant amounts of galena, quartz and carbonate), the mechanical homogenization and the recrystallization has resulted in a large number of new, very small grains of galena and non-opaque minerals, now situated along the grain boundaries and at triple junctions in the sphalerite aggregates. Local coarsening of the sphalerite has led to new, irregular grains which are orders of magnitude larger than the otherwise fine grained matrix. The pyrite porphyroclasts present in this ore type suggest that negligible grain growth has taken place after the cessation of movement, as there is no great difference in the grain size between newly incorporated inclusions of sphalerite and galena along the rim of the porphyroclasts and the grain size in the matrix in which the pyrite grew. Contrary to this, in monomineralic sphalerite layers, or in sphalerite layers with minor amounts of galena, a larger grain size has resulted from D_3 annealing recrystallization. The inclusions along the rim of the pyrite porphyroclasts in these areas are at least a factor of ten smaller than the grain size of the same minerals in the matrix. This indicates that a substantial grain growth has taken place which has resulted in a grain size of the same order of magnitude as the D_1 aggregates.

The above features demonstrate that the post-deformational annealing microstructures largely reflect inhibition-dependent grain growth, in which the presence of a minor phase effectively locked the grain boundaries particularly at triple junctions (Stanton and Gorman, 1968; Stanton, 1972; Lawrence, 1973). Where the aggregates were relatively free from "impurities", a normal grain growth took place, terminating either as a result of decreasing temperature or, more likely, as a result of the attainment of a stable microstructure, dependent on the amount of impurities present in the aggregates.

DISCUSSION OF FLOW RATES AND FLOW MECHANISMS

The mesoscopic structures of the mine area suggest that two contrasting types of deformation have controlled the tectonic development of the ore body. The phases D_1 and D_3 represent one type which is characterized by mesoscale isoclinal- to open folding and pinch and swell formation. The other type, represented by D_2, is characterized by thrusting. As shown previously, the three phases of deformation took place at a temperature of approximately 500°C and under relatively low confining pressure.

Price (1975) calculated the strain rates during the formation of folds and related structures in nature to be in the range $10^{-12}sec^{-1}$ to $10^{-14}sec^{-1}$. These strain rates correspond well with the strain rates that are imagined to make steady state flow without fracture possible in pyrite, and the flow mechanism can be considered to have been mainly diffusion creep (Graf and Skinner, 1970; Mookherjee, 1971; Atkinson, 1975). The repeated polygonization, recrystallization and plastic deformation observed in galena from the mobilized ore, together with the grain size of the recrystallized galena (1-4 mm) suggest that the dominant flow mechanism in galena during D3 was dislocation creep (Atkinson, 1976, Fig. 2). This flow mechanism may also have been active in galena during D_1. However, it must be borne in mind that these interpretations are based upon the assumption that the microscopically visible effects from later deformation and annealing are very weak in the aggregates under consideration. Due to the lack of relevant experimental data, it is not possible to suggest a similar flow mechanism for sphalerite.

The D_2 deformation phase is believed to have been characterized by notably higher strain rates than the D_1 and D_3 phases. Following Schmid (1975) who presents a mechanical model for the Glarus overthrust that shows many similarities with the thrusts of the Black Angel mountain, strain rates in the order of $10^{-10}sec^{-1}$ seem realistic for this type of deformation. In accordance with this the deformation mechanism of the pyrite during D_2 was largely cataclasis with minor stress-induced recrystallization, and steady state flow may have been obtained in monomineralic pyrite layers by cataclasis along grain boundaries ("cataclastic flow", Atkinson, 1975). The D_2 galena aggregates are characterized by microstructures that are equivalent to the microstructures of the mobilized ore formed during D_3, and as the grain size of the D_2 galena can be estimated to have been 0.01 mm during the steady state flow, these features similarly suggest that the main flow mechanism of the galena during D_2 was dislocation creep (Atkinson, 1976, Fig. 1). The observed cyclic recrystallization without any microscopically visible signs of recovery in sphalerite suggest that during D_2 this mineral flowed in a manner similar to hot working (Nicolas and Poirier, 1976, p. 134) particularly as sphalerite has been shown experimentally (Clark et al., 1977) to demonstrate slow rates of dislocation climb.

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