Controls On Mineralisation In The Howley District, NT: A Link Between Granite Intrusion And Gold Mineralisation

Granite Intrusion And Gold Mineralisation: Howley District N.T.

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Abstract

Gold and base-metal mineralisation in the Pine Creek Geosyncline is commonly found in close association with granites and, as such, have been classified as high temperature contact aureole deposits. A simple relationship between gold mineralisation and granite intrusion has been described for deposits in the Howley district. A secondary host rock control has also been suggested, with the association between gold mineralisation and carbonaceous metasedimentary rocks considered to be important. However, much of the gold mineralisation occurred after the main intrusive phase of the intrusion of the Cullen Batholith and the relationship of gold mineralisation to carbonaceous rocks is not the most important control on mineralisation. Rather, gold mineralisation is structurally controlled, occurring in brittle-ductile structures at

the greenschist-amphibolite facies boundary and hence has an epigenetic origin. The mineralisation also has an association with HHP granites and there is an input from both magmatic and metamorphic sources for the fluid that transported the gold mineralisation.

Those areas in the Howley District that have developed duplex thrust fold systems appear to be significantly more mineralised than areas with buckle folding or basin and dome structures. The presence of shear systems linking anticlines higher in the sequence appear to have provided the ideal fluid focussing mechanisms to localise gold-bearing fluids. Another important factor in the localising of gold mineralisation in the Howley District and the Pine Creek Geosyncline is the presence of the younger HHP leucogranites. Gold-bearing fluids have mixed metamorphic and granite fluid sources and the heat from the intrusion and the prolonged intrusive and cooling history of the younger granites, coupled with pre-existing duplex thrust fold structures, allowed regional-scale long lived hydrothermal systems to channel fluids from both granite and metamorphic sources.

Introduction

The contribution from gold deposits in Australian Proterozoic sedimentary basins to the total gold produced in Australia has increased significantly in the last five years. Consequently many Proterozoic basins are now considered high priority exploration targets. The Pine Creek Geosyncline, located in the northern part of the Northern Territory in Australia (Figure 1), has been part of this exploration and mining boom, with new operations in the Howley District (2 million ounces), Rustlers Roost (0.5 million ounces), Mount Todd (2.5 million ounces) and Union Reefs (1 million ounces).

Much of the recent exploration success is due to new exploration techniques being applied to the area as a result of advances in the understanding of the genesis of gold mineralisation and new technology, such as low-level analytical techniques, remote sensing and image enhancement of geophysical data. A variety of genetic models, ranging from magmatic through hydrothermal to syngenetic, have been postulated in the past for the formation of gold deposits in the Pine Creek Geosyncline (eg., Sullivan and Iten 1952, Warpole *et al*., 1968 and Stuart-Smith and Needham 1984). In the last ten years Needham and Roarty (1980), Goulevitch (1980), Nicholson and Eupene (1984), Nicholson and Eupene (1990), Oepen *et al*.,. (1988) and Kruse *et al*.,. 1990, suggested an exhalative syngenetic origin for gold mineralisation, especially that associated with South Alligator Group rocks. However recent work has shown that syngenetic models for gold mineralisation are not valid in the Pine Creek Geosyncline (Wall 1989, Partington 1990, Partington *et al*., 1994, Klominsky *et al*., 1996, Matthai *et al*., 1995a; Matthai *et al*., 1995b).

Gold and base-metal mineralisation in the Pine Creek Geosyncline is often found in close association with granites and as such have been classified as high temperature contact aureole deposits (Wall 1989, Wall and Taylor, 1990; Wyborne *et al*., 1994; Matthai *et al*., 1995a). For example in the Howley District, which has been, and is continuing to be one of the main areas of gold production in the Pine creek Geosyncline, a simple relationship between gold mineralisation and granite intrusion has been described for deposits in this area (Matthai *et al*., 1995a). A secondary host rock control has also been suggested, with the association between gold mineralisation and carbonaceous metasedimentary rocks considered to be important (Wyborne *et al*., 1994; Matthai *et al*., 1995a; Matthai *et al*., 1995b). However there is evidence that the relationship between mineralisation and granite intrusion is not simple, that much of the gold mineralisation occurred after the main intrusive phase of the Cullen Batholith and that the relationship of gold mineralisation to carbonaceous rocks is not the overriding control on mineralisation (Klominsky *et al*., 1996).

This paper is therefore intended to review the geological setting of gold mineralisation in the Pine Creek Geosyncline using the Howley District as an example. A structural framework is provided to aid in timing granite intrusion and gold mineralisation. A spectrum of deposits is described, in which deposit style appears to be dependant on structural position rather than the composition of the host rocks. Geochemical data from the deposits are used to constrain chemical controls on mineralisation, and fluid inclusion and isotope data are presented that indicate a possible fluid source for gold mineralisation. A review of the controls on mineralisation from a macroscopic or mine scale to a mesoscopic or regional scale is made, and a model presented that links the distribution of gold mineralisation to granite intrusion, structural and

metamorphic setting, and the mechanical properties and geochemistry of the host rocks.

Regional Setting

Location and Stratigraphy

The Howley District is located 40 km southeast of Adelaide River in the Pine Creek Geosyncline (Figure 1). The Geosyncline comprises a supracrustal sequence that consists predominantly of fine-grained clastic sedimentary rocks, BIFs, minor evaporites and platform carbonates, acid volcanic rocks and basic intrusive rocks, which overly granite migmatite complexes of Archaean age (ca 3300-2400 Ma using Sm-Nd age dating, Rb-Sr whole rock ratios and U-Pb and ion microprobe zircon ratios as dating methods; Stuart Smith *et al*., 1993).

Sedimentation and volcanism occurred between 2000 to 1870 Ma in an intracratonic basin formed by crustal extension of the predominantly Archaean granitic basement (Needham *et al*., 1988). This was followed by intrusion of dolerite sills, complex multiple deformation, regional metamorphism and granitoid intrusion with associated contact metamorphism. More detailed descriptions of the stratigraphy, metamorphism and deformation within the Pine Creek Geosyncline are given by Needham and Roarty (1980), Johnston (1984), Needham and Stuart-Smith (1985), Page (1988), Needham *et al*., (1988) and Ahmad *et al*., (1993) and Klominsky *et al*., (1996). Although all the lower Proterozoic rocks have been metamorphosed to some degree, precursor rock types can be recognised and, therefore, original lithological names are used where appropriate and the prefix “meta” is assumed.

The area of interest is in the central part of the Pine Creek Geosyncline in an area bounded by the Hayes Creek fault to the south, the Pine Creek shear zone to the east and the Shoobridge fault to the west (Figure 1). The area has been chosen because it forms a well defined structural block within the Geosyncline that is intensely mineralised. It is also an area where the relationship between granite intrusion and hydrothermal mineralisation is relatively clear.

The host rocks to gold mineralisation in the Howley District belong to the Mount Partridge Group, South Alligator Group and Burrell Creek Formation, which have been subdivided into five distinct formations (Kruse *et al*., 1990). The rocks have been tightly folded to form a series of north to northwest trending folds (Figures 2 to 6). The oldest formation preserved locally is the Wildman Siltstone (Mount Partridge group; Figures 3 and 6). This formation is exposed in the south of the Cosmo Howley pit in the core of the Howley Anticline and in the contact of the Burnside Granite, and is predominantly a pelitic sequence containing up to 10% psammitic rocks. The Wildman Siltstone has been divided into two members on the basis of dominant rock type (Stuart-Smith 1985), and its contact with the overlying Koolpin Formation is either poorly exposed or tectonic. However, an unconformity has been recognised between the two formations further to the east (Stuart-Smith *et al*., 1984; 1987). The rocks that form the Wildman siltstone have been metamorphosed during the intrusion of the Cullen Batholith and now consist of quartz mica schist or carbonaceous phyllite interbedded with banded siltstone and micaceous sandstone.

The rocks which form the South Alligator group occur in the north around the Burnside Granite, at Mount Paqualin and south in the core of the Howley Anticline (Figures 2 to 6). In the south, the Cosmo Howley mine is hosted by

Middle Koolpin BIFs and in the north, carbonaceous shales of the Upper Koolpin host the mineralisation at Bridge Creek. The Koolpin Formation, which is the lowest formation within the South Alligator Group, comprises a series of alternating beds of mudstone, mudstone with chert nodules, shale, carbonaceous pyritic shale, ironstone and yellow tuffaceous siltstone. The upper contact of the Koolpin with the Gerowie Tuff has generally been the focus for the intrusion of sills of Zamu Dolerite (Figures 3 and 6). The Gerowie Tuff, which is stratigraphically above the rocks of the Koolpin Formation (Figures 3 and 6), comprises a sequence of bedded chert, mudstone and yellow and grey-blue tuffaceous siltstone. The chert is commonly finely laminated and consists of alkali-feldspar, albite, quartz with minor garnet, biotite, chlorite, muscovite, sericite and tourmaline. Many feldspars have a curvilinear texture reminiscent of an original glass shard texture (Kruse *et al*., 1990). The Gerowie Tuff hosts mineralisation at Chinese Howley, Kazi and Brocks Creek (Figures 2 to 6). The rocks that comprise the Mount Bonnie Formation occupy the central part of the Howley Anticline (Figures 2 to 6), and are stratigraphically above the cherts that form the Gerowie Tuff. The first occurrence of the Mount Bonnie Formation is taken to be a coarse-grained greywacke, which forms a distinctive regional marker horizon. This horizon appears to be preferentially mineralised at the Western Arm, Howley Ridge, Woolwonga, Brocks Creek and Fountain Head (Figures 2 to 6). The Mount Bonnie Formation consists of interbedded phyllite, siltstone, feldspathic greywacke, banded iron-rich chert and minor massive chert with tourmaline-rich horizons. The greywacke generally consist of quartz, muscovite and alkali feldspar, and grades from coarse-grained rocks with lithic fragments to finely laminated mudstone with cross bedding and graded bedding.

The Burrell Creek Formation conformably overlies or is faulted against the Mount Bonnie Formation (Figures 3 and 6). It generally consists of tombstone-like outcrops of massive dark grey greywacke, interbedded with red-brown phyllite and locally pebble conglomerate with dacitic clasts.

Intrusive Rocks

The sedimentary units of the Koolpin Formation, Gerowie Tuff and Mount Bonnie Formation are intruded at various levels by thin sills of dolerite to thicker sills of differentiated gabbro (Figures 3 and 6). The dolerites also form pods and sheets which cross-cut bedding, but have been metamorphosed and deformed along with the sedimentary rocks. The sills, regionally termed the Zamu Dolerite, are dominantly a massive greenish, fine to medium grained quartz dolerite (Stuart-Smith 1985). Descriptions of the dolerite with detailed petrology and geochemical analysis can be found in Stuart-Smith *et al*.,. (1993).

The sediments and dolerite sills in the local area were intruded by granites that are part of the Cullen Batholith (Figures 3 and 4; Klominsky *et al*., 1996). The Cullen Batholith represents the central part of a larger plutonic complex, which has been variously described as " late intrusive leucogranite ", as typical of " post-tectonic or late-syntectonic magmas " (Smart *et al*., 1976), as " solid state diapiric intrusions " and as " I-type mantle-derived syn-to post-orogenic granitoids " (Stuart-Smith *et al*., 1993).

According to Stuart-Smith *et al*.,. (1993), the Cullen Batholith is composed of twenty three plutons which coalesce or interconnect at shallow depths of less than 4 km (Figure 1). The total area of exposed granites in the Cullen Batholith is about 3,300 km^2, which consists of one large almost continuous granite outcrop and several smaller satellite bosses (Figure 1). The presence of

numerous roof pendants, the distribution of the thermal aureole around the batholith, and the presence of K-feldspar-cordierite facies contact mineral assemblages all suggest a shallow level of intrusion (about 1-3 km). This is confirmed by the presence of co-magmatic felsic volcanic rocks within the Edith River group (Klominsky *et al*., 1996). Further, the level of intrusion of the Batholith appears to have been restricted to the same stratigraphic level as the intrusion of the Zamu Dolerite sills (Figures 3 and 6).

Isotopic age dating of the Batholith is based largely on U-Pb zircon, Rb-Sr whole rock and K/Ar mineral data, which are summarised along with the field relationships of the granites in Klominsky *et al*., (1996) and Stuart-Smith *et al*., (1993). Based on geological relationships, geochemistry and geochronology the batholith has been subdivided into three separate suites (Klominsky *et al*., 1996), the younger of which appears to be related to the gold mineralising event. The emplacement age of the older granites is taken to be 1835-25 Ma, the emplacement age of the transitional granites is taken to be 1818-25 Ma, and the emplacement age of the younger granites is taken to be 1800 Ma (Klominsky *et al*., 1996; Stuart-Smith *et al*., 1993). This represents a 15-20 Ma time difference between the intrusion of individual suites. There is a clear relationship between the younger granites and mineralisation with the most fractionated and often most radiogenic granites spatially associated with the larger hydrothermal systems and gold mineralisation (Figures 4 and 6).

The detailed topography of the roof of the Batholith and the overall shape and volume of individual plutons have been some of the key factors influencing the development of the thermal aureole around the Cullen Batholith, which consequently has controlled the dimensions and channelling of hydrothermal systems and the distribution of economic tin and gold mineralisation. The

majority of the granites in the Cullen Batholith have concentrations of radioactive elements significantly above those typical of granites (Klominsky *et al*., 1996). As a consequence, the granites are characterised by unusually high heat production and heat flow rates. Because they are in an advanced state of fracturing and weathering, these granites are also excellent potential sites for post-magmatic hydrothermal convection. With an average heat production value of 5.79$\mu W/m^3$ the Cullen Batholith has twice the average granite heat production at 2.5 $\mu W/m^3$, and the heat production of the younger granite suite, with values up to 10 5.79$\mu W/m^3$, can be up to four times higher than the average granite heat production (Klominsky *et al*., 1996). The Cullen Batholith is more radiothermal than many of the well studied high-heat-producing (HHP) granites, including the Cornubian Batholith in Britain (4.0-5.7 $\mu W/m^3$; Webb *et al*., 1985), the radiogenic Bushveld granites (4.2-12.8 $\mu W/m^3$; McNaughton *et al*., 1993), and for radiogenic granites from northern Australia (5.7-6.3 $\mu W/m^3$) invoked by Solomon and Heindrich (1991) as the heat source for the giant Pb-Zn deposits of the Mount Isa and McArthur River areas.

The principal granites in the Howley District include members of the older transitional and younger granite suites as defined by Klominsky *et al*., (1996). Five main granites crop out in the area. However, it is clear from the distribution of the contact metamorphic isograds in the area, as interpreted from gravity, digital terrain, enhanced aeromagnetic and enhanced satellite maps, that several other granites are hidden at depth throughout the area (Figure 4 and 6). It is these granites, which are interpreted to be part of the younger intrusive suite, that appear to have a spatial and temporal association with gold mineralisation in the Howley District.

The Fenton and Burnside Granites belong to the younger intrusive suite and crop out northeast of Bridge Creek and southwest of Cosmo Howley (Figures 2, 3 and 4). Both granites have similar compositions, being fine-grained equigranular biotite leucogranites that commonly have veins of quartz, aplite, pegmatite and microgranite on their margins. Subhorizontal cryptic layering in the Burnside Granite and numerous roof pendants in the Fenton granite indicate that both granites are currently exposed close to their roof zones. The Burnside Granite also has a concentric magnetic anomaly in its centre. A shallow arching of cryptic layering has been also detected by systematic chemical changes of the granite composition from the margins to the centre (Klominsky *et al*., 1996). Both granites have radiothermal heat production values in the range of 5-7.5 $\mu W/m^3$ (Klominsky *et al*., 1996).

The other granites in the area that have a less clear association with gold mineralisation include the Shoobridge Granite, which appears to be significantly younger than the Burnside suite (at 1770 Ma; Stuart-Smith *et al*., 1993). Pegmatites associated with this granite crosscut gold-bearing quartz veins at the Mount Shoobridge mine (Burke, 1987). This granite is a small circular intrusion in the west of the district that is about 1.5 km in diameter (Figures 3 and 4). The granite has a distinctive concentric zonation and an exceptional variation in mineralogy and chemical composition almost completely covering the range of differentiated granites in the Cullen Batholith. The outer zone comprises mesocratic tonalite, with a more porphyritic granodiorite toward the centre, and a core consisting of a fine- to medium-grained leucogranite. The normal concentric zoning indicates two magmatic pulses: an older, more mafic pulse, at the periphery and roof, and a younger pulse in the centre. The granite is zoned with a core of leucocratic adamellite and a margin of hornblende-biotite granodiorite with an intervening zone of hornblende-biotite adamellite (Stuart-

Smith, 1985). The Shoobridge Granite, which may represent a late stage intrusion related to the younger granite suite, has a radiothermal heat production value in the range of 4.5-5.5 $\mu W/m^3$ (Klominsky *et al*., 1996). The Margaret and McMinns Bluff Granites, which occur to the northeast of the Burnside Granite and east of the Fenton Granite, respectively, belong to the older granite suite. These are coarse grained, porphyritic hornblende-biotite granites that are less fractionated than the Burnside and Fenton Granites, and have lower radiothermal heat production values in the range of 2.5-5.5 $\mu W/m^3$ (Klominsky *et al*., 1996).

Structural Geology

The earliest structures in the area (D1) are preserved as rare small recumbent folds in the hinge area of the Howley Anticline and a weak bedding parallel fabric identified in thin section (Cooper, 1990). The folds are isoclinal to tight asymmetric and are confined to individual bedded chert horizons in the hinge zone of the Howley Anticline. These are associated with a bedding parallel spaced fabric, and because these folds are folded around the hinge of the Howley Anticline and have an opposite sense of vergence to parasitic folds associated with the Howley Anticline they are considered to have formed before the main folding event. This deformation event is considered to represent the early D1 deformation event of Johnston (1984).

The main structures in the area are dominated by D2 regional thrusts, upright to overturned D2 folds such as the Howley Anticline and a series of crosscutting anastomosing brittle-ductile shear zones and faults with associated quartz veining, such as the Shoobridge Fault, Hayes Creek Fault and the Pine Creek Shear Zone (Figures 4, 5 and 6) that deform the earlier fold structures

(Klominsky *et al*., 1996). These structures can be correlated with the regional D3 deformation sequence described by Johnston (1984). The regional folds associated with the main deformation event (D2), are best described as tight, doubly plunging, upright to overturned, asymmetric, noncylindrical folds that can be traced for over 60 km (Figures 4, 5, 6 and 7). The doubly plunging folds form crests and troughs along the length of their fold axes (Figures 4, 5 and 6). In some areas, (eg, around Bridge Creek, Figures 4, 5 and 6), this has been accentuated by cross folding related to D4. On a regional scale, however, the troughs and crests were formed during the D2 event due to the continuing interaction between D2 folding and thrusting. The D2 domes and basins appear to have formed in the roof of duplex thrust zones possibly related to ramping of a sole thrust at depth up through the stratigraphy (Figures 4, 5 and 6). The noncylindrical nature of the D2 folding is well developed in the vicinity of the Cosmo Howley mine, where the Howley Anticline plunges to the north and the fold axis strikes to the northwest, but plunges to the south with the fold axis striking to the north in the Bridge Creek area (Figures 4, 5 and 8; Klominsky *et al*., 1996).

A prominent axial planar cleavage is present in the finer grained sedimentary rocks, and can vary due to refolding of the fold axes by D3 and D4 folds, between 330° to 010° (eg, the Howley Anticline between Cosmo Howley and Bridge Creek). In detail the D2 folds are dominantly asymmetric in section with bedding on the eastern limb steep to overturned (Figures 6 and 7). There are numerous small-scale M-folds and asymmetric parasitic folds in the limbs. These folds range from 3-5 cm to metres in wavelength and amplitude (Figure 7). The short limbs of these folds are commonly sheared and veined (Klominsky *et al*., 1996). The axial plane fabric is weakly developed with the intensity of the fabric commonly rock type-dependent, ie. S2 is preserved in the more

competent cherts and tuffs as a weak, spaced fracture cleavage whereas the phyllitic rocks preserve the fabric as a weak slaty cleavage.

The D2 thrust faults contain well developed down-dip stretching lineations, C-S structures, asymmetric pressure shadows and en echelon vein sets. These structures all confirm that movement along these zones was dominantly reverse, although a minor component of oblique slip movement may be present locally. The relationship between the thrusts and folds suggests that these structures formed contemporaneously as part of duplex thrust systems (Figure 6). The sole thrust of this system appears to have been focused at the contact between the Wildman Siltstone and the Lower Koolpin Formation which, from its relationship with the Howley Anticline, suggests that the anticline may have formed due to the ramping of this structure up stratigraphy towards the Burnside Granite. Buckle folding is dominant to the west of the Howley Anticline and east of the Burnside Granite, and these areas lack the break thrusts apparent on the Howley Anticline. In contrast, in the Mount Paqualin area to the west of the Burnside Granite, a duplex system can be mapped that appears to be separated from the fold-dominated regime to the south by a series of northeasterly trending faults (Figures 5 and 6). There is a well developed frontal ramp in this area, with a series of overturned anticlines separated by a series of break and stretch thrusts rather than synclines (Figures 5 and 6).

A second generation of folds (D3), which are only locally developed (eg, near Goodall where they form northeast-trending cross-folds) occur in the area (Figures 3 and 5). These folds the S2 cleavage locally, and the deformation event has been assigned to the Maude Creek Event by Needham *et al*.,. (1988). These folds also pre-date granitoid intrusion.

Late faults that are part of the D4 deformation event of Johnston (1984) offset the D2 and D3 structures. These faults have conjugate dextral and sinistral strike-slip movements (eg. the Pine Creek shear zone or the Hayes Creek Fault; Klominsky *et al*., 1996). There is evidence that some of the major cross faults, such as the Hayes Creek Fault and the Shoobridge Fault, were active during D2, forming bounding faults to the D2 thrusts, and may even be reactivated faults related to the initial opening of the Geosyncline. Most of the D4 structures, however, are associated with granitoid intrusion, forming open east-west trending folds (eg, the open folds that refold the Howley Anticline around the Burnside Pluton; Figures 3 and 5). This deformation event formed the broad dome and basin structures evident around the Burnside Granite and in the Burrundie Dome area (Figure 1), and is probably part of the Shoobridge event as described by Stuart-Smith *et al*.,. (1993). Deformation appears to have been concentrated in the northwest-trending strike slip zones around the granite margins. D2 folds and thrusts were also reactivated, tightening D2 folds due to bedding parallel shearing as a result of movement along D2 sole and duplex thrusts. The main mineralising event in the Pine Creek Geosyncline is synchronous with D4 deformation, which has concentrated the main gold deposits in the area into the regional scale D2 structures.

The final deformation event in the district is represented by a series of east-west cross faults that had a dominant normal movement throughout their history. These structures postdate granite intrusion and gold mineralisation, and can offset ore shoots by up to 15 m.

Metamorphism

The Howley-Brocks Creek district has undergone regional upper greenschist facies metamorphism (Stuart-Smith, 1985; Stuart-Smith *et al*.,. 1993). The assemblages at the Bridge Creek deposit are consistent with peak metamorphic conditions of upper greenschist facies. This is based on the mineral assemblages within the sedimentary rocks and preservation of small spherical garnets in siltstone layers. These garnets are almandine-rich in composition, are free of inclusions and formed pre- to syn- the formation of the D2 fabrics, which wrap around the garnets. The garnets have been retrogressed to chlorite during later metamorphism and/or hydrothermal activity. Other diagnostic minerals formed in the sedimentary rocks during the regional metamorphic event are biotite and chlorite, which define the S1 and S2 cleavages. Pre-tectonic garnet poikioblasts at the Western Arm deposit have increasing almandine contents towards their rims, which is consistent with growth during prograde metamorphism. Prismatic andalusite porphyroblasts with remanent chiastolite crosses have been recognised at Bridge Creek, which appears to have formed syn-D2 (Zerovich, 1994). The andalusite has been replaced by granoblastic plagioclase, biotite and chlorite. Garnet-biotite geothermometry from both Bridge Creek and Western Arm deposits gave a mean temperature for the regional metamorphism of 360^{o}C (Zerovich, 1994). The Zamu Dolerite sills have been metamorphosed to an amphibole, chlorite, sericite, biotite and minor albite assemblage. Compositions obtained from electron microprobe data for actinolites in the alteration assemblage are also indicative of upper greenschist facies metamorphism (Cooper, 1990).

The effects of regional metamorphism are largely overprinted by contact metamorphism during granite intrusion. Contact metamorphic assemblages are best distinguished by their overgrowth of the D2 fabrics by randomly oriented minerals such as garnet, cordierite and amphibole. Rare K-feldspar-cordierite

hornfels rocks to the south of the Howley District suggest that the granites of the Cullen Batholith intruded at depth less than 6 km (Stuart-Smith *et al*., 1993). At such depths, contact aureoles would be expected to only extend up to 750 m from any granite contact. However, the contact aureole around some of the granites in the Cullen Batholith can extend up to 15 km. It is clear from the distribution of the metamorphic isograds around the Burnside Granite (Figures 3 and 4) that there is not a simple relationship between the current granite outcrop pattern and the surrounding contact metamorphic halo. This is due in part to the Burnside Granite having shallowly dipping margins to the west and north (Klominsky *et al*., 1996), but more importantly to the presence of several buried granites adjacent to the Burnside Granite. These can be clearly identified using enhanced magnetic, DTM and satellite imagery. Many of the hydrothermal mineral deposits in the Howley District are more easily related to structures in the roof zone of buried granites rather than at the margins of the currently outcropping granites.

The contact aureole around the granites in the Howley District comprises a rare narrow inner zone of sillimanite hornfels-facies rocks that is followed by a zone of hornblende hornfels facies rocks. The boundary between these facies is marked by the appearance of hornblende in mafic and calcareous rocks and almandine and cordierite porphyroblasts in more pelitic units. The boundary to the hornblende hornfels facies rocks is generally within 500 m of the granite contacts. However, in some areas (eg., Cosmo Howley and the Western Arm) this boundary is laterally over 10 km away from the nearest outcropping granite. The albite-epidote hornfels facies has been divided into two parts extending out from the granite contacts. The appearance of biotite marks the inner boundary within which all rocks are recrystallized, usually with unstrained foliated fabrics. Typical assemblages in this zone include albite, epidote, biotite, muscovite,

chlorite, actinolite, tourmaline and garnet. The presence of pyrrhotite in shale and tuff and metamorphic magnetite in greywacke results in enhanced magnetisation in this and the hornblende hornfels facies zone. The outer part of the albite-epidote hornfels facies zone is poorly defined due to the similarities between the regional metamorphic assemblages and the overprinting contact metamorphic assemblages. Pelitic rocks are usually phyllitic with fine-grained muscovite and chlorite, and locally spotted due to chlorite after cordierite and andalusite.

Pressure-temperature estimates for the contact metamorphism in the area have been made by Zerovich (1994), and suggest that hornblende hornfels facies metamorphism at the Western Arm deposit occurred at about 500-550^{o}C whereas the biotite part of the albite-epidote hornfels at Bridge Creek occurred at lower temperatures, about 400-450^{o}C (Cooper, 1990). Contact metamorphism at Cosmo Howley reached the hornblende hornfels facies with temperatures calculated by Matthai *et al*. (1995) in excess of 550^{o}C. However, many of the contact metamorphic assemblages are strongly retrogressed (Matthai *et al*., 1995), and inclusions of contact metamorphic minerals in gold-bearing quartz veins at Cosmo Howley suggests that the gold mineralisation post-dated the peak contact metamorphism. Similar retrogression of contact metamorphic assemblages occurs at the Bridge Creek (Cooper, 1990), Western Arm (Zerovich, 1994) and Kazi (Clayton, 1996) deposits.

Mineralisation

History and Location

Gold, tin, lead, zinc and copper, have been mined in the region since the early 1870s. Gold mineralisation in the area forms linear belts up to 20 km in length that occurs within but trend across and out of the thermal aureole of the Burnside, Fenton and Shoobridge Granites, as defined by gold geochemical anomalies (Figure 4). In contrast, tin and base-metal mineralisation are spatially related to the immediate contact aureoles of the McMinns Bluff, Fenton and Shoobridge granites, and tend to cluster around granite contacts. Gold mineralisation occurs in all units of the South Alligator Group and Burrell Creek Formation in the Howley District (Figures 3, 4 and 6), and is related spatially to D2 regional anticlines, northeast-trending strike slip shear zones and duplex thrusts (Figures 4, 5 and 6; eg., Woolwonga, Fountain Head, Brocks Creek, Cosmo Howley). The total resource base for all deposits, including past production and current mining operations, in the Howley District is about 5 million ounces of gold.

The largest gold deposits in the area are located as a line of deposits along the D2 Howley Anticline. These deposits include Cosmopolitan Howley, which produced 80,000 tonnes of ore at 10.5 g/t gold at the turn of the century, and, more recently, a resource of 885,000 ounces gold has been defined to 270 m deep (Matthai *et al*., 1995a). This resource is open at depth and in the area drilled is estimated to have a remaining underground resource upward of 260,000 ounces of gold. Gold mineralisation at Cosmo Howley is contained within the middle Koolpin Formation, which consists of alternating BIF and mudstone units (Figures 3 and 7). The main gold mineralisation appears to have preferentially replaced the BIFs, especially towards the top of the formation. The mineralisation is controlled by the Howley Anticline which plunges 50^{o} to the north west in the area of the mine (Figures 3, 7 and 8). On a broad scale the gold mineralisation is stratabound but is confined to the BIF

units in parasitic folds in the hinge zone of the Howley Anticline (Figures 3 and 7). Gold is spatially associated with crosscutting quartz veins, which occur as veins up to 20 cm thick, and fine stockwork zones. Five phases of quartz veining have been recognised at Cosmo Howley, with the second-generation quartz veins hosting the main phase of gold mineralisation. The early veins appear to be synchronous with D2, have been recrystallized during contact metamorphism and are barren, whereas the later veins are vuggy and commonly contain pyrite and minor base-metal mineralisation. The gold-bearing veins are concentrated in zones of competency contrast within nodular horizons in the Middle Koolpin BIFs, and along sheared contacts between Zamu Dolerite sills and Middle Koolpin and Upper Koolpin mudstone. These veins are believed to have formed by crack seal processes and, since fragments of garnet, K-feldspar and andalusite are incorporated within rock fragments in veins, the veins must postdate the contact metamorphic assemblages. The metamorphic assemblages are also overprinted by hydrothermal alteration, which retrogresses minerals such as cordierite to chlorite. High grade mineralisation, (8-30 g/t gold), usually occurs in zones adjacent to the veins associated with haematite, arsenopyrite and pyrrhotite alteration (Matthai *et al*.,. 1995a,b). Because many of the quartz veins away from the middle Koolpin BIFs are barren, a chemical host rock control on mineralisation by the carbonaceous upper Koolpin shale has been inferred (Matthai 1995 a, b).

The Chinese Howley group of deposits are located north along strike from Cosmo Howley, and about 150 m above the BIFs that host the mineralisation at Cosmo Howley (Figures 3, 7 and 8). The gold mineralisation occurs as a series of subvertical quartz veins within axial planar parallel shear zones in siltstone and shale of the Gerowie Tuff, and along sheared margins of Zamu Dolerite. As at Cosmo Howley an early barren recrystallized set of quartz veins is

present. However, these veins are mineralised where they are cut by later gold-bearing veins. There does not appear to be any stratigraphic control on mineralisation, apart from sheared dolerite contacts. Rather, mineralisation is structurally controlled by duplex D2 thrusts and D2 axial planar cleavage (Figures 3, 7 and 8). There is also no obvious host rock control, with no association of ore shoots with carbonaceous-rich sedimentary rocks. The deposits currently have a combined open-cut resource of 180,000 ounces of gold.

The Big Howley deposit is 3 km north of the Chinese Howley group, again higher in the stratigraphy (Figures 3, 7 and 8). The gold mineralisation at Big Howley is hosted by bedding-parallel quartz veins that form 1-2 m thick saddle reefs in the hinge zone of the Howley Anticline. The Big Howley deposit has a remaining open-cut resource of 24,000 ounces of gold.

The Bridge Creek deposit lies about 8 km north of and lower in the stratigraphy compared to the Big Howley deposit, suggesting that the plunge of the Howley Anticline must flatten and reverse from south to north between Cosmo Howley and Bridge Creek (Figures 3 and 8). The gold mineralisation at Bridge Creek occurs as a stockwork of centimetre-wide subvertical quartz veins that postdate an early set of barren recrystallised quartz veins. The gold-bearing veins occur in axial planar, parallel shear zones within carbonaceous shale of the Upper Koolpin, siltstone and shale of the Gerowie Tuff, and along sheared margins of Zamu Dolerite. The gold mineralisation in the metasedimentary rocks occurs at a gradational contact between carbonaceous mudstone and overlying Gerowie Tuff below a Zamu Dolerite sill. The ore shoots form elongate (200-300 m), narrow (10-15 m), subvertical pods that are vertically continuous. The higher grade ore shoots are characterised by a sharp increase in vein density.

Sulphides associated with mineralised intersections consist of pyrite, chalcopyrite, bornite, arsenopyrite, sphalerite and galena. Gold generally occurs as inclusions with chalcopyrite within pyrite, and as free grains associated with fine wallrock slivers included in quartz-sulphide veins.

The Ban Ban Springs area hosts three ore bodies associated with regional scale anticlines, which die out towards the Burnside Granite to the northwest (Figures 3, 4 and 5). These deposits have a combined resource of about 800,000 ounces of gold (Ahmad *et al*., 1993). All three deposits are situated on the margins of domal structures on D2 anticlines and appear to be related to blind duplex thrusts, possibly related to a de´collement zone which is marked by the disappearance of these folds to the west (Figures 3, 4 and 5). The gold is hosted by quartz veins at all three deposits, with veins occurring either parallel to bedding within the Lower Mount Bonnie turbidite sequence or within shears that are parallel to the S2 axial planar cleavage. The mineralisation is associated with massive pyrite and arsenopyrite veins, which contain minor galena and chalcopyrite, and are associated with quartz, siderite, K-feldspar and tourmaline (Ahmad *et al*., 1993).

The Western Arm deposit, which has a current resource of 105,000 ounces of gold, is located 5 km west of the Bridge Creek ore body (Figures 3, 4 and 5). The mineralisation lies on a domal structure on the southern flank of the D2 Western Arm anticline (Figures 3, 4 and 5). Outcrop in the area is poor and consists of early Proterozoic rocks of the South Alligator Group, mainly the Mount Bonnie Formation. In contrast to the ore bodies at Cosmo Howley, two early vein sets have been identified at the Western Arm. Both quartz vein types are barren, the first predates contact metamorphism and is recrystallised while the second appears to be related to granite intrusion, containing muscovite and

intergrown quartz and K-feldspar. These veins, although sulphide-rich, are more pegmatitic in nature. The gold-bearing quartz veins at the Western Arm occur parallel to the west limb and as saddle reefs and within mesoscopic scale duplex structures in a parasitic fold on the western limb of the Western Arm anticline. The mineralisation is associated with silicified wallrock and pyrite-arsenopyrite alteration. The higher grade zones are confined to bedding-parallel laminated quartz veins and are associated with veins of K-feldspar and pyrite, haematite and arsenopyrite alteration. Sulphides associated with gold mineralisation at Western Arm are, in order of decreasing abundance, pyrite, chalcopyrite, arsenopyrite, pyrrhotite, sphalerite and galena. The main low-grade mineralised zone appears to occur at the contact between a major sequence of greywacke, siltstone and mudstone in the hangingwall, and carbonaceous shale, sulphidic shale, tuffaceous mudstone, nodular mudstone, felsic tuff and porphyry in the footwall. Visible free gold occurs in late fractures, spider veinlets, and near the contact between carbonaceous mudstone and quartz veins.

The northern part of the Howley District hosts three ore bodies, which have a combined resource of 385,000 ounces of gold. At Goodall mineralisation occurs on the southern margin of a domal structure on a regional D2 anticline (Figures 3,4, 5 and 7), which is interpreted to be the northern continuation of the Howley Anticline. The Goodall deposit is hosted by a sequence of turbidites within the Burrell Creek Formation (Quick, 1994). The mine geology is dominated by lithic sandstone-greywacke with intercalated shale and mudstone. The shales, which generally define the tops of turbidite sequences, contain mineral assemblages suggestive of albite-epidote hornfels facies. However, minerals such as cordierite and andalusite have all been retrogressed to chlorite, sericite and quartz. Mineralisation at Goodall occurs on the western

limb of a D2 fold as a well-defined subvertical zone associated with thin vein arrays that are parallel to S0 and the S2 axial planar cleavage. These veins cut an early recrystallised vein set that is bedding parallel, and form saddle reefs in the hinge zone of the D2 anticline . Gold at Goodall occurs in the late quartz veins and is associated with pyrite, arsenopyrite, pyrrhotite, galena and sphalerite, and an alteration assemblage of chlorite, K-feldspar, tourmaline and minor carbonate.

In contrast to most other deposits in the Howley District, the mineralisation at the Kazi and Rhodes deposits, where a combined resource of 160,000 ounces of gold has been established, occurs in a D2 duplex system (Figures 3,5 and 6). The gold mineralisation occurs in massive sulphide veins in altered Gerowie Tuff and Zamu Dolerite, in shear-parallel quartz veins and en enechelon veins in the hangingwall of D2 thrust planes that dip 50^{o} to the west. There is a strong correlation with arsenopyrite at Kazi with high grade gold veins (30 g/t gold) associated with up to 15% arsenic. Other sulphides at both deposits include pyrrhotite, galena, and pyrite. Chlorite-sericite alteration associated with the mineralised zones is common, with pre-existing albite-epidote hornfels facies assemblages retrogressed to sericite and green biotite.

The Golden Dyke to Mount Bonnie group of mines occur in the east of the area associated with the Hayes Creek fault (Figures 3, 4 and 5). A series of small, but high grade, deposits has been mined from this area since the turn of the century and, more recently, 40,000 ounces gold was mined from the enriched oxide zone of the Mount Bonnie, Iron Blow and Golden Dyke mines (Ahmad *et al*., 1993). In contrast to all other deposits in the Howley District, the Mount Bonnie and Iron Blow mines are polymetallic, with a combined resource of 110,000 ounces of gold plus 1.7 mt of 7.9 wt% Zn, 1.32 wt% Pb, 0.5 wt% Cu

and 161 g/t Ag. The mineralisation at both these mines is hosted by interbedded mudstone, carbonaceous mudstone, greywacke and tuffaceous iron-rich cherts of the Mount Bonnie Formation. The main sulphide minerals include pyrrhotite, sphalerite, galena, pyrite and chalcopyrite. The alteration associated with the mineralisation consists of chlorite, talc, quartz, actinolite, calcite, and minor garnet. Goulevitch (1980), Nicholson and Eupene (1984), Eupene and Nicholson (1990) considered the mineralisation to be syn-sedimentary in origin, with deposition occurring within a local trough in the sedimentary sequence.

At Brocks Creek the resource of 891,000 ounces of gold is contained in the Faded Lily and Alligator deposits. Both these areas were mined early in the century for alluvial gold by Chinese miners. The Brocks Creek gold deposits occur along the Brocks Creek-Zapopan anticline within the contact aureole of the Burnside Granite (Figures 3, 4 and 5). There are several ore bodies in a regional shear zone on the western limb of the anticline in steeply dipping quartz-pyrite-arsenopyrite veins within host rocks belonging to the Gerowie Tuff and Mount Bonnie Formation. The gross geometry of the Brocks Creek shear zone suggests that is related to the D2 deformation event, with the axial planar cleavage of the fold steepening away from the granite contact. This suggests that the original structures were inclined to recumbent, and that the shear zone was possibly a D2 thrust that has been steepened by the doming caused by the intrusion of the Burnside Granite. Contact metamorphism has reached hornblende hornfels facies with garnet-cordierite-andalusite assemblages common. These assemblages have been retrogressed by a late muscovite-sericite-chlorite alteration, which is intimately associated with the gold-bearing quartz veins.

There are several other small gold-bearing vein and 'reef' deposits in the southwest of the area spatially associated with the Shoobridge Fault and Shoobridge Granite (Figures 3 and 4). All these prospects are all hosted by the Burrell Creek Formation, and are small, low tonnage and low to moderate in grade. Descriptions and production records are given by Warpole *et al*.,. (1968), Stuart-Smith (1985), Kruse *et al*., (1990), Ahmad *et al*., (1993) and Stuart-Smith *et al*., (1993).

Timing

The timing of the gold mineralisation can be constrained by using stratigraphic, structural and geochronological data. The crosscutting or replacement nature of most of the mineralisation, which is also hosted by Zamu Dolerite, indicates that mineralisation postdates the intrusion of the Zamu dolerite. Tension fractures hosting gold mineralisation in shear zones are commonly refolded, boudinaged and overprint S2 and S3, suggesting that mineralisation was synchronous with D4 faulting, folding and reactivation of D2 and D3 structures. None of the gold deposits show evidence of metamorphism so mineralisation must postdate peak regional metamorphism. Granitoid intrusion and contact metamorphism also appear to have pre-dated the mineralisation because some deposits within the contact aureoles of granites retrogress the contact metamorphic assemblages (eg, Cosmo Howley, Goodall, Western Arm and Brocks Creek). Geological data from the Mount Shoobridge area (Burke, 1987) indicate that gold mineralisation is older than tin-bearing pegmatites related to the intrusion of the Shoobridge granite. However, hydrothermal activity and D4 deformation, which are associated with granitoid intrusion, appear to be synchronous with gold mineralisation. The upper age of this gold mineralisation is constrained by the deposition of Middle Proterozoic sediments.

Style

The style of gold mineralisation can be subdived into a continuum between two end-member types (Figure 9), with the deposit style directly related to the hosting structure, and contrast in host rock competency and mineralogy. Those rocks which are brittle with low geochemical contrast form vein-stockwork mineralisation (eg., Western Arm, Fountain Head, Woolwonga and Goodall), whereas those with both contrasting competency and geochemistry form vein and replacement deposits (eg., Cosmo Howley, Kazi, Mt Bonnie and Iron Blow). The size of the deposit can also be related to the size of the controlling structure and the spatial relationship of that structure to granite intrusions, especially if the structures occur in the roof zones of the granites.

The Mount Bonnie, Iron Blow, Bridge Creek and Cosmo Howley deposits are all cited as examples of stratiform syngenetic style mineralisation by Ahmad *et al*., (1993), Nicholson and Eupene (1984), Von Oepen (1989), Nicholson and Eupene (1990), and Nicholson *et al*.,. (1994). However, recent work suggests that these gold deposits are good examples of the alteration-replacement end-member of gold mineralisation (Matthai *et al*., 1995a,b; Partington 1990; Partington *et al*., 1994; Klominsky *et al*., 1996). The presence of gold mineralisation at Mount Bonnie and Iron Blow within late fractures not associated with base-metal mineralisation, and fluid inclusion and isotope data (Ahmad, 1993), which implicate a significant metamorphic and magmatic input to the fluids responsible for the mineralisation, all suggest that the gold mineralisation at Iron Blow and Mount Bonnie was late in the paragenetic sequence, possibly post-dating the base-metal mineralisation. Further work is

required at both these mines to establish the relationship between base-metal and gold mineralisation and granite intrusion.

The other end-member types includes Goodall, Glencoe, Fountain Head, Woolwonga and Western Arm, where mineralisation forms broad stockwork zones located in the hinge zones and on the limbs of D2 folds (Figure 6 and 9). Gold is generally associated with thin 5 to 50 mm vein arrays, which form subparallel to earlier structures such as bedding, reactivated shear zones, and S2 cleavage. These vein systems can be continuously mineralised over widths of up to 300 m, strike extents of 1500 m and depth extents of up to 1000 m. The veins are usually composed of quartz and variable amounts of pyrite, arsenopyrite, chlorite, K-feldspar and carbonate. Gold is late, and generally sited in fractures and at grain boundaries.

The range of deposits between these two end-member styles includes many of the shear zone hosted and quartz stockwork/saddle reef style of mineralisation ± alteration zones (eg., Brocks Creek, Kazi and Rhodes deposits).

Alteration and Fluids

As discussed above, gold mineralisation is either vein-hosted or occurs in both veins and altered wallrock. A simple relationship between higher gold grades with an increasing alteration intensity is noted in all deposits in the Howley District. Localised lithological competency contrasts are also important because high strain zones commonly narrow markedly on contact with more competent host rocks. There is a distinctive symmetric alteration zonation within dolerite-hosted mineralisation, with increasing alteration intensity towards the centre of the zone which shows marked depletion in the elements Ca, Mg and Cu, and strong enrichment in the elements K, Fe, S, Ba, Au, As, Bi, W and Sb (Cooper,

1990). Alteration assemblages grade from a chlorite- and actinolite-dominated assemblage surrounding the vein systems, to a bleached albite-rich zone which grades into a zone of biotite growth. On the basis of this wallrock alteration zonation and preservation of primary textures and mineralogy away from the central zone, fluid-wallrock ratios are interpreted to increase towards the centre of the alteration system. Vein-style mineralisation hosted by sedimentary rocks shows depletion in K, Rb, Ba and Cu, and enrichment in Fe, Ca, Na, S, As, Au, Sb, W, Bi, Pb and Zn (Cooper, 1990). The alteration assemblages in both the dolerites and sedimentary rocks overprint metamorphic assemblages and form a distinct zonation at vein margins away from the shear and fracture zones. Gold distribution in the alteration assemblage is closely related to the intensity of alteration and the relative amount of sulphide within the rock. There is an association between gold and arsenopyrite, but as visible gold is observed in secondary pyrite rimming earlier pyrite, free gold is considered to be the dominant contributor to mineralisation in most deposits.

Preliminary fluid inclusion studies on gold deposits in the Howley District suggest that early quartz veins were deposited from a moderate salinity, $CO_2 \pm CH_4$-rich fluid at moderate-high temperatures and 1 kbar (eg., 450-490^oC at Toms Gully, Sheppard, 1992 and 265-365^oC at Western Arm Ho and Sheperd, 1993). Late fractures, which contain most of the gold mineralisation, record the passage of a second higher salinity fluid in which $CaCl_2 \pm MgCl_2$ were dominant over NaCl with slightly lower deposition temperatures (eg., 180-330^oC at Toms Gully, Sheppard, 1992 and 195-280^oC at Western Arm Ho and Sheperd, 1993). Gold mineralisation appears to have been introduced during the later event. Fluid inclusion studies on vein quartz associated with gold mineralisation at the Western Arm and Bridge Creek confirm the presence of an early $CO_2 \pm CH_4$-rich fluid, which probably contains methane, prior to the main

gold mineralising event. Moderately saline aqueous fluids are confidently related to the mineralisation process (Ho and Shepherd, 1993). It is interpreted that a higher temperature fluid deposited the quartz veins and some sulphides, including arsenopyrite (eg., Matthai *et al*., 1995a,b; Al 1996), and a lower temperature fluid was involved in introduction of gold and cross-cutting vein sulphides. Complex saline inclusions were also trapped in the quartz and are interpreted to represent post-ore fluids containing the cations Ca^{2+}, Mg^{2+} and Na^{+}, rather than being simple $NaCl-H_2O$ systems. The $CO_2 \pm CH_4$-rich inclusions and high-temperature, moderate-salinity aqueous inclusions could represent end-member fluid compositions which were mixed, or resulted from phase separation. The fluid inclusions also suggest fluid contributions from both magmatic and metamorphic sources (Dann and Delaney, 1984; Wygralak and Ahmad, 1990; Zerovich, 1994).

Recent sulphur and oxygen isotopic studies (Figure 10) also suggest a mixed magmatic and metamorphic source for the fluids responsible for gold mineralisation (Golding *et al*., 1990; Wygralak and Ahmad, 1990; Sheppard, 1992; Matthai *et al*., 1995b). This is consistent with the fluid inclusion data. Wygralak and Ahmad (1990) found that $\delta^{34}S$ values for sulphides ranged from +4%*o* to + 10%*o* (Figure 10). δD values in fluid inclusion water ranged from +27%o to -57%o (Figure 10), and the calculated ranges of fluid $\delta^{18}O$ were +5.5%o to +10.3%o implying a mixed magmatic-metamorphic source (Figure 10). Similar studies carried out by Matthai *et al*.,. (1995b) at Cosmo Howley came to similar conclusions that there must have been a significant contribution from both metamorphic and magmatic fluids (Figure 10). Lead isotope studies carried out by Sheppard (1992) and Klominsky *et al*., (1996) show that galena data collected from a variety of hydrothermal deposits in the Pine Creek Geosyncline fall in a linear trend with the initial ratios from granites belonging to

the Cullen Batholith representing one end of the trend (Figure 10). It is clear also from this work and from lead isotope studies by Matthai *et al*., (1995b) at Cosmo Howley that many of the gold deposits have similar initial lead, whereas their spatially related granites have distinctly different initial lead from each other and the deposits (Figure 10). This indicates that if the granites contributed lead to the ore fluids, then the contribution was minor. In addition, the relatively homogenous lead isotopic composition for a significant group of deposits and prospects implies coeval mineralisation and an unusually homogenous lead source on a scale of 100 km. It is concluded that the lead source is not from fluids exsolved from the granites during crystallisation, but metamorphic fluids from the dewatering of the stratigraphic section adjacent to granites of the Cullen Batholith during contact metamorphism and following metamorphism.

Genesis of Mineralisation

Structural Controls

Gold mineralisation occurs in all the rocks of the South Alligator Group and Burrell Creek Formation and in most areas is related spatially to regional D2 anticlinal structures above thrust ramp and duplex structures (eg., Western Arm, Bridge Creek, Woolwonga, Brocks Creek and Cosmo Howley), and in rare cases within duplex thrusts (eg., Kazi and Rhodes; Figures 2, 3, 4 and 5). However, all the gold deposits in the Howley District occur in the hangingwall of a zone of de´collement between the Wildman Siltstone and Koolpin Formation which can be seen on satellite and aeromagnetic images in the dome around the Burnside Granite and to the south of Cosmo Howley where the McMinns Bluff granite has also caused doming of the sedimentary rocks. Suitable trap

sites within these structures also appear to be required, hence the stratabound nature of many of the gold deposits. Many deposits appear to be related to domal structures on the D2 anticlines which, as discussed above, may be related to duplex thrust systems at depth. These thrusts may have acted as channelways for hydrothermal fluids from the larger structures into the anticlines and subsequent trap sites. In the lower stratigraphy of the South Alligator Group Zamu Dolerite sills, and in the upper stratigraphy, many of the thick greywacke horizons, have acted much in the same way as an impermeable horizon would in an oil trap. This has focussed fluid flow to the margins of crests and troughs on D2 anticlines and hence the periodicity of mineralisation (eg., along the Howley Anticline; Figures 2, 3, 4 and 5). Consequently, the style and to some extent size of the gold deposits depends on the size of the hosting structure and on competency contrasts of particular rock packages, which commonly depend on the depth of formation of mineralisation, and the presence of pre-existing structural heterogeneities or alteration such as silicification or hornfelsing due to granite intrusion.

In duplex structures, similar to those that control gold mineralisation in the Howley District, a floor thrust and a roof thrust are linked by fault branches which ramp across bedding. These fault structures display a regular and constant spacing in relation to overlying buckle folds. According to Liu and Dixon (1995), experimental studies on fold duplex systems indicate that buckle folds dominate early in the structural sequence (Figure 11), and these are progressively localised in more competent units in the sequence (eg., in the dolerite sills between the Koolpin Formation and the Gerowie tuff or the thick greywacke units at the base of the Mount Bonnie Formation). As deformation proceeds, the amplitude of the folds increases and thrusts develop in the forelimbs of previously developed folds in the lower part of the sequence

(Figure 11).: The numerous anticline-syncline pairs developed in the Burrell Creek Formation, which represents the upper sequence of Lui and Dixon (1995), compares to the thrust anticline sequence with many missing synclines in the South Alligator Group, which represents the lower part of the sequence (Figure 11). Folding and thrusting alternate during the deformation process and the early folds in lower competent units play a major role in localising later thrust ramps and break thrusts. This sequence of deformation events can be recognised in the Howley District, and also explains the localisation of deformation in particular structures throughout the deformation history. Finite-element modelling of a west to east fold-thrust duplex, similar to the structural sequence in the Howley District (Liu and Dixon, 1995), also shows that high stress areas are concentrated in the overturned steep eastern limbs of the buckle folds (Figure 11). This is where break and blind thrusts form. This regime would also result in fluid flow from the high stress areas on the overturned eastern limbs to the lower stress areas in the hinge zones of anticlines and hangingwall western limb of the folds (Figure 11). The break thrusts fault out the synclines and concentrate hydrothermal fluids into the anticlines, and more particularly into the western limb of the folds. This type of model not only explains the structural sequence in the Howley District, but also the localisation of gold deposits in anticlines, and more particularly in the western limbs of the folds (Figure 12). The presence of ore bodies in duplex thrusts in the Howley District also suggests that gold-bearing fluids were channelled by these structures from the lower structural sequence dominated by ramp anticlines and thrusts to the upper sequence dominated by buckle folds (Figure 12). Smith and Wiltschko (1996) have established by numerical modelling that high fluid pressures, significantly above lithostatic pressure, can occur beneath ramping thrust sheets. This fluid pressure is highly dependent on the permeability of the rock package being deformed. Also important is the

presence of low permeability layers to trap excess pore pressures in the higher permeability layers below. This can explain, in part, the localisation of gold deposits in particular rock packages, eg., below dolerite sills, the carbonaceous shales of the Upper Koolpin Formation or thick greywacke units in the Mount Bonnie Formation.

As discussed by Sibson (1996), the pre-existing structural sequence in the Howley District provided the perfect system to promote fluid flow by providing a fault-fracture mesh that provided a conduit for large-scale hydrothermal fluid flow, as evidenced by early quartz veins in the same structures that host gold mineralisation. However, it was not until after granite intrusion and associated metamorphic dewatering that the hydrothermal system deposited gold mineralisation in similar structural sites. Liu and Dixon (1995) suggest that duplex structures have a regular regional spacing which can be predicted from the wavelength of the overlying buckle fold sequence. This has obvious implications to further exploration for gold mineralisation in the Howley District and may also be applied to other areas in the Pine Creek Geosyncline.

Genetic Model

The association of the mineralisation with the granites and their thermal aureoles suggests that many of the mineral deposits were formed during the initial intrusion, and the following cooling phase, of the Batholith. In particular, deposits characterised by relatively high-medium formation temperatures, such as the tin and gold mineralisation, must have been associated with these stages. Wallrock temperatures adjacent to a granite magma will be in the range between 900°C to 600°C and will cool in a relatively short period of time (less than tens of million years). However the decay of radioactive elements provides

a permanent heat engine inside each granite pluton. The amount of heat produced is controlled by the total radioactive element content, particularly uranium, thorium and potassium. Although initially the amount of heat produced is small, it is generated over a long period of time and therefore can maintain the temperature of an anomalously hot granite above its surroundings for hundreds of millions of years, which is up to 100 times the cooling period of a “normal“ intrusion. The combination of these two heat sources may create paragenetically, chronologically and structurally complicated and successively superimposed pulses of hydrothermal activity and consequently a wide variety of hydrothermal mineralisation over a considerable period of time (in the case of the Howley District 1800 Ma, 1350 Ma, 920 Ma, 100 Ma and 0 Ma; Klominsky *et al*., 1996).

The preferred model for gold mineralisation in the Howley District is that early quartz was deposited from overpressured fluids during D4 reactivation of D2 and D3 structures, in response to the intrusion of the later phases of the Cullen Batholith. Passage of subsequent ore fluids was controlled by further reactivation of the earlier structures, especially duplex zones beneath ramp anticlines and structures associated with emplacement of these granites. These structures would have acted as channelways, for any hydrothermal fluid in the region, focussing fluids along decreasing pressure gradients into structurally and chemically favourable sites for deposition of gold. During crystallisation of the batholith, fluids derived from devolatilisation of graphitic rocks in the thermal aureole were channelled along faults in the country rock and possibly along the contact between the metasedimentary rocks and the silicified margin of the plutons. Near the top of the pluton along its margin, hot CO_2±CH_4-rich fluids mixed with moderately saline, aqueous magmatic fluid exsolved from the granite (Klominsky *et al*., 1996). Fluid mixing, in conjunction with pressure

decreases associated with quartz fracturing, induced phase separation and deposition of quartz sulphide veins ± K-feldspar veins at about 450-490°C (Klominsky *et al*., 1996). Fluids which consisted increasingly of isotopically exchanged formation or meteoric water in equilibrium with the metasedimentary rocks, were focussed along reactivated thrust faults through the relatively oxidised sedimentary rocks comprising the base of the sedimentary sequence. Phase separation associated with brittle fracture along the ore shoots, deposited gold and sulphides from solution in response to elevated CH_4 and/or CO_2 contents in the moderately saline fluid derived from interaction with wallrocks away from the site of ore deposition at approximately 320°C (Klominsky *et al*., 1996).

This fluid would have been trapped by impermeable rocks in suitable structural sites at various levels along anticlinal crests and at the margins of domal structures, thus allowing maximum interaction of the fluid with the wallrocks (eg., the BIFs of the Middle Koolpin Formation). With further reactivation of the hosting structure, fluid pressures would have increased, resulting in hydraulic fracturing of the host rocks and the subsequent deposition of gold mineralisation. This may account for the formation of saddle-like structures at various levels along a fold such as the Howley Anticline. The intrusion of the granites of the Cullen Batholith and accompanying contact metamorphism appears to be the key in the generation of sufficient hydrothermal fluid to scavenge gold and basemetals from the surrounding metasedimentary rocks. These sedimentary rocks were not only the source for the metals but also provided structural and geochemical traps to form economic mineral deposits higher in the stratigraphy as the hydrothermal systems cooled.

Conclusions And Implications For Exploration

Gold mineralisation in the Howley District is structurally controlled, occurring in brittle-ductile structures at the greenschist-amphibolite facies boundary. It therefore has an epigenetic origin, and structural models similar to those proposed for other mesothermal styles of gold mineralisation may apply (eg., Archaean gold mineralisation: Eisenlohr *et al*., 1989; Groves and Ho, 1990, Groves, 1993; Victorian slate belt: Cox *et al*., 1995; Homestake area USA: Caddey *et al*., 1991). The mineralisation has an association with HHP granites and there is an input from both magmatic and metamorphic sources for the fluid that transported the gold. Some deposits, such as Cosmo Howley, can be classified as part of the mesothermal stratiform to stratabound type of gold deposits in BIF or iron-rich metasedimentary rocks (eg., Murchison Province, Western Australia; Morro Velho, Brazil; North Eastern Goldfields Province Western Australia; Homestake mine located in the northern Black Hills of South Dakota). Deposits such as Kazi and Rhodes are more similar to the shear zone style of deposit described from Archaean terrains in Western Australia and Canada. Other deposits such as Woolwonga, Western Arm and Fountain Head have more in common with slate belt styles of mineralisation. The gold mineralisation also has geochemical signatures and alteration styles common to Archaean gold deposits, suggesting that the gold mineralisation may have had similar transporting mechanisms and geochemical controls (eg., Groves and Ho, 1990).

The genesis and structural controls on gold mineralisation have some important implications for exploration, and may explain why, although the whole of the Pine Creek Geosyncline is anomalously mineralised, certain structurally defined districts are intensely mineralised. From a structural point of view, those areas

that have developed duplex thrust fold systems appear to be significantly mineralised (eg, the Howley District) rather than areas with buckle folding (eg, the Adelaide River District) or basin and dome structures (eg, the Burrundie Dome). The presence of shear systems linking anticlines higher in the sequence appear to have provided the ideal fluid focussing mechanisms to localise gold-bearing fluids. Another important factor in the localising of gold mineralisation in the Pine Creek Geosyncline is the presence of the younger HHP leucogranites. It is clear from the fluid inclusion and isotope studies that the gold-bearing fluids have mixed metamorphic and magmatic (granite) sources. The heat from the intrusion coupled with pre-existing duplex thrust fold structures, allowed regional-scale hydrothermal systems to be set up channelling fluids from both granite and metamorphic sources. From an exploration point of view, it is those structures that lie in the roof zones and up plunge of shallowly dipping granite contacts that host the larger gold deposits. On a mine scale, there is a clear lithological control on mineralisation, with competency contrasts being very important. Certain sedimentary sequences, such as the turbidites of the lower Mount Bonnie Formation, the Zamu Dolerite Sills and the BIFs of the Middle Koolpin Formation, provide not only the greatest competency contrasts but also chemical contrasts that appear to have localised the richer and more continuous ore shoots. At higher metamorphic grades, pyrrhotite is usually the dominant sulphide associated with gold mineralisation, especially in hornblende hornfels facies zones, as is the case at Kazi, Rhodes and Cosmo Howley. It is possible therefore to use detailed geophysical and remote sensing techniques at a regional and mine scale to identify target areas more likely to host gold mineralisation.

The Pine Creek Geosyncline, because of its remoteness and rugged terrain, is relatively under-explored compared to other gold provinces in Australia, and it is

critical for continuing exploration success that a robust model for the genesis of gold mineralisation is established and continually refined. All the factors described above can be mapped or measured on a regional scale using new remote sensing techniques. Using these criteria with new GIS technologies should allow the identification of those areas in the Pine Creek Geosyncline that are most likely to host as yet undiscovered gold deposits .

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Figures

Figure 1. Regional location map showing the Howley District in relation to the main operating mines and the location of the Cullen Batholith.

Figure 2. Map of the Howley District with the main gold prospects and mines in relation to regional faults, folds and granite plutons of the Cullen Batholith.

Figure 3. Geology of the Howley District, subdivided according to formation, in relation to mines, regional structures and granite plutons.

Figure 4A. Digital terrain model of the Howley District showing the location of granite plutons, possible buried granite plutons in relation to mines and prospects and regional structures.

4B. Pseudo-colour image of the regional magnetic data covering the Howley District and Burrundie Dome with granite outlines. Note the increased magnetic anomalies peripheral to the granite plutons and possible hidden granites.

4C. Structural satellite map overlain by regional gold soil anomalies. Note the association of the soil anomalies with regional D2 and D4 structures.

4D. Total count radiometric image of the Howley District . Note the high level radiometric anomalies associated with the younger granites such as the Burnside granite in comparison to the older granites such as the Margaret Granite.

Figure 5 Main structural features of the Howley District in relation to the main operating mines and granite plutons. Note the relationship of gold mines to D2 folds and thrusts.

Figure 6 Cross-section from west to east, pre-granite intrusion, showing the relationship of gold mineralisation to D2 buckle folds and thrust duplex systems.

Figure 7 Examples of the main controls on gold mineralisation in the Howley District.

7A. A photograph of the northern face of the Cosmo Howley gold mine (field of view approximately 800 metres across), looking down plunge of the Howley Anticline (Fold). Note the reactivated D2 thrusts, which offset Zamu Dolerite sills (Pdz) and cause repetitions of Gerowie Tuff (Pgs) to the west. The gold mineralisation occurs in the Middle Koolpin BIF units beneath D2 thrusts in the hinge zones of parasitic folds related to the Howley Anticline. Note the permeability and competency contrasts between the Zamu dolerite sills (Pdz) and black carbonaceous shale (Psk) and the underlying mineralised BIFs.

7B. The photograph is approximately 20 metres across, looking north and shows gold bearing quartz veins (dashed) within reactivated D2 shears on the western limb of the Howley Anticline at the Chinese Howley mine. The shear zones only occur in the hangingwall of a D2 thrust duplex zone.

7C. Northern face of the Woolwonga Gold mine (field of view approximately 300 metres across). Controls on mineralisation are similar to the Western Arm deposit, but the scale is an order of magnitude greater. Note the D2 fold is asymmetric and slightly overturned. Note the association of D2 thrust faults with the fold.

7D. Northern face of a trial pit at the Western Arm deposit (field of view approximately 40 metres across). High grade gold mineralisation occurs as bedding parallel veins (dashed) related to flexural slip on beds at the top of turbidite units and in reactivated thrust faults. The bleached coarse-grained units at the base of the turbidites also contain subgrade mineralisation, forming a broad zone of low grade mineralisation within which small and discontinuous high grade shoots occur.

Figure 8 Long section along the Howley Anticline between the Bridge Creek deposit and the Cosmo Howley Gold mine. Note the non-cylindrical nature of the D2 folding results in troughs and crests along the length of the Howley Anticline, and the relationship of the major gold deposits to the crests.

Figure 9 A summary of the various styles of mineralisation in the Howley District in relation to other deposits in the Pine Creek Geosyncline.

Figure 10 Pb and O2 isotope diagrams

Figure 11A. Experimental studies of stress in developing duplex fold-fault systems in comparison to the structural history of the Howley District. Modified after Lui and Dixon (1996). Compare the structural evolution of the fold-thrust system in the experimental model to Figure 6.

11B. Stress contours from the experimental model after Lui and Dixon (1996). Showing the likely fluid path within a fold-thrust system in relation to stress contours.

Figure 12 Possible model for gold mineralisation in the Howley District, it's association with granite intrusion and reactivation of D2 structures during D4 deformation..