The preservation of pre-metamorphic colloform banding in pyrite from the Broken Hill-type Pinnacles deposit, New South Wales, Australia

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Abstract

Two distinct generations of pyrite, with different morphologies, are described from the Proterozoic Broken Hill-type Pinnacles deposit in western NSW. The earlier, py1, forms concentric layers interpreted as colloform banding. Although the textures are somewhat similar to those observed in supergene alteration zones, textural relationships in fresh rocks suggest that these are pre-metamorphic and that the pyrite formed as the result of precipitation from hydrothermal fluids in open veins, vugs and fissures. The second generation, py2, post-dates py1 and forms euhedral overgrowths on it. It is interpreted as being synchronous with the main phase of base metal sulphide mineralisation. The textures reported here are previously unrecorded for Broken Hill-type mineralisation, and have implications for the regional identification of feeder zones to the Broken Hill deposit. The evidence supports a model in which mineralising conditions at the Pinnacles were characterised by slightly higher oxygen and lower sulphur fugacity (further constrained by Fe contents of sphalerite) than at Broken Hill, where pyrrhotite is the major Fe sulphide.

The pre-metamorphic textures observed in the pyrite at the Pinnacles deposit are also unusual because they have survived granulite facies metamorphism and five phases of deformation, whereas previously the preservation of such textures has not been recognised at metamorphic grades greater than amphibolite facies.

KEYWORDS: pyrite, colloform banding, Pinnacles deposit, Broken Hill-type mineralisation, Australia.

Introduction

THE iron sulphide, pyrite, is one of the most common constituents of massive sulphide orebodies (Ramdohr, 1980) and can provide important information relating to the physico-chemical conditions during ore formation. Because of its refractory nature, pyrite is capable of preserving primary depositional textures up to at least upper-greenschist facies metamorphism (e.g. Sullivan deposit, Canada: McClay and Ellis, 1983; Lianxing and McClay, 1992), and amphibolite facies where the sulphur activity remains high (Craig and Vokes, 1993). Such textures have not previously been recorded in pyrite at metamorphic grades greater than this. Furthermore, most other sulphide phases recrystallise at much lower temperatures and pressures, thus destroying any pre-existing textural evidence. Consequently, in many low- to medium-grade metamorphic massive sulphide rocks, pyrite provides the only textural information relating to the pre-metamorphic history of a deposit.

The preservation of primary depositional and diagenetic textures in non-deformed, pyrite-bearing orebodies is well documented (e.g. Edwards, 1947; Ramdohr, 1980; Lianxing and McClay, 1992). Common textures include spher-

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oidal structures such as framboids and microcrystallites, equi-dimensional overgrowths, and concentric growth bands which occur as crustiform and colloform banding. Colloform banded pyrite has been reported in the literature as a low-temperature diagenetic mineral (e.g. Ramdohr, 1980). In addition, concentric growth banding is common in many sulphide orebodies and is indicative of precipitation in unrestricted, open spaces (Craig, 1990). Growth bands may be due to changing compositions in the ore-bearing fluid or fluctuating environmental conditions. They form by the precipitation of sulphide minerals from saturated solutions and are a common feature of hydrothermal conduits and mineralised vug-like cavities such as hydrothermal veins (e.g. Graf and Skinner, 1970; Cox *et al.*, 1981; McClay and Ellis, 1983; Craig, 1990). Colloform textures may also develop in weathering profiles by the oxidation of pyrrhotite.

The effects of progressive deformation on pyrite have also been studied in detail (McClay and Ellis, 1983, 1984; Cox, 1987; Lianxing and McClay, 1992). In particular, McClay and Ellis (1983) constructed a 'deformation mechanism map' relating stress, pressure and temperature to the style of deformation observed in pyrite. During low- to medium-grade metamorphism, pyrite deforms cataclastically and cracking and fracture textures are common. In areas of increased deformation, pyrite bands are commonly boudinaged and broken. With further increase in metamorphic grade, the pyrite grains coarsen and exhibit thermal annealing textures and eventually recrystallise. According to McClay and Ellis (1983), complete recrystallisation of pyrite is achieved at amphibolite facies metamorphism; there are no reported occurrences of

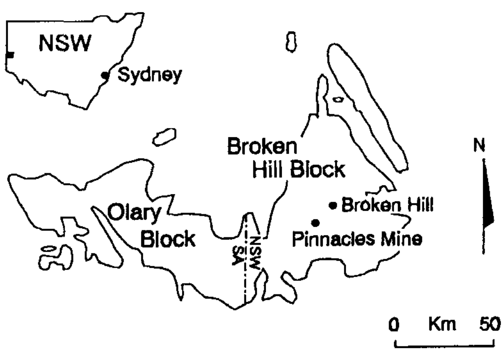

FIG. 1. Map showing outcrop of Proterozoic rocks in western New South Wales (NSW) and eastern South Australia (SA) and the location ofthe Pinnacles mine in the Broken Hill Block.

primary depositional textures preserved at grades above this.

This paper describes textures observed in pyrite from the Broken Hill-type Pinnacles deposit in western New South Wales, Australia, where textures can be recognised which are interpreted as of a primary deposition origin despite granulite facies metamorphism. In particular, two generations of pyrite are observed, both of which predate metamorphism; the earlier generation exhibits primary colloform-like growth banding. The recognition of these textures is important for two reasons: (1) occurrences of primary depositional textures in pyrite at greater than amphibolite facies metamorphic grade are previously unrecorded; and (2) the occurrence of open-space growth banding in pyrite has a direct bearing on any model for the genesis of the Pinnacles orebody and has broader implications for Broken Hill-type mineralisation.

Geological setting

The Pinnacles deposit lies 15 km southwest of Broken Hill in New South Wales (Fig. 1). The deposit lies in the Proterozoic rocks of the Broken Hill Block which forms part of the Willyama Supergroup (Stevens *et al.*, 1983; Willis *et al.*, 1983) and is the second largest Broken Hill-type orebody in the area after the Broken Hill deposit itself (Stevens *et al.*, 1988). Of the estimated ore reserves of 6×10^5 tonnes at the Pinnacles (Department of Mineral Resources 1981), approximately 2×10^5 tonnes have been extracted. The orebodies comprise several strata-bound massive sulphide lenses of variable Pb–Zn–Ag ratios that are hosted in a suite of pelites, psammopelites and meta-exhalites (Parr, 1994). Four ore-bearing lenses have been identified, one major galena-rich unit, the 'Pb lode', and several thinner sphalerite-rich units, the 'Zn lodes', which lie in the footwall and hanging wall to the Pb lode. Average grades of the main Pb lode are 6–11% Pb, 2.5% Zn and 300–500 g/t Ag, whereas in the less continuous Zn lodes, ore grades are 1% Pb, 10–15% Zn and 30 g/t Ag (Barnes, 1988).

The Willyama Supergroup consists of a complex suite of Early to Mid Proterozoic metasedimentary and metavolcanic rocks which were deposited between 1670 and 1690 Ma (U-Pb dating of zircons; Page and Laing 1990). The lower part of the supergroup comprises felsic gneiss together with lesser volumes of mafic gneiss which represent bimodal magmatism. In contrast, the upper part of the stratigraphic sequence is dominated by metasedimentary rocks which represent clastic deposition in an increasingly deep, subaqueous environment (Stevens *et al.*, 1983, 1988; Willis *et al.*, 1983). Stratabound base metal sulphide mineralisation is concentrated, although not exclusively located, at the transition from volcanic to sedimentary derived sequences, which is a characteristic of Broken Hill-type mineralisation (Parr and Plimer, 1994). The mineralisation is associated with a suite of chemically unusual rocks such as garnetites, quartz–garnet, quartz–gahnite, quartz–magnetite, magnetite–garnet and tourmaline–quartz rocks all of which have been interpreted as the metamorphic equivalent of exhalites (Stanton, 1972; Barnes, 1980; Lottermoser, 1989; Parr, 1992*a*). Although alternative tectonic models have been proposed (Haydon and McConachy, 1987; Wright *et al.*, 1987), the overall stratigraphic sequence of the Willyama Supergroup is believed to represent deposition in an evolving intracontinental rift environment which formed as the result of extensional tectonism of young Proterozoic crust (Willis *et al.*, 1983; Stevens *et al.*, 1988).

Prograde metamorphism and intense deformation of the Willyama Supergroup occurred during the Olarian Orogeny (1600 $\pm$8 Ma; Marjoribanks *et al.*, 1980; Phillips, 1980; Page and Laing, 1990). Isograds established for the supergroup indicate that metamorphic grade increases from andalusite-bearing amphibolite facies rocks in the northern area to two pyroxene-bearing granulite facies rocks in the southwest (Phillips, 1980). Three major episodes of folding and a major shearing event associated with retrograde metamorphism are recorded regionally. Large scale nappe-like folds (F_1) with amplitudes over tens of kilometres are refolded by two, more localised, episodes of tight, upright folding (F_2 and F_3). Locally, an additional episode of deformation is recognised: for example at the Pinnacles Mine itself, a gentle warping of F_2 foliation is locally defined as F_3 and which predates F_4 (the regional F_3) folding (Laing, 1978; Parr, 1991). Large-scale mylonitic shear zones (local D_5) are associated with retrograde metamorphism. These sericitic zones cross-cut all other structures and have index minerals which suggest that retrograde metamorphism represents isobaric cooling of the supracrustal pile, rather than a separate metamorphic event (e.g. kyanite-bearing shear zones in sillimanite-grade rocks: Corbett and Phillips, 1981).

Since the Late Proterozoic, the Willyama Supergroup has been subject to several periods of weathering associated with uplift and erosion. It has been estimated that up to 60 Mt of primary sulphide ore was removed from the Broken Hill orebody during these periods (Plimer, 1984; Stevens, 1986). This complex history of repeated episodes of exposure and oxidation resulted in oxidation of the orebody to depths of 60–100 m and has led to a highly complex mineralogy due in part to the complex primary composition of the Broken Hill orebody (Plimer, 1984).

At the Pinnacles mine (Fig. 2), the stratabound base metal mineralisation is hosted by a sequence

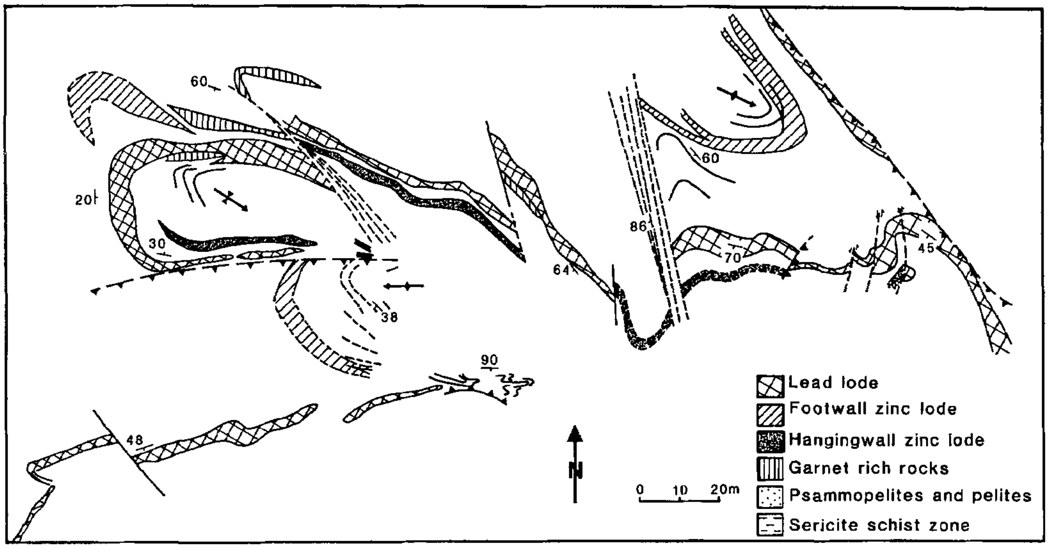

FIG. 2. Geological map of the Pinnacles deposit at the 100 foot level (No. 2). Standard structural symbols are used; after Parr (1994).

of sillimanite- and garnet-bearing pelites interlayered with more siliceous psammopelitic rocks (S_0). These micaceous metasediments volumetrically dominate the stratigraphy and exhibit well developed metamorphic fabrics (see below). The sulphide orebodies are interlayered with a suite of garnet-rich (garnetites and quartz-bearing garnetites; Spry and Wonder, 1989) and quartz–gahnite meta-exhalites (Parr, 1992*a*). On the surface, but not in the mine itself, country rocks which are exposed include amphibolites, quartz–magnetite rocks and garnet–magnetite and garnet–hematite rocks.

Prograde metamorphism at the Pinnacles deposit attained granulite facies and is characterised by hedenbergite–almandine–quartz, hedenbergite–hornblende–magnetite ($\pm$ almandine) and sillimanite–quartz–almandine assemblages and by the development of strong mineral foliations (Parr, 1994). In particular, S_2 metamorphic fabrics are defined by sillimanite, replaced extensively by retrograde muscovite, and prograde muscovite and biotite; cross-cutting S_3 fabrics are rare. Macroscopic F_4 folds (wavelengths $\sim$ 100 m), which have a major influence on the shape of the mineable orebody, have near-vertical axial planes orientated E-W and have formed a series of anticlines and synclines whose fold hinges are thickened, producing the best ores, and whose limbs are commonly cut by, and sheared out along, D_5 retrograde shear zones (Fig. 2). Axial planar S_4 fabrics are additionally defined by the fine grained muscovite and the partial dissolution of garnet and gahnite along foliation planes. The D_5 shear zones represent zones of intense mylonitisation, and, although displacement vectors across the zones are only tens of meters (Parr, 1994), they have acted as zones of intense strain partitioning. The retrograde metamorphism is characterised by the formation of muscovite from sillimanite, and zincian staurolite from gahnite, muscovite and quartz. In some samples fine grained chlorite is also abundant and probably indicates continued re-equilibration at lower temperatures and pressures. In mylonitic shear zones less than 1 km to the north of the deposit, kyanite locally replaces sillimanite inferring isobaric cooling during this late stage metamorphism.

Like the orebodies at Broken Hill, the Pinnacles orebody has been subject to post deformational weathering and oxidation up to depths of 45 m and at greater depths along cross cutting shear zones.

Sulphide mineralogy

Over 100 polished thin sections were studied, of which approximately 20 contained the pyrite textures described in this paper. These 20 samples were distributed throughout the mine and in a variety of structural settings: only those from fresh samples taken from the lowest level are discussed here, unless otherwise stated.

The sulphide mineralogy of the Pinnacles deposit consists of the main ore minerals, galena and sphalerite, and a variety of other sulphide phases including a suite of sulphosalts (Stillwell, 1926; Ramdohr, 1950; McQueen, 1984, 1987) (Table 1). Pyrite occurs at least as a minor phase in most ore specimens and also occurs in minor quantities in the pelitic host rocks.

TABLE 1. Mineralogy of the sulphide orebodies in the Pinnacles deposit

Pb lode		
	Major sulphides	galena, pyrite
	Minor sulphides	sphalerite, arsenopyrite, chalcopyrite, pyrrhotite, tetrahedrite, gudmundite, berthierite, falkmanite, boulangerite
	Gangue minerals	quartz, garnet ($\pm$gahnite, calcite, muscovite, biotite, apatite, pyroxene, amphibole, chlorite)
Zn lode		
	Major sulphides	sphalerite, pyrite, galena,
	Minor sulphides	pyrrhotite, chalcopyrite, arsenopyrite, gudmundite, berthierite, ?jamesonite
	Gangue minerals	quartz, gahnite, garnet, calcite ($\pm$apatite, biotite, muscovite, chlorite, zircon, magnetite)

Sulphides from the Pb lode consist of medium to coarse grained galena with minor sphalerite, pyrite, pyrrhotite, arsenopyrite, chalcopyrite, tetrahedrite and Pb-Sb (-Fe) sulphosalts. Gangue minerals include subhedral almandine, calcite, quartz, apatite, pyroxene, hornblende, gahnite, biotite, and chlorite. The Zn lodes are generally finer grained and more siliceous, and consist of sphalerite, with lesser quantities of pyrite and galena, and minor chalcopyrite, pyrrhotite and Pb-Sb(-Fe) sulphosalts. Gangue minerals are dominated by quartz, gahnite, and almandine garnet, but include calcite, biotite, and muscovite with minor apatite.

Coarse grained galena has been extensively remobilised and recrystallised during metamorphism and deformation. Because of the relative ductility of galena, the Pb sulphide is characteristically observed as an interstitial phase and has been commonly remobilised along fractures and grain boundaries. It exhibits typical equilibrium textures with sphalerite in all ore lenses, for example concave margins (Parr, 1994). The black-coloured sphalerite is also totally recrystallised and exhibits no internal structures. In some samples, sphalerite contains inclusions of other sulphides which are in metamorphic equilibrium with the zinc sulphide, including chalcopyrite, pyrrhotite and pyrite, as well as porphyroblasts of arsenopyrite. The zinc spinel, gahnite is a common gangue mineral: inclusions of sphalerite in gahnite suggest that at least some of the gahnite formed by the desulphidisation of sphalerite (Spry, 1987; Parr, 1994), although in other cases sphalerite includes relict gahnite crystals suggesting the reverse reaction may have occurred.

Minor sulphide phases, other than pyrite, are pyrrhotite, chalcopyrite, arsenopyrite and a variety of sulphosalts. Hexagonal pyrrhotite is a common minor phase and a major constituent of a small number of samples of sphalerite-rich ores.

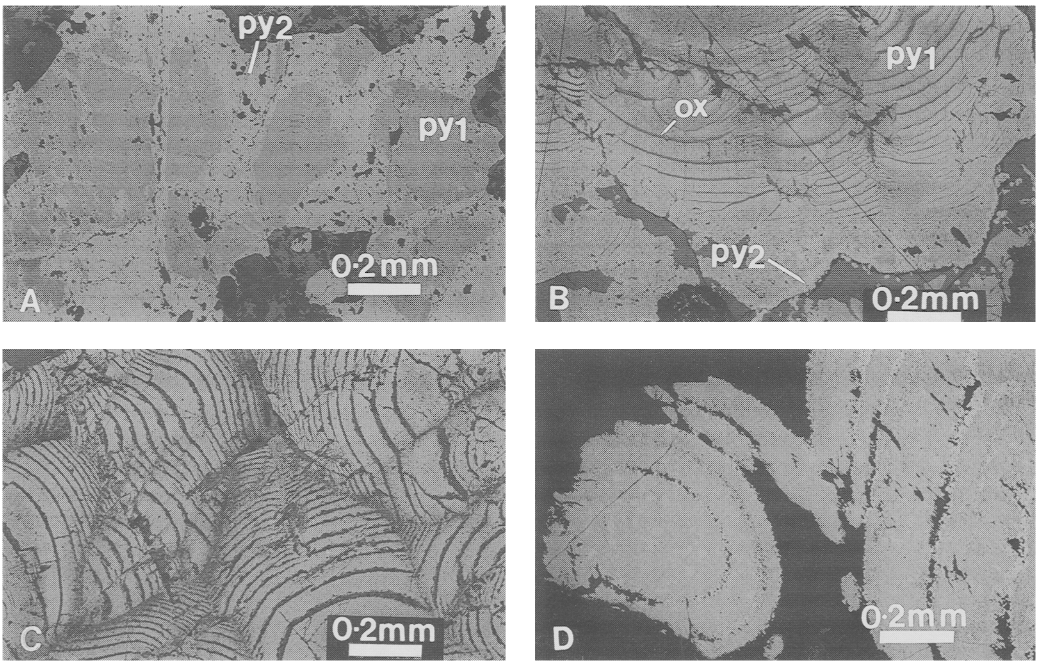

FIG. 3. Photomicrographs of textures observed in pyrite from the Pinnacles mine: (A) Two generations of pyrite: fragments of py1 (etched), which exhibit growth banding are overgrown by brighter py2. (B) Concentric growth banding in py1 — darker layers interleaved with the pyrite are Fe oxides (?goethite), probably due to incipient weathering. (C) Less common texture in py1: coalescing of growth bands towards one point, probably as gradual filling of a cavity. (D) Unusual complete concentric growth bands in py1, perhaps indicating concretionary growth and physical transportation of pyrite fragments during py1 precipitation. All samples in reflected light in air; samples A, B and D etched using warm 20% HNO_3.

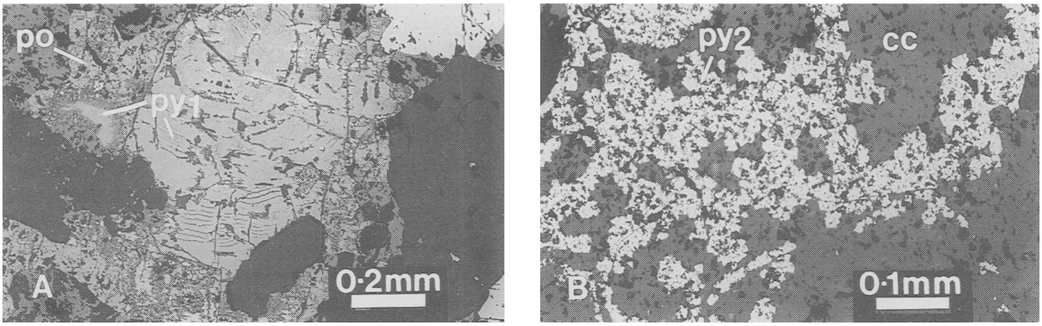

FIG. 4. Photomicrographs of replacement textures in pyrite from the Pinnacles mine: (A) Pyrrhotite (po) replacing cloudy, growth-banded py1. (B) Bright euhedral crystals of py2 replacing calcite (cc). All samples in reflected light in air.

Textural equilibrium is exhibited between the pyrrhotite, sphalerite and galena. The pyrrhotite also occurs as exsolution blebs and laminae in sphalerite; locally pyrrhotite replaces pyrite and this is discussed more fully below. Inclusions of pyrrhotite are also observed in garnet and rarely in gahnite. Chalcopyrite is also a minor sulphide phase and occurs in the Zn lodes as anhedral masses in textural equilibrium with sphalerite and as laminae within the sphalerite. Arsenopyrite is a common accessory mineral, particularly in the galena-rich ores. It is also observed as an accessory mineral in garnetites and gahnite-bearing schists and in some wall rocks even forms thin (<1 mm) monomineralic layers and lenses. It is characterised throughout the deposit by well formed lozenge shaped crystals which are locally aligned to the dominant foliation.

A wide variety of antimony-rich sulphosalts including meneghinite, boulangerite, falkmanite (McQueen 1984, 1987), berthierite and gudmundite (Stillwell, 1926) are found at the Pinnacles deposit. The presence of these minerals, together with the locally abundant occurrence of arsenopyrite, reflects the Sb- and As-rich nature of these sulphide orebodies.

Pyrite mineralogy

Pyrite is the most abundant iron sulphide in thc Pinnacles deposit and makes up to 30% of the sulphide orebody in marginal parts of the Pb lode and 20% in the Zn lodes. The pyrite is most abundant at the margins of the sulphide orebodies, but is also present as a minor phase in the pelites and meta-exhalites. Textures observed in pyrite from the orebodies are also observed in the host rocks, although they are not as common. Two generations of pyrite can be defined texturally: the earlier, py1, is characterised by concentric growth banding, whereas the later generation, py2, does not exhibit internal textures and forms overgrowths on py1 (Fig. 3A, B).

Py1 occurs in both Pb and Zn orebodies. The pyrite most commonly occurs as fragments with irregular edges, which have random orientation and vary in size from 0.1 to 5 mm. Py1 is very fine grained and has a slightly cloudy appearance and, consequently, a dull polish. Its main textural feature is the development of concentric bands (Fig. 3A–D). The concentrically layered pyrites commonly have approximately flat bases (Fig. 3B) which infer uni-directional growth and are consistent with growth of pyrite from wall rocks into an open space or fissure. A less common form of growth banding is shown in Fig. 3C. Banding in these pyrites has coalesced at a central point, inferring simultaneous growth of pyrite from all sides of a cavity or fissure. Complete concentric banding is also observed in py1 (Fig. 3D) in which py1 layers have formed both complete and partial spheroidal layers up to 2 mm diameter. Nuclei to the spheroids are not observed so that their mode of precipitation is unclear, although unobstructed growth is inferred. Back scatter imagery of py1 indicates that there are no major compositional variations between layers and that the pyrite is a homogeneous mix of Fe and S with no detectable trace elements.

In rare samples, pyrrhotite is observed replacing py1 (Fig. 4A). A reduction reaction is required for this process. The replacement of pyrite by pyrrhotite is consistent with pyrite decomposition and pyrrhotite formation due to increases in sulphur activity during prograde metamorphism (Craig and Vokes, 1993).

The second generation of pyrite, py2, does not exhibit any internal textural features and occurs as fresh subhedral and euhedral pyrite crystals which attain a good polish. Py2 forms homogeneous layers, up to 1 mm thick, which encrust the outermost layers of py1 fragments, and as interstitial pyrite around angular fragments of py1 (Fig. 3A, B). Py2 occurs in equilibrium with other sulphide minerals, such as sphalerite, galena and chalcopyrite and is clearly intimately associated with the main body of mineralisation. In particular, it occurs with these minerals as an interstitial phase to the prograde silicate assemblage. In galena-rich samples py2 locally replaces calcite (Fig. 4B) and occurs along biotite cleavage planes. Porphyroblastic pyrite occurs locally in association with porphyroblastic arsenopyrite.

Both generations of pyrite grains have nonconformable lateral and basal terminations against prograde and retrograde minerals (Fig. 5A, B), implying a pre-metamorphic origin. Pieces of py1 exhibiting good colloform banding, are crosscut by prograde garnet, pyroxene and gahnite (Fig. 5A: locally associated with retrograde mica rims) and also by retrograde muscovite (Fig. 5B). Regional prograde metamorphism attained granulite facies at the Pinnacles deposit and retrograde metamorphism was at kyanite-grade. Despite the high grades of metamorphism enjoyed by the deposit, the textures observed in py1 have survived and show little evidence of brittle or ductile deformation associated with post-depositional episodes of deformation and metamorphism. Instead, the randomly orientated, well preserved pieces of py1 are suggestive of fragmented relics of larger pieces of pre-metamorphic colloform banded pyrite which formed in non-constrained environments such as cavities and conduits in the upper levels of a hydrothermal system.

Late-stage incipient oxidation and alteration is evident in samples located near shear zones. Here the bands of py1 are locally interleaved with thin layers of iron oxide (Fig. 3B): in some samples this is magnetite, but in others it has a deep red colour in transmitted light and is goethite. Locally, goethite has partially replaced py1 and forms a matrix between the separate fragments. This textural relationship confirms that sulphides close to shear zones have undergone oxidation, probably associated with surficial weathering.

Sphalerite chemistry

Microprobe analyses of sphalerite samples from various locations within thc orebodies were undertaken using a JEOL JSM840 scanning electron microscope fitted with a TRACOR TN5500 energy dispersion spectroscopy EDS system, at the University of Newcastle, NSW. An accelerating potential of 15 kV and an emission current of 2 nA were used. For these samples the standards used were hematite (Fe), rhodonite (Mn), willemite (Zn) and pyrite (S). Six representative analyses are given in Table 2.

The data give consistent Zn:Fe molar ratios of 83:17, which is similar to figures quoted for the Broken Hill deposit (Scott *et al.*, 1977). The Zn:Fe ratio, in conjunction with the mineralogical data, can be used to help constrain the sulphur and oxygen fugacity of the ore-forming fluids (Barton and Skinner, 1979). The Fe content of the sphalerite is high relative to the greater abun-

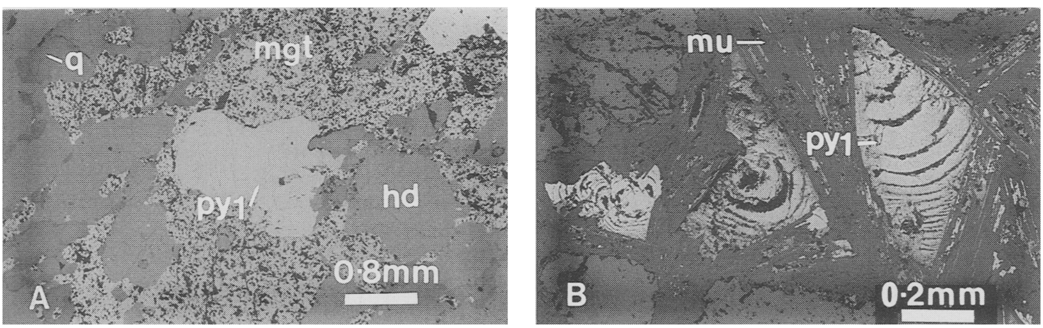

FIG. 5. Photomicrographs of metamorphic textures associated with pyrite from the Pinnacles mine: (A) Prograde hedenbergite (hd), quartz (q), almandine (not in figure) assemblage with magnetite (mgt) and py1. (B) Retrograde muscovite (mu) with minor amounts of sphalerite along cleavage planes overgrowing py1 exhibiting good growth banding. All samples in reflected light in air.

TABLE 2. Microprobe analyses of sphalerite from Zn ore material (wt%)

Sample No.	22	24	25	27	28	29
Zn	56.2	56.8	56.4	54.6	54.7	55.1
Fe	9.5	8.5	9.9	10.7	10.9	10.4
S	31.7	32.1	31.9	31.9	31.6	32.0
Cd	1.0	1.1	1.0	0.8	1.0	1.1
Mn	b.d.	0.1	0.1	b.d.	b.d.	b.d.
Total	98.3	98.6	99.3	98.0	98.1	98.5

b.d. = below detection

dance of pyrite over pyrrhotite and is consistent with f_{O_2} and f_{S_2} of the hydrothermal fluids close to the pyrite–pyrrhotite boundary. This can be interpreted as an early episode of py1 mineralisation prior to sphalerite precipitation and a lack of equilibration between these phases during subsequent metamorphism and deformation. The presence of later pyrite (py2) together with pyrrhotite, which are in textural equilibrium with the sphalerite, is consistent with the ore-forming fluids having fugacities close to the pyrite-pyrrhotite boundary. This is in contrast to the Broken Hill deposit where pyrrhotite is the dominant Fe sulphide and more reduced conditions are inferred.

Discussion

The textures observed in pyrite (py1) from the Pinnacles deposit are typical of textures observed by the precipitation of minerals in open spaces such as cavities and fissures. The cross-cutting relationships of both prograde and retrograde minerals with the pyrite, and the fragmental nature and random orientation of pieces of banded py1 within py2, indicate cataclasis and disruption prior to regional metamorphism. The timing of the pyrite relative to the base metal mineralisation, is less clear. The textures observed could be interpreted as an early episode of diagenetic pyrite formation prior to the main episode of base metal mineralisation, followed by the formation of pyritic overgrowths (py2) synchronous with mineralisation. Eldridge *et al.* (1993) make a similar interpretation, on the basis of variable $\delta^{34}S$ data, for the two generations of pyrite observed at the McArthur River deposit. However, bulk sulphide $\delta^{34}S$ data for base metal sulphide mineralisation from the Pinnacles deposit have a well defined hydrothermal magmatic signature (Parr, 1992*b*) with no indication of contamination from a secondary, sedimentary source. Alternatively, py1 formed during the main episode of mineralisation, but, unlike the other sulphide minerals, was able to retain its internal features because of its refractory nature. Py2 may, then, have formed in response to retrograde metamorphism.

At Broken Hill, a wide variety of secondary minerals -mostly Mn and Fe oxides and hydroxides- have been recorded (Plimer, 1984). Secondary pyrite is not recorded, although colloform sphalerite is reported as a deeply deposited supergene mineral precipitated around primary sulphide ores which lie on fault planes. The textures described in this paper might be interpreted as similar, deeply deposited supergene minerals associated with post deformation uplift and weathering. However, the textural relationships observed, suggest that the formation of py1 in particular, predated any metamorphism and deformation. Pre-metamorphic uplift and erosion should not, therefore, be discounted.

McClay (1991) concluded that colloform growth banding is characteristic of massive sulphide orebodies formed proximal to a hydrothermal vent, whereas pyrite, formed in more distal locations, is characterised by framboidal structures and microcrystallites. This is consistent with the origin of similar colloform banding described for the Kuroko deposits in Japan (Eldridge *et al.*, 1983). The early pyrite at the Pinnacles deposit could, therefore, represent initial venting of hydrothermal fluids which deposited Fe sulphides on conduit walls which, in places, coalesced to form intricate convergent patterns (e.g. Fig. 3C). Such an interpretation is consistent with the sulphur isotope data discussed above. In this model, pyrite mineralisation represents the early stages of the main episode of base metal mineralisation and reflects the initiation of the hydrothermal system. The pyrite may either be *in* *situ*, in which case the Pinnacles deposit lies at the site of hydrothermal venting, or it may have been transported as fragments of pre-existing veins and/or sulphide precipitates, by sulphide-rich ore-fluids to a more distal site. Given the wide dispersion of py1 within the orebody, together with its excellent preservation, a small amount of transportation is predicted, perhaps controlled by palaeotopography.

This interpretation is supported by the minor occurrence of py1 in the pelitic wall rocks of the deposit. Textures indicative of proximal hydrothermal vents have not been previously recorded for Broken Hill-type deposits in the Willyama Supergroup and the lack of any evidence has previously been ascribed to the intense deformation and metamorphism (Plimer, 1984; Stevens *et al.*, 1988). The evidence presented here, however, indicates that, although the vein stockwork itself may have been destroyed, textural data can survive which can be used to infer its existence.

Deformation studies indicate that pyrite is the strongest common sulphide and that deformation is characterised by brittle failure and cataclasis (e.g. Graf and Skinner, 1970; Gilligan and Marshall 1987). Deformation mechanism maps constructed for pyrite (McClay and Ellis, 1983) indicate that with increasing strain rates and temperature, pyrite undergoes further modification by pressure solution, dislocation gliding and finally dynamic recrystallisation and static annealing. Furthermore, on the basis of empirical data, these studies argue that primary depositional textures are often preserved to upper greenschist–amphibolite facies, but that at greater metamorphic grades complete annealing and recrystallisation takes place (McClay and Ellis, 1983; Lianxing and McClay, 1992). Despite these predictions and findings, primary depositional structures in the form of colloform growth banding have been preserved at the Pinnacles deposit, which has undergone granulite facies prograde metamorphism and five phases of deformation. The survival of these textures has probably been due to ductility contrasts within the mixed sulphide orebodies, where weaker minerals, in particular galena, have acted in a highly ductile manner and mylonitic shear zones have been associated with the partitioning of strain. Therefore, the observations made here suggest that, whereas in most instances pyrite is recrystallised and exhibits annealing textures at increased metamorphic grades, in cases of intense strain partitioning, such as at the Pinnacles deposit, relict primary depositional textures in pyrite may survive.

Conclusions

Two generations of pyrite with distinct morphologies are observed at the Pinnacles deposit. The earlier one, py1, exhibits well-formed concentric banding interpreted as colloform banding. The second generation, py2, post-dates py1 and forms euhedral overgrowths on it. Similar textures occur in some supergene environments, but textural evidence suggests that both generations observed here predate regional metamorphism and deformation.

The textures reported here have not been recorded previously for Broken Hill-type mineralisation, in particular in the Proterozoic Willyama Supergroup of New South Wales. However, similar growth banded textures are observed in sulphide deposits formed at sites proximal to hydrothermal vents, for example in the Kuroko ores of Japan. The fragmental nature of the pyrite suggests that py1 may represent relict fragments of a hydrothermal vent which have been transported a short distance.

The primary growth textures observed in the pyrite have survived granulite facies metamorphism and five phases of deformation. This is in direct contrast to previous studies of progressive deformation in pyrite (e.g. McClay and Ellis, 1983), which suggest that complete recrystallisation and annealing takes place at metamorphic grades greater than amphibolite facies. This unusual case of preservation appears to be due to ductility contrast in the sulphide mineralogy and strain partitioning associated with cross-cutting mylonitic shear zones.

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