Controls on mineralisation in the Howley District, Northern Territory: a link between granite intrusion and gold mineralisation

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Contrôle de la minéralisation dans le district de Howley, Territoire-du-Nord : un lien entre intrusion granitique et minéralisation aurifère

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Mots-clés : Granite, Or, Proterozoïque, District de Howley, Territoire-du-Nord, Australie.

Abstract

Gold and base-metal mineralisation in the Pine Creek Geosyncline are 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. The mineralisation also has an association with high-heat-producing (HHP) granites and fluid-inclusion and isotope data suggest that 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 focusing 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. 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.

Résumé

La minéralisation à or et métaux de base du Géosynclinal de Pine Creek est étroitement associée à des granites ; elle a donc été classée dans le type "gisements associés à une auréole de contact de haute température". Dans les gisements du district de Howley, on décrit une relation simple entre la minéralisation aurifère et l'intrusion granitique. Un contrôle secondaire par l'encaissant a également été évoqué, avec une association entre la minéralisation aurifère et des métasédiments carbonatés. Cependant l'essentiel de la minéralisation aurifère se place après la principale phase de l'intrusion du batholite de Cullen, et la relation entre minéralisation et roches carbonatées n'est pas le contrôle principal de la minéralisation. La minéralisation aurifère apparaît plutôt structuralement contrôlée par des structures ductiles cassantes générées à la limite du faciès schistes verts - amphibolites. La minéralisation est associée à des granites à production élevée de chaleur (HHP), et les données d'inclusions fluides et isotopiques suggèrent que la source du fluide qui a transporté l'or est d'origine magnétique et métamorphique.

A l'échelle du district de Howley, les zones caractérisées par des systèmes de «pli-chevauchement en duplex» apparaissent significativement plus minéralisées que les zones de plissements par flexion, ou structurées en dômes et bassins. La présence de systèmes de cisaillement reliant les anticlinaux situés plus haut dans la séquence semble avoir fourni le mécanisme idéal de concentration de fluides à or. Un autre facteur important dans la localisation les minéralisations aurifères dans le district de Howley et dans le Géosynclinal de Pine Creek est

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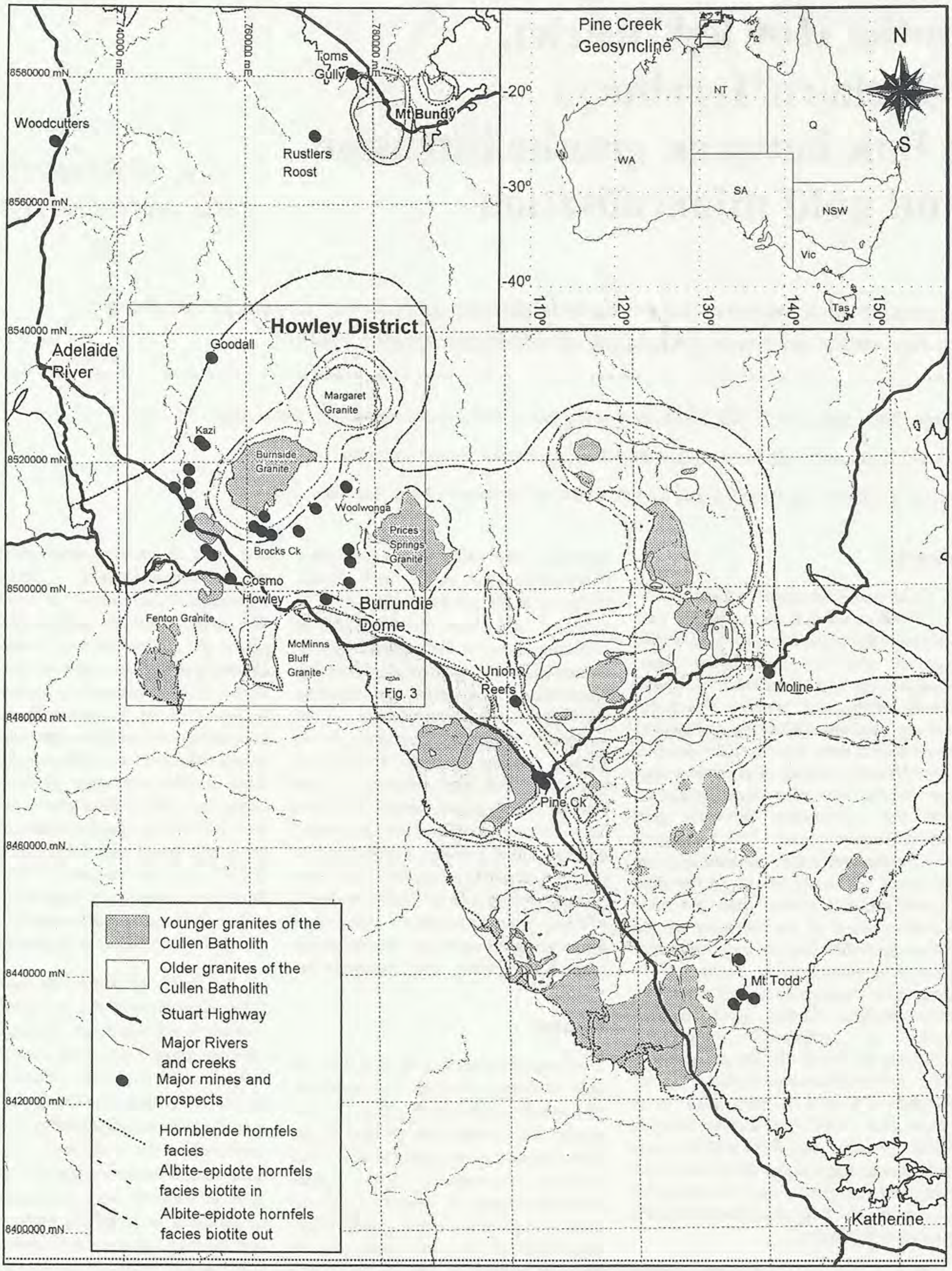


Fig. 1.- Regional location map showing the Howley District in relation to the main operating mines and the location of the Cullen Batholith and contact metamorphic isograds as mapped by AGSO (Stuart-Smith *et al.*, 1993).

Fig. 1.- Carte montrant le District de Howley, avec les principales mines en activité, et la localisation du batholite de Cullen, ainsi que les isogrades du métamorphisme de contact cartographiés par l'AGSO (Stuart-Smith et al., *1993).*

la présence de leucogranites tardifs. La chaleur de l'intrusion, son effet prolongé et l'histoire du refroidissement des granites tardifs, couplé à la présence de pli-chevauchement en duplex ont permis aux systèmes hydrothermaux de canaliser, sur une longue période, les fluides provenant à la fois de sources granitiques et métamorphiques.

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 (Fig. 1), has been part of this exploration and mining boom, with new operations in the Howley District (2 million ounces of total resources), Rustlers Roost (0.5 million ounces total resource), Mount Todd (2.5 million ounces total resource) and Union Reefs (1 million ounces total resource).

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-detection analytical techniques, remote sensing and image enhancement of geophysical data. A variety of genetic models, ranging from magmatic through hydrothermal to syngenetic, has been postulated in the past for the formation of gold deposits in the Pine Creek Geosyncline (e.g., Sullivan and Iten, 1952; Warpole *et al.*, 1968; 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, b).

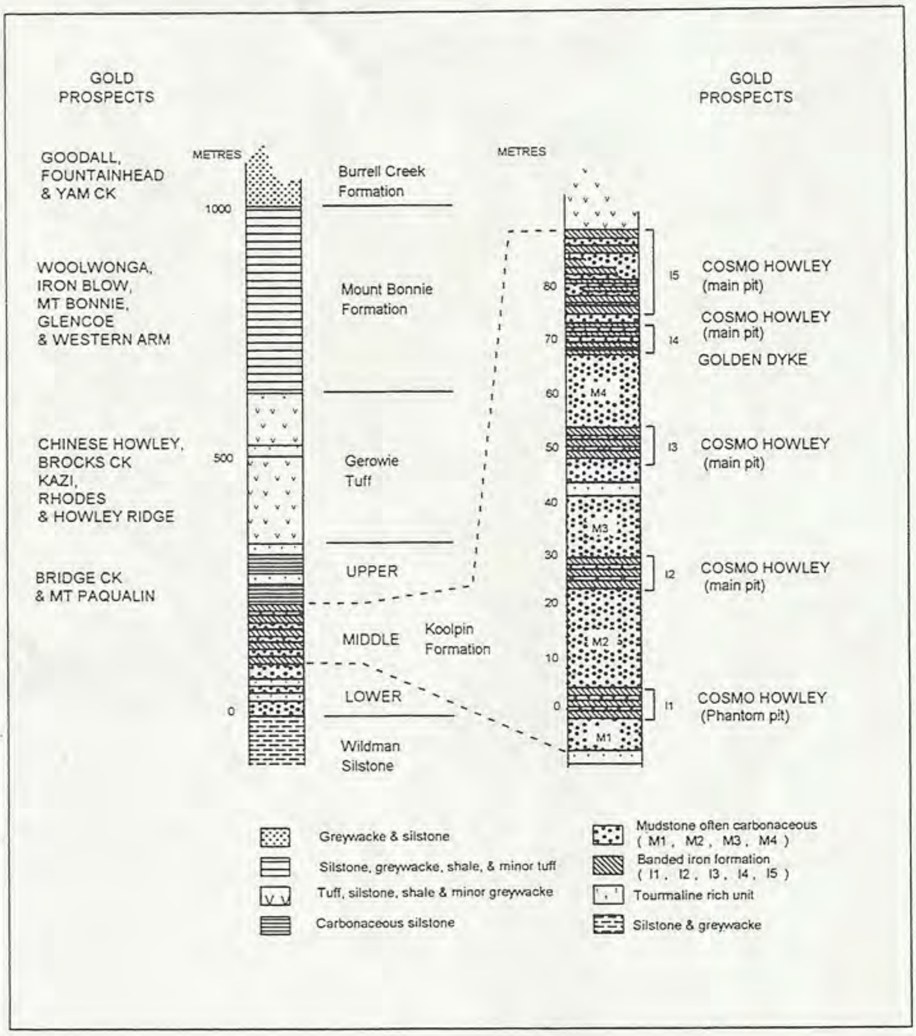


Fig. 2.- Stratigraphic column showing the main subdivisions of the Lower Proterozoic lithologies in the Howley District.

Fig. 2.- Colonne stratigraphique montrant les principales subdivisions dans le Proterozoïque inférieur du District de Howley.

Gold and base-metal mineralisation in the Pine Creek Geosyncline are 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; Wyborn *et al.*, 1994; Matthai *et al.*, 1995a). For example in the Howley District, which is a main historical and current area of gold production in the Pine Creek Geosyncline, a model whereby gold mineralisation was introduced from high temperature magmatic fluids during granite intrusion has been described for deposits in the area (Matthai *et al.*, 1995a). A secondary host rock control has also been suggested, with the association between gold mineralisation and carbonaceous meta-sedimentary rocks considered to be important (Wyborn *et al.*, 1994; Matthai *et al.*, 1995a; b). 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 associated with lower temperature fluids 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 for the timing of granite intrusion and gold mineralisation. A spectrum of deposits is described, in which deposit style appears to be

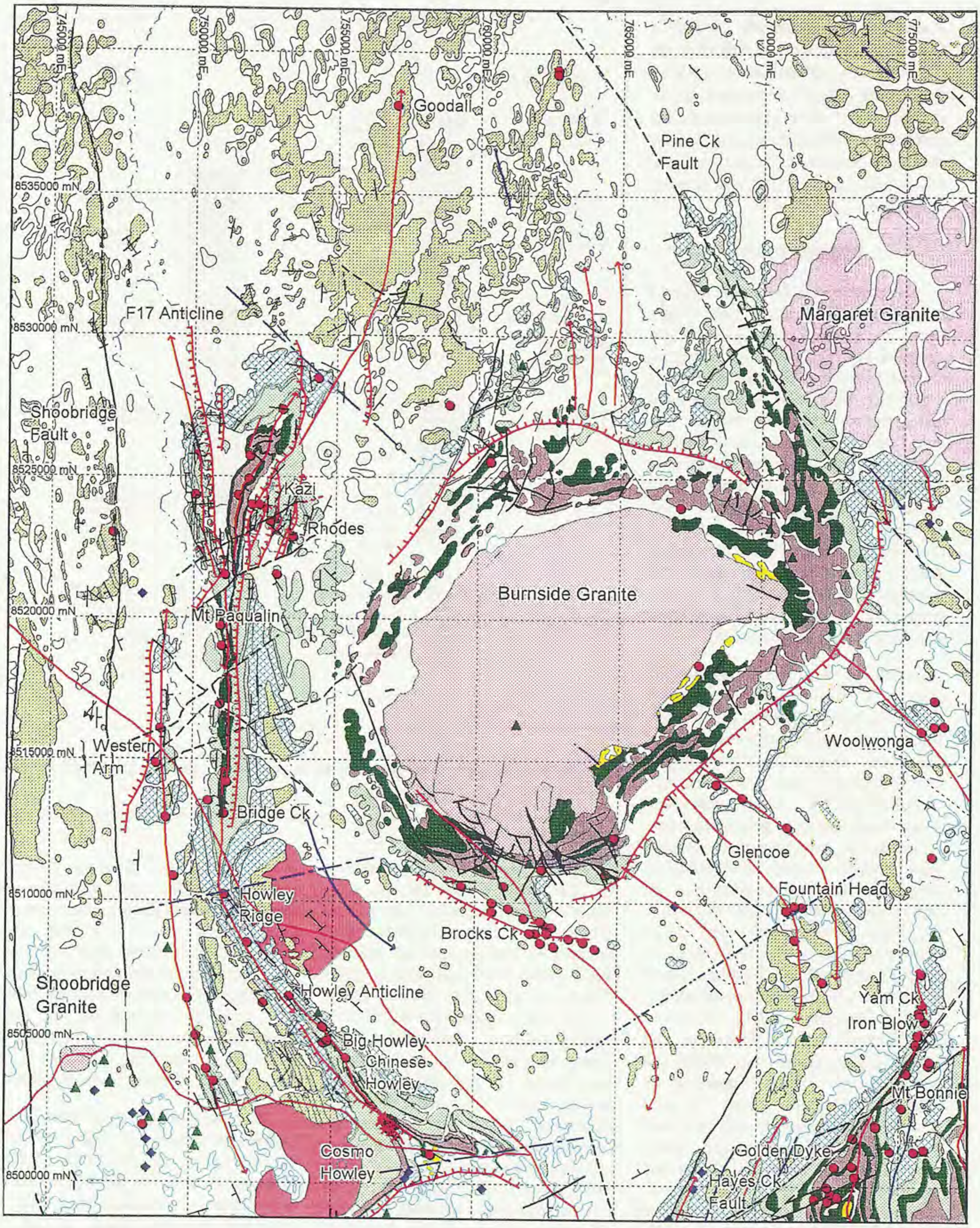
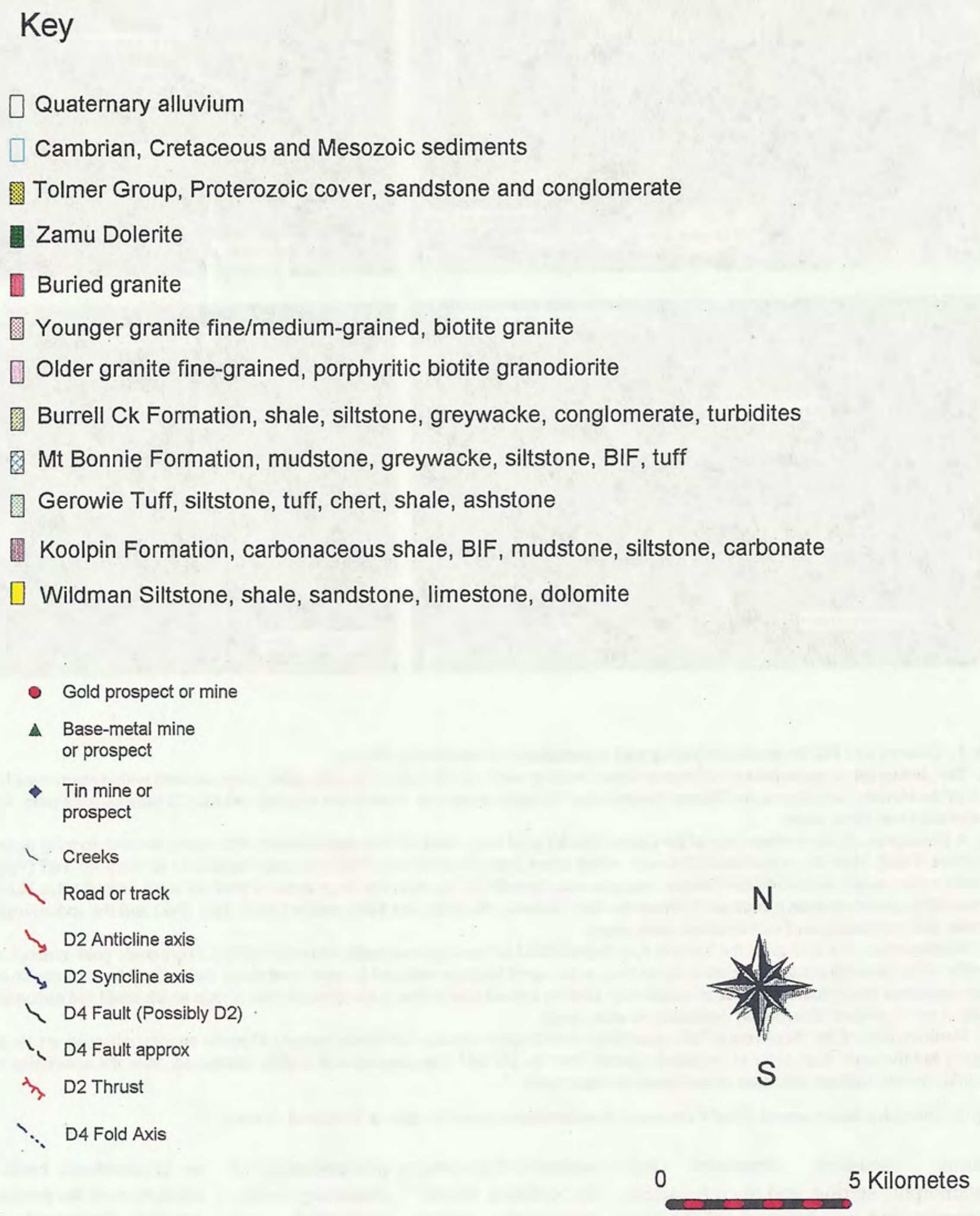


Fig. 3.- Geology of the Howley District, subdivided according to formation, in relation to mines, regional structures and granite plutons of the Cullen Batholith. This map is a compilation of 1:10,000 to 1:25,000 scale mapping carried out in the area by Northern Gold since 1989.

Fig. 3.- Géologie du district de Howley.



dependant on structural and, to an extent, stratigraphic position. Geochemical data from the deposits are used to constrain chemical controls on mineralisation, and fluid inclusion and new 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

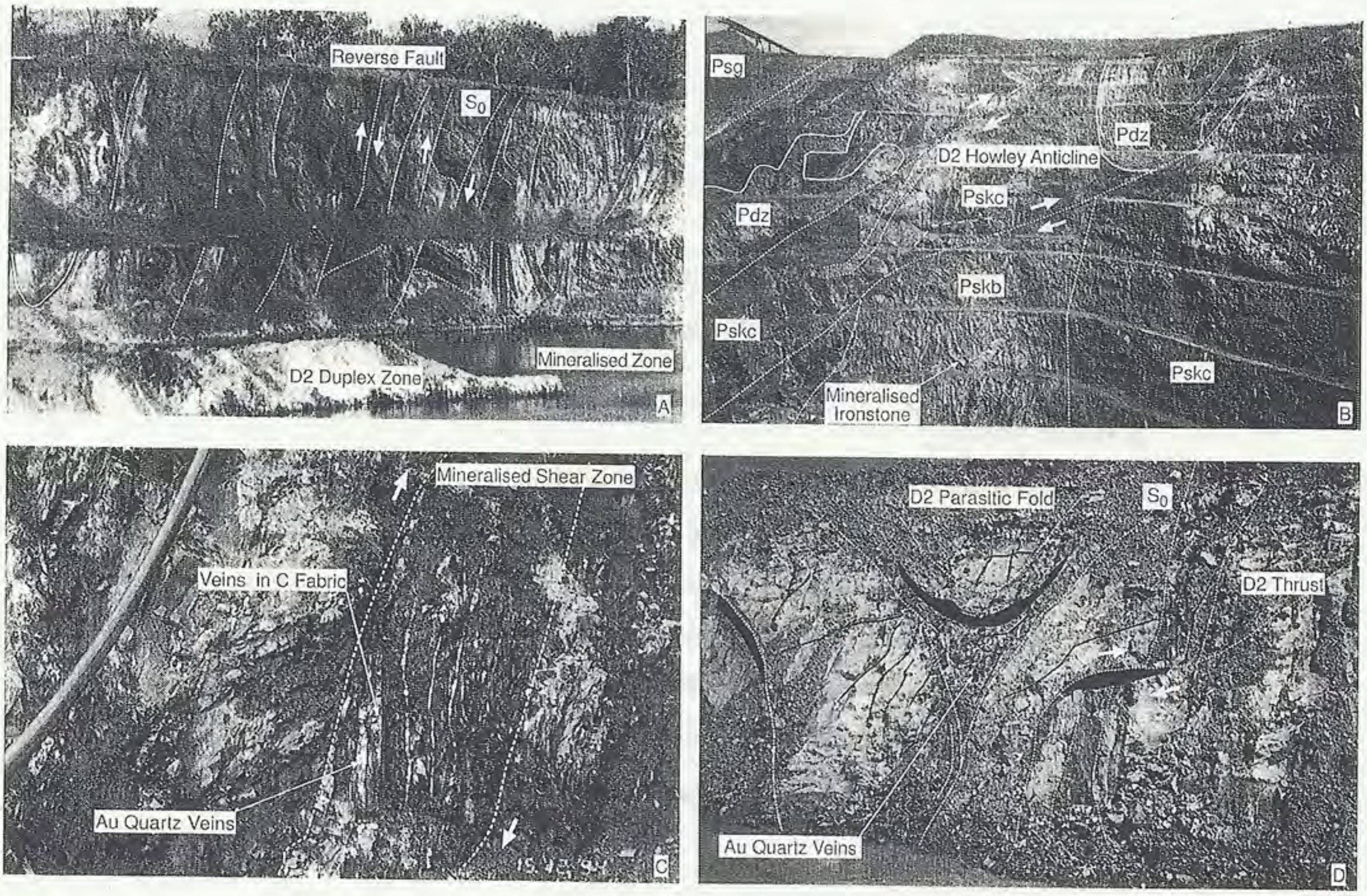


Fig. 4.- Examples of D2-D4 structures hosting gold mineralisation in the Howley District.
4A: The photograph is approximately 20 metres across, looking north and shows gold bearing quartz veins (dashed) within reactivated D2 shears on the western limb of the Howley Anticline at the Chinese Howley mine. The shear zones only occur in the hanging wall of a D2 thrust duplex zone. Arrows indicate direction of movement on shear zones.
4B: 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 ironstone 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 ironstones. Arrows indicate direction of movement on shear zones.
4C: 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. Arrows indicate direction of movement on shear zones.
4D: 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. Arrows indicate direction of movement on shear zones.

Fig. 4.- Exemples des structures D2-D4 encaissant la minéralisation aurifère dans le District de Howley.

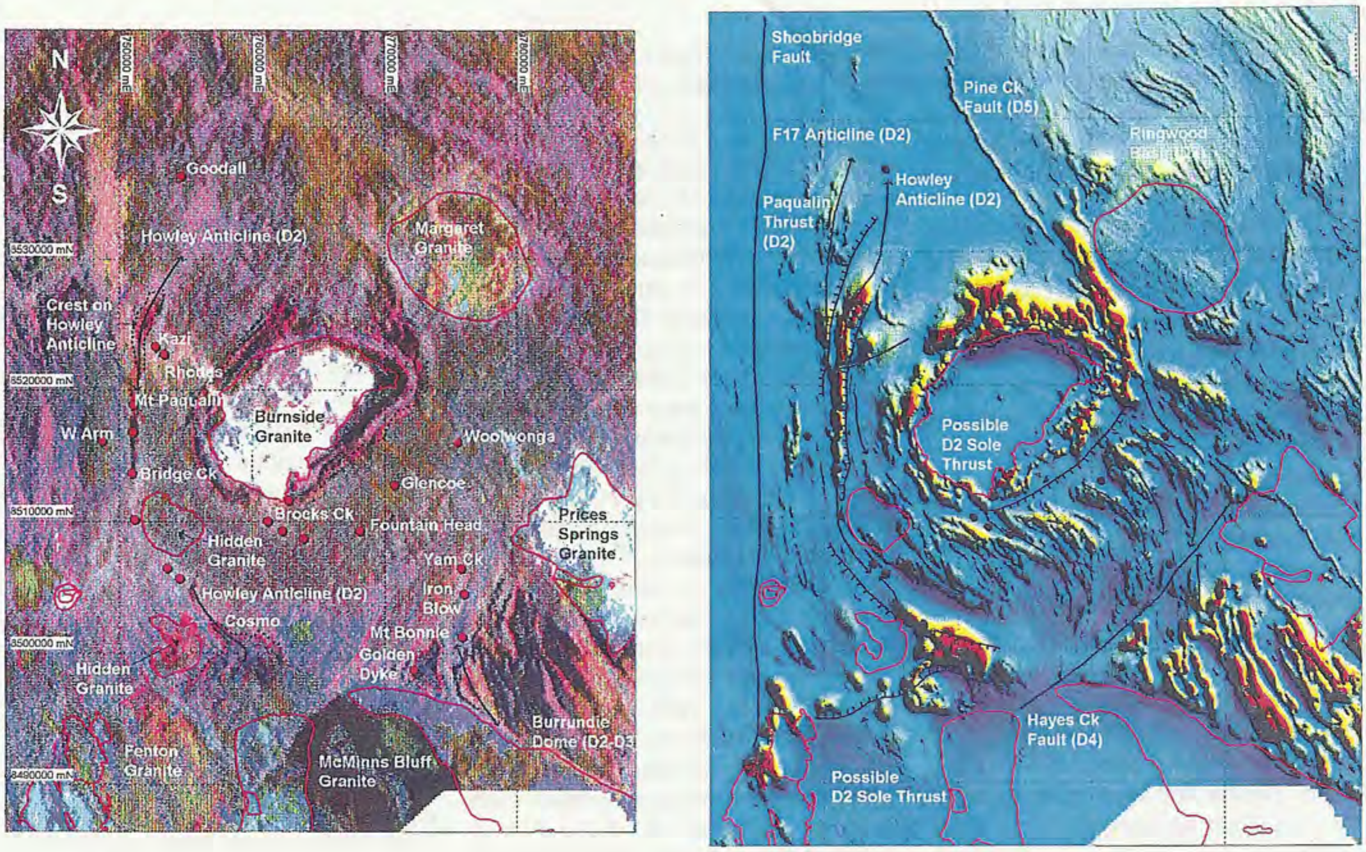
granite intrusion, structural and metamorphic setting, and the mechanical properties and geochemistry of the host rocks.

Regional Setting

Location and stratigraphy

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

Sedimentation and volcanism occurred between 2000 and 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), Stuart-Smith *et al.* (1987), Page



A B

Fig. 5.- **A**: Total count radiometric image of the Howley District. Note the high level radiometric anomalies, in white, associated with the younger granites such as the Burnside Granite in comparison to the older granites such as the Margaret Granite. Also the grouping of gold deposits along structures adjacent to the "Hot Granites". The linear trends in black that define the Burrundie Dome correspond to subcropping Zamu Dolerite and the brown/red linear trends immediately south of Cosmo Howley and around the Burnside Granite correspond to subcropping sulphidic, carbonaceous, black shale of the Upper Koolpin Formation.
B: Pseudo-colour image of the regional magnetic data covering the Howley District and Burrundie Dome with granite outlines. The granites can be distinguished by their low magnetic susceptibilities in relation to the increased magnetic anomalies, in red/white, peripheral to the granite plutons and possible hidden granites due to pyrrhotite in contact metamorphosed sediments.

Fig. 5.- A : Image radiométrique en coups totaux du District de Howley ; B : Image en fausses couleurs des données magnétiques régionales du District de Howley et du Dôme de Burrundie, avec position des granites.

and Williams (1988), Needham *et al.* (1988), 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, the Howley District, lies 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. 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 spatial 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 Finniss River Group, which have been subdivided into the Burrell Creek Formation, the Mount Bonnie Formation, the Gerowie Tuff, the Koolpin Formation and the Wildman Siltstone (Kruse *et al.*, 1990). A detailed stratigraphic column is shown on Figure 2 and a detailed geological fact map given in Figure 3. A more detailed discussion of the stratigraphy is given by Kruse *et al.* (1990), Ahmad *et al.* (1993), Stuart-Smith *et al.* (1993), and Klominsky *et al.* (1996).

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 (Fig. 3). The dolerites also form pods and sheets which cross-cut bedding, but have been metamorphosed and deformed along with the sedimentary rocks (Fig. 4B). 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 (Figs. 1 and 3; 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), 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 6 km. 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 (Fig. 1). The presence of numerous roof pendants, the distribution of the thermal aureole around the batholith (Fig. 1), and the presence of K-feldspar-cordierite facies contact mineral assemblages all suggest a shallow level of intrusion. 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 (Fig. 3).

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 youngest of which appears to be related to the gold mineralising event. The emplacement age of the oldest granite phases is taken to be 1835-1825 Ma, the emplacement age of the transitional granite phases is taken to be 1825-1818 Ma, and the emplacement age of the younger granite phases is taken to be ca. 1800 Ma (Klominsky *et al.*, 1996; Stuart-Smith *et al.*, 1993). This represents a ca. 20 m.y. time interval before the intrusion of the youngest suite. There is a spatial relationship between the younger granites and mineralisation with the most fractionated and often most radiogenic granites associated with the larger hydrothermal systems and gold mineralisation (Fig. 5A). For example, on a regional scale the clustering of gold deposits around the Burnside Granite contrasts with the lack of deposits around the Margaret Granite (Fig. 5A).

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. With an average heat production value of 5.79 mW/m^3 the Cullen Batholith has twice the average granite heat production at 2.5 mW/m^3, and the heat production of the younger granite suite, with values up to 10 mW/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 mW/m^3; Webb *et al.*, 1985), the radiogenic Bushveld granites (4.2-12.8 mW/m^3; McNaughton *et al.*, 1993), and the radiogenic granites from northern Australia (5.7-6.3 mW/m^3), invoked by Solomon and Heindrich (1992) 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 (Fig. 1), as interpreted from gravity, digital terrain, enhanced aeromagnetic and enhanced satellite maps, that several other granites are hidden at depth throughout the area (Fig. 3 and 5). 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, especially along the Howley Anticline. Detailed descriptions of the granites in the Howley District are given by Kruse *et al.* (1990), Ahmad *et al.* (1993), Stuart-Smith *et al.* (1993), and Klominsky *et al.* (1996).

Structural Geology

The earliest preserved structures in the area (D1) are 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. They are associated with a bedding-parallel spaced fabric, and because they 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. A more detailed description of the geosyncline scale regional deformation sequence and its relationship to the local deformation sequence in the Howley District is given by Johnston (1984).

The dominant structures in the area are D2 regional thrusts (Figs. 3 and 6), upright to overturned D2 folds such as the Howley Anticline and a series of cross-cutting anastomosing brittle-ductile shear zones and faults with associated quartz veins, such as the Shoobridge Fault, Hayes Creek Fault and the Pine Creek Fault (Fig. 3) that deform the earlier fold structures (Klominsky *et al.*, 1996). 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 (Figs. 3 and 5). In some areas, (e.g. around Bridge Creek, Fig. 3) these have been accentuated by cross folding related to D4. On a regional scale, however, the crests and troughs were formed during the D2 event due to the continuing interaction between D2 folding and thrusting. The D2 crests and troughs 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. 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 axial plane strikes to the northwest, but plunges to the south with the fold axial plane striking to the north in the Bridge Creek area (Fig. 7; Klominsky *et al.*, 1996).

A prominent axial planar cleavage is present in the finer grained sedimentary rocks, and can vary in orientation due to refolding of the fold axes by D3 and D4 folds, between 330° to 010° (e.g. the

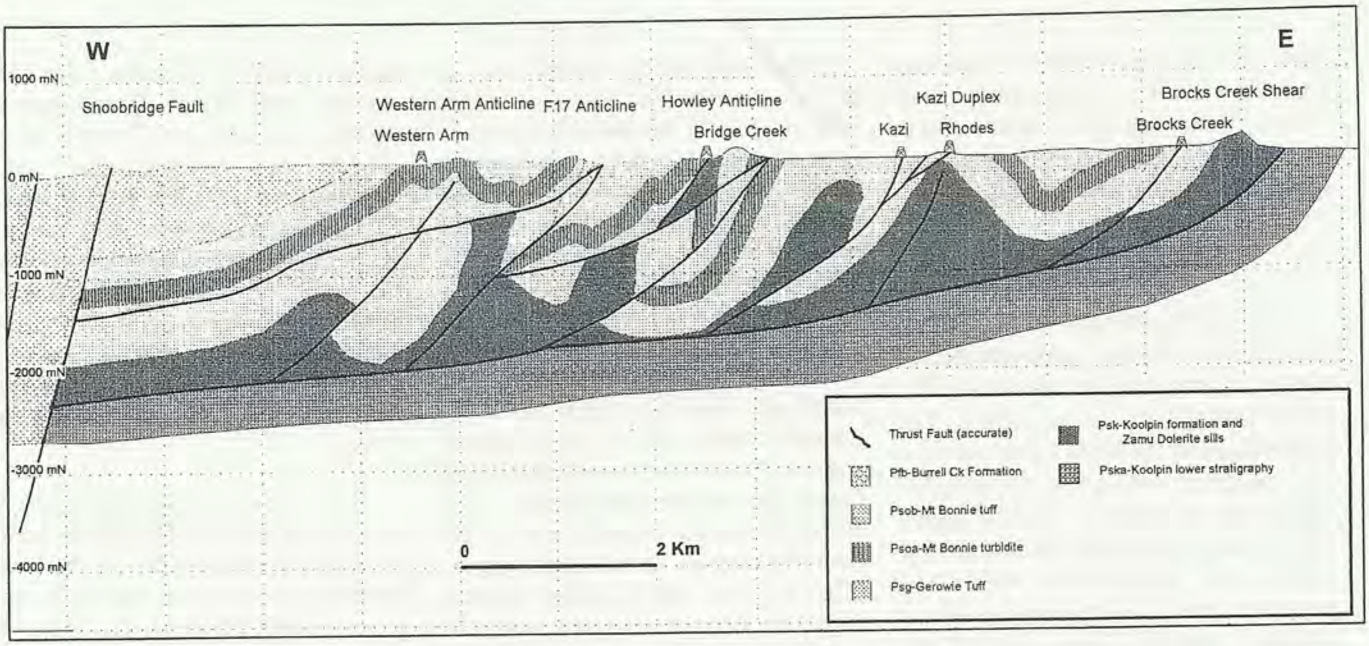


Fig. 6.- A west to east interpreted cross-section derived from Northern Gold mapping showing the relationship of gold mineralisation to D2 buckle folds and thrust duplex systems in the northwestern part of the Howley District.

Fig. 6.- Coupe interprétative montrant les relations entre la minéralisation aurifère et les plissements par flexion dans la partie nord-ouest du District de Howley.

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 (Figs. 4B and 6). 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 (Fig. 4B). The short limbs of these folds are commonly sheared and veined (Fig. 4C; Klominsky *et al.*, 1996).

The D2 thrust faults contain well developed down-dip stretching lineations, C-S structures (Fig. 4C), asymmetric pressure shadows and en echelon vein sets (Fig. 4D). These structures all confirm that movement along these zones was dominantly reverse (Fig. 4), although a minor component of oblique slip movement may be present locally that may be the result of D4 reactivation. The relationship between the thrusts and folds suggests that these structures formed contemporaneously as part of duplex thrust systems (Fig. 6). The sole thrust of this system appears to be localised along the contact between the Wildman Siltstone and the Lower Koolpin Formation which (Figs. 3 and 5B), 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 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 (Fig. 3). There is a well-developed frontal ramp in this area, with a series of overturned anticlines separated by a series of thrusts rather than synclines (Figs. 3 and 6).

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

D4 deformation in the Howley District is associated with the intrusion of the Cullen Batholith, forming open east-west trending folds around the margins of the Cullen Batholith (e.g. the open folds that refold the Howley Anticline around the Burnside Pluton; Figs. 3 and 5B). This deformation event formed the broad dome and basin structures evident around the Burnside Granite and in the Burrundie Dome area (Fig. 5), and is probably part of the Shoobridge event as described by Stuart-Smith *et al.* (1993). Deformation also appears to have been concentrated in northwest-trending strike- slip zones around granite margins. Overprinting slickensides and lineations on D2 thrusts and on bedding planes indicate that D2 folds and thrusts were reactivated in the roof zone and margins of the granites during intrusion. This caused localised tightening of D2 folds due to bedding parallel shearing and movement along duplex thrusts. Faults related to D4 deformation also offset D2 and D3 structures. These faults form conjugate sets and have dextral or sinistral strike-slip movements (e.g. the Shoobridge Fault 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 (Fig. 5B), and may even be reactivated faults related to the initial opening of the geosyncline. 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, respectively. Prismatic andalusite porphyroblasts with remanent chiastolite crosses have been recognised at Bridge Creek, and appear 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 gives a mean temperature for the regional metamorphism of 360°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 have been largely over-printed 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.

The contact aureole around some of 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 (Fig. 1). 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 external boundary of the hornblende hornfels facies rocks is generally within 500 m of the granite contacts. However, in some areas (e.g. Cosmo Howley and the Western Arm) this facies extends laterally over 10 km from the nearest outcropping granite (Fig. 1). 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, resulting from the contact metamorphism of pyrite, in shale and tuff, and metamorphic magnetite in greywacke, results in enhanced magnetisation in this and the hornblende hornfels facies zones and these facies can be mapped using aeromagnetic data (e.g. Fig. 5B). 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°C whereas the biotite part of the albite-epidote hornfels at Bridge Creek occurred at lower temperatures, about 400-450°C (Cooper, 1990). Contact metamorphism at Cosmo Howley reached the hornblende hornfels facies with temperatures, using the assemblage K-feldspar+andalusite+biotite+quartz, calculated by Matthai *et al.* (1995a) in excess of 550°C. However, many of the contact metamorphic assemblages are strongly retrogressed (Matthai *et al.*, 1995a), and inclusions of contact metamorphic minerals in gold-bearing quartz veins at Cosmo Howley suggests that the gold mineralisation post-dated the peak of contact metamorphism. Similar retrogression of contact metamorphic assemblages occurs at Bridge Creek (Cooper, 1990), Western Arm (Zerovich, 1994) and Kazi (Clayton, 1996).

Rare K-feldspar-cordierite hornfels rocks to the south of the Howley District suggest that the granites of the Cullen Batholith intruded at a depth of less than 6 km (Stuart-Smith *et al.*, 1993). The distribution of the metamorphic isograds around the Burnside Granite (Fig. 1) indicates 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 (Figs. 3 and 5).

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 occurs in linear belts up to 20 km in length that are within but trend across and out of the thermal aureole of the Burnside, Fenton and Shoobridge Granites (Figs. 1 and 3). 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 (Fig. 3). Gold mineralisation occurs in all units of the South Alligator Group and Burrell Creek Formation in the Howley District, and is related spatially to D2 regional anticlines, northeast-trending strike-slip shear zones and duplex thrusts (Figs. 3 and 6; e.g. Woolwonga, Fountain Head, Brocks Creek, Cosmo Howley). The total resource base for all deposits in the Howley District, including past

Mine	Discovery	Resources	Au Oz	Host Rock	Structure	Length	Width	Depth
COSMO HOWLEY	1873 Historic alluvial/eluvial and hard rock mining	Production of 6.9 Mt ore @ head grade of 2.14 g/t from Resource 14.6 M @ 3.01 g/t. Underground	1,414,632	Middle Koolpin Formation Iron rich mudstone.	Stratiform quartz vein and replacement lodes associated with thrust faulting in the NW trending and plunging Howley anticline. West limb dips 60 degrees to the west and east	>800m	Hinge 100-150m	Open below 600m from the surface
BROCKS CREEK Faded Lily and Alligator	1872 Historic alluvial/eluvial and hard rock mining	Resource 18.4 Mt @ 1.41 g/t Au .	834,118	Mt Bonnie Formation Greywacke Siltstone + Tuff.	Steep southerly dipping quartz veins in shear zone in south plunging anticline.	>4000m	50m	Open below 160m from the surface
WOOLWONGA	1871 Historic alluvial/eluvia and hard rock mining	Production of 2.98 Mt ore @ head grade 2.51 g/t.	222,000	Mt Bonnie Formation Greywacke + Siltstone.	Saddle reefs, quartz stockworks and discordant veins in tight southeast plunging anticline with bounding footwall thrust. Mineralised envelope subvertical.	>1500	30	Open below 175m from the surface
GOODALL	1981 Helicopter rock chip	Production of 4.095Mt ore @ head grade 1.99 g/t.	228,000	Burrell Creek Formation Shale, Greywacke + Siltstone.	Subvertical, north trending sheeted vein sets within shear/fault fracture zone on eastern limb of Howley Anticline.	>1500	15	Open below 150m from the surface
Chinese Howley	1871 Historic alluvial/eluvia and hard rock mining	Resource of 7,000, 000 @ 1.6 g/t Au .	360,000	Gerowie Tuff siltstone, tuff and chert and Zamu dolerite.	Quartz stockworks and discordant veins in a wide duplex system on the Howley Anticline.	2500	300	150 open
Kazi	1994 soil and magnetics	Resource of 1,583,360 @ 2.07g/t Au .	105,124	Gerowie Tuff siltston, tuff and chert.	Quartz veins parallel to a D2 thrust with associated flat tension veins associated with arsenopyrite alteration zones.	200	15	180 open
Western Arm	1989 soil anomaly	Resource of 2,696,450 @ 1.48 g/t Au .	128,368	Mt Bonnie Formation turbidite.	Saddle reefs, quartz stockworks and discordant veins in tight north plunging parasitic fold on D2 anticline.	1100	20	100 open
Fountain Head	1883 Historic alluvial/eluvia and hard rock mining	Resource of 1,601,150 @ 1.70 g/t Au .	87,631	Mt Bonnie Formation turbidite.	Saddle reefs, quartz stockworks and.discordant veins in tight southeast plunging parasitic fold on D2 anticline.	800	12	170 open
Bridge Ck	1871 Historic alluvial/eluvia and hard rock mining	Resource of 1,635,000 @ 1.56 g/t Au .	82,242	Gerowie Tuff siltstone, shale, Upper Koolpin carbonaceous shale and Zamu Dolerite	Subvertical, south plunging sheeted vein sets within shear/fault fracture zone in the hinge of the Howley anticline.	700	15	220 open
Rhodes	1989 soil and magnetics	Resource of 771,150 @ 1.88 g/t Au .	46,544	Gerowie Tuff, siltstone and chert and Zamu dolerite.	Quartz veins in D2 thrusts and splays localised along the hangingwall contact of a dolerite sill.	300 open	20	160 open
Howley Ridge	1871 Historic alluvial/eluvia and hard rock mining	Resource of 1,214,000 @ 1.34 g/t Au .	52,247	Gerowie Tuff, siltstone and chert and turbidites of the Lower Mt Bonnie Formation.	Saddle reefs, quartz stockworks and discordant veins in tight south plunging Howley anticline.	800	4	70
Big Howley	1871 Historic alluvial/eluvia and hard rock mining	Resource of 348,700 @ 2.11 g/t Au .	23,656	Gerowie Tuff shale, chert, tuff and greywacke.	Saddle reefs, quartz stockworks and discordant veins in tight north plunging Howley anticline.	450	12	120 open
Yam Ck	1870 Historic alluvial/eluvia and hard rock mining	Resource of 1,457,000 @ 1.28 g/t Au .	59,960	Burrell Creek Formation Shale, Greywacke + Siltstone.	Stacked en echelon quartz veins confined to coarse sandstone beds in turbidites on west limb of Yam Ck anticline.	1200	18	70 open
Iron Blow	1873 Hard rock mining	Resource of 1,069,315 @ 2.16 g/t Au includes 6.8% Zn, 1% Pb and 117 g/t Ag.	74,259	Mt Bonnie Formation shale, siltston and greywacke.	West limb of Margaret Syncline. Lode dips 40 degrees to the west and trends 030 degrees.	150	30	200
Mt Bonnie	1902 Historic hard rock underground mining	Resource of 647,568 @ 1.69 g/t Au includes 7% Zn, 1.8% Pb and 186 g/t Ag.	35,185	Mt Bonnie Formation shale, siltston and greywacke.	East limb of Margaret Syncline. Lode dips 75 degrees to the west and trends 010 degrees.	150	15	90 open
Glencoe		Resource of 300,000 @ 2.3 g/t Au.	23,000	Mt Bonnie Formation turbidite.	Saddle reefs, quartz stockworks and discordant veins in tight south east plunging D2 anticline.	1200	12	100 open
Golden Dyke		Production of 100,000 @ 7.5 g/t Au.	24,000	Middle Koolpin Formation Iron-rich mudstone.	Stratiform quartz vein and replacement lodes associated with ironstones.	200	4	50

Table 1.- Summary of resource and production figures from the main gold deposits in the Howley District.

Tabl. 1.- Ressources et productions des principaux gisements d'or du District de Howley.

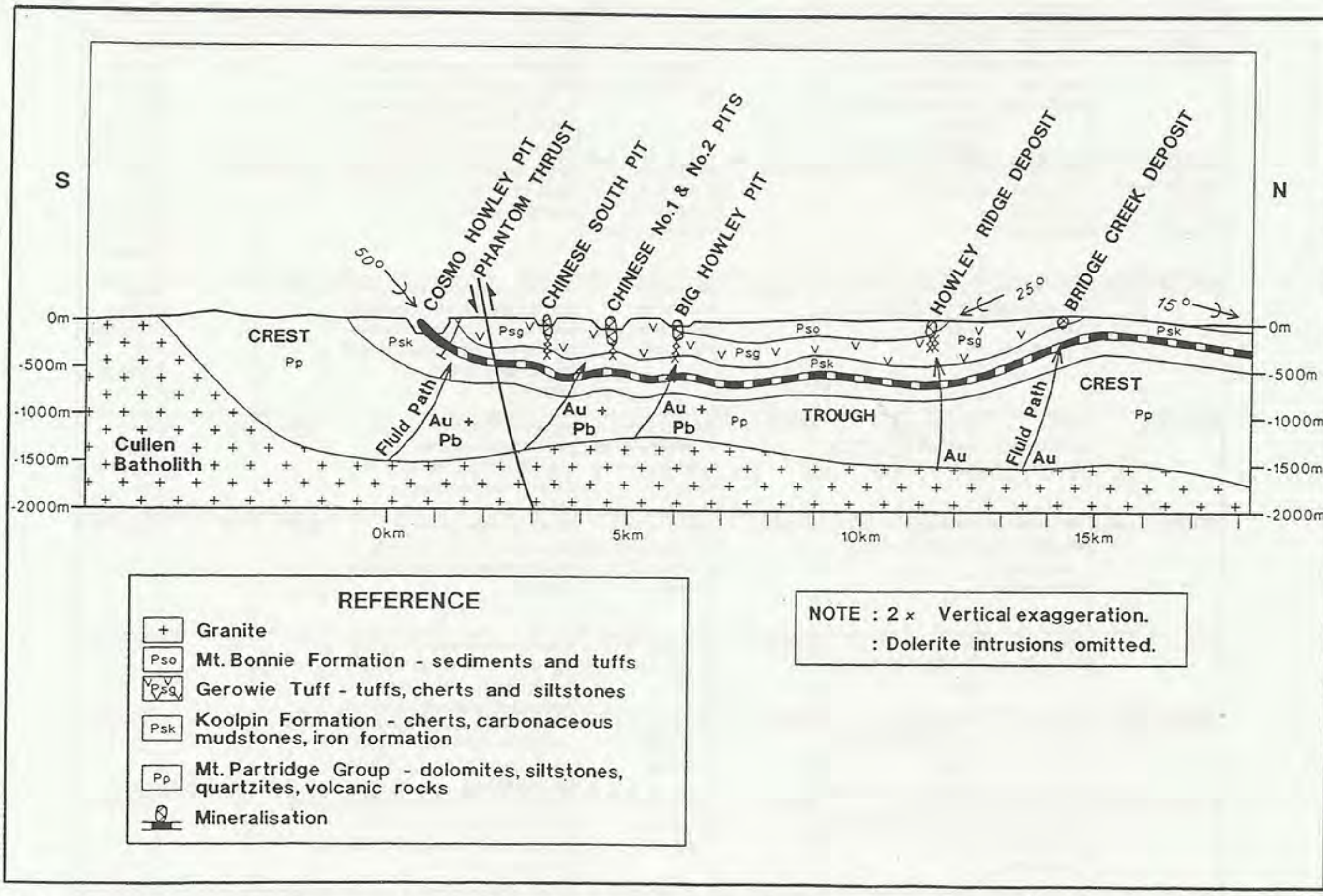


Fig. 7.- Long section along the hinge zone of the Howley Anticline between the Bridge Creek deposit and the Cosmo Howley gold mine. Note the non-cylindrical nature of the D2 folding results in troughs and crests along the length of the Howley Anticline, and the relationship of the major gold deposits to the crests.

Fig. 7.- Section le long de la zone charnière de l'anticlinal de Howley entre le gisement Bridge Creek et la mine Cosmo Howley Gold.

production and current mining operations, is about 5 million ounces of gold (see Table 1 for details of production and resources).

Deposit Descriptions

The main gold deposits in the area are located as a line of deposits along the D2 Howley Anticline (Figs. 3 and 5A). The largest is located at Cosmo Howley where gold mineralisation is contained within the Middle Koolpin Formation, which consists of alternating ironstone and mudstone units (Fig. 4B). The main gold mineralisation appears to have preferentially replaced the ironstones, especially towards the top of the formation. The mineralisation is controlled by the Howley Anticline which plunges 50° to the north-west in the area of the mine (Fig. 7). On a broad scale the gold mineralisation is stratabound but within the ironstone units is confined to parasitic folds in the hinge zone of the Howley Anticline (Fig. 4B). Gold is spatially associated with cross-cutting 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 (Matthai *et al.*, 1995a). The early veins appear to be synchronous with D2, have been recrystallized during contact metamor-phism and are barren, whereas the veins later than the gold bearing quartz 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 ironstones. Since, as described by Matthai *et al.* (1995a), fragments of garnet, K-feldspar and andalusite are incorporated within rock fragments in these 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 ironstones are barren, a chemical host-rock control on mineralisation by the carbonaceous Upper Koolpin shale has been proposed by Matthai (1995a, b) with the gold mineralisation being introduced by high temperature fluids derived from the McMinns Bluff Granite during intrusion.

The Chinese Howley group of deposits are located north along strike from Cosmo Howley, and about 150 m stratigraphically above the ironstones that host the mineralisation at Cosmo Howley (Fig. 7). The gold mineralisation occurs wthin, and in narrow alteration zones around, a stockwork of subvertical quartz veins within shear zones that are parallel

to the axial plane of the Howley anticline, 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 only 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 (Fig. 4A). There is also no obvious host-rock control, with no association of ore shoots with carbonaceous-rich sedimentary rocks.

The Big Howley deposit occurs 3 km north of the Chinese Howley group, again higher in the stratigraphy (Fig. 7). 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 Bridge Creek deposit lies about 8 km north of, and lower in the stratigraphy than 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 (Figs. 3 and 7). 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 stockwork 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 in mineralised rocks are 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 area east of the Burnside Granite hosts three ore bodies,' Woolwonga, Fountain Head and Glencoe, which are associated with regional scale D2 anticlines (Figs. 3 and 5A). All three deposits are situated on the margins of crests on D2 anticlines (Figs. 3 and 5B) that appear to be related to blind duplex thrusts, possibly related to a sole thrust which is marked by the disappearance of these folds towards the Burnside Granite to the west (Fig. 5B). 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 (Fig. 4C). 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 is located 5 km west of Bridge Creek (Figs. 3 and 5A). The mineralisation lies on a parasitic fold on the southern flank of a D2 anticline. 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 sets are barren; the first predates contact metamorphism and is recrystallised whereas the second appears to be related to granite intrusion, containing muscovite and intergrown quartz and K-feldspar. These veins, although sulphide-rich, are pegmatitic in nature. Gold occurs in quartz veins and their alteration selvedges in saddle reefs and reverse faults (Fig. 4D). The mineralisation is associated with silicified wallrock and pyrite-arsenopyrite alteration. The higher grade zones are confined to bedding-parallel laminated quartz veins that cut, and are cut by, veins containing K-feldspar and pyrite and a haematite and arsenopyrite alteration selvedge. Sulphides associated with gold mineralisation at Western Arm are, in order of decreasing abundance, pyrite, chalcopyrite, arsenopyrite, pyrrhotite, sphalerite and galena. Visible free gold occurs in late fractures, spider veinlets, and near the contact between carbonaceous mudstone and quartz veins (Fig. 4D).

A group of gold deposits occur in the northern part of the Howley District within the northern part of the contact aureole of the Burnside Granite (Figs. 1 and 5). At Goodall mineralisation occurs on the southern margin of a crest on a regional D2 anticline (Fig. 3), 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 units, 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 occurs in a D2 duplex system (Figs. 3 and 6). The gold mineralisation occurs in massive sulphide veins in altered Gerowie Tuff and Zamu Dolerite, in shear-parallel quartz veins and in en echelon veins in the hanging wall of D2 thrust planes that dip 50° to the west. Gold occurs as fine particles in both the quartz veins and with their alteration selvedge. There is a strong correlation with arsenopyrite at Kazi with high grade gold veins (30 g/t gold) associated with up to 15% arsenopyrite. Other sulphides at both deposits include pyrrhotite, galena, and pyrite. Chlorite-sericite-biotite alteration associated with the mineralised zones is common and pre-existing albite-epidote hornfels facies assemblages are also retrogressed to a similar assemblage.

The Golden Dyke to Mount Bonnie group of mines occur in the east of the area, associated with the Hayes Creek fault (Figs. 3 and 5). In contrast to all other deposits in the Howley District, the Mount Bonnie and Iron Blow mines are polymetallic. 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. Gold mineralisation at Mount Bonnie and Iron Blow is present in late fractures not associated with base-metal mineralisation, and fluid inclusion and isotope data (Ahmad, 1993) implicate a significant metamorphic and magmatic input to the fluids responsible for mineralisation and that gold mineralisation possibly postdates the base-metal mineralisation. Further work is required at both these mines to establish the timing of base-metal and gold mineralisation.

The Brocks Creek gold deposits occur along the Brocks Creek-Zapopan Anticline within the immediate contact aureole of the Burnside Granite (Figs. 1 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 it 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 (Fig. 3). 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 (Fig. 3). All these prospects are 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 of Mineralisation

The timing of the gold mineralisation can be constrained by stratigraphic, structural and geochronological data. The cross-cutting or replacement nature of mineralisation, hosted by Zamu Dolerite, indicates that it postdates the intrusion of the Zamu Dolerite. Veins hosting gold mineralisation in shear zones commonly overprint S2 and S3, but are commonly boudinaged and refolded, suggesting that mineralisation was late in the deformation sequence, 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 predated the mineralisation because alteration associated with some gold deposits within the contact aureoles of granites retrogress the contact metamorphic assemblages (e.g. Cosmo Howley, Goodall, Western Arm and Brocks Creek). Hydrothermal activity and D4 deformation, which are synchronous with, and postdate, granite intrusion appear to be synchronous with gold mineralisation. 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 younger Shoobridge Granite.

Mineralisation Style

The style of gold mineralisation can be subdivided into a continuum between two end-member types (Fig. 8), with the deposit style directly related to the host structure, and to the contrast in host rock competency and mineralogy. Those rocks that are brittle in turbidite sequences form vein-stockwork mineralisation (e.g. Western Arm, Fountain Head, Woolwonga and Goodall; Fig. 8), whereas those with both contrasting competency and geochemistry form stratabound vein and replacement deposits (e.g. Cosmo Howley, Kazi and Golden Dyke; Fig. 8).

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 (e.g. Brocks Creek, Kazi and Rhodes deposits).

Alteration and Ore Fluids

A distinctive symmetric alteration zonation has been described for dolerite-hosted mineralisation in some deposits in the Howley District, with increasing alteration intensity towards the centre of the zone. There is a marked depletion in elements such as Ca, Mg and Cu, and strong enrichment in the elements such as K, Fe, S, Ba, Au, As, Bi, W and Sb within proximal alteration zones (Cooper, 1990). Alteration assemblages grade from a distal chlorite- and actinolite-dominated assemblage, to a bleached albite-rich zone, and into a zone of biotite growth adjacent to the vein. 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). 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±CH_4-rich fluid at moderate-high temperatures and 1 kbar (e.g. 265-365°C at Western Arm; Ho and Shepherd, 1993). Late fractures, which contain visible gold mineralisation, record the passage of a second higher salinity fluid in which $CaCl_2$±$MgCl_2$ were dominant

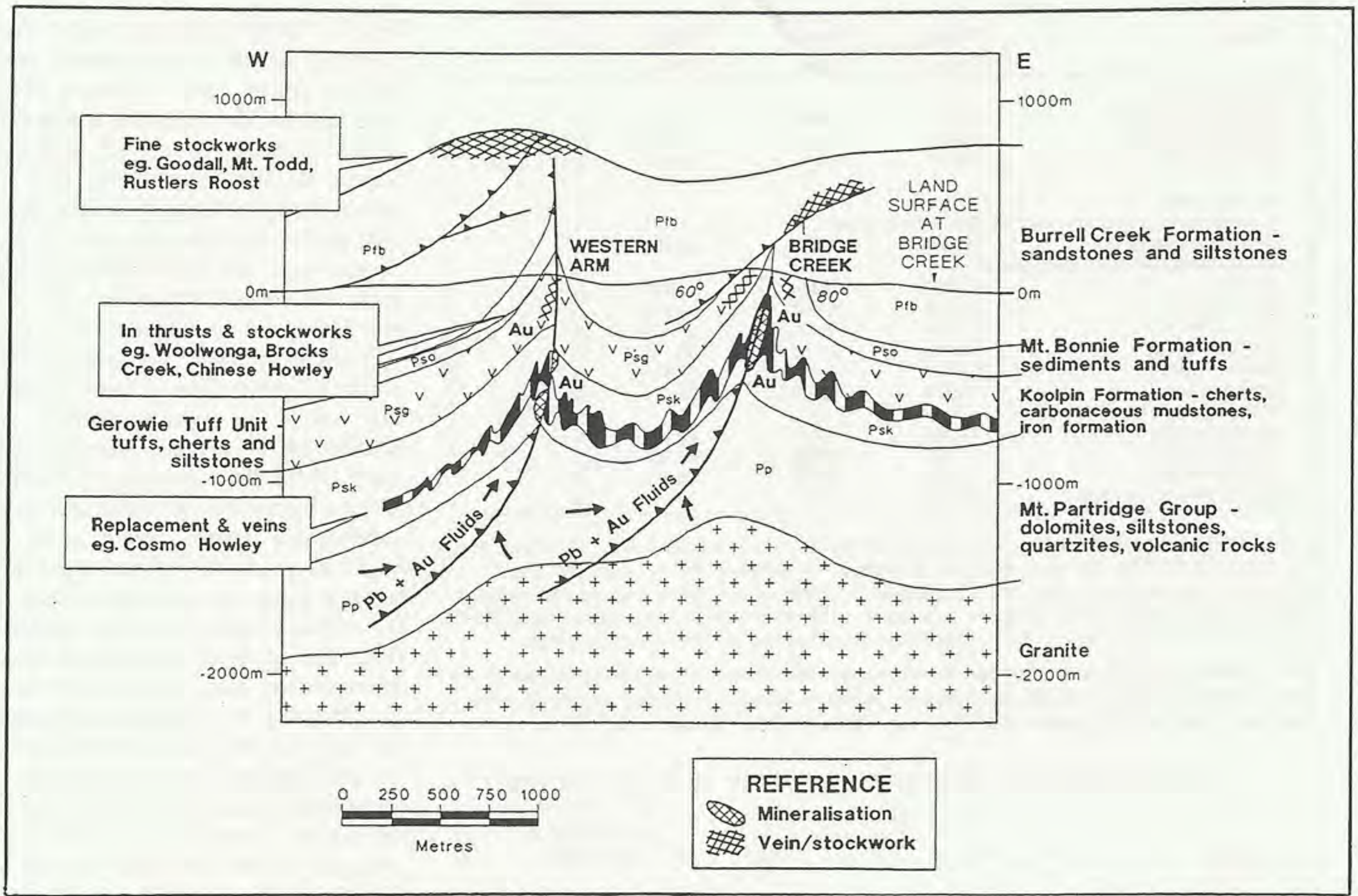


Fig. 8.- A summary of the various styles of mineralisation in the Howley District in relation to other deposits in the Pine Creek Geosyncline.

Fig. 8.- Résumé des différents styles de minéralisation dans le District de Howley, en relation avec les autres gisements du Géosynclinal de Pine Creek.

over NaCl with slightly lower deposition temperatures (e.g. 195-280°C at Western Arm; Ho and Shepherd, 1993). Gold appears to have been introduced during the later event. It is interpreted that the early higher temperature fluid deposited quartz veins and some sulphides, including arsenopyrite (e.g. Matthai *et al.*, 1995a, b; Clayton, 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 early and late fluids 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 also suggest a mixed magmatic and metamorphic source for the fluids responsible for gold mineralisation (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‰ to + 10‰ CDT, whereas δD values in fluid inclusion water ranged from +27‰ to -57‰ SMOW, and the calculated ranges of fluid $\delta^{18}O$ were +5.5‰ to +10.3‰ SMOW implying a mixed magmatic-metamorphic source.

Lead isotope studies by Sheppard (1992), Klominsky *et al.* (1996), Matthai *et al.* (1995a) and this study (Table 2) show that ore-related sulphides collected from a variety of hydrothermal deposits in the Pine Creek Geosyncline, and the initial ratios from granites belonging to the Cullen Batholith, fall on a linear trend (Fig. 9). It is clear from these data that many of the gold deposits have similar initial lead, whereas the spatially related granites have a range of initial lead which is different from the deposits (Fig. 9). This indicates that if the granites contributed lead to the ore fluids, then the contribution was minor. In addition, the relatively homogeneous lead isotopic composition for a significant number of deposits and prospects implies both coeval mineralisation and an unusually homogeneous lead source on a scale of 100 km.

The trend in lead isotope compositions for ores and granites is subparallel to the heterogeneity expected from Archaean basement at the time of mineralisation (Fig. 9). Given that the sedimentary material in the geosyncline is inferred to have derived from the Archaean basement, the dominant source of lead in the deposits is probably either the stratigraphic succession and/or the Archaean basement rocks. It is concluded, therefore, that lead in the ores is not dominantly from fluids exsolved from the granites during crystallisation, but from metamorphic fluids from the dewatering of the stratigraphic section adjacent to granites of the Cullen Batholith during and immediately following contact metamorphism.

Sample	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Ref.
Granite initial Pb				
Mt Bundey Granite	15.131	15.146	35.268	a
Burnside Granite	15.604	15.312	35.543	b
Cullen Batholith	15.696	15.341	35.395	c
Ore sulphides				
Mineralisation within vein cutting Burnside Granite				
Old prospect trenches gn	16.267	15.542	36.070	b
Howley Anticline and nearby areas				
Goodall py	16.037	15.460	35.573	d
Big Howley gn	16.044	15.451	35.235	b
Bridge Creek gn	16.186	15.481	35.822	b
Brock's Creek gn	16.480	15.525	36.183	b
Cosmo Howley po	16.163	15.487	35.435	c
Woolwonga gn	15.924	15.425	35.415	b
Mt Shoobridge area				
Lead prospect gn	16.230	15.492	35.888	b
Barret's Mine gn	16.222	15.488	35.907	b
Full Hand Mine gn	16.160	15.476	35.842	b
Pyromorphite prospect gn	16.188	15.494	35.891	b

Table 2.- Lead isotope data for ore sulphides from the Howley area (Klominski *et al.*, 1996; this study), and the initial Pb from the least radiogenic K-feldspar compositions for the Burnside Granite, Mt. Bundey Granite (Sheppard, 1992) and Cullen Batholith (Matthai *et al.*, 1995a). Only the least radiogenic sulphide data for each deposit are shown. References: a: Sheppard (1992); b: Klominsky *et al.* (1995); c: Mattahi *et al.* (1995a); d: this study. Abbreviations: gn: galena; po: pyrrhotite; py: pyrite.

Tabl. 2.- Données isotopiques du plomb pour les sulfures des minerais de la zone de Howley (Klominski et al., *1996 et cette étude) et plomb initial des feldspaths potassiques les moins radiogéniques pour le granite de Burnside, de Mt Bundey (Sheppard, 1992) et pour le batholite de Cullen (Matthai* et al., *1995a).*

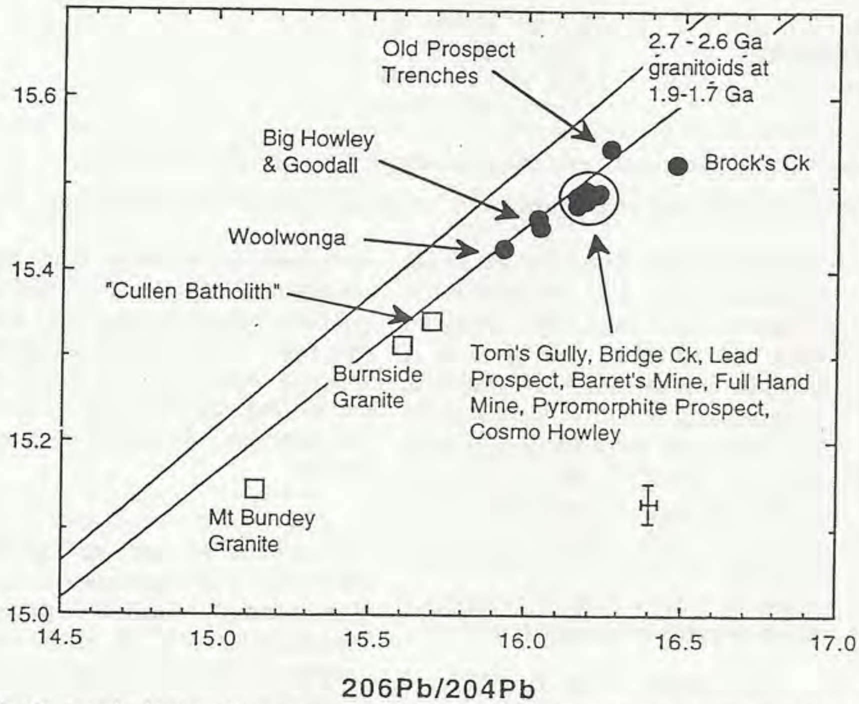


Fig. 9.- Common lead isotope diagram comparing ore fluid and granite initial lead compositions (Table 2) and calculated range of lead from a Late Archaean granitoid basement at ca. 1.8 Ga (modelled from data in Wang *et al.*, 1993).

Fig. 9.- Diagramme plomb commun comparant les compositions initiales en plomb du fluide minéralisé et du granite (Tabl. 2).

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 that formed above thrust ramp and duplex structures (e.g. Western Arm, Bridge Creek, Woolwonga, Brocks Creek and Cosmo Howley; Fig. 6), and in rare cases within duplex thrusts (e.g. Kazi and Rhodes; Fig. 6). Suitable trap sites within these structures appear to be required, hence the stratabound nature of some of the gold deposits. Many deposits appear to be related to crests on the D2 anticlines which, as discussed above, may be related to duplex thrust systems at depth (Fig. 6). These thrusts may have acted as channelways for hydrothermal fluids from the larger structures into the anticlines and subsequent trap sites (Fig. 8). In the lower stratigraphy of the South Alligator Group, Zamu Dolerite sills, and in the upper stratigraphy, the distribution of deposits suggests that many of the thick greywacke horizons have acted much in the same way as an impermeable horizon would in an oil trap. This has locally focused fluid flow to the margins of crests and troughs on D2 anticlines above blind D2 duplexes (Fig. 8), and hence the periodicity of mineralisation (e.g. along the Howley Anticline; Fig. 3). Consequently, the style and to some extent the potential size of the gold deposits depends on the size of the hosting structure (e.g. Table 1) and on competency contrasts of particular rock packages, which commonly depend on the stratigraphic depth 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 present during D2 and reactivated during D4 in the Howley District (Fig. 6), a floor thrust and a roof thrust can be 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, and these are progressively localised in more competent units in the sequence (e.g. 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. The numerous anticline-syncline pairs developed in the Burrell Creek Formation, which represents the upper sequence of Liu 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.

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 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 limbs of the buckle folds. This regime would result in fluid flow from the high stress areas on the overturned limbs to the lower stress areas in the hinge zones of anticlines and hanging-wall limb of the folds. The 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 D2 structural sequence in the Howley District, but also the possible fluid flow and localisation of gold deposits in anticlines in the margins of the granites of the Cullen Batholith during D4 reactivation as a result of compression in the contact zone of the intruding granites (e.g. Fig. 8).

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 (e.g. Fig. 8). 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 as traps. This can explain, in part, the localisation of gold deposits in particular rock packages, e.g. below dolerite sills, the carbonaceous shales of the Upper Koolpin Formation or thick greywacke units in the Mount Bonnie Formation.

As in examples discussed by Sibson (1996), the pre-existing structural sequence in the Howley District can be regarded as a fault-fracture mesh that provided conduits for large-scale hydrothermal fluid flow. It was not until after granite intrusion and associated metamorphic dewatering in the contact aureole of the Cullen Batholith that the hydrothermal system deposited gold mineralisation in these 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 in the Howley District and may also be applied to other areas in the Pine Creek Geosyncline.

Genetic Model

The spatial association of mineralisation with granites and their thermal aureoles suggests that many of the mineral deposits were formed during the intrusion, or during the cooling, of granites of the Cullen Batholith. In particular, deposits characterised by relatively high or medium formation temperatures, such as tin and gold mineralisation, must have been associated with these stages. Metamorphic and experimental data suggest that wallrock temperatures adjacent to an intruding granite magma will be in the range between 900°C to 600°C (Mason, 1990) and will cool in a relatively short period of time (less than tens of millions of years). However, the decay of radioactive elements provides a permanent "heat engine" inside each granite pluton (e.g. Fehn *et al.*, 1978; McNaughton *et al.*, 1993). 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 (McNaughton *et al.*, 1993). 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.

The preferred model for gold mineralisation in the Howley District is that early quartz was deposited from overpressured fluids during continuing movement along D2 structures during D4 reactivation, in response to the intrusion of the late 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, focusing 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 $CO_2 \pm CH_4$-rich fluids, probably derived from the devolitisation of graphitic units in the contact aureoles of the granites, mixed with moderately saline, aqueous magmatic fluid exsolved from the granite (Klominsky *et al.*, 1996). Fluid mixing, in conjunction with pressure decreases associated with failure along faults and fractures, induced phase separation and deposition of quartz sulphide veins ± K-feldspar veins at about 450-490°C (Klominsky *et al.*, 1996). Fluids increasingly in equilibrium with the metasedimentary rocks, were focused along reactivated thrust faults through the relatively oxidised sedimentary rocks comprising the base of the sedimentary sequence.

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 chemically reactive wallrocks if present (e.g. the ironstones of the Middle Koolpin Formation). This may account for the formation of saddle-like structures at various levels along a fold such as the

Howley Anticline (e.g. Fig. 8). 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 lead and possibly gold from the surrounding metasedimentary rocks. These sedimentary rocks were not only the dominant 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 within the hornblende and albite epidote hornfels facies zones of the contact aureole of the Cullen Batholith. Structural models similar to those proposed for other mesothermal styles of gold mineralisation may therefore apply (e.g. 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. Some deposits, such as Cosmo Howley, can be classified as part of the mesothermal stratiform to stratabound type of gold deposits in ironstone or iron-rich metasedimentary rocks (e.g. Murchison Province, Western Australia; Morro Velho, Brazil; Northeastern 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 (e.g. 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 (e.g. the Howley District) rather than areas with buckle folding (e.g. the Adelaide River District) or basin and dome structures (e.g. the Burrundie Dome). The presence of shear systems linking anticlines higher in the sequence appear to have provided the ideal fluid focusing 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 ironstones 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 in the hornblende hornfels facies zone of the contact aureole of the Cullen Batholith, 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 possible hydrothermal pathways that 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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