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Post-recrystallisation phenomena in metamorphosed stratabound sulphide ores: a comment

RECENTLY, Vokes and Craig (1993) described and illustrated evidence for sequential mobilisation of sphalerite, chalcopyrite and quartz in the small Gressli deposit in central Norway during Caledonian amphibolite-facies metamorphism. These authors stressed the need to study other similarly deformed and metamorphosed deposits to determine if similar textures might be present. The classic Cu–(Zn) pyritic deposits at Sulitjelma in northern Norway (Cook *et al.*, 1990, 1993) are already well known as being excellent examples of stratiform massive sulphide deposits in which the effects of polyphase amphibolite grade metamorphism and deformation have contributed significantly to the observed textures within the sulphide assemblages. Extensive modification of the sulphide bodies during metamorphism and evidence for remobilisation within the large Giken II deposit in the centre of the orefield (Fig. 1) has been described by Cook *et al.* (1993). As well as mobilisation of the more ductile sulphides (pyrrhotite, chalcopyrite), these processes have also played a significant role in the redistribution of precious metals within the deposit (Cook, 1992).

Continuing study of massive sulphide samples from this locality has revealed textures very similar to those described by Vokes and Craig (1993). The samples examined were collected from levels −371 and −396 near the eastern edge of the Giken II deposit, shortly after it closed in the summer of 1991. This area of the mine was known for copper contents higher than in other parts of the deposit and also for elevated concentrations of Ag, Au, Sb, As, Pb and Bi (Cook *et al.*, 1992). Abundant quartz veins cross-cut the stratabound sulphides and carry significant chalcopyrite, pyrrhotite and galena. This area was the source of samples in which widespread (re)mobilisation phenomena have been previously observed. Study of other

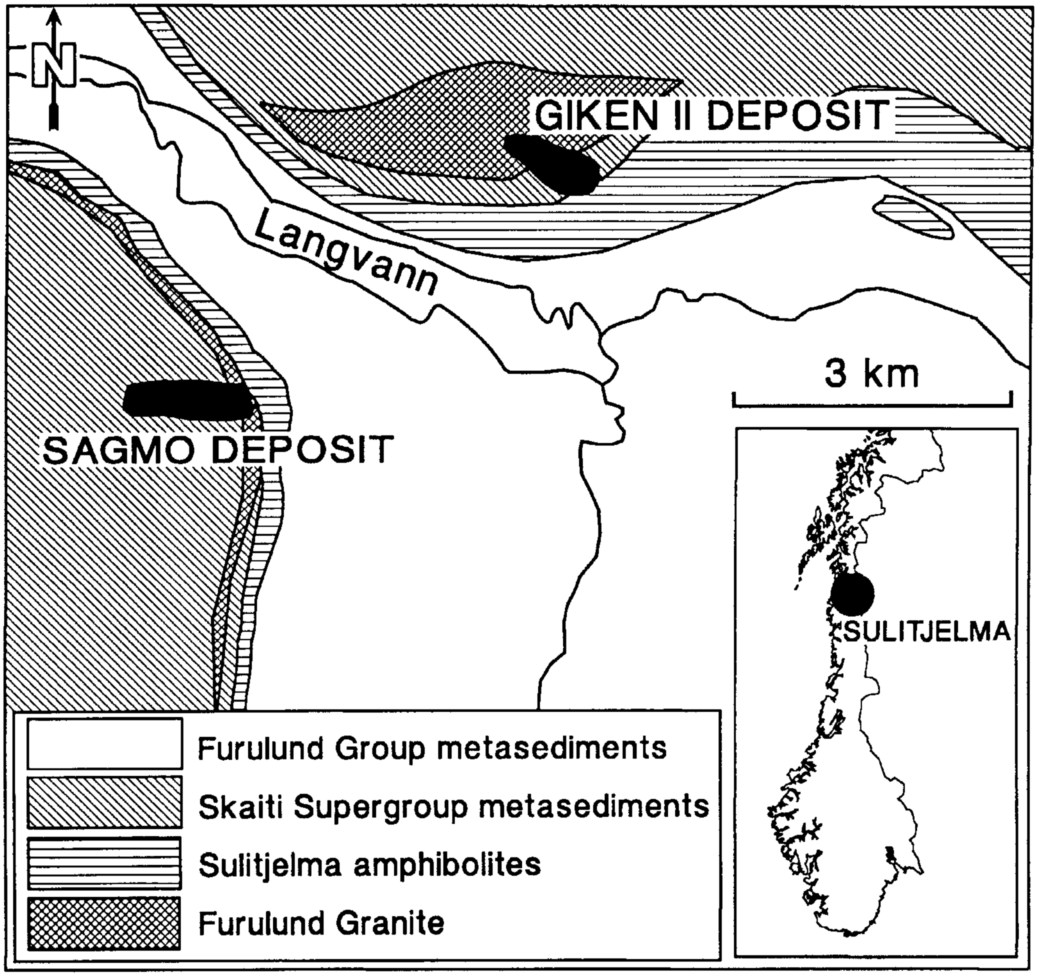

FIG. 1. Sketch map showing location and setting of the Giken II and Sagmo deposit, Sulitjelma district, Norway. The deposits are shown projected to the surface.

deposits at Sulitjelma (Cook, 1987) indicates that remobilisation phenomena are not restricted to the Giken II deposit.

Of particular note is a series of late chalcopyrite- and pyrrhotite-bearing quartz veins which cross-cut the massive part of the Sagmo deposit. However, the textures shown in this contribution have thus far only been observed in samples from the Giken II deposit, and it is not known how widespread the phenomena are in the district as a whole.

Previous work on sulphide petrography at Sulitjelma has shown that pyrite exhibits evidence of deformation in both the brittle and ductile fields. Rounding of the pyrite metablasts took place during metamorphism as the pyrite underwent a 'Durchbewegung' process; rotation in a sheared matrix of ductile sulphides and silicates. Brittle deformation is most evident in the large pyrite porphyroblasts which have undergone clastic deformation (cataclasis). Movement of the more ductile sulphide phases, most typically chalcopyrite but more rarely also pyrrhotite and sphalerite, into fractures in the harder sulphides such as pyrite is very common throughout the Sulitjelma massive sulphides. In some cases, there is also replacement of pyrite along the margins of the fractures. Fracture infilling within the cataclastically deformed pyrite porphyroblasts clearly took place after prograde pyrite growth.

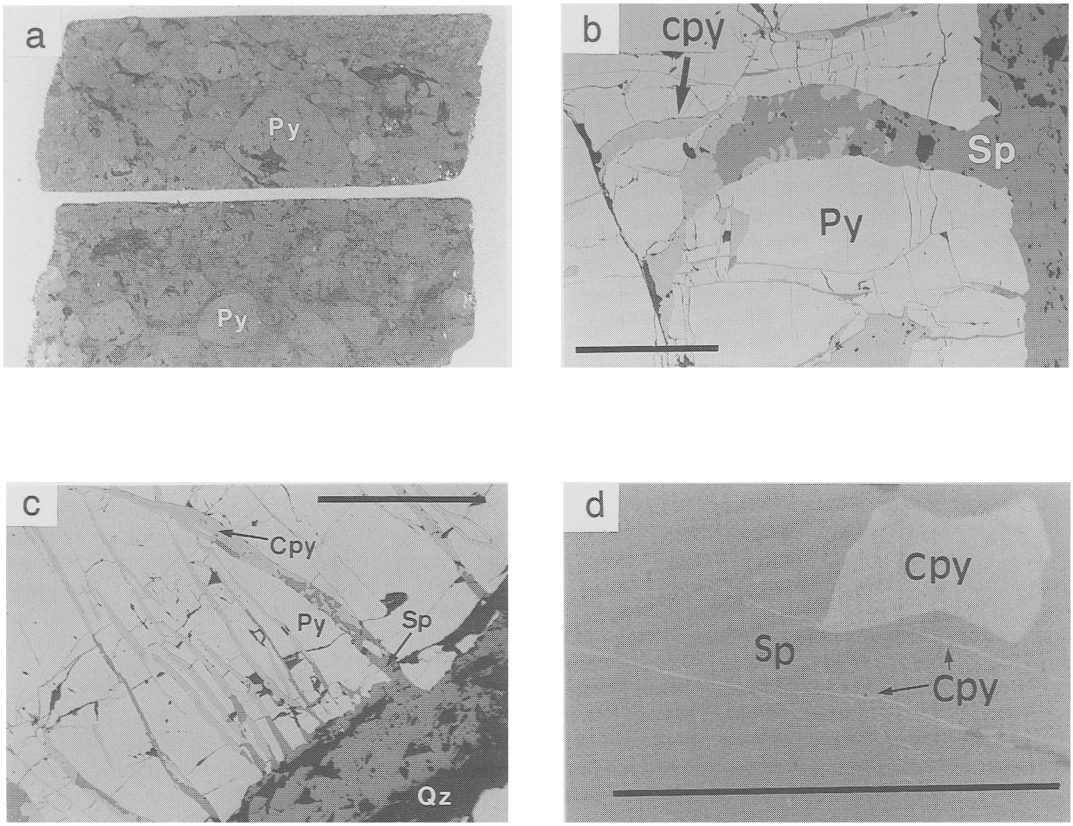

FIG. 2. (*a*) Hand specimen of massive sulphide rock from level −371, Giken II Mine, showing characteristic coarse-grained pyrite (py) in a matrix of pyrrhotite, chalcopyrite and sphalerite. Drillcore is 3.5 cm in diameter. (*b*) Photomicrograph showing fractures in porphyroblastic pyrite (py) being infilled by chalcopyrite (cpy) and sphalerite (sp). Scale bar is 100 μm long. Sample Su 58 (level −396, Giken II Mine). (*c*) Photomicrograph showing a series of fractures in porphyroblastic pyrite (py) healed and infilled by chalcopyrite (cpy) and sphalerite (sp). qz: quartz. Scale bar is 100 μm long. Sample Su 59 (level −396, Giken II Mine). (*d*) Photomicrograph showing fractures in sphalerite (sp) being infilled by chalcopyrite (cpy). Scale bar is 100 μm long. Sample 5833 (level −352, Giken II Mine).

It has been interpreted as occuring during the retrograde portion of the metamorphic cycle, at pressure and/or temperature conditions below those of peak metamorphism, but at which the chalcopyrite still behaves in a ductile manner.

The massive sulphide rock examined (samples Su58, Su59) is composed of greater than 80% sulphides and is dominated by coarse grained pyrite porphyroblasts, up to 2.5 cm in diameter, which are commonly rounded. The pyrites are embedded in a matrix of the more ductile sulphides, chiefly chalcopyrite, pyrrhotite and sphalerite (Fig. 2*a*). Galena and arsenopyrite are also present in lesser quantities, within the matrix and as small euhedral porphyroblasts respectively. The following minerals have also been identified in the samples and their identity confirmed by electron probe microanalysis: electrum (67% Au, 33% Ag), native antimony, freibergite (which contains 17% wt. % Ag), gudmundite (FeSbS), breithauptite (NiSb) and empressite (AgTe). The freibergite, electrum, breithauptite and gudmundite are associated with galena, as in the assemblages described by Cook (1992). The native antimony and empressite occur as inclusions in chalcopyrite and sphalerite respectively.

In samples Su 58 and 59, the largest pyrite porphyroblasts have suffered considerable fracturing, either by cataclastic deformation or by other mechanisms. The fractures in the pyrite which are largely, but not exclusively, along cleavage planes have been healed and infilled first by chalcopyrite, and then by sphalerite, in the same manner as at Gressli. Chalcopyrite occupies the innermost or deepest part of the fractures and sphalerite is found towards the edge of the metablast and on the grain margins. In several examples, it appears that chalcopyrite has clearly preceded sphalerite into the fractures (Fig. 2*b* and *c*). This is true for some of the narrower fractures (5–20 μm wide), as well as the largest fractures (50–100 μm wide).

The similarity with the textures observed at Gressli (Vokes and Craig, 1993) is not limited to the relationship between chalcopyrite and sphalerite. Quartz is normally a minor component of the Sulitjelma massive sulphides, but one which is almost always present. Within the mass of sphalerite that has infilled fractures in pyrite, there are masses of quartz, totally enclosed by the sphalerite. The limited evidence available does not permit a conclusive interpretation about the heritage of this quartz and does not imply that this quartz must also have been involved in a mobilisation process, but its presence is of interest.

As in the Gressli examples (Vokes and Craig, 1993), it appears that there has been significant replacement of the earlier generation infilling chalcopyrite and possibly also of pyrite along fracture walls by the later sphalerite. It is not clear if the fractures in the pyrite reopened during infillling by the sphalerite. These observations are concordant with the sequence of mobilisation at Gressli and also with the relationship between chalcopyrite and sphalerite which would be expected from experimental considerations (see Marshall and Gilligan, 1987). If chalcopyrite becomes mobile before sphalerite then it is also to be expected that it would remain mobile after sphalerite had ceased to be mobile. Textures present within the Sulitjelma samples, with chalcopyrite infilling what appear to be fractures in sphalerite (Fig. 2*d*) confirm this expectation.

Mechanisms of mobilisation and remobilisation of sulphide mineral phases during regional metamorphism of stratiform massive sulphide ores has received considerable attention from ore petrologists and petrographers (Ramdohr, 1960; Vokes, 1969; Cox *et al.*, 1987; Gilligan and Marshall, 1987; Marshall and Gilligan, 1987 and references therein). Various authors including Marshall and Gilligan (1987) have taken part in the debate in the literature as to whether such (re)mobilisation takes place in the solid or fluid state. These authors came to the conclusion that a mixed process involving both chemical and mechanical transport is most probably involved in most cases. Vokes and Craig (1993) have suggested that in cases like Gressli, where there is extensive corrosion and replacement, fluid-assisted processes have more likely been active, at least for the quartz. The present author would suggest that the rather more limited scale of such phenomena at Sulitjelma perhaps infer that solid-state processes such as pressure solution segregation (Marshall and Gilligan, 1987) have played a more dominant role, and that fluid-state processes were subordinate, at least on a local scale. However, mobilisation processes on a deposit-wide scale in which a whole part of a deposit becomes enriched have most probably involved mass transport by the migration of fluids (Cox *et al.*, 1987; Marshall and Gilligan, 1987). Both structural and lithological controls for fluid migration are offered by the difference in rheology between the phyllosilicate-dominated lithologies enclosing the massive sulphide bodies at Sulitjelma and the sulphide bodies themselves. Marshall and Gilligan (1987) have concluded that such macroscale chemical mobilisation takes place under prograde or retrograde metamorphism at temperature conditions between 350 and 500°C. Work is currently in progress to identify the character of the remobilising fluids at Sulitjelma using fluid inclusion techniques.

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Sulphides with high $\delta^{34}S$ from the Late Precambrian Bonahaven Dolomite, Argyll, Scotland

THE Bonahaven Dolomite Formation (BDF) is about 300 m thick and located immediately above the Port Askaig Tillite in the Argyll Group of the Scottish Dalradian Supergroup; it crops out on the northeast coast of Islay. The greenschist facies dolomitic metasediments are of late Proterozoic age and were deposited in a coastal marine environment (Fairchild, 1980) off the south coast of the Laurentian supercontinent (Anderton, 1985). Fairchild (1985) suggested that some quartz-calcite nodules present in the dolomites could represent pseudomorphs after anhydrite. Sulphur isotope analyses of iron sulphides from dolomites with such nodules were therefore undertaken in order to determine whether the sulphur isotopic signature was indicative of the special evaporitic depositional environment. The part of the sequence sampled, Member 3 of Spencer and Spencer (1972) contains stromatolites. Previous sulphur isotope analyses of sulphides and baryte in mineralized (Willan and Coleman, 1983; Hall *et al.*, 1991) and other unmineralized (Hall *et al.*, 1987, 1988, 1993) Dalradian metasediments suggest that Dalradian (Riphean-Vendian) seawater sulphate was isotopically heavy, with $\delta^{34}S_{sulphate}$ at least +30% and possibly as high as +40%, compared to typical Phanerozoic seawater sulphate values of +15±5% (Claypool *et al.*, 1980). Such high values were therefore considered to be possible for the BDF iron sulphides, especially if the sulphide sulphur originated by thermal reduction