Metamorphism in the Cobar Basin: current state of understanding and implications for mineralisation

Abstract

A metamorphic map of the Siluro-Devonian Cobar Basin highlights a partial disconnect between penetrative deformation, metamorphism and mineralisation in the region. The sedimentary sequences of the Cobar Basin preserve a subtle increase in burial-related metamorphic grade from diagenetic shelf sequences (west) to anchizone basin sequences (east), transitioning back into late diagenetic to low anchizone shelf and marginal basin sequences in the south and east. Volcanogenic sequences preserve rift basin metamorphic grade ranging from zeolite facies to epizone greenschist facies, with local biotite-zone greenschist facies conditions around syn-volcanic intrusions. Inversion of the Cobar Basin, along with reactivation of basement and/or basin-forming faults, folding and localised penetrative cleavage development, occurred from 405 to 380 Ma. The development of slaty cleavage(s) is in part spatially related to metamorphic grade, with high strain rates along faults and shear zones characterised by ductile fabrics associated with epizone ‘hydrous’ regional metamorphism. Mineralisation in the main Cobar mining field is associated with these high strain zones. Importantly, hydrothermal metamorphic highs are also associated with mineral deposits in areas of comparatively lower strain (e.g. Nymagee copper mine, Hera gold mine). These deposits are proximal to the same, or similar, long-lived fault systems as the deposits located within high strain zones. Hydrothermal metamorphic grade around the lower strain deposits reaches biotite-zone greenschist to lowest amphibolite facies (or albite-epidote to pyroxene hornfels facies; T >450°C) conditions, clearly predate the development of epizone penetrative deformation fabrics, and is intimately associated with mineralisation. Localised high-temperature biotite-rich metasomatism, biotite-plagioclase-magnetite veining, garnet–quartz–sulfide veining and areas of garnet–quartz–tremolite–sulfide ± actinolite–zoisite–scheelite–phlogopite–K-feldspar–anorthite–talc–chlorite alteration characterise these zones. Formation of these early-formed, high temperature associations commands a proximal magmatic heat source or hot magmatic fluid. Magmatism in the region occurred c.420–415 Ma, ~ 10 Ma prior to the first recorded deformation-related hydrothermal alteration. It is likely the burial field gradient of the basin was locally perturbed through igneous activity prior to, and possibly up to, the onset of basin inversion. High temperature hydrothermal alteration and mineralisation accompanied this igneous activity. The established, perturbed thermal regime promoted further regional-scale epizone hydrothermal metamorphism during basin inversion, leading to further mineralisation and probable metal remobilisation to from Cobar-type mineralisation in zones of high strain.

Keywords
Cobar Basin, petrography, metamorphism, mineralisation, Conodont Alteration Index (CAI)
Introduction

The study of metamorphic grade and construction of metamorphic maps for deformed, polymetamorphic, very low to low grade terranes dominated by siliciclastic and felsic volcanic sequences is challenging and often requires extensive petrographic and/or microstructural observation, white mica crystallinity and/or chemistry data, or data from other basin maturity indicators such as vitrinite reflectance or Conodont Alteration Index (CAI). Distinguishing the type and timing of metamorphism can also be difficult, but is imperative to understanding the relationship, or lack thereof, between metamorphism and mineralisation.

Past studies

Past metamorphic studies of the Cobar Basin have focused on determining the thermal regime associated with mineralisation and/or regional orogenesis. Only limited reconnaissance work has been carried out on determining syn-depositional and burial metamorphic field arrays for the basin (Pickett 1982; Talent et al. 2003; Downes et al. in prep), or assessing how this relates to the overprinting hydrothermal and/or regional orogenic thermal imprints (Brill 1988; Downes et al. in prep). Nevertheless early workers did comment on the metamorphic grade of the basin relative to the hydrothermal metamorphic grade associated with mineralisation. Rayner (1969) noted:

‘The rocks of the Cobar Group, which are host to the copper ores at Cobar, Nymagee, Shuttleton and Mount Hope, show only low-grade metamorphism…. These host rocks were probably never above temperatures in the range 200–350°C (Turner & Verhoogen 1951) — except locally by metasomatism accompanying ore entry, or perhaps near any igneous intrusion which may be subjacent — and almost certainly were never above 400°C, which would be the order involved in the most intense biotitization (Edwards, Baker & Callow 1956).’

The vast majority of later studies assumed that hydrothermal metamorphic grade around mineralisation reflected the burial and/or regional (orogenic) metamorphic grade of the host basin sequences (e.g. Robertson 1974; Kelso 1982; Suppel 1984; David 2005, 2006). Based on the work of Brill (1988), Lawrie and Hinman (1998) suggested that outside major fluid channels, the basin was only heated to late diagenetic conditions (150–200°C), with hydrothermal alteration to epizone greenschist facies conditions caused by telescoping of the thermal gradient during inversion, as hot rocks were uplifted and exposed to a cooler environment, with hotter fluids brought from depth. The thermal model presented in the synthesis of David (2006) involves increased subsidence, an elevated geotherm
and substantially thicker basin sequences to the east of the Cobar Basin. Metamorphism during basin inversion is believed to have taken advantage of the earlier formed burial metamorphic thermal profile, and as a result, rocks subject to deeper, hotter (biotite-zone greenschist facies) levels of metamorphism are exposed on the eastern margin. In this model, high temperature hydrothermal assemblages are directly related to depth during burial and orogenesis. A regional metamorphic field gradient is implied from a combination of undeformed late diagenetic rocks that only preserve evidence for burial under basin sediments, deformed rocks that may record burial during compressional orogenesis, and hydrothermally altered rocks that preserve hot fluid influx pre-, syn-, or post-deposition or orogenesis. It should also be noted that Glen (1990) describes the Cobar Basin as a double-sided rift, with the greatest fault activity in the east early during basin initiation, followed by a switch of basin margin tectonism to the western side of the basin and greater subsidence in the west to form the accommodation space to accumulate the Amphitheatre Group. During inversion, this steeper margin was rapidly abandoned and inversion switched to the eastern margin minimising deformation on the western side of the basin.

**Relationship to mineralisation**

The distinction and study of type of metamorphism (burial, regional, hydrothermal, rift basin, contact), timing of metamorphism and spatial extent of metamorphism has the potential to help clarify the much-debated genesis of Cobar-type deposits. Two main genetic models, with numerous variants, have been debated over the years. A syn-genetic model involving syn-sedimentary exhalative and subhalative mineralisation that was subsequently remobilised during orogeny was popular with early workers (e.g. Brooke 1975; Gilligan & Suppel 1978; Suppel 1984; Marshall & Gilligan 1993). Syn-rift magmatic rocks were often invoked as the heat engine to the hydrothermal system (e.g. Suppel 1984). Rayner (1969), Suppel (1984), and more recently Cleverley and Barniccoat (2007) suggested the temperatures of alteration and distinctive early mineral associations of Cobar-type deposits are much better explained through an epithermal or magmatic-related ore system. Basin-forming fault systems were assumed to be the dominant fluid pathway (e.g. Suppel 1984). David (2006, 2008) revamped this model suggesting deposits formed in zones of growth faults related to early syn-rifting, as intrusion related epithermal, volcanic-associated massive sulfide (VAMS) and Irish-type deposits. Deposits were structurally overprinted during basin inversion to form ‘Cobar-type’ structurally controlled high-sulfide base metal deposits, quartz vein hosted low sulfide gold deposits and Mississippi Valley Type (MVT) deposits. For a syn-genetic model (burial and magmatic/volcanic related) mineralisation and/or alteration need not have a temporal or spatial relationship with regional metamorphic grade or deformation. To the contrary, alteration systems associated with mineralisation would be expected to predate regional metamorphism and deformation and may have a temporal or possibly spatial relationship to magmatic rocks and basin-forming faults. High thermal contrast may exist between low-grade, host basin lithologies and magmatically heated/derived hydrothermal fluids proximal to a causative magmatic body.

From the late 1980s to the present day a structurally controlled syn-deformational model involving regional metamorphic derived fluids (Glen 1987; de Roo 1989; Brill 1988; Seccombe & Brill 1989; Scott & Phillips 1990; Seccombe 1990) that scavenged both metals and sulfur from basin and basement (Glen 1991; Solomon & Groves 1994) has been the dominant mineral system model for Cobar-type deposits. In this model, mineralisation and/or alteration should display an exclusive temporal and spatial relationship with deformation and regional metamorphic grade. Without the aid of a proximal heat source, distant dehydration-derived fluids would be expected to cool during their ascent through large rock volumes and thermal contrast between the very low grade, buried basin lithologies and alteration should be limited. Indeed hydrothermal alteration associated with the vast majority of orogenic gold deposits is within 100°C of the peak, commonly epizone (300 ± 50°C), metamorphic temperatures experienced by the host rock sequences (Groves et al. 1998). If hot dehydration-derived hydrothermal fluids from a deeper (amphibolite facies) source are to be invoked then peak (highest temperature) hydrothermal alteration would also be expected to occur late in the orogenic cycle at upper crustal levels, allowing time for fluid generation and migration from deeper levels (Groves et al. 1998; Groves et al. 2000; Hagemann & Cassidy 2000; Groves et al. 2003; Goldfarb et al. 2005). The opposite is expected for a sequence that is prograding to high metamorphic grades (amphibolite facies; e.g. Phillips & Powell 2009), which is not the case at the exposed levels in Cobar.

**This study**

We present a ‘first pass’ regional metamorphic study of the Cobar Basin based on the results of a petrographic re-evaluation of secondary mineral assemblages. We include new information on the thermal maturity of the Cobar Basin based on CAI data. Where possible we distinguish and discuss the differences between burial metamorphism, rift basin metamorphism, regional
metamorphism, hydrothermal metamorphism and contact metamorphism. Finally, we relate the timing and distribution of metamorphic grade and the type of metamorphism to mineralisation in the Cobar field. The methodology for construction of a metamorphic map is outlined in Appendix 1.

This metamorphic study was conducted during the development of the Cobar Special 1:500 000 Metallogenic Map of Fitzherbert et al. (2016) and that mapping informs the stratigraphic interpretations used in this paper.

**Terminology**

Integral to this study was the differentiation of metamorphism types, which are defined in Table 1. The nomenclature for metamorphic grade and associated temperature divisions used in this paper is presented in Figure 1a.

<table>
<thead>
<tr>
<th>Table 1 Types of metamorphism</th>
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<tr>
<td><strong>Burial metamorphism:</strong> Metamorphism of regional extent that affects rocks deeply buried under a sedimentary and/or volcanic pile and is typically not associated with deformation or proximal magmatism.</td>
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<td><strong>Rift basin metamorphism:</strong> Modified after Smulikowski et al. (2007), metamorphism of a regional extent that is not associated with obvious compressional or extensional fabric development and is associated with the pervasive, static hydration of primary (usually igneous) mineral assemblages. This type of metamorphism is commonly associated with open system chemical or metasomatic processes and is mostly expressed within volcanogenic lithologies. Hydrothermal metamorphic mineral assemblages are associated with hydration during elevated heat flow and may be related to fluid fluxing and the establishment of hydrothermal cells at the time of volcanism and associated plutonism. Recrystallisation and partial hydration during the later stages of magmatic cooling may be related to fluids exsolved from the igneous rocks themselves (deuteric alteration), or from meteoric or seawater reservoirs. The effects of rift basin metamorphism and contact metamorphism may be indistinguishable around syn-volcanic intrusions.</td>
</tr>
<tr>
<td><strong>Hydrothermal metamorphism:</strong> Metamorphism of a local extent caused by hot, commonly water-rich fluids. Metasomatism and/or alteration and mineralisation are commonly associated with this type of metamorphism. Hydrothermal metamorphism can occur through magmatic, metamorphic and even burial related processes.</td>
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<tr>
<td><strong>Contact metamorphism:</strong> Spatially restricted metamorphism in the country rocks surrounding plutonic bodies. Contact metamorphism at upper crustal levels is not usually associated with obvious compressional or extensional fabric development.</td>
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<tr>
<td><strong>Regional metamorphism:</strong> Modified after Smulikowski et al. (2007), metamorphism of a regional extent associated with compressional or extensional fabric development. Unlike the classical definition of regional metamorphism, which involves increasing dehydration with increased temperature, regional metamorphism in Cobar is intimately associated with water-rich fluid flow along faults, lithological contacts and within permeable horizons. This ultimately led to the development of hydrothermal and/or metasomatic mineral associations of a regional extent during compressional deformation.</td>
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**Regional geology**

The Cobar area resides in the Central Subprovince of the Lachlan Orogen. Three major cycles consisting of crustal extension terminated by regional compressional deformation (orogeny) are recorded in the region: the Benambran Cycle (490–433 Ma; Glen 2005; Fergusson et al. 2005), terminated by the earliest Silurian Benambran Orogeny; the Tabberabberan Cycle (433–380 Ma), terminated by the Middle Devonian Tabberabberan Orogeny; and the Kanimblan Cycle (380—340 Ma), terminated by the Early Carboniferous Kanimblan Orogeny (Glen 2005, 2013; Collins & Richards 2008). Benambran Cycle rocks in the Cobar area include Ordovician turbiditic sedimentary sequences of the Girilambone, Wagga and Bendoc groups. These units were deformed and metamorphosed during the early Silurian Benambran Orogeny. Tabberabberan Cycle crustal extension followed in response to northeast–southwest directed regional maximum extensional strain (Glen et al. 1996), in part exploiting structural weaknesses created during the Benambran Orogeny, and initially expressed by the intrusion of voluminous S-type granitic plutons associated with hard rock tin ± tungsten mineralisation. Rifting continued into the Early Devonian and
<table>
<thead>
<tr>
<th>Facies zone</th>
<th>Metapelite zone (depth, km)</th>
<th>Temperature (°C)</th>
<th>Illite crystallinity</th>
<th>Vitrinite reflectance R,%</th>
<th>Conodont Alteration Index (CAI)</th>
</tr>
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<tbody>
<tr>
<td>Zeolite</td>
<td>3.5–4</td>
<td>100</td>
<td>~1.0</td>
<td>0.5</td>
<td>1 yellow</td>
</tr>
<tr>
<td>sub-greenschist</td>
<td></td>
<td>~0.60</td>
<td>1.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Late diagentic zone</td>
<td>6.5–8</td>
<td>200</td>
<td>~0.42</td>
<td>2.00</td>
<td>2 light brown</td>
</tr>
<tr>
<td>Low anchizone</td>
<td></td>
<td>2.50</td>
<td>~0.25</td>
<td>4.00</td>
<td>3 brown</td>
</tr>
<tr>
<td>High anchizone</td>
<td>10–12</td>
<td>300</td>
<td>~0.25</td>
<td>4.00</td>
<td>5 black</td>
</tr>
<tr>
<td>Greenschist</td>
<td></td>
<td>350</td>
<td></td>
<td></td>
<td>6 grey</td>
</tr>
<tr>
<td>Amphibolite</td>
<td></td>
<td>400</td>
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**Figure 1.** a) Nomenclature for metamorphic facies zones and relationships with physical parameters used in this paper (after Robinson and Frey 1999), b) Relationship between CAI and temperature from Epstein et al. (1977) and used by Pickett (1982).
Figure 2. Distribution of groups of the Cobar Supergroup and basement. Undercover interpretation is based on Fitzherbert et al. (2016).
a number of these plutons were partially unroofed in palaeotopographic highs that flanked a group of north-trending shallow to deepwater basins and/or rifts. Deepwater basins include the Mount Hope Trough in the southwest and the Cobar Basin and Rast Trough in the southeast centre (Figure 2). The volcanogenic Mount Hope Trough was intruded and metamorphosed by syn-rift S-type and A-type granites, which are associated with intrusion- and volcanogenic-related gold–base metal mineralisation (e.g. Mount Allen gold). Palaeotopographic highs include the eastern, shallow marine Mouramba and Kopyje shelves, the latter being associated with epithermal mineralisation at Mineral Hill (Blevin & Jones 2004; Morrison et al. 2004) and Pipeline Ridge (Downes et al. 2016). Early Devonian intrusion-related tin mineralisation is also hosted in Ordovician basement underlying the shelf sequences (e.g. Tallebung). To the west, the basin/trough sequences are flanked by the Winduck Shelf (Glen et al. 1985), which hosts carbonate-hosted Mississippi Valley Type mineralisation at Manuka (Figure 2).

Fluviatile sequences of the Mulga Downs and Coco-parra groups are thought to have blanketed the shelf and exposed basement sequences prior to the onset of the Tabberabberan Orogeny (Downes et al 2016; Sherwin 2016), but there is ongoing debate as to the timing of this fluviatile event. The Cobar Basin was inverted and deformed from 405 to 380 Ma (Perkins et al. 1994; Glen et al. 1996). Basin inversion was initiated with reactivation of major basin/trough margin faults or near margin faults such as the Myrt Fault, allowing fluids to tap metals from Ordovician basement underlying the shelf sequences (e.g. Tallebung). To the west, the basin/trough sequences are flanked by the Winduck Shelf (Glen et al. 1985), which hosts carbonate-hosted Mississippi Valley Type mineralisation at Manuka (Figure 2).

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Widespread mineralisation resulted, with currently accepted mineral systems models including:

- carbonate-hosted silver–lead–zinc mineralisation (e.g. Manuka, Winduck Shelf)
- SEDEX/Irish type zinc–lead–silver–copper–gold (e.g. Endeavor, Cobar Basin; David 2008)
- Structurally controlled high sulfide ‘Cobar-type’ copper–gold–lead–zinc–silver mineralisation (e.g. Great Central and May Day — Mount Hope Trough; Mallee Bull and Shuttleton — southern Cobar Basin; Browns Reef — Rast Trough; CSA, Great Cobar, New Occidental, The Peak gold mines, Nymagee and Hera — eastern Cobar Basin margin).
- Structurally controlled low sulfide gold mineralisation (e.g. Good Friday, The Sunrise — within Ordovician basement; Mount Boppy — at the boundary between basement and basin lithologies; Mount Solitary, Gilgannia goldfield — within Cobar Basin sequences).

Mineralisation is associated with thrust fault systems (e.g. Chesney, Queen Bee and Rookery faults), which often exploited major stratigraphic or basin/trough contacts. The central Lachlan Orogen experienced minor folding and fault reactivation during the Kanimblan Orogeny resulting in minor, structurally controlled, low sulfide gold mineralisation associated with the Yalgogrin Granite. Larger fault displacements locally juxtapose Ordovician basement against Mulga Downs Group.

**Building a baseline thermal maturity map of the Cobar Basin: Conodont Alteration Index**

Conodonts are the microscopic remains of an extinct group of animals that were abundant in Cambrian through to Triassic oceans. They have been used widely in hydrocarbon exploration and basin analysis because of their coupled utility as both chronological and thermal maturity indicators. Individual conodont elements experience progressive colour change as a response to increasing temperatures over time. This was first quantified by Epstein et al. (1977) with the establishment of the conodont Colour Alteration Index. The thermal range of CAI values was extended by Helsen and Königshof (1994).

CAI values are determined by examining the finest parts of conodont elements (outer basal margin, denticle tips) under light (Plate 1). Unaltered conodonts exhibit a pale yellow colour and a smooth surface with silky brightness (CAI 1). Exposure to increasing temperatures results in carbonisation of conodont matter that produces a progressive colour sequence of light to dark brown (CAI 1.5–4) to black (CAI 5). Subsequent colour changes towards grey (CAI 6), white (CAI 7) and finally translucent (CAI 8) are thought to be consequences of the oxidation of organic matter and recrystallisation. Colour Alteration Indices data from conodonts has been used as a proxy for thermal maturation. This technique has not been widely applied in the Lachlan Orogen.

Earlier reconnaissance reports of conodont faunas from the Cobar Basin (e.g. Pickett 1982) suggested variable thermal maturity across the basin, but no systematic trends were identified. It should be noted that the CAI determinations of Pickett (1982) utilised the colour chart and assigned temperature ranges of Epstein et al. (1977). There have been significant modifications to temperature ranges assigned to various conodont colours in recent years (see Figure 1). In this paper, estimated temperatures based on newly reported CAI values use the nomenclature of Merriman and Frey (1999) as shown in Figure 1a, and reported values from Pickett (1982) have been re-assigned based on Merriman and Frey (1999).
is evident in lithologies of the eastern Mouramba Group, southern Kopje Group and Yarra Yarra Creek Group (Figures 3 and 4). Indications of high thermal maturity are also preserved in parts of the Derriwong and Trundle groups to the east; neither these values, nor CAI values from the Darling Basin to the west are considered further in this study. A broad zone of anchizone to epizone metamorphism is depicted on contoured maps of CAI determinations (25 data points) on Figure 3a. There are too few data points within the deepwater basin to rely on the extrapolation across this area. Figure 3b is a contour map of twelve CAI data points supplied in Pickett (1982). The data of Pickett (1982) contains an extra point from Conqueror mine, but this limestone was sampled from an area proximal to hydrothermal alteration and mineralisation in the main Cobar mining field and thus should not be included in the baseline thermal maturity map. Individual CAI values and their relationships to regional metamorphic and localised hydrothermal metamorphic/metamorphic grade have been incorporated into the discussion below.

Building a comprehensive ‘first pass’ metamorphic map of the Cobar Basin

The thermal maturity map discussed above illustrates a burial-related metamorphic grade of late diagenetic zone in shelf sequences to the west and east of the deeper water basin sequences. Southeast of Nyngan the eastern shelf sequences preserve a zone of elevated thermal maturity (epizone) of unknown affiliation. The basin was inverted and sedimentary rocks folded and faulted and in places penetratively deformed during the Tabberabberan Orogeny. A slaty cleavage related to the Tabberabberan Orogeny is in part spatially related to metamorphic grade, with high strain rates along faults associated with anchizone and more commonly epizone regional metamorphic grades. Importantly, local hydrothermal metamorphism associated with alteration and mineralisation in siliciclastic sedimentary rocks commonly reaches biotite-zone greenschist to transitional amphibolite facies (or albite–epidote to pyroxene hornfels facies) conditions. Biotite-zone hydrothermal metamorphic assemblages are for the most part described as forming early in the mineralisation history (e.g. Stegman 2001; Cleverley & Barnicoat 2007) and based on observations during this study the majority predate the development of penetrative deformation fabrics, or may have formed during very early syn-deformation. Volcanogenic sequences preserve evidence of rift basin metamorphism ranging from zeolite facies to biotite-zone greenschist facies conditions. Biotite-zone rift basin and contact metamorphism are spatially associated with syn-volcanic intrusive rocks.

A corpus of new CAI data was accumulated for the current study during an extensive regional investigation to establish the ages of isolated carbonate units (Mathieson et al. 2016). This data indicates that thermal maturity is, for the most part, uniformly low within the shelf sequences of the Cobar Supergroup (CAI = 2–3.5, T = 100–200°C; Figure 3), implying diagenetic to low anchizone burial metamorphic conditions. Interestingly, a distinct zone of high thermal maturity (CAI = 4–6, T = 200 to > 300°C)
Figure 3. Contoured CAI maps: a) based on 25 data points from this study, b) based on 12 data points from Pickett (1982). See text for details of contouring method.
Figure 4. Metamorphic map of the Cobar Basin and surrounding basement. Cross-hatched area indicates a zone of anchizone to epizone Conodont Alteration Index greater than 4 from Figure 3a. Zones of Devonian, Silurian and Ordovician metamorphism have been distinguished.
Below we attempt to separate the effects of burial metamorphism, regional metamorphism, hydrothermal metamorphism, rift basin metamorphism and contact metamorphism for the major tectonostratigraphic units of the Cobar Basin. Important place names, locations of mineralisation and key areas of metamorphism referred to in the text are depicted on Figure 4. Further information on construction of the metamorphic map is outlined in Appendix 1.

**Shelf sequences**

**Kopyje Group**

Units of the northern Kopyje Group (Florida Volcanics, Baledmund Formation, Babinda Volcanics) consistently preserve zeolite to epizone greenschist facies rift basin metamorphic mineral assemblages. There is limited deformation-related recrystallisation and lithologies have not undergone regional or contact metamorphism to any obvious extent. Lithologies of the southern Kopyje Group (Majuba Volcanics and further south) preserve zeolite to epizone greenschist facies rift basin metamorphic mineral assemblages, but there are significant areas of biotite-zone greenschist facies metamorphism in contact/rift basin mineral assemblages associated with syn-volcanic plutons (e.g. Yellow Mountain Granite). For detailed petrographic descriptions and photomicrographs of Kopyje Group volcanic rocks and their associated secondary mineral association see Simpson (2015).

The vast majority of the Baledmund Formation displays partial recrystallisation to the secondary mineral assemblage of sericite, chlorite, clay minerals, iron oxides ± silica, titanite and carbonate. Although non-diagnostic this mineral association is consistent with anchizone to epizone metamorphic conditions. Pickett (1982) recorded a CAI of 4–4.5 for the northernmost exposures of Baledmund Formation at Boomerang Tank (Figure 4), indicating low anchizone burial metamorphic conditions between 200–250°C. A revised CAI of 2.5–3.5 for the Boomerang Tank limestone (this study) indicates late diagenetic to low anchizone zone metamorphic temperatures between 150–200°C. A CAI of 3.5–4 determined from a nearby limestone occurrence at Kopyje (Figure 4) also indicates late diagenetic to low anchizone metamorphic conditions. Talent et al. (2003) reported a CAI of 5, revised to 4.5–5 (this study) from limestone at Beloura Tank (Figure 4), while Pickett (1982) recorded a CAI of 5–5.5. These determinations indicate high anchizone to epizone temperatures of ~250–300°C for the southern Baledmund Formation. Intense chlorite-magnetite ± stilpnomelane-asbestiform amphibole is described in calcareous lithologies at the base of the Baledmund Formation to the east and west of Mount Boppy gold mine (Figure 4), indicating at least localised potential for epizonal hydrothermal metamorphism in this region (Fromager & Granger 1975). Of the relatively few thin sections available for the Baledmund Formation to the south near its contact with the Majuba Volcanics, a number contain decussate, brown hydrothermal or contact metamorphic biotite, particularly those from the region of an interpreted fault that separates the Majuba Volcanics from the host Baledmund Formation. The occurrence of biotite indicates locally higher temperatures (350–400°C) during hydrothermal and/or contact metamorphism.

Many samples of the Florida Volcanics are partly recrystallised and hydrated to an assemblage of sericite, chlorite, quartz and less abundant albite, epidote (clinozoisite, piedmontite), titanite, allanite, clay minerals and iron oxides (Photograph 1). Patches of carbonate appear to be late and overprint the other alteration minerals. A small amount of greenish-brown biotite was observed in some samples, commonly with pre-cleavage chlorite and/or white mica. The above mineral associations are consistent with epizone rift basin metamorphism. The effects of deformation in the Florida Volcanics are weak, with most samples being classified as undeformed. Occasional sericite with rare chlorite is recorded defining a foliation and reflects sub-greenschist facies regional metamorphism.

The secondary mineral associations of the Babinda Volcanics are similar to those of the Florida Volcanics, comprising a sub- to lowest greenschist facies secondary, hydrothermal mineral assemblages of sericite, chlorite, quartz, albite and titanite. One notable differ-

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**Photograph 1.** Spherulitic groundmass of plagioclase-rich dacitic lava. Note also plagioclase and chloritised crystals (top right) and quartz (lower left). The image illustrates the effects of rift basin metamorphism in undeformed Florida Volcanics. Photomicrograph taken under cross-polarised light. GR 442000 6502500. (Photographer C.J. Simpson).
ence is the lack of secondary epidote and prevalence of carbonate as the calcium-bearing phase. These mineral associations are again consistent with pre-deformation, epizone rift basin metamorphism. Most samples are undeformed, apart from a weak cleavage developed in a few of the finer-grained rocks and possible enhancement of flow foliation by shearing in a few dacitic rocks. Where weak cleavage is developed, feldspar phenocrysts record brittle deformation — consistent with low grade, sub-greenschist facies regional metamorphic conditions (Passchier & Trouw 2005).

Much like the Florida and Babinda volcanics, the background secondary mineral assemblage of the Majuba Volcanics in the central part of the Canbelego – Mineral Hills Volcanic Belt is consistent with lowest greenschist facies rift basin metamorphism. It comprises quartz, sericite, chlorite, carbonate, and less abundant epidote, titanite, iron oxides and rare albite. There is evidence throughout the Majuba Volcanics for recrystallisation related to contact, rift basin and regional metamorphism. Granoblastic textures and abundant biotite, with all or some of epidote, carbonate, titanite and chlorite, is recorded in the Majuba Volcanics south of the Yellow Mountain Granite (Photograph 2) suggesting biotite-zone greenschist facies and relatively high static heat flow, possibly reflecting contact metamorphic effects from a greater subsurface distribution of intrusive rocks, such as the porphyry unit mapped on the Gindoono 1:100 000 map sheet area (MacRae & Pogson 1985). Similarly, biotite-zone greenschist facies mineral assemblages occur on the northern side of the Yellow Mountain Granite. Locally developed hydrothermal metamorphic biotite–haematite-bearing rocks are also preserved in the Majuba Volcanics on the eastern side of the Walkers Hill Fault Zone. Decussate biotite is also recorded in possible contact or hydrothermal metamorphic mineral assemblages developed in the Majuba Volcanics at their faulted boundary with the Baledmund Formation along the northerly extension of the Walkers Hill Fault Zone.

A rare tectonic foliation is defined in the Majuba Volcanics, generally associated with sericite ± chlorite (or biotite retrogressed to chlorite). This foliation often mimics the primary flow foliation in the volcanic rocks. Foliation regional metamorphic reflect epizone greenschist facies conditions and distinguishably lower temperature conditions compared to the rift basin and contact metamorphic mineral assemblages described above.

Close to mineralisation, at the Yellow Mountain prospect, fine-grained glassy volcanic rocks and autobrec- cias are cut by secondary chlorite–sulfide–quartz veins. A weak, domainal sericitic white mica fabric overprints the sub-vertical vein system. The early hydrothermal alteration here reflects epizone greenschist facies hydrothermal metamorphism.

There is very little petrographic information and very few historic thin sections for the Mount Knobby Formation, which occurs as a series of fault-bound slivers to the south of the Majuba Volcanics. Previous descriptions of the rock types include chloritic-phyllite and deformed sandstone, suggesting the dominant thermal imprint is probably related to epizone greenschist facies regional metamorphism. Equally there is very little information on the informally named Harts Tank beds (Kopyje Shelf). A sericite-defined foliation is locally described for these beds, and based on the descriptions of Burton et al. (2012) for exposures of the Meryula Formation on the same fault system to the north, they have been assigned to anchizone, sub-greenschist regional metamorphic grade.

Most of the Mineral Hill Volcanics preserve a sub- to lowest-greenschist facies secondary, hydrothermal mineral assemblage mostly comprising sericite, quartz (sometimes chaledonic) and chlorite, with lesser albite, epidote and carbonate. Most samples show very little sign of deformation, with minor straining and fracturing of quartz phenocrysts, and possible weak sericitic enhancement of a primary flow foliation. The overlying Talingaboolba Formation preserves secondary mineral assemblages that are much more consistent with sub-greenschist facies, including chlorite, sericite, smectite, kaolinite and iron oxides. No signs of foliation development were observed in re-assessed thin sections. Sherwin (1996) suggested local contact metamorphism of the rocks. Unfortunately there is almost no petrographic information for the Talingaboolba Formation, just a vague reference in the petrographic database to a weak sericite fabric in places.

Photograph 2. Crystal-rich, vitric sandstone with vitric mudstone clast. Decussate brown, metamorphic biotite is within the mudstone clast (centre right). Sample is from southernmost Majuba Volcanics. Photomicrograph under plane-polarised light. GR 493180 6376000. (Photographer C.J. Simpson).
The mineralised sections of the Mineral Hill Volcanics were not re-assessed as a part of this study, but Bush (1980) and Downes et al. (2016) described chlorite composition varying from Fe-chlorite distal to mineralisation to Mg-chlorite associated with t alc proximal to, but still outside the mineralised zone. Quartz is ubiquitous and paragonite is apparent in the alteration system. Chlorite thermometry (Lanari et al. 2014) suggests temperatures of ~150°C for iron-rich chlorite distal to mineralisation and ~300°C proximal to mineralisation (see Bush 1980 for relevant chlorite analyses). These determinations are consistent with late diagenetic zone burial metamorphic conditions distal to mineralisation and anchizone to epizone hydrothermal metamorphic conditions proximal to mineralisation.

The northern and westernmost exposures of the Kopyje Group comprise the Coronga Peak Quartzite and the Meryula Formation. Felton (1981), Glen (1987) and later Burton et al. (2012) describe a slaty, white mica–defined cleavage within the Meryula Formation, suggesting sub- to lowest-greenschist facies metamorphic conditions within the Sussex and Byrock 1:100 000 geological sheet areas. Pickett (1982) reported CAI values ranging from 4.5 to 5.5 for limestone from the Meryula Formation (Rookery Limestone Member CAI = 4–4.5; White Tank Limestone Member CAI = 4.5–5.0), which are consistent with sub-greenschist, low to high anchizone metamorphic conditions (200–300°C). Interestingly Talent et al. (2003) reported a CAI of 2.5 for the Rookery Limestone Member, implying temperatures as low as ~150°C. A reassessment (this study) of the CAI for the White Tank Limestone Member (CAI = 2–3) and the Rookery Limestone Member (CAI = 2–3) is also consistent with temperatures of 150-200°C and late diagenetic, burial metamorphism for the majority of the Meryula Formation. Pickett (1982) recorded a CAI of 5.5 for limestone at Conqueror mine in the northernmost parts of the Meryula Formation. This limestone has not been reassessed for CAI, but a CAI of 5.5 or above (T ~300°C) is consistent with the description of recrystallised marble recorded by A. Felton at this site (see GSNSW petrographic database). Deformed chlorite-sericite assemblages are associated with mineralisation at Conqueror mine and Mallee Tank, thus a zone of epizone greenschist facies regional metamorphism has been defined for this area on Figure 4.

The southernmost Ootha Group, here included with the Kopyje Shelf (see Simpson 2015) comprises mostly vitric-rich mudstone/siltstone that has been silicified, with varying degrees of clay alteration. Chlorite, sericite and carbonate are also locally abundant. There are no signs of foliation development and the secondary mineral assemblage implies zeolite facies, burial or rift basin metamorphism.

Mouramba Group

The Mouramba Group comprises basal arkosic sandstone and conglomerate (Burthong Formation) overlain by fine- to medium-grained sandstone. There are minor volcanic units in the lower part and an interfinger thick sequence of sandstone in the upper part of the group. CAI values of 4.5 to 5 (Pickett 1982) and 2.5 to 3 (Talent et al. 2003) have been reported for the nearby Mountain Dam Limestone; the latter being consistent with the results of this study. These results reflect late diagenetic conditions (150–200°C). The nearby Beloura Tank Limestone Member records a low to high anchizone CAI of 4.5 to 5 (~250°C) (Talent et al. 2003; this study). Suppel (1984) described parts of this limestone as foliated quartz–epidote/clinozoisite-chlorite–albite calc-silicate after limy siltstone, consistent with or possibly reflecting higher temperatures than the reported CAI data.

In thin section, the majority of sandstones from the Mouramba Group preserve detrital textures and detrital micas (including abundant detrital biotite; Photograph 3) that may be partially replaced/overgrown by sericitic white mica ± chlorite (see also Barron 1980). An often weak, but locally intense cleavage defined by sericite and clay minerals ± chlorite is locally developed, and quartz dissolution and precipitation is evident, especially in the vicinity of faults. Although the mineral associations are non-diagnostic the preservation of detrital fabrics and micas implies sub-greenschist facies conditions. Biotite is particularly unstable during late diagenesis and anchizone metamorphism, and its excellent preservation implies temperatures below ~270°C (Tarantola et al. 2009), roughly concurring with the CAI determinations. Glaucnite pellets are recorded in some of the petrographic descriptions.

Photograph 3. Lithic sandstone with well-preserved equant to rounded clots of detrital biotite (centre and lower-left) and slender detrital muscovite (top right). There is very little evidence of cleavage development in this sample from the Burthong Formation, Mouramba Group. Photomicrograph taken under plane-polarised light. GR 438750 6433700. (Photographer J.A. Fitzherbert).
also consistent with diagenetic recrystallisation. Primary minerals in volcanic members within the formation are variably hydrated to chlorite, epidote, titanite, albite or sericite, reflecting epizone greenschist facies rift basin metamorphism. The Mouramba Group has been assigned to the late diagenetic to low anchizone burial metamorphic zone on Figure 4.

A number of samples present evidence of thermal highs associated with the Ironbark Fault, including biotite veins and pervasive biotite metasomatism similar to that described for the overlying Lower Amphitheatre Group at Nymagee and Hera mines (Figure 4). Very local exposures of strongly hornfelsed and/or metasomatised Mouramba Group were noted along the northern margin of the Erimeran Granite (GR 433400 6430200), in close association with a number of small, north-trending faults that offset the northern margin of the granite in this area. If truly within the Burthong Formation these local high grades are unrelated to the older Erimeran Granite. Actinolite–magnetite hornfels is also described at GR 733785 6428111, but its age affiliation is not certain.

To the south, the Boothumble Formation preserves abundant detrital micas. A very locally developed and weak sericite-defined cleavage and minor quartz suturing and sub-graining are the only evidence of deformation within the formation. On this basis the Boothumble Formation has been assigned to the late diagenetic to low anchizone burial metamorphic zone (Figure 4). Sericite- and chlorite-rich alteration was observed in one sample suggesting very local attainment of epizone hydrothermal metamorphic grades in the formation.

Winduck Group

Limited petrographic re-evaluation of the Winduck Group was conducted for the current study. Glen (1987) reported that the group is essentially unmetamorphosed. Detrital muscovite, biotite and chlorite are partially replaced by fine-grained white mica. Micas are kinked, and quartz displays minor undulose extinction and suturing due to compaction. There is little evidence of deformation-related fabrics in the shelf sequences. Talent et al. (2003) recorded a CAI of 2.5 from the Booth Limestone Member at Manuka mine, reassessed as 2.5–3 in this study. This range reflects late diagenetic, burial metamorphic conditions (T ~150°C). Conodonts from limestone at Multigoona display a CAI of 2.5–3, also consistent with late diagenetic zone burial conditions (T = 150–200°C). Giles (1993) also reported fluid inclusion derived temperatures of ~150°C from Manuka mine. The mineralogy recorded in hyperspectral logs of core from Manuka mine is also consistent with the late diagenetic determination (Downes et al. 2016).

Yarra Yarra Creek Group

There is very little petrographic data for the Yarra Yarra Creek Group. Sherwin (1996) described widespread folding and extensive grain-suturing and recrystallisation of quartz within regional fold hinges in the group, but otherwise there is very little evidence of penetrative deformation. Pickett (1982) reported CAI values of 3–3.5 and 5 for limestone (Jerula Limestone Member) from Bogong Station and Boona Gap respectively. These CAI values imply sub-greenschist, late diagenetic to lower anchizone metamorphic conditions (150–250°C). Both limestone occurrences were reassessed as part of this study and while the Bogong Station values remained the same, the CAI for Boona Gap was revised to 6, reflecting T >300°C and lower greenschist facies metamorphic conditions. CAI values from limestone in the nearby Derriwong Group record a similar higher thermal imprint, with CAI values of 4 to 6 (Figures 3 and 4). The elevated CAI value at Boona Gap may be reflective of a northerly increase in thermal maturity. Interestingly, the Jerula Limestone Member is interpreted as Pragian in age (1996), placing a lower age limit on the elevated thermal maturity in this area of ~410 Ma.

Cobar Basin

Amphitheatre Group

The Amphitheatre Group is best described in three parts: northwestern, northeastern and southern. Glen (1987) noted development of fine-grained, white mica-defined cleavage folia in areas of S1 and S2 cleavage, suggesting sub-lower greenschist metamorphic grades.

Northwestern Amphitheatre Group

Talent et al. (2003) report a CAI of 3 for an allochthonous block of Lerida Limestone Member from The Bluff in the Biddabirra Formation. Limestone at the Bluff and McKinnons gold mine were re-assessed and a revised CAI of 2–3 is reported for both occurrences, reflecting late diagenetic temperatures of 150–200°C for the Amphitheatre Group at those localities. Pickett (1982) recorded a slightly higher CAI of 4.5–5 for the Lerida Limestone Member in the Lower Amphitheatre Group on the Wrightville 1:100 000 map sheet area, reflecting low anchizone metamorphic conditions of 200–250°C. Unfortunately this site was not reassessed.

Most samples listed within the GSNSW petrographic database from the northwestern and central Cobar Basin have very little information about secondary mineral assemblages. The most common reference is to a weak sericite-defined foliation that is almost certainly of sub-greenschist, probable, low anchizone regional metamorphic origin. A review of historic thin sections
from the northwestern Cobar Basin during this study revealed only a very weak discontinuous cleavage commonly defined by sericitic white mica, with or without chlorite, but more often as carbonaceous stylolites. Many sandstones preserve primary sedimentary and overprinting diagenetic textures (pressure solution, stylolites, dust lines, overgrowths) with limited signs of deformation-related recrystallisation. Siltstone samples preserve a detrital muscovite and biotite foliation that may be partially enhanced by a fine, sericite–chlorite cleavage. The petrographic observations made here are consistent with the reported CAI values for the area and reflect diagenetic to anchizone burial metamorphic conditions (Figure 4).

The extent of the aureole around the Gilgunnia Granite, or associated with undercover extensions of the Boolahbone Granite, is not well constrained due to a dearth of petrographic information. MacRae (1987) described contact metamorphism in the Lower Amphitheatre Group around the Gilgunnia Granite. A thin zone of contact metamorphism is shown on Figure 4, but the aureole may be more extensive.

Thermal highs are strongly localised within the northwestern Amphitheatre Group and are associated with hydrothermal metamorphism and mineralisation. There is a direct correlation with increased intensity of deformation and increasing hydrothermal metamorphic grade. Seccombe (1990) presented fluid inclusion data from the Endeavor (formerly Elura) mine (located in the CSA Siltstone) suggesting a temperature range of 170–225°C from quartz veins in the wall rocks, reflecting late diagenetic to low anchizone metamorphic conditions. Higher temperatures (also based on fluid inclusion data) of 298–354°C were reported for mineralised zones at Endeavor mine. Sun and Seccombe (2000) inferred similar temperatures of 268–374°C for the mineralising events at Endeavor mine, and reported wall-rock alteration comprising quartz, sericite, muscovite, chlorite, carbonate and locally albite. Thin sections from the GSNSW petrographic database display siderite and ankerite porphyroblasts, enveloped by a moderately strong foliation, form a distinctive halo several tens of metres wide around the ore bodies (Photograph 4). Brill (1988) also suggested high anchizone to low epizone temperatures (illite crystallinity, $\Delta^2\theta_{Cu-Ka} = 0.32–0.25$ indicating $T \sim 280–300^\circC$) for muscovite in the hydrothermal alteration zone at Endeavor mine.

Forster and Seccombe (1999) recorded epizone peak temperatures of 320–340°C for mineralisation at McKinnons gold mine in the lower part of the Amphitheatre Group. The authors describe a penetrative, continuous cleavage defined by chlorite and muscovite, as well as early-formed carbonate spotting, Much of the mineralisation at the mine is interpreted as structurally controlled, having formed during the basin inversion phase with a late phase of gold mineralisation related to a deep intrusion.

Based on the above observations and inferences, the northwestern Amphitheatre Group is assigned to the late diagenetic to anchizone of burial metamorphism on Figure 4, but has clearly experienced localised epizone hydrothermal metamorphism associated with mineralisation.

**Northeastern Amphitheatre Group**

There is a large body of previous work detailing the regional metamorphic thermal regime of the northeastern Cobar Basin since this area is host to Cobar-type, structurally controlled, low sulphide base metal deposits. The majority of past work has focused on high strain zones associated with hydrothermal alteration and mineralisation and there is a dearth of information about metamorphic grade distal to mineralisation.

A review of historic thin sections from the northeastern Cobar Basin was conducted as part of this study. Distal to mineralisation, sandstone, siltstone and shale preserve a detrital fabric defined by muscovite and chlorite, which have replaced all of the original detrital biotite (Photograph 5). This is consistent with epizone metamorphic conditions. Glen (1994) suggested that the axis of the Myrt Syncline marked the divide between intensely cleaved eastern and uncleaved to weakly cleaved western Cobar Basin sequences. The vast majority of samples preserve a continuous, high anchizone to epizone slaty cleavage often defined by sericitic white mica and chlorite. Proximal to mineral-
mineralisation, rocks are pervasively chloritised, often displaying a penetrative, chloritic epizonal slaty cleavage. Glen (1994) noted biotite within the slaty cleavage of the eastern Amphitheatre Group. In this study, cleavage-defining biotite was not observed in any of the 240 historic thin sections of the northeastern Cobar Basin, but this does not negate its possible presence. Sericitic white mica and chlorite are the dominant cleavage-defining minerals.

Proximal to mineralisation, Brill (1988) described consistent epizone temperatures derived from white mica crystallinity ($\Delta^220\text{Cu-K}\alpha$) from CSA mine (0.25–0.21, indicating T ~300–320°C). Kyne (2014) reported comparable high anchizone to epizone white mica crystallinity ($\Delta^220\text{Cu-K}\alpha$) values (0.24–0.27) from the least-altered samples observed in drillcore from CSA mine. Robertson and Taylor (1987) recorded vitrinite reflectance values from within an ore zone near CSA mine of 3.3–3.4, indicating temperatures of ~280°C.

Giles and Marshall (2004) recorded slightly higher, fluid inclusion-derived, peak metamorphic temperatures of 350–380°C from mineralised zones at CSA mine. Kyne (2014) described gangue mineralogy from CSA mine that included stilpnomelane, plagioclase and rare biotite, indicating at least local biotite-zone hydrothermal metamorphism associated with mineralisation. In thin sections from CSA mine, textures are similar to those observed in the southeastern Amphitheatre Group (e.g. Hera and Nymagee mines, see below). Here, early biotite, plagioclase and chlorite veins crosscut siltstone and sandstone. These veins have been subsequently deformed during the development of a locally pervasive chloritic slaty cleavage. These early vein systems signify a moderate to high temperature thermal peak (350–400°C) prior to or very early syn-deformation. Early formed sphalerite–pyrite mineralisation is also clearly deformed and remobilised within the talcose S1 foliation.

Brill (1988) also reported white mica $b_0$ values of 0.9013–0.9017 (mean 0.9016) from CSA mine reflecting pressure of ~3 kbar using the P–T–b spacing grid of Guidotti and Sassi (1986). From these results Brill (1988) interpreted a lithostatic load of ~11 km (for a rock density of ~2.7 g/m$^3$) during burial metamorphism of the Cobar Basin. Kyne (2014) reported a range of $b_0$ values from CSA mine of 9.0221–9.056Å (mean 9.030) suggesting a comparable depth of burial of ~10 km. Glen (1987) and Giles and Marshall (2004) suggest a pressure of 1–2 kbar and 1.5–2 kbar respectively, based on an estimated stratigraphic thickness excluding middle–late Devonian fluvialite sequences (Mulga Downs Group).

The northeastern Amphitheatre Group has been placed in the epizone to biotite-zone greenschist facies of regional metamorphism on Figure 4 and reflects a coupled zone of high strain and moderated grade hydrothermal metamorphism (see Glen 1987). Early-formed biotite-bearing veins possibly suggest peak temperatures of 350–400°C pre- or early syn-deformation, much like that experienced by less-deformed sequences of the Cobar Basin to the north and south.

**Southern Amphitheatre Group**

Distal to mineralisation the Amphitheatre Group in the south and east of the area is distinctly low grade, with only minor sericite and chlorite present after lithic clasts and detrital micas. The southern central and eastern Amphitheatre Group sandstones generally preserve diagenetic overgrowths and the effects of compaction and dissolution are variable (Photograph 6). Detrital biotite and muscovite are well preserved in most rock types. MacRae (1987) described a single foliation, axial planar to the single, upright fold set in the southeastern Amphitheatre Group. The development of this S1 chlorite-sericite foliation is strongly domainal and discontinuous. A sericite ± chlorite foliation is slightly more prevalent in the east and occurs closer to mapped faults. The foliation overprints localised, early-formed and distinctly higher-grade hydrothermal assemblages. The burial metamorphic imprint is interpreted to be low anchizone, similar to the underlying Mouramba Shelf sequences. Zones of weak sericite–chlorite development reflect anchizone regional metamorphic conditions. The early-formed hydrothermal highs are discussed below with respect to associated mineralisation and subsequent deformation.

As mineralisation is approached at the Nymagee copper mine (Lower Amphitheatre Group) the host sequences become distinctly biotite-rich, in the form of randomly oriented biotite porphyroblasts (Photograph 5).
7a). Biotite, chlorite, plagioclase and zoisite-bearing veins also crosscut the bedded sequences and have been deformed and recrystallised in the S1 foliation, often persisting as chloritic clots. Similarly, biotite porphyroblasts are enveloped by the chlorite–sericite-rich S1 foliation (Photograph 7b). The mineralogy within the interpreted centres of the hydrothermal systems at Nymagee is very distinctive with combinations of randomly oriented, commonly radiating biotite, stiphnolomite, actinolite–tremolite, Mg-rich chlorite, talc, and locally abundant garnet and minor scheelite (Photograph 7c). Hyperspectral data reported in Downes et al. (2016) from Nymagee mine (drillhole NMD068) depicts a close spatial association between assayed copper and gold grades and area of high temperature alteration. Magnesium-rich chlorite and talc are often retrograde phases after garnet and tremolite. Sphalerite is also evident in thin section, replacing garnet as a retrograde phase. Page (2011) detailed temperatures of 292–394°C based on chlorite thermometry from 292–394°C and 240–360°C (based on fluid inclusion studies) at Nymagee. A garnet–tremolite–actinolite–scheelite–phlogopite mineral association implies hydrothermal flooding at T >400°C in the hottest parts of the alteration system.

At Hera gold mine the secondary mineral association is similar to those at Nymagee, although the spatial relationship of high-temperature alteration and mineralisation is less well constrained. Biotite, Mg-chlorite and talc are prominent adjacent to some mineralisation, but not necessarily gold mineralisation. Biotite-bearing veins traverse samples and have been deformed during the development of a chlorite–sericite-bearing foliation (Photograph 8). Page (2011) described and illustrated biotite intimately intergrown with sphalerite and galena in mineralised zones. Garnet–actinolite/tremolite–quartz ± chalcopyrite–galena–sphalerite–rich veins and breccia infill are common throughout the Hera mine, along with intense silicification and proximal zones of tremolite, zoisite and/or phlogopite flooding in host rocks adjacent veins and breccia infill (Photographs 9a,b,c). Scheelite was also observed within the veins (Photograph 10a) and coarse splays of wollastonite have been observed in a single drill hole. The host

rocks to the veins are intensely silicified and flooded with fine-grained garnet, fibrous tremolite and zoisite within 10s cm of the veins (Photographs 10b,c). Page (2011) detailed chlorite thermometry of $T = 270–365^\circ\mathrm{C}$ at Hera, but this is only an indication of the retrograde thermal regime — garnet-rich vein systems imply substantially hotter peak hydrothermal temperatures. The presence of garnet–tremolite–vesuvianite and even rare wollastonite implies amphibolite (or pyroxene hornfels facies) temperatures greater than 450°C for the hottest parts of the hydrothermal systems.

Further west, at the Mallee Bull deposit (near the boundary between the lower and upper parts of the Amphitheatre groups), Brown et al. (2015) described local metamorphism to biotite grade. Alteration is described as contemporaneous with deformation and metamorphism. Alteration is chlorite–sericite-dominated Fe–Mg-chlorite, quartz, sericite, carbonate, albite, stilpnomelane, biotite and magnetite. Much like at Nymagee and Hera, Chapman (2012) described Mg-chlorite and biotite associated with sphalerite–galena–pyrite mineralisation, and Fe-chlorite and minor biotite associated with chalcopyrite–pyrrhotite–quartz–chlorite. Chapman (2012) also describes paragenetically late stilpnomelane veins at Mallee Bull. Chlorite thermometry temperatures of $<320^\circ\mathrm{C}$ were reported by Chapman (2012) associated with massive sphalerite–galena–pyrite dominant mineralisation and $T = 340–400^\circ\mathrm{C}$ associated with chalcopyrite–pyrrhotite dominant mineralisation. These temperature estimates are consistent with the observed gangue mineralogy.

Barron (1974) noted: 'there is no metamorphic foliation in predominantly thick-bedded sandstones of the Shume Formation'. The majority of the re-assessed thin sections for the Shume Formation preserve sub-green-schist facies (probable lower anchizone) sericite ± chlorite–rich secondary mineral associations (locally defining a cleavage). There are rare occurrences of chlorite–sericite defined slaty cleavages associated with faulting through the northeastern parts of the formation. Rare volcanic rocks within the formation display
chlorite-sericite-carbonate-clay alteration consistent with zeolite facies to epizone greenschist facies rift basin metamorphism.

Thin sections cut from core (drillhole LN3) from the mineralised zone at Lowan North prospect (Shume Formation) reveal pervasive static chlorite alteration, which is overprinted by a sub-greenschist facies, sericite-defined foliation. Similar chlorite-rich alteration occurs at Shuttleton and Commonwealth mines within the same formation. As a result, a zone of potential lower greenschist facies hydrothermal alteration or metamorphism is inferred on Figure 4 over the area extending from the Mallee Bull prospect (which locally reaches biotite grade, based on Brown et al. 2013, 2015) to the Lyell prospect.

Overall, the southeastern and central Amphitheatre Group has been placed in the late diagenetic to low anchizone on Figure 4, but there are localised zones of elevated, lower greenschist and middle greenschist facies conditions associated with mineralisation. Thus an additional zone of potential lower to middle greenschist hydrothermal alteration overprinting the burial metamorphic regime is shown. A zone of potential overprinting of transitional amphibolite facies (or pyroxene hornfels facies) hydrothermal metamorphism or alteration has been defined in the east, mostly associated with the Burthong Formation and Lower Amphitheatre Group in the vicinity of the Ironbark and Rookery faults (Figure 4).

**Nurri Group**

The Nurri Group comprises the *Chesney Formation* and the *Great Cobar Slate*, the latter being host to most Cobar-type mineral deposits. Glen (1987) described the Nurri Group as low metamorphic grade based on the preservation of detrital biotite and growth of fine, sericitic white mica, although Glen (1987) also described chlorite and muscovite after detrital biotite in the Chesney Formation, along with beards on detrital grains and a non-persistent muscovite–chlorite–sericite-defined cleavage. Quartz is described as displaying undulose extinction, grain suturing, sub-grain formation and bulge nucleation. Glen (1987) described the Great Cobar Slate as having a slaty cleavage defined by sericitic muscovite and chlorite. Detrital micas are preserved. Baker et al. (1975) described biotite and chlorite in the recrystallised mudstone matrix of Chesney Formation sandstone, but little context was provided.

Of the historic thin sections re-assessed from the Nurri Group, there were relatively few available within the petrographic database for samples distal to mineralisation. Re-assessed thin sections from the Chesney Formation display a sub-greenschist facies (probable anchizone) foliation defined by sericitic white mica and chlorite. Northern and eastern parts of the Chesney Formation mostly comprise weakly cleaved (sericitic white mica) lithic sandstone and siltstone. Detrital biotite is commonly preserved, but may be partially chloritised. Samples from the Great Cobar Slate display both vein-hosted, static replacement-
lated and slaty cleavage-defining sericitic white mica and chlorite-rich assemblages, reflecting epizone regional metamorphism.

Proximal to mineralisation in the Great Cobar Slate, Brill (1988) inferred consistent lower greenschist facies temperatures derived from white mica crystallinity values (\(\Delta^{20\text{Cu-K}\alpha}\)) of 0.20–0.25 from Chesney mine (0.26–0.18; ~300–350°C), Queen Bee mine (0.21–0.19; ~320–350°C) and The Peak mine (0.29–0.21; ~280–320°C). Brill (1988) also reported \(b_0\) results for The Peak mine (mean 0.9011) and Chesney mine (mean 0.9021). Silica contents in white mica (3.11–3.20 per half unit cell) from these mines is also consistent with \(P \sim 3\) kbar. A white mica \(b_0\) result was also reported for the Queen Bee mine (two analyses with a mean of 0.9032), but this result is inconsistent with the other results and predicts an excessive pressure of >4 kbar. Hinman (1992) recorded substantially lower mica \(b_0\) values (indicating \(P = 0.8–1.2\) kbar) at The Peak mine. Talc–chlorite alteration is the dominant alteration type described in association with mineralisation (e.g. Plierersek 1982 — Peak mine; Kelso 1982 — Queen Bee). Chloritic slate was the dominant lithology observed in thin section from all of these deposits, which is entirely consistent with the reported lower greenschist facies regional metamorphic conditions.

Robertson (1974) described biotite in samples from CSA, Gladstone, New Cobar, Chesney and Occidental mines, as well as the Llewong prospect, and suggested it partially replaced chlorite and was post-tectonic. However, textural relationships depicted in figures 86 and 89 of Robertson (1974) imply biotite crystallisation pre- or early syn-deformation. All biotite occurrences observed during the current study are interpreted to have formed pre- to early syn-deformation.

In thin section, siltstone and sandstone from the Leslie mine (Chesney Formation) are crosscut by early biotite–plagioclase–chlorite veins (Photograph 11) and sandstones are commonly flooded by brown hydrothermal biotite. The veins have been deformed during the development of a weak sericitic, sub-greenschist facies slaty cleavage.

In thin sections from Mount Drysdale gold mine, textures are similar to those observed in the Leslie mine samples. In this case, Nurri Group siltstone and sandstone are crosscut by early biotite–chlorite veins. These veins have been deformed during the development of a weak sericitic, slaty cleavage. Early formed, pervasively chlorite-replaced biotite was also observed in thin sections from the Tharsis or Phoenix mine in the Chesney Formation.

In summary, the northern parts of the Nurri Group are characterised by the common preservation of detrital biotite and/or muscovite and impersistent foliation.


Mount Hope Group

Secondary mineral associations for the predominantly volcanogenic Mount Hope Group were described by Scheibner (1987) as weak to strong alteration to chlorite, biotite, titanite, carbonate, sericite, epidote and sporadic alunite replacing matrix and phenocrysts, and quartz, chlorite, alunite and biotite infilling vesicles. Bull (2006) documented the assemblage albite, sericite, chlorite, biotite, quartz, actinolite, titanite, epidote and rare carbonate. Bull (2006) also described a variably developed, spaced S1 cleavage, defined by chlorite and fine white mica, that overprints compacted pumice clasts. The author interpreted a syn-deformation regional metamorphic grade of biotite-zone greenschist facies hydrothermal metamorphic assemblages. A re-evaluation of historic thin sections from the Mount Hope Group (Simpson 2014) provides a context to the distribution of various secondary minerals (Figure 4). Coherent volcanic and volcaniclastic rocks from the northern outcrops of the Mount Halfway Volcanics dominantly display chlorite–sercite alteration after ferromagnesian phenocrysts, with little evidence
of a tectonic fabric. Volcanic rocks on the western side of the Gilgunnia Granite show clear evidence of hornfelsing, with a strongly recrystallised groundmass and abundant randomly oriented biotite and white mica. A wide zone of biotite-bearing lithologies (up to 6 km) surrounds the eastern margins of the Gilgunnia and Boolahbone granites (Figure 4 and Photograph 12). Contact metamorphic textures are not as evident here, with primary volcanic textures such as perlitic cracking being enhanced by fine biotite trails and clusters (Photograph 13). Vesicles are often infilled with both brown and green biotite, epidote and quartz. This zone extends around the western side of the Boolahbone Granite. To the east and south, chlorite is present in the place of biotite in the hydrothermal mineral assemblage. Epidote is more commonly associated with biotite-grade alteration around the granites, while carbonate alteration is mostly confined to the east of this zone and associated with chlorite.

At Mount Allen gold mine, mineralisation is associated with early-formed chlorite–carbonate veins within clastic-dominated sequences. Sandstone horizons are pervasively chloritised and siltstone and volcanogenic rock packages are crosscut by quartz–chlorite–magnetite veins. Closer to the Mount Allen Granite the Nombiginni Volcanics (formerly the Double Peak Volcanics) are strong recrystallised to granoblastic textures, with contact metamorphic biotite and skarn-related diopside– epidote–tremolite assemblages recorded at one locality close to the granite. At Wagga Tank prospect, clastic lithologies are crosscut by chlorite–quartz–sulfide veins and the majority of the sandstones have been pervasively chloritised. Siltstones display weak, sericitic, white mica–defined cleavage, and stain fringes defined by quartz–chlorite are common around the vein-hosted sulfides.

Undeformed volcanic and volcaniclastic lithologies dominate at Great Central mine and the effects of hydrothermal alteration have served to enhance primary volcanic textures. Hydrothermal metamorphic mineral assemblages include biotite, chlorite, epidote, muscovite and titanite (pinnate after cordierite) proximal to mineralisation, and, most commonly, chlorite–carbonate–titanite–sericite in the more distal regions. There were very few thin sections available for lithologies of the Broken Range Group, with the exception of the Mount Solar prospect (from drillhole SLPD14, as described in Downes et al. 2016). Distal to the mineralised zone, fine-grained sandstones, granular conglomerate and sandstones preserve detrital micas (muscovite and biotite) and sedimentary structures, with a weak overprint of sericitic white mica and chlorite. The group has been depicted as anchizone burial metamorphic conditions on Figure 4. Proximal to mineralisation, sandstones are strongly chloritised and are crosscut or brecciated by a network of quartz–chlorite-bearing veins. These veins have been deformed during the development of a weak cleavage.

Burton (2012) suggested mineralisation at May Day mine (at the eastern boundary of the Mount Halfway Volcanics and the Amphitheatre Group) was pre- to early-deformation, but favoured early syn-deformation alteration (chlorite–talc) and mineralisation — a single cleavage was described by Burton (2012). Thin sections were cut from drillhole (MY2) that intersected mineralisation (see Downes et al. 2016). The majority of the alteration comprises carbonate, talc, sericite, chlorite ±
actinolite, predating the dominant cleavage in the area. Carbonate–quartz–talc–sulfide veins are strongly folded and dissected by the dominant cleavage (Photograph 14a). Perlitic textures are highlighted by early chlorite–carbonate–talc alteration and progressively flattened in shear fabrics (Photograph 14b,c), that envelope and are associated with boudinage of early-formed carbonate.

Rast Group

Historic thin sections of the *Ural Volcanics* were reassessed for their secondary mineral associations. Hydrothermal metamorphic assemblages vary from chlorite–albite–zeolite–sericite to chlorite–epidote–titanite–white mica (Photograph 15), with fluorite or zeolite veins locally abundant. These mineral associations reflect sub-greenschist (zeolite facies) to epizone greenschist facies geothermal or hydrothermal activity during rift basin metamorphism. Secondary mineral associations are particularly well developed in glassy, coherent volcanic rocks, often replacing perlitic domains (Photograph 15), or as fracture and vesicle infillings. Bull (2006) described the development of secondary mineral associations in the Ural Volcanics through the diagenetic and geothermal processes of glass hydration, devitrification, and porosity infill and reduction. The distribution of thin sections through the Ural Volcanics was insufficient to assess the presence of any systematic variation from zeolite facies through epizone hydrothermal mineral associations. The Ural Volcanics have been placed in the zeolite to epizone greenschist facies of rift basin metamorphism on Figure 4.

The host sequences (siltstone, sandstone, carbonaceous siltstone) of the *Preston Formation* preserve abundant detrital mica, with minor secondary sericitic white mica. The effects of deformation are limited, with rocks displaying a weak discontinuous cleavage often defined by stylolitic carbonaceous trails and radiolarians displaying local evidence of dissolution (Photograph 16). Thin sections (drillhole BR3; Downes et al. 2016) of the Preston Formation at Browns Reef prospect comprise an upper volcanic unit underlain by bedded carbonaceous radiolarian siltstones. Sandstone and conglomerate underlie the siltstone and the mineralised zone is associated with these horizons (see Downes et al. 2016). Mineralisation is associated with intense silicification of sandstone and conglomeratic horizons, and comb-textured veins of quartz, carbonate, Fe-poor sphalerite, galena and pyrite traverse the samples. Locally a very weak sericite-defined foliation post-dates alteration and mineralisation. The Preston Formation has been placed in burial-related, late diagenetic to anchizone metamorphic conditions on Figure 4. Chlorite thermometry from Browns Reef reported by Downes (2009) gave a mean temperature of 291°C for 15 analyses using the calculation of Xie et al. (1997),

Photograph 14. a) Thin, folded, strongly altered carbonate–chlorite–sericite–talc-rich sandstone horizon within a strongly cleaved, locally chloritic, sericitic and talcose slate. Sample is from Mount Halfway Volcanics, May Day mine. b) Carbonate–chlorite–sericite altered glassy volcanic rock. Perlitic cracking is well highlighted by this alteration style. c) Sheared carbonate and chlorite altered glassy volcanic rock. Flattened perlitic cracking is evident within the small shear zone. Photomicrographs taken under cross-polarised light, drillhole MY2, GR 6411773 406714. (Photographer J.A. Fitzherbert)
Bootheragandra Group

Barron and Forster (2005) place the Bootheragandra Group in their M1 zone (clay–carbonate–epidote–sericite–albite). The only feature recorded by Colquhoun et al. (2005) is minor sericite regrowth and cementation. A rare zone of phyllite and slate is described adjacent to the Scotts Craig Fault and a zone of strong silicification has been described in association with the Bootheragandra Fault. In the petrographic database records, a vague sericite cleavage is described in some samples associated with faults, along with quartz suturing and subgraining. The group has been placed in the late diagenetic to low anchizone on Figure 4, although localised high anchizone hydrothermal metamorphic assemblages may be developed near faults.

Walters Range Group

Very little petrographic data is available for the Walters Range Group. Quartz overgrowths and minor grain suturing are described in sandstones, with minor subgrain formation, weak undulose extinction and a vague cleavage with minor sericitic white mica. Colquhoun et al. (2005) placed them in their M1 (clay–carbonate–epidote–sericite–albite) facies. We place these rocks in the late diagenetic to low anchizone. Scheibner (1987) described the Walters Range Group as ‘cleavage absent’ on the Mount Allen 1:100 000 map.

Discussion

Mapping the variation in metamorphic grade across the Cobar Basin presents many challenges, one of which is to separate the timing of the effects of burial metamorphism, rift basin metamorphism, contact metamorphism, hydrothermal metamorphism and regional metamorphism. Only then can the important relationship between metamorphism and mineralisation be understood.

Burial-related basin thermal maturity, hydrothermal alteration and conditions of compression-related metamorphism

David (2006) suggested the deepwater sedimentary rocks of the Cobar Basin thicken from 2 km to 9 km from west to east. Thickness estimates of up to 12 km were suggested by Glen (1987) for the Amphitheatre Group, while Brill (1988) suggested a similar, 11 km thick lithostatic load based on mica b0 spacing. It should be noted that if the deepwater basin was once blanketed by a now completely eroded 4 km thickness of Mulga Downs Group then the 11 km lithostatic load will reflect only ~7 km thickness of Cobar Basin.
seds. Unfortunately it is not realistic to speculate on the presence or absence of cover sequences and their effect on the Siluro-Devonian basin thermal maturity without knowing at least rough thickness estimates for the basin and cover sequences. For a range in geothermal gradient of 25–35°C/km, the base of a 9 km thick sequence should have reached low anchizone to epizone greenschist facies metamorphic temperatures of 225–315°C during burial, while for an estimated thickness of 12 km the base of the sequence should have reached epizone greenschist facies to transitional amphibolite facies temperatures of 300–420°C.

Diagenetic to low anchizone burial metamorphic conditions were experienced by shelf and deepwater basin sequences, probably reflecting an average geothermal gradient of 25°C/km within the sedimentary basin. The regional metamorphic temperatures expected for lithostatic loading during burial do not differ considerably to those reported for the development of subsequent compression-related fabrics (see below). This implies very limited, if any further burial of the basin or basement during the Tabberabberan Orogeny. Zones of marginal basin magmatism would be expected to have experienced rift basin, contact and/or hydrothermal metamorphism at an elevated geothermal gradient.

Although the number of analyses are limited and clearly biased towards limestone-bearing shelf sequences, the updated CAI values for the majority of limestone occurrences within the Cobar Supergroup depict a fairly uniform late diagenetic zone burial metamorphic grade (CAI = 2–3, T = 100–200°C) for the western shelf sequences (in the vicinity of Wonawinta and Multigoona). Late diagenetic temperatures are consistent with petrographic observations, including lack of penetrative foliation, preservation of diagenetic textures including syntaxial overgrowths, dust lines, and in some cases primary porosity and preservation of detrital micas, particularly biotite. Previously published fluid inclusion and chlorite thermometry studies also concur with these results (Giles 1993). These conditions equate to burial depths of 4–6 km for the western shelf and western basin margin sequences. Burial of these sequences under the Mulga Downs Group (~4 km) sufficiently explains CAI values of 2–3. There is no thermal contrast between the burial metamorphic regime here and MVT mineralisation (Giles 1993). Limestones to the east (The Bluff, Lerida Limestone, McKinnons, Endeavor/Elura) hosted by the flanking basin sequences record slightly warmer late diagenetic zone to low anchizone burial conditions (150–250°C). Temperatures for mineralisation here are quoted over a wide range, but high anchizone to epizone hydrothermal metamorphic temperatures (250–350°C) are most consistently quoted and the chlorite and/or carbonate-rich alteration associated with mineralisation is consistent with these temperatures. The ~100°C thermal contrast here between burial metamorphism, hydrothermal metamorphism and mineralisation is consistent with the Irish-type model of David (2008), where deposits formed in association with major basin growth faults, by mixing of metamorphic fluids derived from basement buried beneath the basin and basinral brines, prior to basin inversion. Overprinting deformation fabrics in this zone approach epizone temperatures in association with mineralisation and alteration, while poorly developed fabrics distal to mineralisation do not exceed temperatures expected for the burial metamorphic regime.

Limestone that records epizone thermal maturity occurs within the southeastern shelf sequences (Mouramba Group, southern Kopyje Group and northern Yarra Yarra Creek Group), along with a single occurrence in the northeast (Conqueror mine). The elevated CAI values at these localities may reflect a broad zone of greater thermal maturity, as depicted in Figures 3 and 4, or alternatively may reflect localised highs within a zone of higher heat flow (see below). The elevated CAI values correspond very well with the petrographically defined zone of known and potential middle biotite-zone greenschist to lowest amphibolite facies (or albite-epidote to pyroxene hornfels facies) hydrothermal metamorphism and/or metasomatism depicted on Figure 4. In a purely burial-related regime and for a geothermal gradient of 25°C/km a CAI of 5–6 (300–350°C) equates to 12–14 km of burial. Clearly this is an unrealistic depth of burial for the eastern shelf sequences. The youngest exposed group here is the Yarra Yarra Creek Group (maximum thickness 1.7 km based on Sherwin 1996) and this group has itself experienced similar temperatures. It is possible that a thick cover of Mulga Downs Group once blanketed the entire region, including the eastern shelf sequences and intervening deepwater basin, but the distinctly elevated thermal maturity in the south suggests that a locally perturbed geothermal gradient has affected the area and is not inferred to reflect uniform depth of burial.

Late diagenetic to low anchizone conditions (150–250°C) are proposed for the southeastern Amphitheatre and Mouramba groups. Zones of calc-silicate, calc-potassic and potassic hydrothermal alteration associated with mineralisation locally overprint this background thermal regime. These zones record hydrothermal metamorphic temperatures in excess of 400°C and imply a thermal contrast of ≥200°C between burial and local hydrothermal metamorphic conditions in this area. Overprinting deformation-related mineral assemblages developed at cooler temperatures, ranging from anchizone to epizone, distal and proximal to mineralisation respectively. A similar thermal contrast (~150°C) and timing relationships are inferred for the northeastern Nurri Group (Mount Drysdale area) and central Cobar Basin (Mallee Bull prospect). The effects of hydrous regional metamorphism are much more pervasive in the high strain zone around Cobar township (Zone 1 of Glen 1982), but the prevalence of early-formed biotite-bearing hydrous assemblages.
associated with early-stage mineralisation (see below) is consistent with early, high thermal contrast between host rocks and hydrothermal alteration systems. Mineralisation in the vicinity of Cobar township is again associated with major basin growth faults and high thermal contrast between the burial metamorphic regime and localised hydrothermal metamorphism and/or alteration by mixing of hot fluids that have interacted with basement buried beneath the basin and basinal brines, possibly prior to basin inversion.

The thermal regime within the major volcanicogenic centres (Mount Halfway Volcanics, Ural Volcanics, Majuba Volcanics and Florida Volcanics) is distinct from that of the siliciclastic basin-fill and carbonate-rich shelf sequences. Volcanic lithologies of the Mount Hope Group preserve a rift basin and/or contact metamorphic field gradient with biotite-zone greenschist facies proximal to the Gilgunnia, Boolahbone and Mount Allen granites, and chlorite-zone greenschist facies distal to the granites. Granite-related gold mineralisation is present at Mount Allen gold mine. Other deposits that are associated with high heat flow during volcanism and/or plutonism in this area include Great Central mine and possibly May Day prospect. A very similar field gradient is evident within the Majuba Volcanics in the vicinity of the Yellow Mountain Granite and other unnamed Early Devonian intrusive rocks. An epithermal model is applied to mineralisation at Pipeline Ridge to the north. No syn-volcanic intrusive rocks have been mapped within the Ural Volcanics, Florida Volcanics or the Babinda Volcanics, all of which display uniform sub-greenschist (250°C; zeolite facies) to lowest greenschist facies (~300°C; epizone) rift basin metamorphic conditions. Importantly, thermal highs within the volcanicogenic troughs/belts can be directly related to syn-volcanic intrusions.

**Timing of hydrothermal metamorphism and/or metasomatism**

Perkins et al. (1994) obtained 40Ar/39Ar ages of 401.5 ± 1.0 Ma for an early formed cleavage at Peak mine associated with Au–Cu–Pb–Zn mineralisation and 384.0 ± 1.4 Ma for an overprinting cleavage associated with Ag–Pb–Zn mineralisation. Glen et al. (1992) recorded a slightly older whole-rock K–Ar date of ~405 Ma and an Ar–Ar date of ~404 Ma from cleaved whole rock samples near Peak mine. It should be noted that whole rock mica ages in these low grade rocks may be affected by preserved detrital white mica. These are deformation (regional metamorphic) and inversion related ages and the fabrics are associated with mineralisation. These age determinations are not representative of early-formed high-temperature hydrothermal metamorphism and associated mineralisation. Syn-deformation-related hydrous regional metamorphic and/or metasomatic mineral assemblages are clearly present in Amphitheatre and Nurri group lithologies in the high-strain zone associated with the Myrt, Chesney and Rookery faults in the vicinity of Cobar township (Zone 1 of Glen 1982). This zone has been depicted as lower to middle greenschist facies syn-orogenic hydrothermal metamorphism on Figure 4. Fluid inclusion and chlorite thermometry data for this area consistently indicates syn-deformation epizone temperatures in the range of 300–350°C associated with mineralisation and regional metamorphism. The petrographic findings of the current study are entirely consistent with this determination in this zone.

Early-formed stilpnomelane and trace biotite (T = 350–400°C, Cleverly & Barnicoat 2007) is associated with the initial phase of magnetite gold–bismuth mineralisation in the Cobar mining field (e.g. Peak, Perseverance, New Occidental, Chesney, New Cobar, Gladstone, Great Cobar mines; Barron 1974; Stegman 2001; Berthelsen 2006). These early assemblages are strongly overprinted and/or replaced by Mg-chlorite-rich alteration associated with chalcopyrite–cubanite–pyrrhotite–pyrite mineralisation and later sphalerite–galena–pyrrhotite–pyrite mineralisation.

Early-formed biotite and stilpnomelane have been described at CSA mine (Kyne 2014), and at Mount Drysdale gold mine McClatchie (1983) described biotite and stilpnomelane. Early-formed biotite ± plagioclase veins were observed in thin sections from Mount Drysdale mine and reflect pre- or early-syn-deformation growth. A biotite–stilpnomelane–magnetite-bearing mineral assemblage is also described in alteration zones at Mallee Bull prospect in the central southern Cobar Basin and Brown et al. (2015) suggested that local biotite-grade mineralisation is contemporaneous with deformation in that area, although the timing of biotite alteration is not clear when compared with chloritic alteration.

Suppel (1984) made mention of biotite haloes associated with mineralisation at Nymagee copper mine. At that site, a broad zone of pre- or early-syn-deformation biotite porphyroblasts and veins are deformed in a chlorite-bearing foliation. Focused zones of plagioclase–zoisite–tremolite/actinolite, garnet, biotite, stilpnomelane, calc-potassic to calc-silicate alteration occur throughout the biotite-rich zone and display a very strong correlation with copper–gold mineralisation. The mineral association within this hydrothermal zone reflects temperatures >400°C. Zones of intense retrogression transect these high-temperature zones and are reflected by pervasive chlorite and talc-rich alteration, with garnet typically being replaced by chlorite, galena and sphalerite. High-temperature alteration at Nymagee mine appears to have occurred...
early (pre-deformation). Very similar biotite alteration and garnet–actinolite rich veins occur at Hera mine, to the south of Nymagee copper mine. Similarly, biotite occurs as early-formed porphyroblasts, or in veins that are folded and enveloped by a pervasive chlorite-rich foliation. Garnet–zoisite–quartz–actinolite ± vesuvianite veins grade out to garnet–actinolite–zoisite flooded siltstone adjacent to, flanking or surrounding the veins, grading to a wider zone of biotite alteration distal to the veins. The textures preserved at both of these mines imply early (pre-deformation) high-temperature deformation developed as veins and contact metamorphic-like porphyroblastic assemblages, and are directly associated with Cu–Au–Pb–Zn mineralisation. Chlorite-zone hydrothermal metamorphism accompanied deformation and possibly replaced sphalerite–galena mineralisation in these areas.

Further west, carbonate-rich alteration and mineralisation at Endeavor and May Day mines also either predated penetrative deformation fabrics or, possibly, formed very early during their development (David 2008; Burton 2012).

**Early Devonian magmatism and zones of elevated heat flow?**

The regional distribution of Early Devonian intrusive rocks is depicted on Figure 4. Several minor magmatic units that are spatially, but not necessarily genetically associated with mineralisation have also been shown (see David 2006 for a list of the minor magmatic units). Figure 4 illustrates a clear concentration of Early Devonian intrusive rocks within volcanogenic packages to the east and west of the Late Silurian Erimeran Granite (Mount Hope Group to the west and Kopyje Group to the east), and intruding the granite itself. An obvious and expected observation is that Early Devonian intrusive rocks consistently occur within known zones of biotite-zone greenschist facies contact and/ or hydrothermal metamorphism. The A-type Boolahbone Granite (420 ± 2.5 Ma, Black 2007; 415.8 ± 3.1 Ma, Downes et al. 2016), S-type Mount Allen Granite (422.8 ± 2.7 Ma, Downes et al. 2016) and S-type Gilgunnia Granite (422.5 ± 3.6 Ma, Downes et al. 2016) intrude the Mount Hope Group and are genetically related to a wide zone of biotite-zone greenschist facies rift basin and/or contact metamorphism grading out to background, chlorite-zone, greenschist facies rift basin metamorphic conditions in the host volcanic packages (Figure 4).

There are very few Early Devonian magmatic rocks exposed further to the east in the Amphitheatre Group of the southern-central Cobar Basin. The only notable occurrence is the Shuttleton Rhyolite Member which falls within an area of potential epizone to biotite-zone hydrothermal metamorphism placed over Mallee Bull prospect, Shuttleton and Lowan North.

Further east and based on interpretation of gravity and aeromagnetic data, the subsurface Early Devonian Tolligo Granodiorite and Fountaingdale Granodiorite (420 ± 2.0 Ma) intrude Ordovician basement along the eastern and southern margins of the Erimeran Granite, and directly beneath the Mouramba Shelf sequences. The Fountaingdale Granodiorite is associated with a wide zone of potassic to calc-potassic (tremolite) alteration grading out to chlorite–magnetite-rich propylitic alteration in both the granodiorite and wall rocks (Blevin & Jones 2004). Blevin (2005) suggested that magnetic patterns in the Erimeran, Rosedale and Tollingo regions, and the recognition of moderately oxidised I-type intrusions, and within the outcrop area of the reduced Erimeran Granite represent a nest of similar I-type intrusions and associated magnetite-bearing hydrothermal alteration zones within the intrusions and their wall rocks. To the north of the Erimeran Granite, the slightly younger Nymagee felsic dykes (415 ± 2.7 Ma, Downes et al. 2016) intrude Mouramba Group lithologies, and the Tarran Volcanics, defined by MacRae (1987) and of similar age to the felsic dykes (415 ± 3.9 Ma, Downes et al. 2016) have intruded the Rookery and Iron Bark Fault systems through the centre of the Erimeran Granite. Hornfels and biotite-zone hydrothermal metamorphic assemblages have been recorded in the GSNSW petrographic database within the Burthong Formation immediately north of the Erimeran Granite, and a zone of potential biotite-zone greenschist to amphibolite facies (or albite-epidote to pyroxene hornfels facies) hydrothermal metamorphism, which encompasses Nymagee and Hera mines, occurs just to the north.

Early Devonian intrusions into the southern Kopyje Group include the I-type Mount Walton Porphyry and Yellow Mountain Granite in the north and a number of unnamed porphyries in the south (MacRae & Pogson 1985). As previously discussed, this southern zone of the Kopyje Group is characterised by pervasive biotite-zone greenschist facies hydrothermal and/or contact metamorphism, which may be overprinted by a weak foliation defined by sericite ± chlorite. Further east again, the I-type Wilmatha Granite intrudes and is associated with biotite-zone contact metamorphism of Ordovician basement east of the Mineral Hill Volcanics. Mineral Hill itself is interpreted as an Early Devonian epithermal deposit within the zone of Devonian I-type intrusions by Blevin and Jones (2004) and Morrison et al. (2004). There is limited large-scale Early Devonian magmatic activity recorded along the northeastern margin of the Cobar Basin, although mineralisation at The Peak gold mine is spatially associated with an intrusive rhyolite
Complex that displays peperitic margins with the host Chesney Formation (Stegman & Pocock 1996), dated at 418.3 ± 3.0 Ma (U–Pb zircon date, Bodorkos et al. 2013). The I-type Wild Wave Granodiorite, dated at 418.0 ± 2.0 Ma (Rb–Sr whole rock biotite pairs, Glen et al. 1983), intrudes basement in an old mine shaft beneath the Meryula Formation. This area needs to be revisited to assess the relationship between the Wild Wave Granodiorite and metamorphism of the overlying Meryula Formation.

Also of interest is a basement thermal high (biotite-zone) indicated by historic petrographic data and depicted in the metamorphic map of Felton et al. (1983), just south of Mount Boppy gold mine in the Girilambone Group. Details of this thermal high are not well documented, although petrographic descriptions record decussate or porphyroblastic biotite with the implication of hornfelsing. Skarn-like mineralogy is also described in association with calcareous rocks at the base of the Baledmund Formation in drillhole logs from the C2A and C5 prospects (Woodland et al. 1975) — this is another area that needs to be revisited.

Conclusions and a ‘best of all worlds’ model for Cobar-type deposits

The Cobar Basin preserves a diagenetic to anchizone burial metamorphic imprint, based on petrography and CAI values. Rift basin metamorphism in volcanogenic troughs, belts and basins ranges from zeolite facies to epizone greenschist facies, with broad zones of biotite-zone greenschist facies hydrothermal and/or contact metamorphism spatially associated with syn- to post-volcanic intrusions. Epithermal (Mineral Hill, Pipeline Ridge), intrusion-related gold (Mount Allen) and some VAMS (possibly May Day) deposits are associated with these zones.

Mineral deposits of the western Cobar Basin and Winduck Shelf preserve evidence of late diagenetic to epizone conditions for mineralisation. Thermal contrast between burial metamorphism and mineralisation–related hydrothermal metamorphism is moderate (Endeavor mine) to negligible (Manuka mine) and mineralisation and/or alteration occurred pre- to early syn-basin inversion. These characteristics are consistent with the Irish-type SEDEX and MVT models proposed previously for that area. David (2008) described these deposits as syn-diagenetic, replacement, massive sulfide deposits formed by mixing of metamorphic fluids derived from basement buried beneath the basin and basinal brines discharged along major growth-faults. Fluids have interacted with and then breached the basal limestone packages and mineralisation is hosted within the overlying siliciclastic turbidite packages and enveloped by a pre-deformation carbonate-altered halo.

In the central and eastern Cobar Basin, early (pre-penetrative fabric development) recrystallisation of very low grade basin lithologies occurred within localised zones of biotite-zone greenschist facies to transitional amphibolite facies (or albite–epidote to pyroxene hornfels facies) hydrothermal metamorphism and is associated with mineralisation (Brown et al. 2015). Major fault zones again display a strong spatial association with mineralisation (Brown et al. 2015). Early-formed potassic, biotite-rich alteration has been described in strongly deformed units from the northeastern and parts of the central Cobar Basin. High-temperature garnet–zoisite–tremolite–biotite-rich calc-silicate, calc-potassic and potassic alteration is associated with mineralisation in the southeastern Cobar Basin.

High hydrothermal temperatures (>400°C), high thermal contrast between host basin rocks and hydrothermal fluids (>200°C), calc-silicate alteration, and pre- to early syn-deformation timing are inconsistent with the vast majority of orogenic mineral systems, but entirely consistent with magmatic-related mineral systems.

In the southern Cobar Basin, zones of early (pre-penetrative fabric development), hot hydrothermal fluid flow and mineralisation can be correlated with a broad zone that hosts 420–415 Ma intrusive rocks. The same major growth faults that are spatially associated with high temperature hydrothermal alteration acted as pathways for the intrusion of younger (c. 415 Ma) magmatism (Nymagee dykes, Tarra Volcanics). Early Devonian magmatism is evident in the northeastern basin, but appears to be less extensive, or may be concealed to a greater degree beneath the basin sequences.

As previously proposed for the northeastern Cobar Basin, chronologically early (Au–Bi–magnetite; Photograph 17) mineralisation coupled with high hydrothermal temperatures, moderate to high thermal contrast between host basin and hydrothermal alteration, and early timing of moderate temperature alteration is strongly suggestive of an early magmatic input, either as a heat source for hydrothermal convection or for direct hydrothermal fluid and metal supply. Lead isotope data (Downes et al. 2016) records both basin and basement metal input to the mineral systems, reflecting the possible depth of intrusion in basement rocks beneath the basin unconformity. Sulfur isotopes often record mixed magmatic and seawater sources (particularly at Nymagee and Hera mines), consistent with, but not exclusive to a model of hot magmatic fluids interacting with cool basin brines through focused flow along the major basin-forming faults (Downes et al. 2016).
There is no doubt that epizone (300–350°C) hydrothermal regional metamorphism occurred during basin inversion in zones of high strain associated with reactivation of major growth faults and newly generated thrust faults in the eastern Cobar Basin. Deformation fabrics here display an intimate association with mineralisation (e.g. Peak and CSA mines).

Dating of penetrative cleavages and magmatic rocks implies a gap of as little as 10 Ma between extension-related magmatism and the development of penetrative compressional deformation fabrics in the region. Future dating of thermally robust minerals within pre-deformation, medium to high temperature alteration zones has the potential to close this time gap further.

There is very little evidence for regional-scale deep burial of shelf, basin or basement rocks during the Tabberabberan deformation beyond that expected from syn-basin fill lithostatic loading. It is hard to imagine that this orogenic event created any significant thermal

*Figure 5.* Cartoon cross-sections (not to scale) depicting the evolution of the southern Cobar Basin (based on Suppel 1984 and van der Wielen & Korsch 2007). a) Late syn-rift phase, with Devonian intrusions exploiting large extensional fault systems, generating elevated heat flow and biotite-zone to amphibolite (or pyroxene hornfels) facies hydrothermal alteration and mineralisation in a diagenetic to anchizone basin sequence. b) Basin inversion culminating in deformation, localised cleavage development, and retrograde, epizone hydrothermal alteration and mineralisation. Subsurface intrusions are shown beneath the Kopyje Group to the east, to account for the observed biotite-zone contact/rift basin mineral assemblage there.
perturbation in the basin or basement, particularly when compared with the perturbed geothermal gradient created during back-arc spreading and magmatism. It is more likely that metamorphic-derived fluids were generated through basin sedimentation (lithostatic loading, as in the Irish-type model of David 2008) and back-arc magmatism (e.g. Suppel 1984; David 2005, 2006), rather than dehydration during compressional loading and orogeny. Inversion was actually initiated along the retrograde hydrothermal path for the terrane, most likely associated with large basin-forming faults and serendipitously, zones of prior magmatic heating related to basin opening (Figure 5).

Mineralisation in the Cobar Basin can be characterised as a continuum from extensional, burial and magmatic-related mineral systems that were rapidly inverted, to a compressional, structurally controlled mineral system. Major growth faults impart a first order control on mineralisation within the basin sequences, forming the locus for magmatism (particularly in the southern Cobar Basin; Figure 5), hydrothermal fluid and subsequent deformation. Lithostatic loading, coupled with a perturbed geothermal gradient through synrift magmatic heating, aided further regional-scale epizone hydrothermal metamorphism, spatially associated with reactivated major growth fault systems during basin inversion and the development of Cobar-type high sulfide structurally controlled mineralisation (Figure 5).

**Future work**

There is still a substantial amount of work required before the true nature of Cobar-type deposits is revealed. A key part of future work in the Cobar Basin should involve isotopic dating and characterisation of fluid sources for early moderate- to high-temperature alteration systems and associated mineralisation. The GSNSW is currently undertaking dating of thermally robust minerals such as garnet and titanite, sulfur and lead isotopic analyses for comparison with the current database of analyses (see Downes et al. 2016), fluid inclusion studies, and deuterium–oxygen analyses of hydrosilicates (actinolite/tremolite) associated with early formed high-temperature hydrothermal mineral associations exposed at Hera and Nymagee mines. Work is continuing to be conducted on the relationship between high-temperature hydrothermal alteration and mineralisation (i.e. sulfide phases and timing). Clearly at deposits such as Nymagee copper mine there is a direct correlation. In addition to the new petrographic and hyperspectral work conducted on deposits on the Nymagee 1:250 000 map sheet area (see Downes et al. 2016) the GSNWS is conducting further hyperspectral and petrographic studies on drillcore from The Peak gold mine, CSA mine and Endeavor mine. The findings of these studies will hopefully encourage further isotope and dating studies of the Cobar mining field and shed light on the similarities/differences between the Cu–Au–Pb–Zn deposits of the southeastern Cobar Basin and the main Cobar mining field in the north.

The CAI determinations presented in this study are strongly biased towards shallow water shelf sequences, rather than deeper water basin fill, but have a demonstrated ability to map broad thermal variation within the shelf sequences. Vitritine reflectance has been applied successfully in the Cobar Basin (Brill 1988) and could be applied much more extensively on carbonaceous black shale from the deeper water sequences (e.g. Preston Formation or Nurri Group). New petrographic work and thin sections from areas of interest may also reveal new areas of thermal perturbation. One of the most effective means of mapping thermal maturity on a basin-wide scale is white mica crystallinity and Kübler Indices (e.g. Talent et al. 2003). The Cobar Basin stratigraphy has been separated into two distinct depositional phases, an early active syn-rift phase and a more passive post-rift or sag phase (Glen 1990). Unfortunately the CAI and petrographic data from the current study cannot resolve the variation in thermal maturity between these two rifting phases. A detailed basin-wide Kübler index study may be able to distinguish between these two depositional phases.

The link between mineralisation and zones of elevated hydrothermal temperature needs to be thoroughly studied for its potential to vector towards mineralisation. Detailed Kübler index studies should also be conducted on individual deposits to determine the extent of a measurable thermal imprint associated with mineralisation which would be otherwise cryptic to petrographic determinations. Frey and Robinson (1999) noted that ‘cryptic’ aureoles (i.e. those only observed through variations in mica crystallinity) around granites may be up to three times the lateral extent of the observable aureole. Thus the hidden footprint of hydrothermal alteration may be significantly more extensive than the known alteration extent. Armed with the results of these detailed studies, Kübler index data should be collected along selected traverses (using outcrop and drillcore) with the idea of developing a high-resolution thermal map of the basin as a tool to vector towards mineralisation.
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References


Hinman M.C. 1992. The structural and geochemical genesis of the Peak base and precious metal deposit, Cobar, New South Wales, Australia. PhD thesis, James Cook University, Townsville (unpubl.).


MATHIESON, D., MAWSON, R., SIMPSON, A.J., TALENT, J.A. 2016. Late Silurian (Ludlow) and Early Devonian (Pragian) conodonts from the Cobar Supergroup, western New South Wales, Australia. Bulletin of Geosciences.


PAGE D.G. 2011. Geology of the Hera (Pb–Zn–Au) and Nymagee (Cu) deposits, New South Wales. BSc Honours thesis, University of Wollongong (unpubl.).


Appendix 1

Methodology for construction of the metamorphic map

This study used petrographic information from the Geological Survey of NSW petrographic database which contains over 11000 entries for the Cobar Basin region. The petrographic information in the database resides in text fields and can only be searched with the aid of simple SQL queries. For example, to extract point data for hornfelsed metasedimentary rocks, multiple fields (e.g. primary mineralogy, petrography) were queried for several possible terms (e.g. cordierite, andalusite, hornfels, spotting). To capture more data the first letter of each term was removed (to account for capital letters) and a wildcard character was inserted before and after the mineral name (e.g. cordierite = %ordierit%) to account for commas, hyphens and question marks. A similar process was used to extract relevant point data from the MetIndEx (Metallics, Industrial minerals and Exploration) database of the GSNSW. Misspellings are overlooked using this method, but an extensive visual audit of the database suggested that there were very few instances of misspelling. Both databases can be accessed at http://dwh.minerals.nsw.gov.au/CI/warehouse.

All entries that contained terms referring to the former presence of an indicator mineral were scrutinised, for example ‘after cordierite’, ‘cordierite’ and ‘replacing cordierite’. Because of the generally low metamorphic grades in the Cobar Basin and surrounding basement lithologies, relic or primary mineralogy represents a major stumbling block in querying the database and moreover for reinterpreting the rocks. The majority of thin sections from the Cobar Supergroup held by the GSNSW were also re-assessed optically for their secondary mineral associations as part of this study. Reconnaissance fieldwork was carried out in all of the major tectonostratigraphic units, with a limited number of samples being collected to validate field observations. A total of 60 thin sections were cut from selected drillholes associated with mineralisation throughout the Cobar Basin (see Downes et al. 2016 for brief descriptions). Field observations and full petrographic descriptions of the thin sections can be downloaded from http://dwh.minerals.nsw.gov.au/CI/warehouse. Hyperspectral drillhole logs were used where available (see Downes et al. 2016). Published pressure (P) and temperature (T) constraints were also used in the construction of the metamorphic map. Published methods for P-T estimation include fluid inclusion studies, vitrinite reflectance, white mica chemistry B0 spacing and Kübler indices, and chlorite thermometry. An updated thermal maturity map of the basin is presented and based on new Conodont Alteration Index (CAI) determinations (Figure 3). The contour maps were created in ArcMap® software using the Spatial Analyst Nearest Neighbour interpolation method and manual classification divides. The resultant images represent broad regional scale averages and are not suitable for detailed analyses due to low sample density and masked patterns in certain regions.
New Cobar products

Future papers:

‘A 3D model for the Koonenberry Belt from geologically constrained inversion of potential field data’
by R.J. Musgrave & S. Dick.

‘Origin of negative magnetic anomalies on the southwestern margin of the Thomson Orogen’
by S. Wong, R.J. Musgrave, A.C. Hack & W.J. Collins

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