Sulphide mylonites from the Renström VMS deposit, Northern Sweden

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Abstract

Sulphide mylonites are fine-grained massive sulphides which have deformed in a plastic manner. In the Renström Zn–Pb–Cu–Ag–Au VMS deposit, one of several operating mines in the Early Proterozoic Skellefte District in Northern Sweden, shear-zone metamorphism has resulted in the development of mylonitic fabrics within the sulphides. The massive sulphide ore is hosted in a shallow submarine to subaerial volcano–sedimentary sequence which has been variably metamorphosed and deformed. Initially, the sequence underwent burial metamorphism which was followed by an amphibolite grade regional metamorphic event at pressures of around 7.5 kbar and temperatures of 540–600 °C. This has been overprinted by a retrogressive metamorphic event at greenschist facies (at *ca.* 400 °C) with concomitant ductile deformation. Finally the area was uplifted to shallower crustal levels with associated cataclastic deformation.

Both the regional and dynamic metamorphic events have resulted in the development of specific textures in the sulphide ores. Textural evidence indicates that pressure solution has been mainly responsible for the plastic deformation in pyrite, while the weaker sulphide minerals such as pyrrhotite, chalcopyrite and galena have generally recrystallised in response to the high strains.

Sulphide mylonites are probably common rocks in many polydeformed massive sulphide deposits like Renström. They may have previously been misinterpreted as primary depositional textures.

KEYWORDS: volcanogenic massive sulphide deposit, Sweden, sulphide, mylonite, pressure solution.

Introduction

MYLONITES are rocks found in shear zones where intense plastic deformation has resulted in grain size reduction. There are various micro-scale processes that serve to accommodate the strain in these shear zones; these include pressure solution, dislocation glide, dislocation creep, grain boundary sliding, deformation twinning and dynamic recrystallisation. The types of process that are operative are largely dependent on temperature and strain rate (Knipe, 1989), and also to a lesser extent, on confining pressure, fluid activity and permeability within the deformation zone. Most volcanogenic massive sulphide (VMS) deposits now exposed on land have been subjected to some degree of metamorphism and deformation, but despite this, many deformation textures in the sulphides are either not recognised or not reported, and may have been misinterpreted as primary textures.

Experimental work has provided much of the information about deformation mechanisms within sulphide minerals and the resulting micro-textures. It has been shown that the strength of sulphides decreases with an increase in temperature, and is largely independent of confining pressure (Clark and Kelly, 1976). Cox *et al.* (1981) showed that pyrite can deform by dislocation processes at temperatures between 400 and 700 °C. McClay and Ellis (1983, 1984) introduced the idea that pressure solution was an important deformation mechanism for pyrite under conditions of greenschist facies metamorphism. Cox (1987) investigated flow mechanisms in sulphide minerals and concluded that dislocation creep is an important flow mechanism in many sulphide minerals in a range of crustal environments. However, it is most commonly observed as a deformation mechanism under conditions of medium grade metamorphism. The weaker sulphides, such as galena, dynamically recrystallise during dislocation creep at temperatures at least as low as 250 °C, chalcopyrite recrystallises at about 300 °C at natural strain rates; whilst at similar low temperatures sulphides such as pyrite

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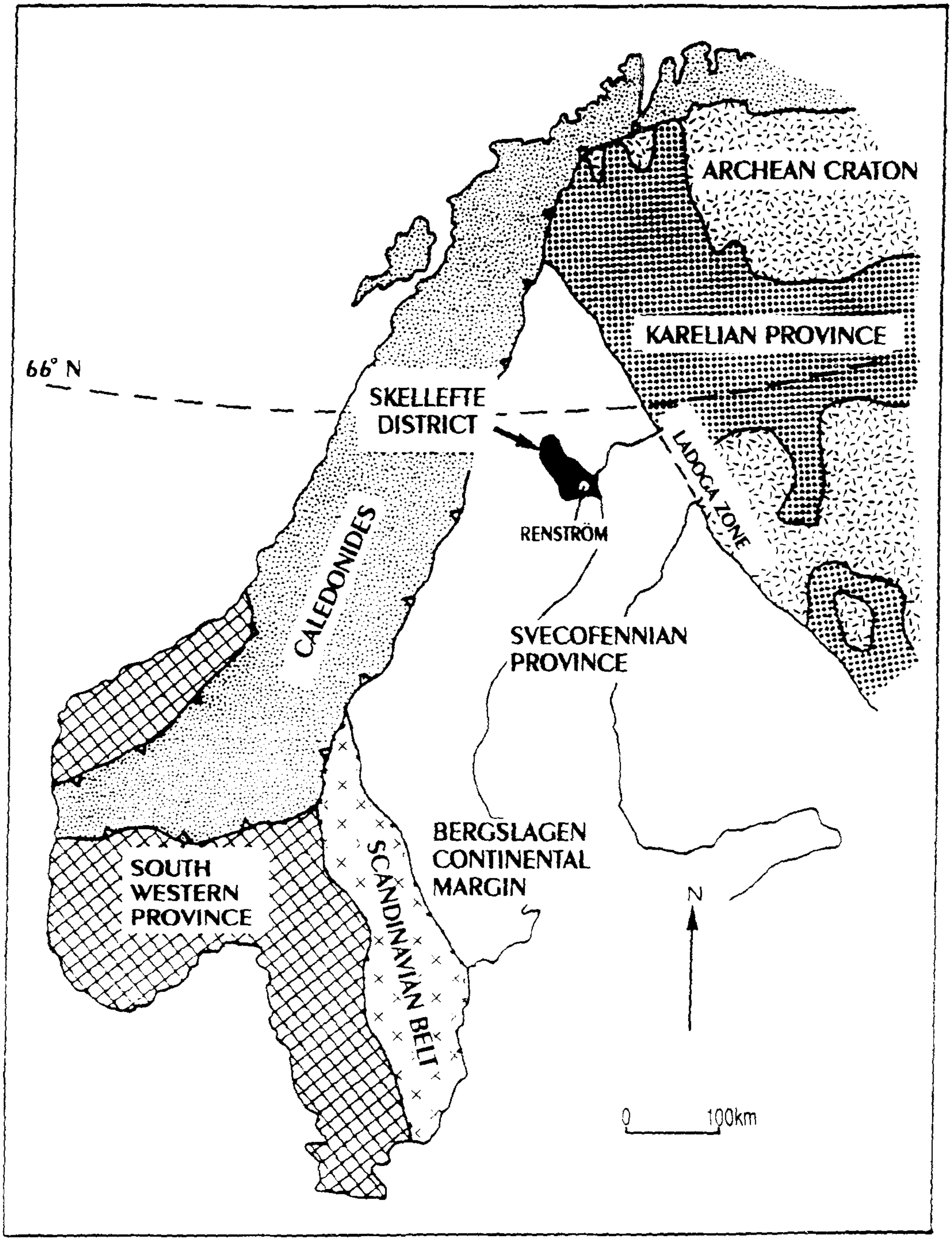


FIG. 1. Map of Scandinavia showing the major tectonic units and the location of Renström within the Skellefte District (modified after Rickard, 1986; Skiöld, 1988; and Gaál, 1990).

and arsenopyrite may deform by brittle failure and cataclastic flow, particularly if effective confining pressures are low.

Geology of the Renström area

The Renström Zn–Pb–Cu–Ag–Au mine is located in the Eastern Skellefte District of Northern Sweden (Fig. 1). The Skellefte District is an Early Proterozoic (1.89 Ga) belt of metamorphosed volcanites and sediments which have been intruded by several granitoid bodies. The district is *ca.* 200 km long and hosts many VMS deposits, as well as epigenetic gold, porphyry-type deposits and nickel mineralisations.

The Renström deposit consists of many thin (0.5–5 m) sub-vertically orientated pyrite–sphalerite lenses hosted in metadolomites. The dolomites are enclosed in a sequence of chlorite–sericite altered dacitic–andesitic volcanites with minor intercalated pelitic sediments (Duckworth, 1991) (Fig. 2). The ores are mineralogically simple with pyrite, sphalerite, chalcopyrite, galena, arsenopyrite and minor tetrahedrite. Gold and silver occur as native elements and as electrum and gold-silver amalgam. The gross tonnage of the deposit is 9 million tonnes, at grades of 6.5% Zn, 1.5% Pb, 0.8% Cu, 155 g/tonne Ag and 2.8 g/tonne Au. At present, the mine is worked to a depth of 900 m.

Deformational history

The Renström area is structurally complex and has undergone polyphase folding, transposition and shearing during regional and shear-zone metamorphic episodes (Duckworth, 1991). These events have resulted in the extreme elongation of the ore lenses (Fig. 3). Firstly, the area was buried and regionally folded and metamorphosed. Three-fold phases have been recognised in the field, but the relative timing of these is unclear. Transposition followed the folding and so subsequently destroyed many of the fold structures. After this compressional episode, the area was subjected to a ductile deformation event focused along narrow (0.1–20 m) dip-slip shear zones, with concomitant retrogressive metamorphism. Underground, shear zones in the alteration zones adjacent to and enclosing the sulphides are defined by regions of strong chloritic alteration with sub-vertical foliations that in places are wrapped around dolomitic shear pods. These 1 cm to 1 m long shear pods are orientated vertically, parallel to the regional foliation. Sulphides in these zones are vertically banded. Shear zones through the surrounding less altered volcanic units are characterised by elongate volcanic clasts which have length : width ratios of up to 40 : 1, ellipsoidal accretionary lapilli and shear pods. These elongate features are aligned with their long axes parallel to the sub-vertical (*ca.* 80°) foliations and lineations. In surface outcrops, shear zones through the volcanic rocks are 0.01–1 m wide and the rocks in these zones are L-S tectonites with parallel near-vertical foliation and lineations.

Tectonic uplift of the area to shallower crustal levels was accompanied by cataclastic deformation, and this post-dates the shearing and appears to be the final tectonic event to have affected the area.

Sulphide isotopic geothermometry and sphalerite geobarometry were employed in order to constrain the *P–T* conditions of the regional metamorphic event in the area and the temperature of the later retrogressive event. The $\delta^{34}S$ values of co-existing sphalerite-galena pairs used for the isotopic thermometry are shown in Table 1, and employing the equations of Ohmoto and Rye (1979), these data translate into two temperature ranges which correspond to sheared and unsheared parts of the ore, and therefore to the retrograde and prograde metamorphic temperatures. These temperature ranges (which include error bar calculations) are 320–450 °C and 540–600 °C respectively.

Sphalerites buffered by co-existing pyrite and pyrrhotite (at least co-existing in two dimensions) that were analysed from unsheared parts of the ore showed a relatively homogeneous mole % FeS of 11.5–13% (Table 2). This corresponds to maximum pressures of around 7.5 kbar utilising the temperature versus mole % FeS graph of Scott (1973) for the regional metamorphism at 540–600 °C. Therefore it appears that the area was metamorphosed at crustal depths of around 25 km.

Sulphide microtextures

The shear-zone metamorphism of the sulphides in the Renström area has produced a variety of textures and fabrics which provide information on the mechanisms of the deformation. Some parts of the ore exhibit no obvious characteristics of directed pressures; this is probably due to the domainal aspect that shear zones usually develop, with lenses of undeformed material enclosed in sheared material. These undeformed sulphides have textures that do not show any preferred orientation of the minerals, and typically are characterised by subhedral to euhedral pyrite cubes within a sphalerite matrix (Fig. 4) or a chlorite-dolomite matrix (Fig. 5).

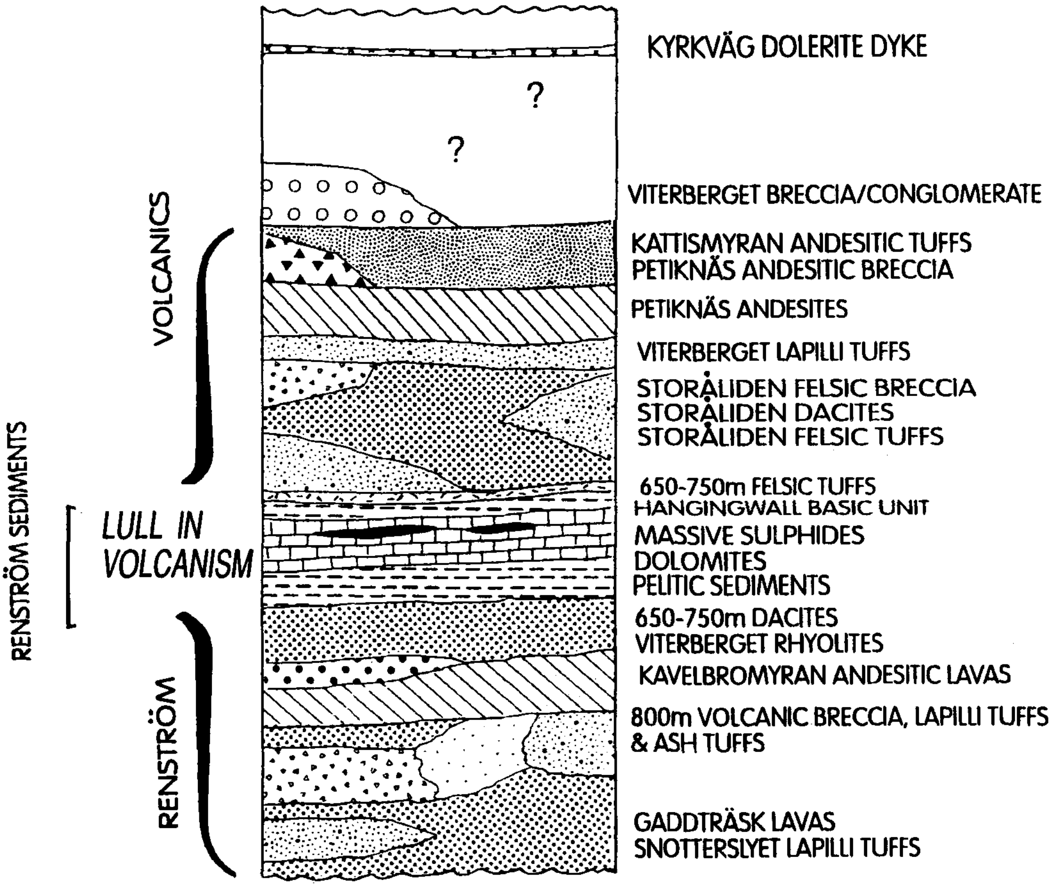


FIG. 2. Stratigraphy of the Renström area showing the sulphide deposits hosted in carbonates within a volcanic sequence. The thickness of the units is not known, but the volcanics are probably around 1 km thick in the area.

The most common deformational fabrics in the shear zones are a lenticular elongate pyrite orientation (Fig. 6) and pyrite banding (Fig. 7). The banded pyrite ore constitutes one of the main ore types that can be mapped on the meso-scale. It has previously been interpreted as a primary bedding feature by company geologists, but etching of polished sections reveals that pressure solution has resulted in the development of careous grain boundaries, and in places the grain boundaries have been truncated where the pyrite has been dissolved and reprecipitated at sites of low strain (Fig. 8). This has produced a sub-vertical pressure solution cleavage defined by discontinuous layers of pyrite separated by insoluble chlorite-rich material (Fig. 9). This ribbon-like pyrite texture also shows C-S shear fabrics, with the S-fabric defined by the sub-vertical pyrite lenses. Individual pyrite grains that form these lenses are 10–25 μm long, whereas pyrite euhedra in undeformed parts of the deposit are between typically 0.2–2 mm in diameter. Therefore it appears as though the pressure solution has modified the grain shapes, re-orientated the grains and resulted in an overall grain-size reduction.

Pressure solution seems to have been a ubiquitous process during the retrogressive metamorphism in the host rocks as well as the sulphide ores. Incongruent pressure shadows are common around resistant quartz and feldspar phenocrysts in the volcanic units (Fig. 10), and meso-scale tectonic stylolites are also visible in these andesitic–dacitic lithologies (Fig. 11).

Grain boundary sliding appears to have locally accompanied the pressure solution, this has also produced irregular pyrite grain boundaries (E. Rutter, pers. comm., 1990). In Fig. 12 this

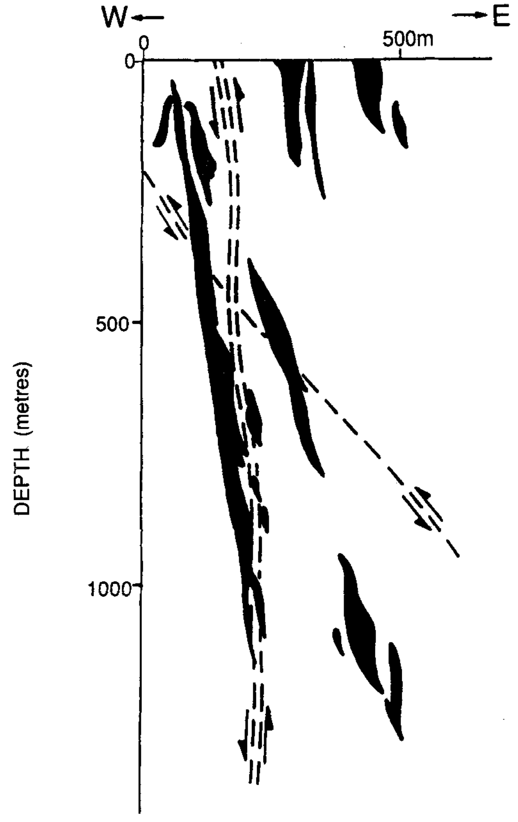


FIG. 3. Schematic diagram illustrating the orientations of the main shear zones crosscutting the elongated sulphide ore (black). One thin shear zone appears to cut the ore at an angle of *ca.* 45° at the 450 m level and another wider sub-vertical shear zone seems to intersect it at around the 800 m level (Duckworth, 1991).

Table 1. Sulphur isotopic values for sphalerite and galena pairs

Sample	mineral	$\delta^{34}S$ (per mil)
897006	sphalerite	+3.14, +3.03
	galena	+1.36, +1.27
700RD	sphalerite	+2.08, +1.98
	galena	+0.66, +0.60
88165	sphalerite	+1.91, +1.57
	galena	+0.99, +0.90

Table 2. Sphalerite Analyses

sample		wt% S	wt% Zn	wt% Fe	total(%)	mole% FeS
88164	1	32.63	58.06	7.93	98.62	12.20
	2	33.26	58.26	7.42	98.94	11.48
	3	32.97	58.73	7.61	99.31	11.65
	4	32.81	58.01	7.97	98.79	12.29
B589	1	33.23	57.37	8.14	98.74	12.62
	2	32.80	58.61	7.65	99.06	11.67
	3	33.01	57.26	8.38	98.65	12.94
	4	33.16	56.88	8.46	98.50	13.10
	5	33.09	57.93	8.21	99.23	12.56
88163	1	32.64	58.35	7.92	98.91	12.14
	2	33.19	59.04	7.78	100.01	11.54
	3	32.95	59.02	7.71	99.68	11.69
	4	33.08	57.78	8.37	99.23	12.84
	5	33.29	59.05	7.77	100.11	11.78
88162	1	32.53	58.49	7.96	98.98	12.11
	2	32.49	59.02	7.29	98.80	11.17
	3	32.28	59.14	7.34	98.76	11.15
	4	32.37	58.83	7.85	99.05	11.97

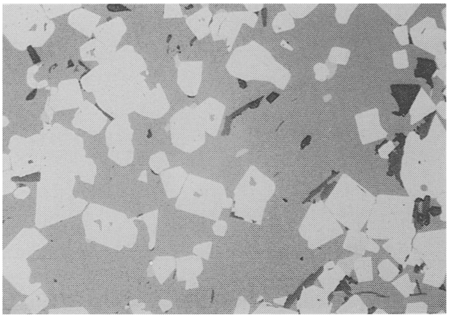
micron-scale movement is also shown by the relative positioning of a projection on the edge of a grain and a similar sized indentation on the opposite grain boundary. The strain has therefore been partially accommodated by sliding of the grains within a fluid, under pressure, along the grain boundaries.

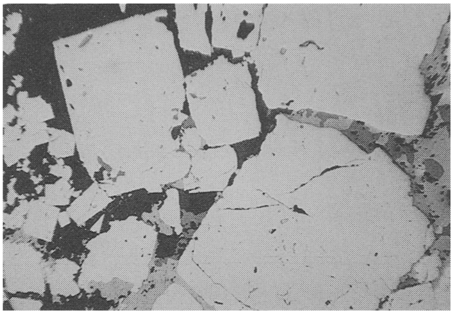
Durchbewegung structure is also common within both the pyrite and sphalerite ores. This is composed of juxtaposed and intercalated mixed clasts of varying rheologies (Marshall and Gilligan, 1989). Rounded and sigmoidal clasts of altered foliated chloritic and sericitic wall rock (Fig. 13), quartz pebbles and dolomite clasts are all found rotated within the sulphides, and this sulphide matrix exhibits plastic deformation features such as those described above. Therefore, this 'ball ore' (Vokes, 1973) is also a type of mylonitic texture.

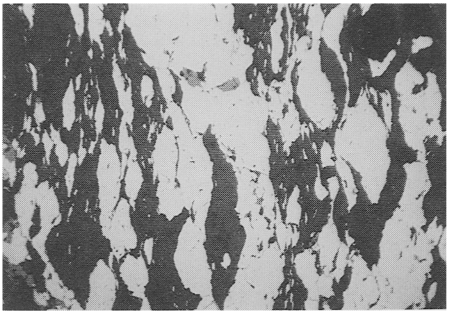
Discussion

From the microtextures observed in the Renström sulphides it can be seen that pressure solution and grain boundary sliding have occurred during the shear zone metamorphic event.

With reference to the *P–T* diagram of Marshall and Gilligan (1987) (Fig. 14), pyrite in the Renström sulphides would have behaved in a plastic fashion under the conditions of both the regional and shear-zone metamorphism. Therefore, pressure solution and associated grain boundary sliding are theoretically possible within the sulphide ores of Renström. The microtextures of the host rocks suggest deformation in the tempera-







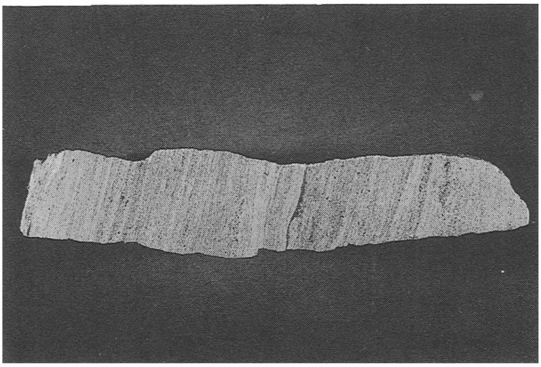
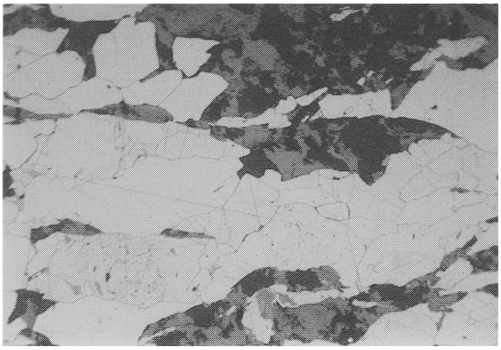
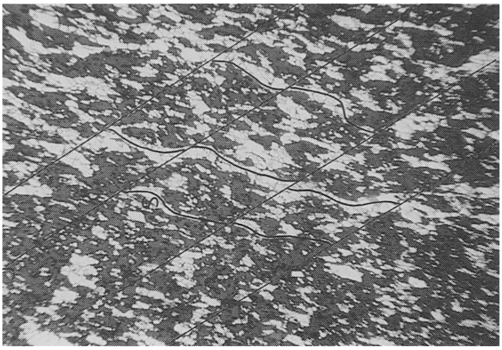


FIG. 4 (*Top left*). Unsheared ore section showing the preservation of pyrite euhedra within a sphalerite matrix. Reflected light photomicrograph, field of view = 2 mm. FIG. 5 (*Top right*). Reflected light photomicrograph showing subhedral pyrite associated with chalcopyrite and sphalerite in a chlorite–dolomite matrix (black). Field of view = 2 mm. FIG. 6 (*Bottom left*). Reflected light photomicrograph showing the commonly developed sub-vertical lenticular fabric in pyrite. Field of view = 2 mm. FIG. 7 (*Bottom right*). Sample of the banded pyrite ore showing the vertical layering that has resulted from plastic deformation. Width of specimen is 20 cm.

ture range 300–>400 °C. For instance, quartz shows extensive dynamic recrystallisation (Fig. 15), which indicates temperatures over 300 °C (Nicolas and Poirier, 1976). Also, bent twin planes and deformation twinning in dolomite suggests temperatures of greater than 400 °C (Higgs and Handin, 1959). The temperature of deformation indicated from microtextural features is in agreement with that indicated by the sulphide isotopic thermometry, i.e. 320–450 °C.

Deformational textures are more commonly observed in pyrite rather than in the other sulphide minerals in the Renström ores, probably due to the higher relative strength of pyrite compared with the other sulphide minerals. Pyrrhotite does show pressure lamellae in most sections studied optically, but as pyrrhotite is weak at low temperatures and pressures, it could be argued that these were produced after the main shearing episode, possibly on uplift to shallower crustal levels. Pyrite that has been sheared shows later cataclastic textures and arsenopyrite often shows cataclastic textures, with fine-grained fractured arsenopyrite associated with euhedral pyrite grains. This suggests that arsenopyrite failed in a brittle manner in areas where pyrite recrystallised, indicating that arsenopyrite may have been stronger than the pyrite. Many authors (e.g. Stanton, 1972; Clark and Kelly, 1976; Marshall and Gilligan, 1987) have suggested that galena is the weakest sulphide, followed in increasing strength order by pyrrhotite, chalcopyrite, sphalerite, and pyrite. These authors also suggested that these middle three sulphides are probably of similar strength to most carbonate rocks and that some silicates may be weaker than pyrite. These ideas are in agreement with what is observed in the Renström deposit. However, the meta-dolomite at Renström appears to have been stronger than the pyrite as it forms resistant porphyroclasts and boudin structures within the pyrite ores. This indicates that dolomitic carbonates are stronger than calcite limestones and sulphides.





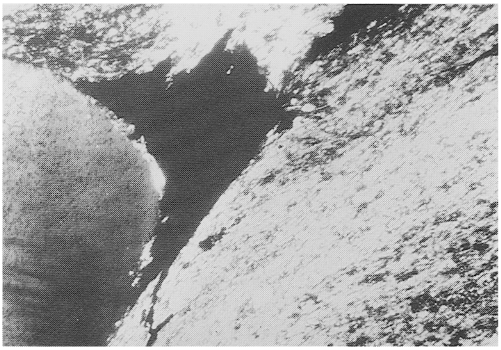
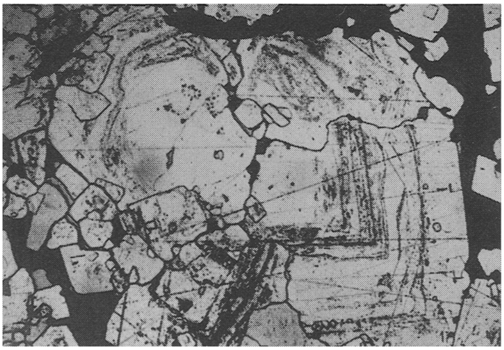


FIG. 8 (*Top Left*). Reflected light photomicrograph showing the effects of pressure solution in the development of the banded pyrite ore. Section has been etched with conc. nitric acid; field of view = 100 μm. FIG. 9 (*Top right*). Reflected light photomicrograph showing the discontinuous nature of the pyrite lenses at lower magnification than Fig. 8. Note the development of the S-C fabrics due to the pressure solution processes. Section has been etched with conc. nitric acid. Field of view = 2 mm. FIG. 10 (*Bottom left*). Transmitted light photomicrograph showing incongruent pyrite (black) pressure shadow around a quartz phenocryst which also shows deformation lamellae. The altered sericitic matrix bends around the porphyroclast. Field of view = 2.5 mm. FIG. 11 (*Bottom right*). Stylolite preserved in dacitic volcanics northwest of the Renström mine.



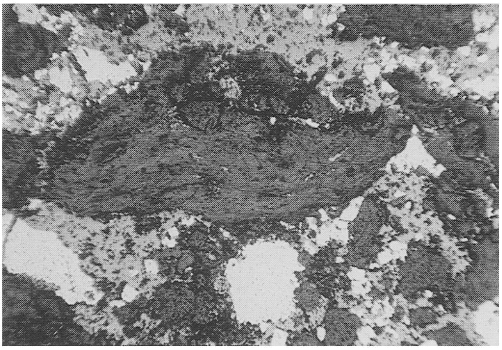


FIG. 12 (*Left*). Irregular pyrite grain boundaries indicate that grain boundary sliding accompanied the pressure solution during the ductile deformation of the sulphide ores. Field of view = 2 mm. In the centre of the photograph the movement of the grain boundaries is charted by the opposing indentation and projection of the pyrite grains. Etching of the section using conc. nitric acid has made the growth zoning in the pyrite visible. FIG. 13 (*Right*). Durchbewegung texture in the sulphide ores. Rounded foliated clast of chloritic wall rock has been tectonically emplaced in the deformed sulphides. Field of view = 2 mm.

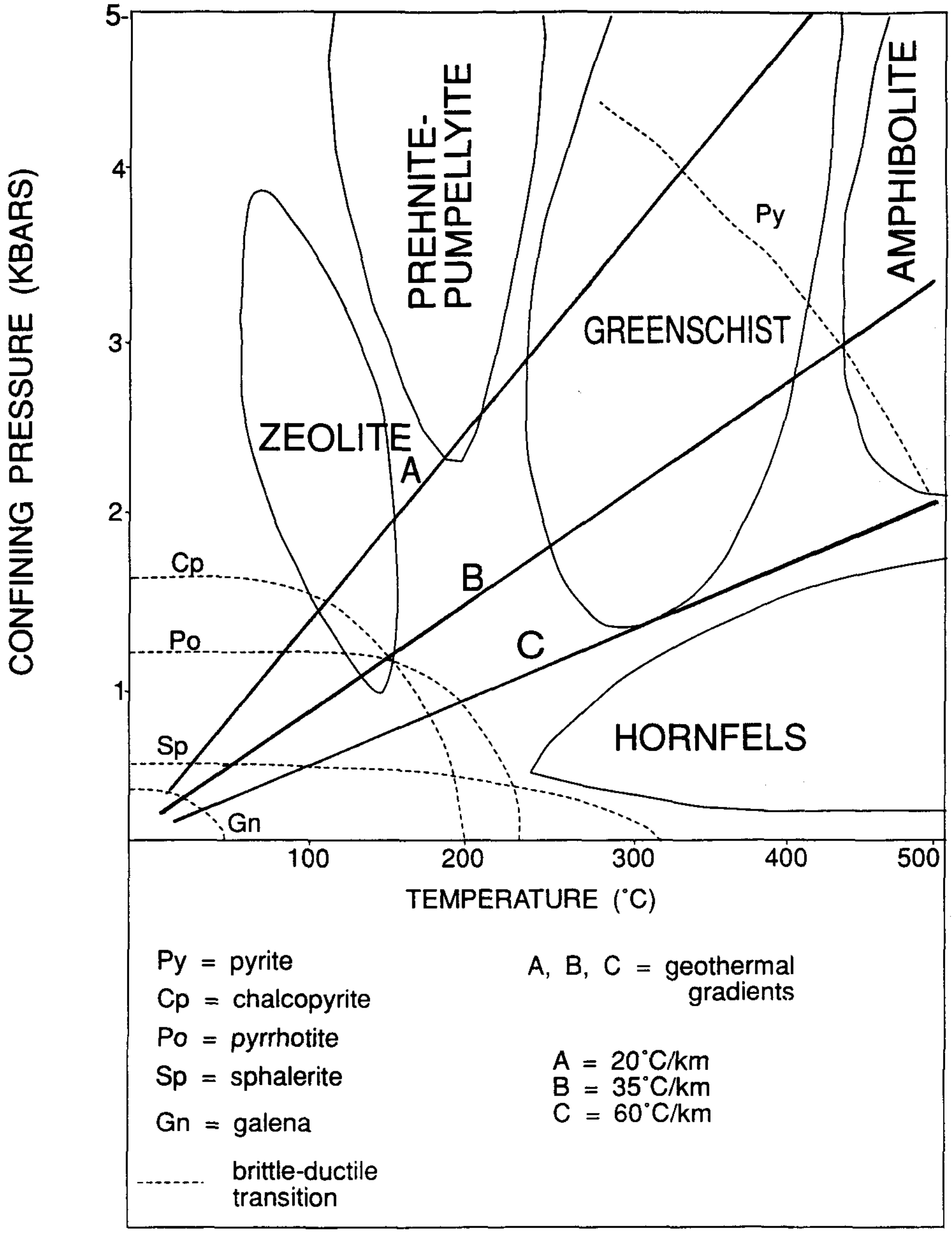


FIG. 14. The brittle-ductile transitions of some common sulphide minerals plotted onto a metamorphic *P–T* diagram (modified from Marshall and Gilligan, 1987). During regional metamorphism, the Renström area was metamorphosed to lower amphibolite facies, at conditions that plot just off the diagram at the top right hand corner. However, during the retrogressive metamorphism around 400 °C, pyrite would have been in the ductile field, which supports the textural evidence seen in the Renström sulphides.

Conclusions

Sulphide mylonites in the Renström VMS deposit have formed by pressure solution processes that have been initiated as a response to high strains and water:rock ratios experienced in discrete shear zones that crosscut the area. Similarly deformed sulphides are probably common in

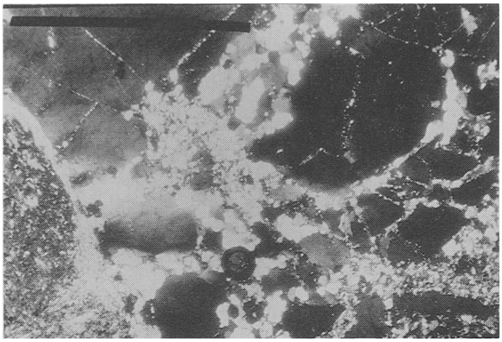


FIG. 15. Transmitted light photomicrograph showing extensive dynamic recrystallisation in quartz phenocryst. Field of view = 2 mm.

other ancient VMS deposits, but have not been widely reported. The microtextures of the Renström sulphides, especially the pyrite, indicate that extensive plastic deformation has occurred. The dolomite that hosts the sulphides appears to be the strongest mineral in the ore zones, followed in order of decreasing strength by arsenopyrite, pyrite, sphalerite, pyrrhotite, chalcopyrite and galena. This agrees with that proposed from experimental work on the deformation of the common sulphides by authors such as Stanton (1972, and references therein), Clark and Kelly (1976), and Marshall and Gilligan (1987). The temperature of the retrogressive shearing event at Renström was around 400 °C; this is shown by sulphide isotopic thermometry and from interpretation of deformation textures within the sulphides and the host rock carbonates and silicates. Pressure solution appears to have been the most common deformation mechanism, producing banded pyrite mylonites and indicating a fluid-assisted deformation episode.

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