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ARTICLE

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Evolution of the Peak Hill high-sulfidation epithermal Au–Cu deposit, eastern Australia

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Abstract The early Palaeozoic Macquarie Arc, south-eastern Australia, hosts a variety of major late Ordovician to earliest Silurian subduction-related deposits (e.g., Cadia East, Ridgeway, Cadia Hill, Cowal and Northparkes). However, there is uncertainty about whether coeval high-sulfidation epithermal deposits, which occur in intra-oceanic metallogenic belts elsewhere in the West Pacific, (e.g., Lepanto and Chinkuashih), are also present in the Macquarie Arc. This has led to suggestions that their absence may be due to the poor preservation potential of deposits that form at relatively shallow crustal levels in ancient rocks. We present here an interpretation for evolution of the Peak Hill Au–Cu deposit based on the distribution of alteration facies, sulfur isotope data from several textural forms of pyrite and barite, and an assessment of the regional volcanic and sedimentary facies architecture. These data show that the Peak Hill deposit displays a distinct sub-vertical zoning with a pyrophyllite and vuggy-quartz core, that today extends about 350 m east–west and at least 550 m north–south, which grades out through paragonite+muscovite, kaolinite to a chlorite+epidote alteration zone at the margin. The alteration zoning reflects both lower temperatures and neutralisation of acid fluids with increasing distance from the core, which represents the conduit along which hot acidic hydrothermal fluids were channelled. Several temporally overlapping events of silicification, bladed-quartz-pyrite veining, brecciation and pyrite veining occurred during the last stages of hydrothermal alteration, although most appear to predate mineralisation. Au–Cu mineralisation was associated with late quartz-pyrite-barite veins, and the highest gold grades occur mainly in microcrystalline-quartz-altered rocks in the paragonite+muscovite alteration zone, generally within 50 m outward from the boundary of the pyrophyllite and vuggy-quartz core. Sulfur- and lead-isotope data, and the characteristic zoning of ore minerals and alteration assemblages support a magmatic source for the hydrothermal fluids. Similarities in many of the isotopic signatures between Peak Hill and deposits such as Northparkes support generation of the high-sulfidation mineralisation during the Late Ordovician to earliest Silurian (possibly ca. 440 Ma) metallogenic event. The Late Ordovician to Early Silurian volcanic and sedimentary facies associations at Peak Hill are consistent with alteration and mineralisation occurring in rocks deposited in a submarine setting.

Keywords Peak Hill · High sulfidation · Epithermal gold · Lachlan orogen · Australia

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Introduction

Ordovician to early Llandovery (early Early Silurian) metallogenesis in the intra-oceanic Macquarie Arc, south-eastern Australia, produced major porphyry Au-Cu (e.g., Cadia, Holliday et al. 2002; Lickfold et al. 2003; Wilson et al. 2003; North Parkes, Heithersay and Walshe 1995), carbonate-base metal (Cowal, Bywater et al. 2004) and skarn Au (Big and Little Cadia, Foster et al. 2004) deposits. Although Degeling et al. (1995) and Cooke et al. (2002) inferred that the highly deformed Peak Hill and Gidginbung deposits may represent the products of late Ordovician (to early Llandovery) high-sulfidation mineralisation, uncertainty about their age and evolution has led to other highly varied interpretations of the origin of these deposits. Alternate interpretations for evolution of the Peak Hill and Gidginbung deposits include Early Devonian shear-zone hosted deposits (Allibone 1998; Allibone et al. 1995), middle to late Silurian (ca. 422 Ma) high-sulfidation deposits (Thompson et al. 1986) or the broadly constrained mid-Palaeozoic high-sulfidation deposits (Masterman et al. 2002). Masterman et al. (2002) recognised that Peak Hill is similar to many other ancient highly deformed high-sulfidation deposits, such as the Palaeoproterozoic Enåsen deposit, Sweden (Hallberg 1994), the late Proterozoic to early Cambrian Brewer deposit, South Carolina (Scheetz 1992) and the late Proterozoic Hope Brook deposit, Canada (Dube et al. 1998). High-sulfidation deposits represent an important class of deposit for exploration geologists, because they may be Au-rich and display distinctive hydrothermal alteration assemblages that make them ideal exploration targets. Therefore, recognition of high-sulfidation deposits related to the world-class late Ordovician to early Llandovery metallogenic event (Squire and Miller 2003) is important for Au explorers in the region.

The Peak Hill and Gidginbung Au–Cu deposits display broad zones of advanced argillic alteration minerals (e.g., pyrophyllite, muscovite and kaolinite) and high-sulfidation-state minerals (e.g., enargite, tennantite and covellite), which Thompson et al. (1986) and White (1991) suggested were characteristic of magmatic fluid sources. The age of mineralisation at Peak Hill was originally interpreted by Degeling et al. (1995) to be coincident with porphyry–copper mineralisation in the region (i.e., ca. 440 Ma, (Perkins et al. 1990). However, Allibone et al. (1995) and Allibone (1998) argued that mineralisation was synchronous with Early Devonian deformation and continental magmatism. Evidence for this included an $^{40}Ar/^{39}Ar$ isotopic age of 408.7±2.4 Ma for sericite at Peak Hill (Perkins et al. 1995), the presence of hydrothermally altered sedimentary rocks that were inferred to be late Llandovery Cotton Formation and limited microstructural observations. Detailed microstructural evidence and limited spectral analyses by Masterman et al. (2002) showed that hydrothermal alteration and mineralisation actually pre-dates the main deformation fabrics preserved at Peak Hill, and thus the 408.7±2.4 Ma isotopic age represents the minimum age of mineralisation. Cooke et al. (2002) inferred that the Peak Hill and Gidginbung deposits are related to late Ordovician to early Llandovery magmatism; however, the absence of a definitive isotopic age date means the exact age remains uncertain.

Here, we describe the distribution of volcanic facies that host the Peak Hill deposit, and then assess what controls, if any, they have on hydrothermal alteration zoning. In addition, we present sulfur isotope compositions of several textural forms of pyrite in a partial review of the isotopic characteristics of the deposit. These data contribute to a new interpretation for evolution of the Peak Hill deposit that involved late Ordovician to early Llandovery high-sulfidation mineralisation that possibly occurred in a submarine depositional setting.

Regional geological setting

The Peak Hill deposit is located near the centre of a 50-km-long belt of Ordovician to early Llandovery, submarine volcanic and shallow intrusive rocks of the Junee-Narromine Volcanic Belt in the northeastern Lachlan Fold Belt (Fig. 1) (Glen et al. 1998; Wyborn and Chappell 1983); (Fig. 2). The volcanic and intrusive rocks of the Junee-Narromine Volcanic Belt (and the nearby Molong, Rockley-Gulgong and Kiandra volcanic belts) have calc-alkaline to shoshonitic compositions, which are geochemically similar to some modern intra-oceanic island arc lavas (Wyborn 1992). They have primitive radiogenic isotope compositions that are isotopically consistent with derivation from MORB-source mantle (Barron et al. 1991; Carr 1995; Wyborn and Sun 1993) and preclude significant crustal contamination or the involvement of OIB-type mantle in their petrogenesis. Glen et al. (1998) postulated that extension during the Early Silurian (Benambran Orogeny) resulted in the dismembering of a single Ordovician arc and arc apron system (the Macquarie Arc) into the four narrow belts exposed today.

The late Early to Middle Silurian sequences have markedly different sedimentary and volcanic facies reflecting a shift from the deep-marine, oceanic environment of the early Palaeozoic to a mature continental margin setting (Cas 1983; Powell 1983; Chappell et al. 1988; Marsden 1988; Vandenberg 1988). This change is also recorded by radiogenic isotope data in the Silurian and Devonian volcanic and I- and S-type granitoid plutonic rocks, which have more crustally contaminated signatures (Chappell et al. 1988; Wyborn and Sun 1993; Whitford et al. 1993; Raymond and Sun 1998). A major regional unconformity overlain by Late Devonian–Early Carboniferous continental successions records the final change to a non-marine depositional setting.

Peak Hill is located about 4 km northeast of the inferred northern extension of the Parkes Thrust (Hilyard et al. 1996); (Fig. 2). The Ordovician to early Devonian rocks west of the Parkes Thrust are generally only very weakly deformed and folded, lack a well-developed axial-planar cleavage and display phrehnite–pumpellyite metamorphic assemblages (Sherwin 1996). In contrast, the Ordovician to Silurian rocks east of the thrust are moderately to intensely deformed, with open to tight folds, strong axial-planar cleavage, well-developed down-dip stretching lineations and lower greenschist metamorphic assemblages.

Peak Hill has produced about 750,000 ounces of gold, of which the majority, ~600,000 ounces, was from shallow high-grade deposits mined by open cut and underground workings from 1904 to 1917 (Allibone 1998). Between 1996 and 2005, Alkane Exploration Limited produced a further 153,655 ounces by heap leaching of oxide ore, averaging 1.56 g/t Au from five open cut mines. The hypogene sulfide zone remaining beneath the existing workings contains an additional, moderately refractory resource of 11.3 million tonnes at 1.29 g/t Au and 0.11% Cu (Alkane Exploration 2006).

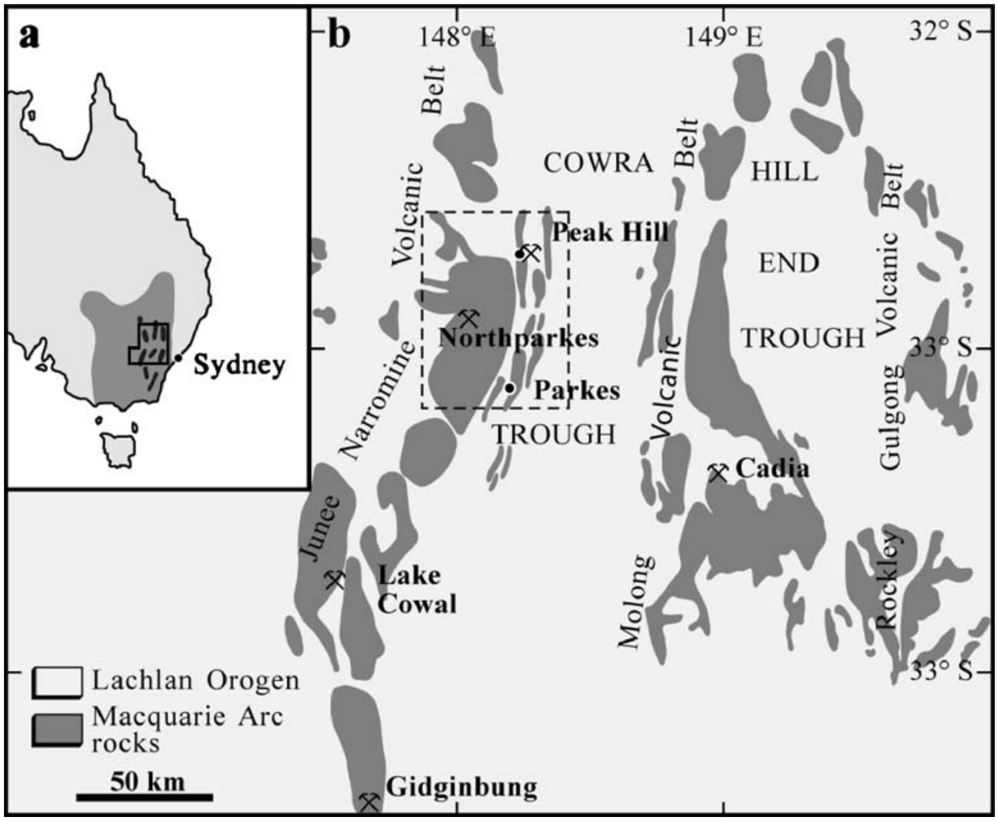

Fig. 1 Simplified geological maps. **a** Location of the Lachlan Orogen in Australia, showing the approximate distribution of the Ordovician to Early Silurian volcanic and intrusive rocks of the Macquarie Arc (black). *Outline* of **b** location is shown. **b** Distribution of the three northernmost volcanic belts of the Macquarie Arc (Junee-Narromine, Molong and Rockley-Gulgong) and the Siluro-Devonian Cowra and Hill End troughs. *Box* shows location of (Fig. 2). Modified after Walshe et al. 1995)

The gold deposits are focussed in near vertical, tabular, and pipe-like quartz+pyrite bodies in the pyrophyllite-bearing core of a zoned pervasive advanced argillic alteration system. Highest-grade zones of gold+copper mineralization (>1 g/t Au) exist in quartz+barite+sulfide veins localised near the intersections of lenses of quartz-altered facies and northwest trending faults in the central part of the system (Allibone 1998; Degeling et al. 1995). Sulfides in the veins are dominantly pyrite, with minor amounts of bornite, tennantite–tetrahedrite, covellite and chalcocite. Degeling et al. (1995) cited the local Te-enrichment of tennantite, and inclusions of calaverite (Au-telluride) and low-Ag native gold in pyrite, as evidence of deposition at shallow epithermal levels in a high-sulfidation hydrothermal system. Minor occurrences of tennantite-enargite±chalcopyrite were taken as implications of increasing hydrothermal temperatures at depth in the southern part of the system.

Local geological setting

The Peak Hill Au–Cu deposit is hosted by a succession of andesitic volcaniclastic breccias, lesser sandstone, and minor lavas and black mudstone that correlated with the late Ordovician to early Llandovery Goonumbla Volcanics (formerly Mingelo Volcanics; (Sherwin 1996); (Fig. 2). Well-stratified sandstones and cherts of the Late Ordovician to late Llandovery Cotton Formation (Allibone 1998) lie immediately east of the deposit, separated from the volcanic rocks by a large fault, although elsewhere in the region the contact is inferred to be conformable (Sherwin 1973, 1996). Fault-bounded slices of Goonumbla Volcanics, Cotton Formation and Late Silurian sandstone and mudstone of the Mumbidgle Formation occur between Peak Hill and Coolac–Narromine Suture, 10 km to the east. Silicified sandstone and siltstone of the Mugincoble Chert also exist in this zone, although their age and stratigraphic relationships are uncertain (Sherwin 1996). Late Devonian quartz-rich sandstones of the Hervey Group occur east of the Coolac–Narromine Suture.

Allibone (1998) and Masterman et al. (2002) recognised at least three periods of deformation at Peak Hill. A steeply dipping, dominantly north–south trending S_1 foliation with a sub-vertical extension lineation (L_1), which reflects a period of east–west compression, is the most prominent fabric. Narrow thrust surfaces (I_2), or a crenulation cleavage (folded about S_2) that overprint and are slightly oblique to S_1, characterise the second deformation. The third deformation is recorded by low-amplitude open cross-folds with east–west S_3 axial surfaces that occur in both the Goonumbla Volcanics and the Cotton Formation. Masterman et al. (2002) suggested that both the hydrothermal alteration and mineralisation at Peak Hill pre-dated the regional deformation. Evidence for this included fractured and boudinaged sulfide grains and curved quartz crystals in crack-seal veins interpreted to indicate post-mineralisation brittle and plastic deformation, and recrystallisation and grain boundary migration. In addition, multiphase microveins and crack-seal veins that contained quartz, pyrophyllite, sericite and kaolinite in the vein fillings developed during S_2 indicated control by the

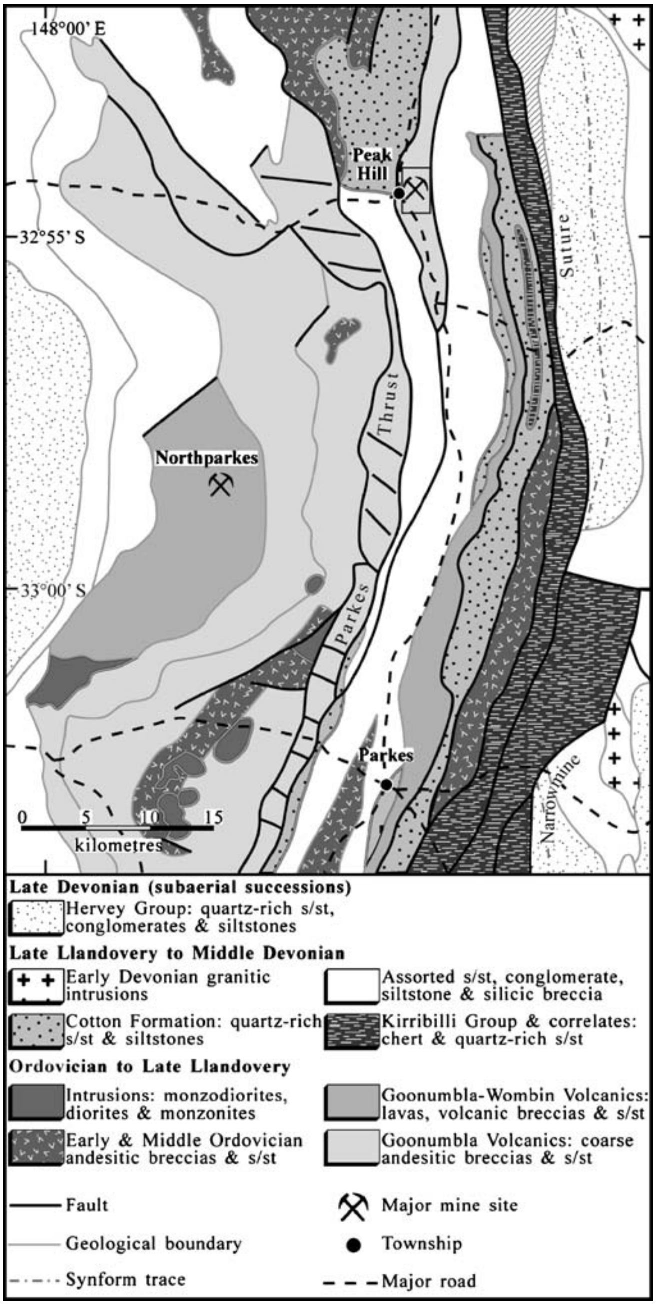

Fig. 2 Regional distribution of the principal basement units of the Parkes-Northparkes-Peak Hill region. *Blank areas* are of post-Carboniferous rocks. *Box* shows location of Fig. 4. Modified after Glen and Fleming (1999)

dominant wall-rock mineralogy (i.e. dissolution and redeposition of pre-existing pre-deformation alteration assemblages). Rare northwest- to west-northwest-trending faults were interpreted by Masterman et al. (2002) to dextrally displace alteration boundaries and post-date D_3. However, Degeling et al. (1995) suggested that northwest-trending structures may have formed pre- or possibly syn-D_1 and thus acted as fluid conduits controlling the distribution of mineralisation.

The Au–Cu ore at Peak Hill occurs in steeply plunging shoots that broadly coincide with a distinctively zoned alteration system (Masterman et al. 2002; Degeling et al. 1995; Allibone 1998). Pyrophyllite in the core of the alteration system grades out through white-mica-bearing alteration assemblages to propylitic chlorite±epidote-bearing margins. This altered zone extends at surface for about 3 km north-south and 500 m east-west (Masterman et al. 2002), and Degeling et al. (1995) speculated that steeply dipping pyroclastic units in its core represented important controls on the geometry of the ore shoots. Masterman et al. (2002) and Degeling et al. (1995) considered the hydrothermal alteration assemblages, ore minerals and textures to be consistent with emplacement at relatively shallow crustal levels (cf. 3 to 5 km, Allibone 1998), similar to modern epithermal deposits.

Late Ordovician to Early Silurian facies architecture

Major differences in the depositional environments (submarine or subaerial) and/or provenance of the Late Ordovician to early Llandovery successions at Peak Hill, record regional palaeogeographic and palaeotectonic events. The timing and nature of these events have important implications for metallogenesis. Therefore, we present here brief descriptions and interpretations of the volcano-sedimentary facies, facies relationships and ages of the Goonumbla Volcanics and Cotton Formation. Despite the relatively poor exposure and intensely altered and deformed nature of the rocks near the deposit, they permit broad interpretation of the facies architecture.

Goonumbla Volcanics at Peak Hill

The Goonumbla Volcanics at Peak Hill are composed of volcanic sandstone, volcanic lithic breccia, coarse volcanic lithic breccia with sandstone matrix, and coherent plagioclase-phyric andesite (Fig. 3, Table 1). These facies exist in approximate volumetric proportions of 70% combined breccia facies, 20% volcanic sandstone and less than 10% andesite. The dominance of feldspar and pyroxene grains and basaltic to andesitic lithic fragments, and the absence of volcanic or metamorphic quartz, indicate derivation from mafic to intermediate volcanic sources. The volcanic lithic fragments are non- to weakly vesicular, strongly porphyritic and were most likely derived from lavas or shallow (<2–3 km) intrusions. The fine-grained, well-sorted nature of the volcanic sandstone indicates that the detritus must have passed through a high-energy subaerial, shoreline and/or shallow-marine setting before deposition. These clast compositions and textures indicate derivation from an emergent mafic to intermediate volcanic source.

The occurrence of massive, graded and parallel-stratified beds, marine microfossils (discussed below) and the absence of wave-generated sedimentary structures, suggest that deposition occurred in a marine, below-wave-base setting. Normal grading is a feature of deposits from turbidity currents (Bouma 1962). However, the absence of

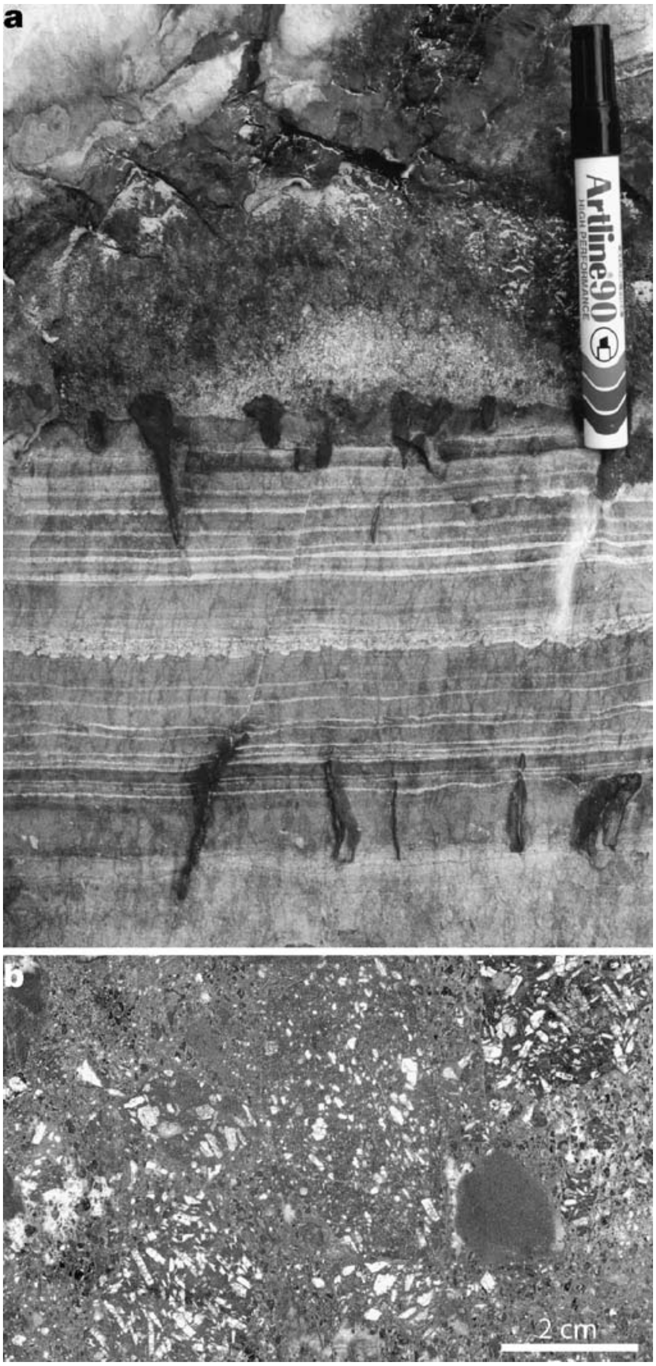

Fig. 3 Volcanic facies of the Goonumbla Volcanics from Peak Hill. **a** Well stratified volcaniclastic sandstone and siltstone from Parkers Pit (24654 E, 78164 N). Beds are laterally continuous in outcrop, have sharp, scoured bases and are massive to normally graded with siltstone tops. The detrital component is dominated by feldspar with lesser pyroxene and rare angular mafic to intermediate volcanic lithic fragments. Texta is 14.5 cm long. **b** Volcanic lithic breccia composed of poorly sorted angular pebbles and cobbles of plagioclase±clinopyroxene-phyric mafic to intermediate lithic fragments with lesser (about 15%) angular clasts of massive laminated sandstone and siltstone. Sample from dam wall about 4 km north of the Peak Hill Mine (AMG 612350E 6382700N)

cross-bedding may represent rapid deposition in which traction was inhibited in the waning current. Therefore, the turbidity currents may have travelled only relatively short distances and not been fully turbulent (e.g., Walker 1967). The thick, poorly sorted, weakly stratified and graded beds of volcanic lithic breccia, and coarse volcanic lithic breccia with sandstone matrix, may represent products of high-density turbidity currents (e.g. Lowe 1982; Middleton 1967). The plagioclase-phyric andesite is non− to weakly vesicular, highly porphyritic with a microcrystalline or formerly glassy groundmass and, therefore, was most likely emplaced as a lava or shallow (<2–3 km) intrusion.

Cotton Formation at Peak Hill

The Cotton Formation is composed of well-stratified, thinly bedded quartzose sandstone and laminated siltstone and chert (Sherwin 1996). The fine-grained, well-sorted nature of the sediments and presence of marine microfossils (Sherwin 1984, 1996) indicate a submadrine, below-wave-base depositional setting. The Cotton Formation represents a lower energy (more distal?) environment than the high-energy submarine setting of the Goonumbla Volcanics. An exposure of hydrothermally altered, fine-grained sandstone in the northeast corner of the Parkers Pit, which was formerly interpreted by Allibone (1998) as Cotton Formation, contains abundant detrital feldspar but no quartz and, thus, is now considered to form part of the Goonumbla Volcanics (i.e. volcanic sandstone facies).

Age of the Goonumbla Volcanics and Cotton Formation

Radiogenic isotope data (e.g. Butera et al. 2001; Lickfold et al. 2003; Perkins et al. 1990) and rare Late Ordovician fossils near Northparkes (Sherwin 1996) suggest that the Goonumbla Volcanics are of Late Ordovician to early Llandovery age (up to ca. 440 Ma). Sherwin (1996) suggested that the Cotton Formation was Late Ordovician to late Llandovery based on the presence of late Llandovery graptolite fauna in sandstones and mudstones about 6 km south-southwest of Peak Hill and Late Ordovician (possibly late Eastonian to Bolindian: ca. 455–443 Ma) graptolites in cherty siltstones near Tomingley (Sherrard 1954, 1956; Sherwin 1984). However, the absence of early Llandovery fossils indicates a lack of continuity from the Late Ordovician to late Llandovery in the Cotton Formation. Also, the Late Ordovician age assigned for fossil localities in the Cotton Formation is based on fine-grained sediments and cherts, for which the detrital component (quartzose or felspathic) was not recorded. The change from volcanic to continentally derived detritus in the middle to late Llandovery represents a significant palaeogeographic and palaeotectonic event in the Macquarie Arc (Squire and Miller 2003). Despite this, the depositional setting remained submarine and below wave-base until the Late Devonian when subaerial successions of the Hervey Group were deposited. Although it is beyond this paper to provide a thorough review of the regional biostratigraphic

Table 1 Summary of characteristics of the volcanic lithofacies at Peak Hill

Facies	Description
Volcanic sandstone (Fig. 3a)	Pale brown to pale grey sandstone; beds up to 10 cm thick that are laterally continuous in outcrop; beds generally have sharp scoured bases, and are massive to normally graded; contain abundant feldspar and less common pyroxene crystal fragments and rare subangular mafic to intermediate lithic fragments up to 5 mm; andesitic lithic fragments are generally concentrated near the base of the coarser and thicker beds where, in some cases, the fragments may form up to 10%
Volcanic lithic breccia (Fig. 3b)	Green to grey-brown, typically normally graded or internally massive, poorly sorted, thin to thick beds; beds are generally laterally continuous in outcrop, have sharp scoured bases and grade normally into volcanic sandstone; composed of angular to subangular, mafic to intermediate volcanic pebbles and cobbles and angular clasts up to 5 cm of massive and laminated volcanic sandstone; non- to weakly vesicular, plagioclase-pyroxene-phyric basalt to basaltic andesite volcanic lithic fragments comprise up to 70% of the facies, and contain 30–70% phenocrysts dominated by plagioclase phenocrysts up to 8 mm; massive and laminated siltstone clasts amount to about 15% and are generally slightly elongate, <40 mm long, and consist of well sorted, thinly bedded sandstone and siltstone similar to the volcaniclastic sandstone facies; clasts are supported by a poorly sorted matrix of angular fragments of feldspar, pyroxene and mafic to intermediate volcanic lithic fragments
Coarse volcanic lithic breccia (Fig. 3c)	Grey-brown, matrix-supported, internally massive, poorly sorted, thick beds; contain 10 to 60% angular clasts of non- to weakly vesicular, porphyritic basalt to basaltic andesite up to 15 cm, and laminated siltstone clasts up to 10 cm; size and abundance of phenocrysts in the basaltic to andesitic clasts are highly variable between clasts, as per volcanic lithic breccia; sandstone matrix is massive and contains feldspar and pyroxene grains with minor (<5%) basaltic to andesitic lithic fragments
Coherent plagioclase-phyric andesite	Dark green, weakly to non-vesicular, strongly plagioclase-phyric (basaltic?) andesite in units up to several tens of metres thick; plagioclase phenocrysts are generally less than 2 mm long, comprise up to 50%; lower and upper contacts were not observed

and lithostratigraphic characteristics of the Cotton Formation, we suggest here that the Cotton Formation did not coexist with the Goonumbla Volcanics but was restricted in age to the late Llandovery (i.e., ca. 435–428 Ma). Therefore, the Late Ordovician marine fossils near Peak Hill (Sherwin 1984, 1996; Sherrard 1954, 1956) are most likely from fine-grained sandstones and mudstones of the Goonumbla Volcanics.

Hydrothermal alteration zones

Analytical methods

Short-wavelength-infrared (SWIR) spectral analyses of some 2,800 drill core and surface samples using a PIMA-SP spectrometer were used to delineate the spatial distribution of alteration phases such as pyrophyllite, alunite, kaolinite and other white micas (possibly muscovite and paragonite; (Fig. 4), which are otherwise difficult to distinguish by visual and optical means. These data are compared with the distribution of Au grades to establish the vertical and lateral relationships between the alteration zones and ore shoots.

The PIMA-SP manufactured by Integrated Spectronics is a field-portable spectrometer that measures reflectance in the 1.3 to 2.5 μm wavelength SWIR band. This wavelength range encompasses harmonics of fundamental absorption features attributed to vibrations in OH, H_2O, AlOH, FeOH, MgOH and CO_3 molecular bonds, which are diagnostic for a wide range of hydroxylated silicates, hydrous sulfates and carbonates, of which many are common in hydrothermal alteration assemblages. SWIR spectroscopy enables rapid identification of SWIR-absorbing minerals and simple mineral mixtures in all types of geological materials with no sample preparation required, beyond drying. It is particularly suited to identification or discrimination of clays, pyrophyllite, white micas, topaz and alunite in advanced argillic assemblages (Thompson et al. 1999).

White micas produce strong AlOH absorption features in SWIR spectra at variable wavelengths between about 2,190 and 2,228 nm, according to the proportions of Al in the mica composition (Jones et al. 2005; Post and Noble 1993). Al-rich white micas typically have significant Na contents and they produce AlOH absorption features at wavelengths <2,200 nm. In this paper, we refer to the low wavelength (<2,200 nm) white micas as 'paragonite' and those with AlOH features between 2,200–2,210 nm as 'muscovite' (see discussion below). Limited electron microprobe analyses of these white micas were used to support these interpretations, although we acknowledge the problems of correct mineral identification using only SWIR spectra.

Alteration zones

The hydrothermal alteration system at Peak Hill is composed of five crudely concentric zones over an area at least 1,200 m long and 800 m wide (Fig. 4). Masterman et al. (2002) suggested that it may extend up to 3 km north-south. It has a 350×500 m core of predominantly vuggy quartz and pyrophyllite that grades outwards through

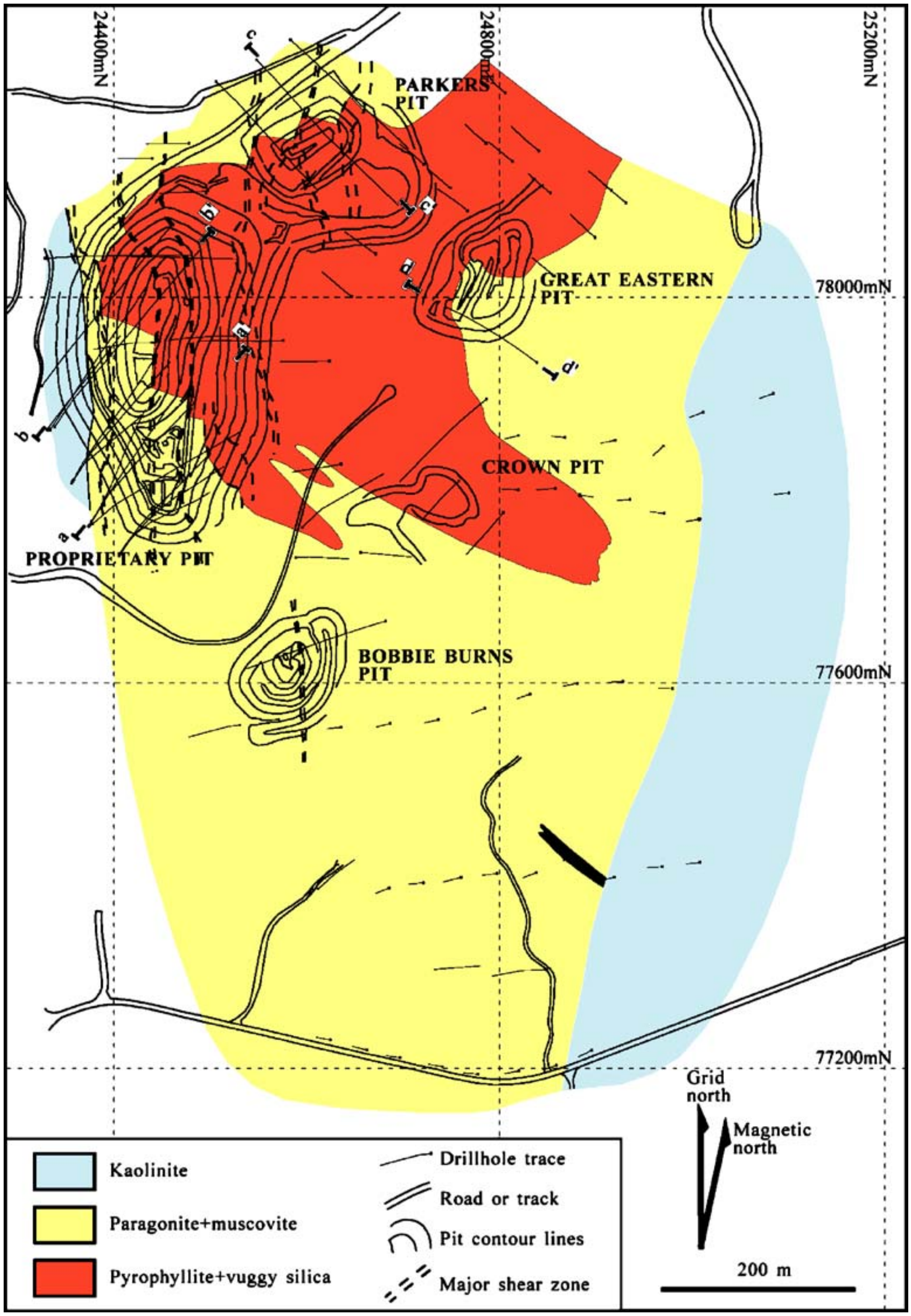

Fig. 4 Map showing the location of the open-cut pits at Peak Hill, which occur predominantly in the paragonite-muscovite zone adjacent to the pyrophyllite-vuggy-quartz core. The alteration zoning was determined by spectral analyses of drill hole and in-pit surface samples. *Location of sections* from Fig. 6 is also shown

paragonite+muscovite to kaolinite to chlorite+epidote alteration facies at the margin. A microcrystalline-quartz alteration facies is also present but is not restricted to the broadly concentric alteration displayed by the other five zones.

Vuggy-quartz zone

Vuggy quartz, not recognised by previous workers at Peak Hill, is characterised by massive microcrystalline quartz with abundant small irregular-shaped vugs (Fig. 5a). The vugs comprise between 10 and 40 volume percent (vol.%) of the facies and are generally<3 mm in diameter, though rare vugs up to 1 cm are present. Late cross-cutting veins of pyrophyllite and pyrite comprise up to 10 and 20 vol.% of the zone, respectively, and accessory alunite, topaz, kaolinite (all <5 vol.%) are common. Vuggy quartz was only recognised in drill cores in the northern and north-eastern part of the Propriety pit and the southern end of the Parkers pit.

Pyrophyllite zone

This zone is dominated by pyrophyllite (30–70 vol.%) with abundant quartz (<40 vol.%), pyrite (<15 vol.%) and accessory kaolinite, alunite, dickite, topaz and barite (<3 vol.% each). There are two textural forms and generations of pyrophyllite: fibrous white pyrophyllite in irregular veins up to 5 mm thick in either vuggy-quartz or paragonite+muscovite-altered host (Fig. 5b); and abundant, cross-cutting fine veinlets of strongly foliated pyrophyllite (Fig. 5a). Paragonite and muscovite comprise up to 15 vol.% at the outer margins of this zone, although rare elsewhere. The boundary between the pyrophyllite and vuggy-quartz zones is generally gradational over only a few tens of centimetres, whereas the outer boundary with the paragonite+muscovite zone is gradational over several tens of metres. The gradational nature and broadly irregular shape of the contacts between the vuggy-quartz and pyrophyllite zones, together with the dominance of pyrophyllite±paragonite±muscovite in the matrix, suggest that the brecciated outer margin of the pyrophyllite zone probably formed during hydrothermal alteration (cf., cataclasite, (Allibone 1998).

Paragonite+muscovite zone

The paragonite+muscovite zone is the most widespread alteration facies. Paragonite and muscovite are the dominant alteration phases (40 to 80 vol.%) with abundant quartz (<50 vol.%) and pyrite (<20 vol.%) and accessory (<3 vol.% each) chlorite, kaolinite, alunite, topaz, barite and gypsum (Fig. 5b). These micas were initially classified and delineated by SWIR spectral analyses, specifically by

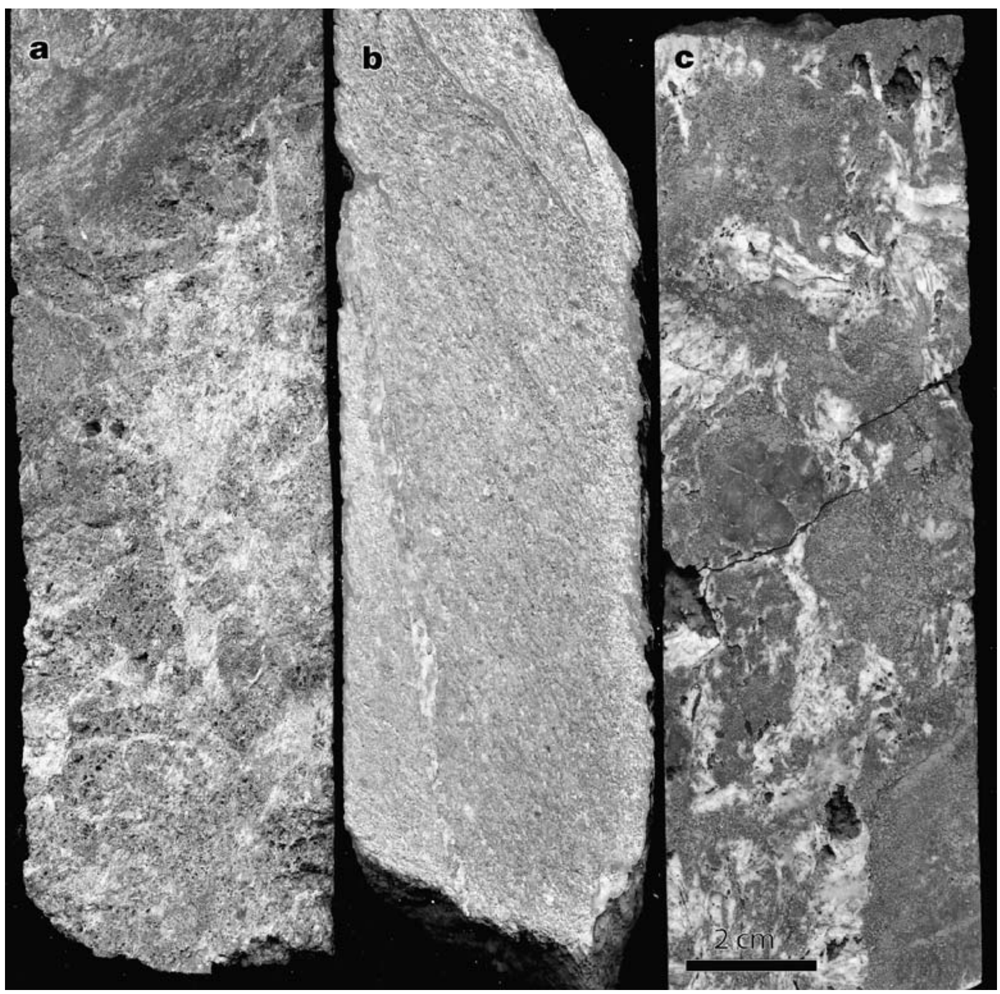

Fig. 5 Representative samples from the alteration zones at Peak Hill. **a** Vuggy-quartz clasts with thin (<3 mm) fractures containing white fibrous pyrophyllite crosscut and brecciated by thick (foliated) pyrophyllite. Sample from drill hole PRD2, 265.0 m. **b** Paragonite+muscovite crosscut by pyrophyllite and secondary pyrite. Sample from drill hole PRD7, 255.5 m. **c** Microcrystalline-quartz zone that predates mineralisation. Sample from drill hole PRD1, 168.9 m

AlOH absorption feature wavelengths. Limited electron microprobe data from four samples at the southwestern part of Proprietary pit show a considerable range in white mica compositions, with molecular Na/(Na+K) ratios up to 0.76, which correspond approximately to variations in AlOH absorption feature wavelengths.

Kaolinite zone

The kaolinite alteration zone generally occurs at the western and eastern margins of the Peak Hill alteration system. Kaolinite is the dominant phase (50 to 80 vol.%), with abundant montmorillonite (10 to 30 vol.%), halloysite (<20 vol.%) and quartz (<30 vol.%). Minor intervals dominated by kaolinite up to 15 m thick are also present in shear zones intersected by the drill core (e.g., drillhole PRD11, 281.3–294 m). Kaolinite in the shears typically overprints the main north-south foliation in several large shears and is, thus, probably a later phase, not associated with the main hydrothermal system. The kaolinite zones at the eastern and western margins have restricted vertical depths, perhaps related to weathering, although they are here considered to represent hydrothermal zones.

Chlorite+epidote zone

This zone contains the least-altered rocks in the Peak Hill region and is generally restricted to the outer margins of the alteration system (e.g., the northern dam wall about 3 km north of Peak Hill). However, the cores of the thick intervals of coherent andesite may also display a similar alteration style. By contrast with the other alteration zones, primary volcanic textures are generally well preserved (Fig. 3). Plagioclase phenocrysts are replaced by albite and microcrystalline sericite, calcite and epidote, pyroxene varies from fresh to totally replaced by chlorite and/or actinolite, and the former groundmass of the igneous rocks and rock fragments is totally replaced by chlorite and epidote. These characteristics are similar to regional metamorphic alteration in the Junee-Narromine Volcanic Belt (Sherwin 1996), which cannot be distinguished from the outer propylitic zone of Lowell and Guilbert (1970).

Microcrystalline-quartz zone

Sub-vertical microcrystalline-quartz alteration zones (>90 vol.% microcrystalline quartz) cross-cut and thus post-date the above-mentioned alteration zones, but predate mineralisation and the main deformation events at Peak Hill (Fig. 5c). Exposures of the microcrystalline-quartz alteration zones in the pit wall at Great Eastern are very highly irregular and discontinuous. However, drill hole intersections of this zone at the southern margin of the Proprietary pit are relatively planar and have sub-vertical dips (Fig. 6), although the strike of the zones is uncertain and, therefore, is not shown in Fig. 4.

Interpretation of alteration zones

Despite locally intense deformation, the original hydrothermal assemblages preserve a distinct zoning pattern (Fig. 4) that probably reflects both lower temperatures and neutralisation of acid fluids with increasing distance from the core. The presence of pyrophyllite±dickite suggest that temperatures in the inner zones were about 320 to 360°C and the pH of the fluids was about 3 (Stoffregen 1987). The vuggy-quartz zone reflects even lower pH conditions that favoured solubility of aluminium and instability of aluminosilicates and phyllosilicates. Unlike the acid alteration core, the chlorite+epidote zone at the outer margin retained most of the primary rock composition (Pape 1999), indicating that the fluids had equilibrated with the wall rocks.

The contact between the pyrophyllite and paragonite+muscovite zones is sub-vertical (Fig. 6). In the Parkers pit the contact strikes northeast, whereas between the western margin of the Proprietary pit and the Crown pit the same contact strikes west-northwest (Fig. 4) and coincides with zones of high-grade gold mined in the early workings (Stonier 1889). In the Parkers pit, the northeast-trending alteration boundary coincides with the current pit orientation. Although no early (syn-mineralisation) structural fabrics consistent with these orientations were observed, the sub-vertical pipe defined by the vuggy quartz and pyrophyllite zones is considered to represent the conduit along which hot acidic hydrothermal fluids were channelled (cf. Masterman et al. 2002).

Sulfur-isotope geochemistry

We used results from sulfur-isotope analyses (Table 2), of several textural forms of pyrite recognised at Peak Hill, to investigate the links between mineralisation and either early Llandovery (i.e., 440 Ma) or Early Devonian (ca. 405 Ma) regional magmatism. The pyrite samples were selected to spatially represent the various textural forms that occur within the Peak Hill alteration system: blebs of massive pyrite, pyrite stringers, cubic pyrite and disseminated pyrite. Bladed barite and vein barite were also analysed.

Analytical methods

The coarse barite samples were analysed using conventional sulfur isotope techniques at the Central Science Laboratory, University of Tasmania, with a VG Sira Series II mass spectrometer following SO_2 extraction. The fine grain size of many of the pyrite samples precluded sulfur-isotope analysis by conventional techniques, thus, they were analysed by laser ablation. Fifteen 200-μm-thick polished sections were soaked in acetone and dried before analysis at the Central Science Laboratory, University of Tasmania. The pyrites were ablated using an 18-watt Quantronix model 117 Nd:Yag laser, liberating SO_2 upon ignition of the sulfide grain. The liberated SO_2 was

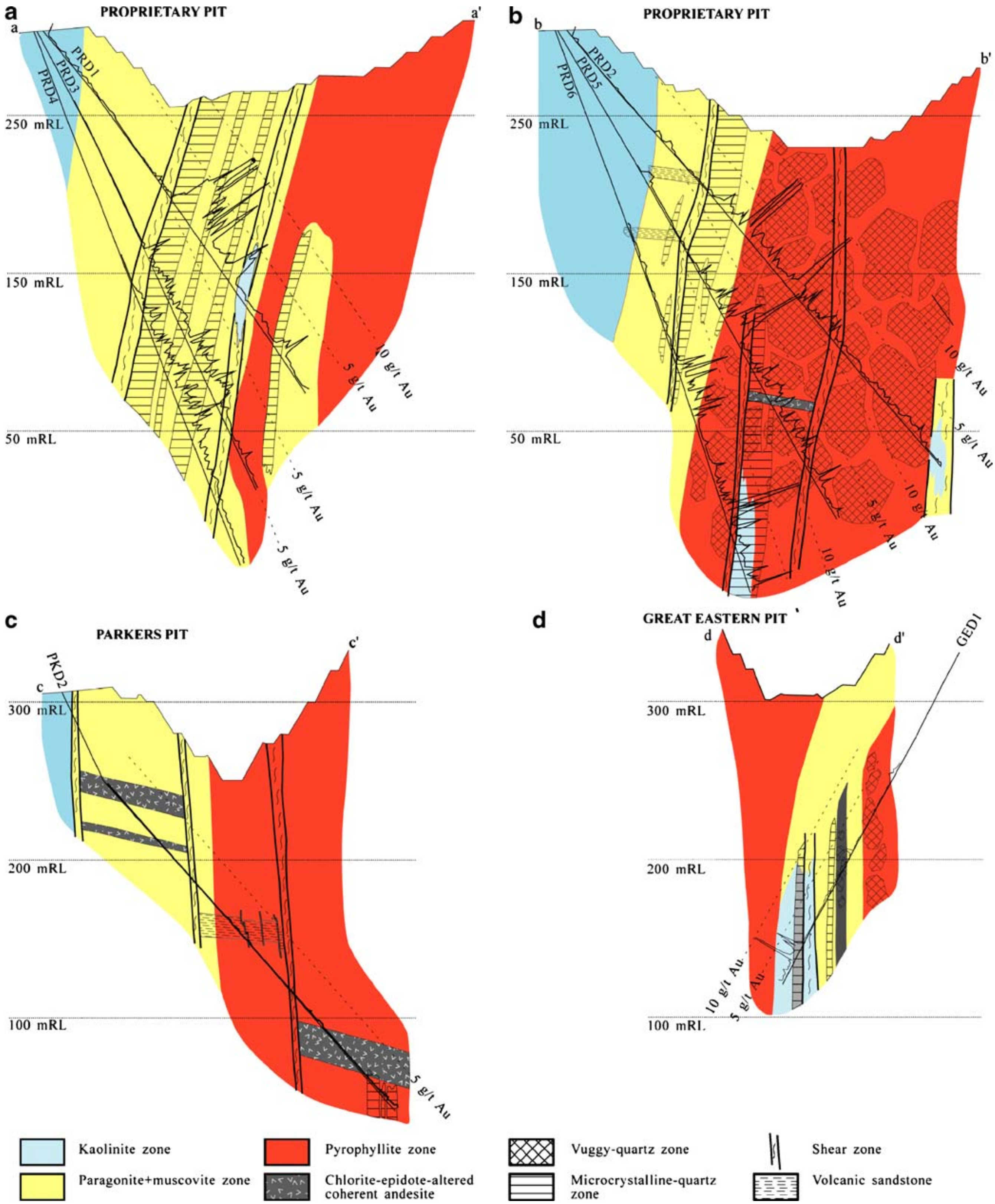

Fig. 6 Sections from the Proprietary, Parkers and Great Eastern pits showing the sub-vertical alteration zoning and their correlation with gold grades, up to 10 g/t, from selected holes. The location of sections *a-a'*, *b-b'*, *c-c'* and *d-d'* are shown in Fig. 4

Table 2 Sample descriptions and sulfur-isotope values for pyrites and barites from the Peak Hill hydrothermal system

Hole	Depth (m)	Sample description	$\delta^{34}S‰_{CDT}$
PRD15	114.3	Cubic pyrite in white mica	−4.6
PKD3	249	Cubic pyrite in white mica	−11.7
PRD16	322.4	Cubic pyrite in sericite-altered volcanic sandstone	−6.8
PRD12	317	Cubic pyrite in fine kaolinite	−6.5
PKD3	282.7	Blebs of massive pyrite within a silica-altered breccia	−11.6
PKD3	282.7	Blebs of massive pyrite within a silica-altered breccia	−9.7
PKD2	150.6	Blebs of massive pyrite in pyrophyllite	−8.8
BBD1	128.3	Blebs of massive pyrite in pyrophyllite and vuggy silica	−9.0
BBD2	210	Blebs of massive pyrite in vuggy silica	−5.5
BBD2	221.4	Blebs of massive pyrite in vuggy silica	−9.7
PKD1	240.3	Blebs of massive pyrite in vuggy silica	−8.8
BBD1	195.8	Pyrite stringers hosted by coarse kaolinite	−7.2
PRD12	125	Pyrite stringer in muscovite	−8.5
PRD12	210.2	Pyrite stringer in muscovite	−5.7
PRD12	210.2	Pyrite stringer in muscovite	−6.8
PRD12	305	Disseminated pyrite in sericite	−7.4
PRD7	276.5	Disseminated pyrite in white-mica-altered volcanic rock	−8.5
PRD7	276.5	Disseminated pyrite in white-mica-altered volcanic rock	−7.3
PRD15	169.9	Barite vein with vuggy-quartz breccia	+10.7
PRD15	197.2	Bladed barite in a chalcedony groundmass	+12.0

collected and analysed in a VG Sira Series 2 mass spectrometer, then the sulfur values were calibrated against standard pyrites from Rosebery ($\delta^{34}S$+12.4‰) and Broken Hill ($\delta^{34}S$+3.4‰) that had an accuracy of 0.15‰. Results from this study displayed a strong correlation with the standards; precision ranged from 0.004 to 0.667‰. These results were standardised relative to Canon Diablo Triolite (CDT) by applying a fractionation factor of 5.75‰ for pyrite.

Discussion and interpretation of results

Sulfur isotope values ($\delta^{34}S‰_{CDT}$) for pyrite range from −11.7 to −4.6 per mil, and for barite from+10.7 to+12.0 per mil (Fig. 7a). These values are consistent with a volcanic source for the sulfur (e.g. Nielsen 1979). Although massive pyrite generally has slightly lower $\delta^{34}S$ values than cubic pyrite, disseminated pyrite and pyrite stringers, all pyrite morphologies show trends to lower values with decreasing depth and, presumably, temperature. In contrast, barite displays higher $\delta^{34}S$ values with decreasing depth. This pattern is consistent with oxidised fluid conditions that preferentially fractionate ^{34}S to sulfates with decreasing temperatures (Rye 1993). The sulfur isotope data from Peak Hill are thus consistent with a common source of sulfur for pyrite and barite that fractionated due to cooling of oxidised fluid.

Sulfur isotope data from the nearby Northparkes porphyry-copper deposits (Heithersay and Walshe 1995) display a strikingly similar $\delta^{34}S$ ranges in sulfides and sulfates (Fig. 7b), suggesting that the sulfur may have been sourced from a similar reservoir. They also show a vertical and lateral $\delta^{34}S$ zonation consistent with involvement of a relatively oxidised fluid. These sulfur isotope values are not consistent with shear-related deposits (cf. Allibone 1998; Allibone et al. 1995) that typically would have values close to zero (e.g., Kerrich 1989). Instead, they closely match sulfur isotope data from other circum-Pacific high-sulfidation epithermal deposits such as Lepanto in the Philippines (Hedenquist et al. 1990; Imai 2000) and Chinkuashih in Taiwan (Folinsbee et al. 1972).

Discussion

Spatial and temporal relationships of alteration and mineralisation

Allibone (1998) recognised that gold grades >1 g/t at Peak Hill are coincident with concentrations of quartz-pyrite-barite veins. However, the Au-Cu ore is not confined to the pyrophyllite-altered core of the hydrothermal system (cf. Allibone 1998), rather, it generally occurs within about 50 m of the outer margin of the pyrophyllite+vuggy quartz core (Figs. 4 and 6). In fact, the zones of highest gold-grades (>5 g/t) generally occur in microcrystalline-quartz-altered domains in the paragonite+muscovite alteration zone (e.g. PRD1 and GED1, Fig. 6). Therefore, fluid chemistry (e.g. fluid pH) and the rheology and composition of the altered host rocks (i.e. brittle microcrystalline-quartz zones) were important in controlling the distribution of mineralisation at Peak Hill. Permeability was also

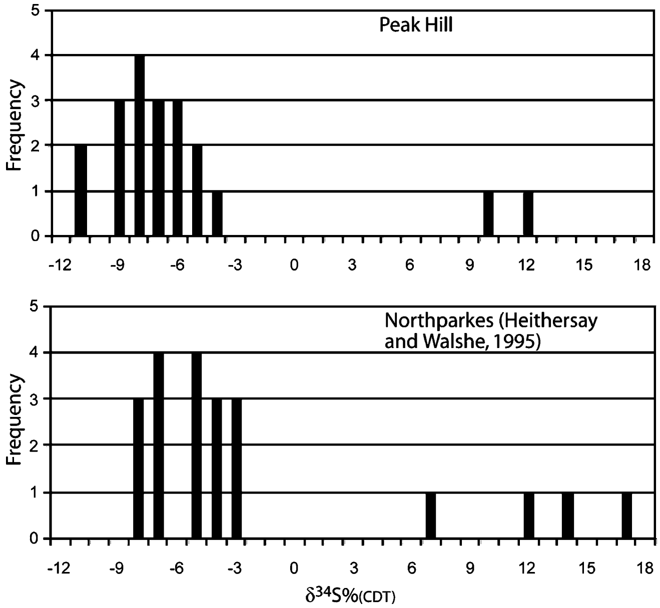

Fig. 7 Comparison of $\delta^{34}S$ values for barite and different textural forms of pyrite from Peak Hill (Table 2) and Northparkes (Heithersay and Walshe 1995). The strikingly similar $\delta^{34}S$ values suggest that a similar magmatic source was involved during generation of both deposits

important, although the abundance of Au-Cu in the paragonite+muscovite zone suggests that this was not entirely controlled by the highly porous vuggy-quartz zone at the core of the hydrothermal system.

Degeling et al. (1995) suggested that the core of the alteration system is confined to a steeply dipping pyroclastic unit. However, primary volcanic textures of any kind are rarely preserved in the vuggy quartz and pyrophyllite zones, and pyroclastic facies have not been observed in any of the less intensely altered zones at Peak Hill. In addition, the layered volcanic sandstones in the northeast corner of Parkers pit consistently dip gently northeast despite the sub-vertical dip of the alteration zones. These features do not support the influence of primary volcanic facies on the distribution of alteration or mineralisation at Peak Hill.

The relative timing between alteration and mineralisation can be determined by a variety of cross-cutting relationships. The microcrystalline-quartz zone does not display the same concentric zoning as the other alteration zones and appears to overprint and thus post-date them. Non-auriferous bladed quartz±pyrite veins up to 30 mm thick are the earliest quartz veins recognised at Peak Hill (cf. mesothermal quartz veins, (Degeling et al. 1995). These veins crosscut all the alteration zones with the exception of the microcrystalline-quartz zone, with which it displays a broadly overlapping temporal relationship. The bladed quartz±pyrite veins are crosscut and commonly brecciated by auriferous quartz-pyrite-barite veins (Fig. 8a). Alunite and less common kaolinite are present in late crosscutting veins up to 25 mm thick (e.g. Proprietary pit: 24382E 78068N) or as cavity fill including the open spaces between the quartz-pyrite-barite veins. The presence of alunite in open cavities was interpreted by Degeling et al. (1995) to represent the collapse of cool acidic fluids onto earlier alteration assemblages. These relationships suggest that mineralisation at Peak Hill occurred just before collapse of the hydrothermal system (cf. Allibone 1998).

Age of deformation, alteration and mineralisation

The paragenesis outlined above indicates that mineralisation occurred during the waning stages of pervasive hydrothermal alteration and before D_1, but this alone does not constrain it to either a late Ordovician to early Llandovery or Early Devonian age. The S-isotope data presented here support a magmatic source for the sulfur at Peak Hill that was very similar to that associated with the late Ordovician to early Llandovery intrusion-related deposits of the Macquarie Arc, such as Northparkes (Fig. 7). In addition, sulfides from Peak Hill have strikingly similar primitive Pb-isotope signatures to the ca. 440 Ma intra-oceanic magmatism such as at Northparkes and Cadia (Carr et al. 1995). These isotopic signatures are quite unlike those associated with Early Devonian continental magma-

Fig. 8 Auriferous bladed quartz-pyrite-barite vein that crosscut and brecciated an earlier quartz vein. Sample from drill hole PRD6, 293.0 m

tism (Chappell et al. 1988; Raymond and Sun 1998; Whitford et al. 1993; Wyborn and Sun 1993), and thus favour the late Ordovician to early Llandovery intra-oceanic magmatism as a potential source of hydrothermal fluids, sulfur and metals.

Evolution of the Peak Hill deposit

We interpret that the distinctive sub-vertical hydrothermal alteration zonation developed from hot acidic hydrothermal fluids channelled up sub-vertical (west-northwest and northeast-striking?) pathways. The system produced a core of vuggy-quartz and pyrophyllite (about 350 m wide and at least 550 m long) and graded out through paragonite+muscovite to kaolinite with chlorite+epidote at the margin. Several broadly overlapping events of silicification, bladed quartz-pyrite veining, brecciation and pyrite deposition occurred late during alteration, although all appear to predate mineralisation. Au-Cu mineralisation, associated with quartz-pyrite-barite veining, occurred during the waning stage of pervasive hydrothermal alteration and was best developed in microcrystalline-quartz domains in the paragonite+muscovite zone, generally less than 50 m from the outer margin of the pyrophyllite+vuggy quartz core (cf. Allibone 1998). The final collapse of the hydrothermal system resulted in alunite and kaolinite filling fractures and cavities. These features are characteristic of high-sulfidation epithermal mineralisation (Masterman et al. 2002) and are strikingly similar to those observed at Gidginbung (Thompson et al. 1986).

The characteristic zoning of ore minerals and alteration assemblages at Peak Hill is indicative of a magmatic source for the hydrothermal fluids (White 1991; Masterman et al. 2002; Degeling et al. 1995). Lead isotope data from Peak Hill match closely the isotopically primitive signatures of the late Ordovician to early Llandovery intrusions of the Macquarie Arc (Carr et al. 1995). The change from an intra-oceanic to continental tectonic setting in the middle to late Llandovery is recorded by a marked difference in the isotopic signature of magmatism in eastern Australia (Chappell et al. 1988; Marsden 1988), and thus precludes the Early Devonian magmatism as a source for the mineralised fluids at Peak Hill (cf. Allibone 1998).

The volcano-sedimentary facies architecture at Peak Hill indicates that the depositional setting was most likely submarine until the Late Devonian (i.e. deposition of the Hervey Group, (Sherwin 1996); local emergent centres may have been present but were not regionally extensive. High sulfidation deposits typically formed in subaerial settings (Sillitoe and Bonham 1984), but the dominance of deep-water volcanic facies suggests that the late Ordovician to early Llandovery mineralization at Peak Hill may have formed in a submarine environment. Although rare, high-sulfidation mineralisation has been recorded on modern seafloors (e.g., Desmos caldera, Gemmell et al. 1999; conical seamount, (Petersen et al. 2002) where they display similar mineralogy, alteration, geochemistry and mineralised vein textures to many subaerial epithermal gold deposits. While the ore mineralogy, hydrothermal alteration zoning and sulfur-isotope data at Peak Hill are consistent with high-sulfidation-type epithermal mineralisation, we propose that the palaeogeographic setting during mineralization may have been submarine, although a subaerial setting cannot be precluded.

Conclusions

The Peak Hill gold deposit formed during the major late Ordovician to early Llandovery metallogenic event in the Macquarie Arc and represents an attractive target for exploration geologists in the region. The coincidence of high-grade (>5 g/t Au) zones in the domains of microcrystalline quartz just beyond the outer margin of the pyrophyllite+vuggy-quartz core is atypical of most high-sulfidation epithermal deposits (e.g., Arribas 1995). We believe that these characteristics represent differences in the rheology and permeability of the host rocks and fluid chemistry and thus controlled the distribution of gold and copper in the deposit. Therefore, future exploration must extend beyond the margins of the highly acidic pyrophyllite+vuggy quartz core of the alteration system, and should not be restricted to volcanic successions deposited in subaerial palaeogeographic settings—there is emerging evidence that high-sulfidation epithermal deposits can also form in submarine volcanic environments.

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