Granites with similar petrological and chemical characteristics were also emplaced around 700 Ma and include the Mount Crofton Granite Complex (Paterson Province) and even around 300 Ma during the Phanerozoic (Tasmania, N. Queensland).

This group is metallogenically very significant among Australian Proterozoic granitic rocks. Some granites contain vein Sn, W, Cu and U deposits, while Au deposits are located near the contact aureoles (Tanami, The Granites, Tarcoola, Telfer, Cullen Mineral Field). The dominant composition of these granites is monzogranite, containing between 70 to 75 % SiO_2. These felsic magmas have marginal I-S type affinities. The chemical variation within these highly siliceous granites is controlled by fractionation and has high-K calc-alkaline to shoshonitic tendencies. These granites may also be classified as "metalliferous", uraniferous, or as high heat production granites. The Proterozoic "metalliferous" plutons differ from their younger equivalents in having generally lower levels of Sn, which may indicate chemical differences in the source area for the granites.

A multi-element primordial-mantle-normalised abundance diagram, Fig. 22 for the Cullen Batholith granites indicates a similar composition for all the igneous suites, suggesting a similar source composition. This spidergram also indicates that the degree of geochemical evolution of the Cullen Batholith is very similar to some distal Phanerozoic granites (eg. Cairngorm granite in Scottish Caledonides and Cornubian Batholith in south-western England, Halls, 1994).

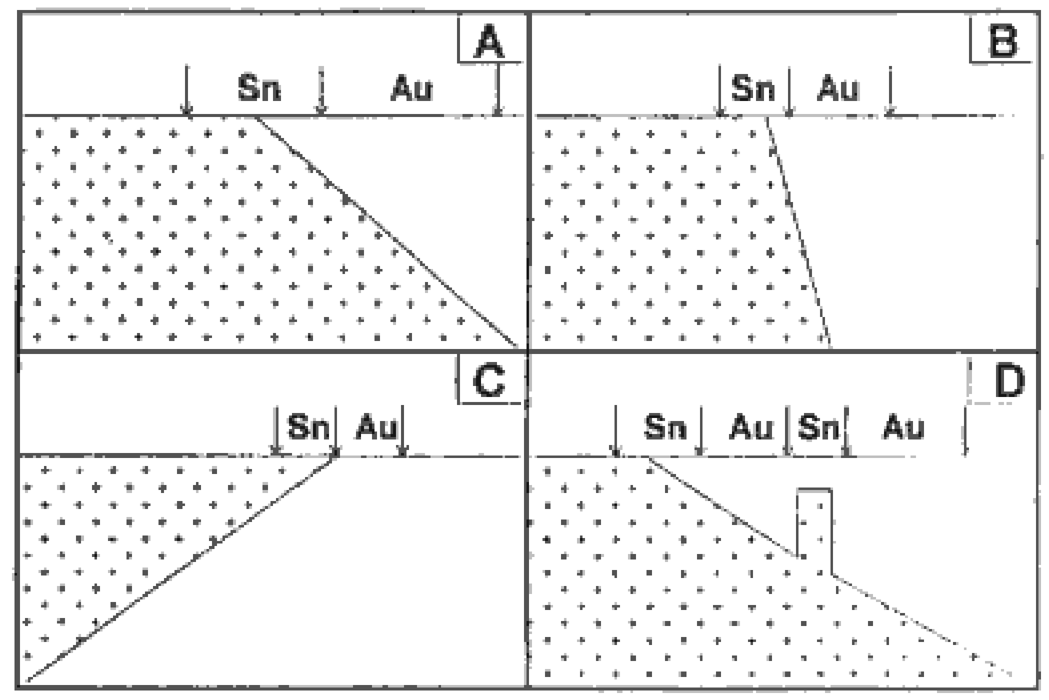

Figure 23. Distribution of the tin and gold mineralisation at the surface according to dip of the granite margin. A – shallow outward-dipping granite contact = broad aureole of the tin and gold mineralisation. B – steep outward-dipping granite contact = narrow aureole of the tin and gold mineralisation. C – shallow inward-dipping granite contact = narrow aureole of the gold mineralisation. D – oscillation of the granite contact produces overlaps of the tin and gold mineralisation.

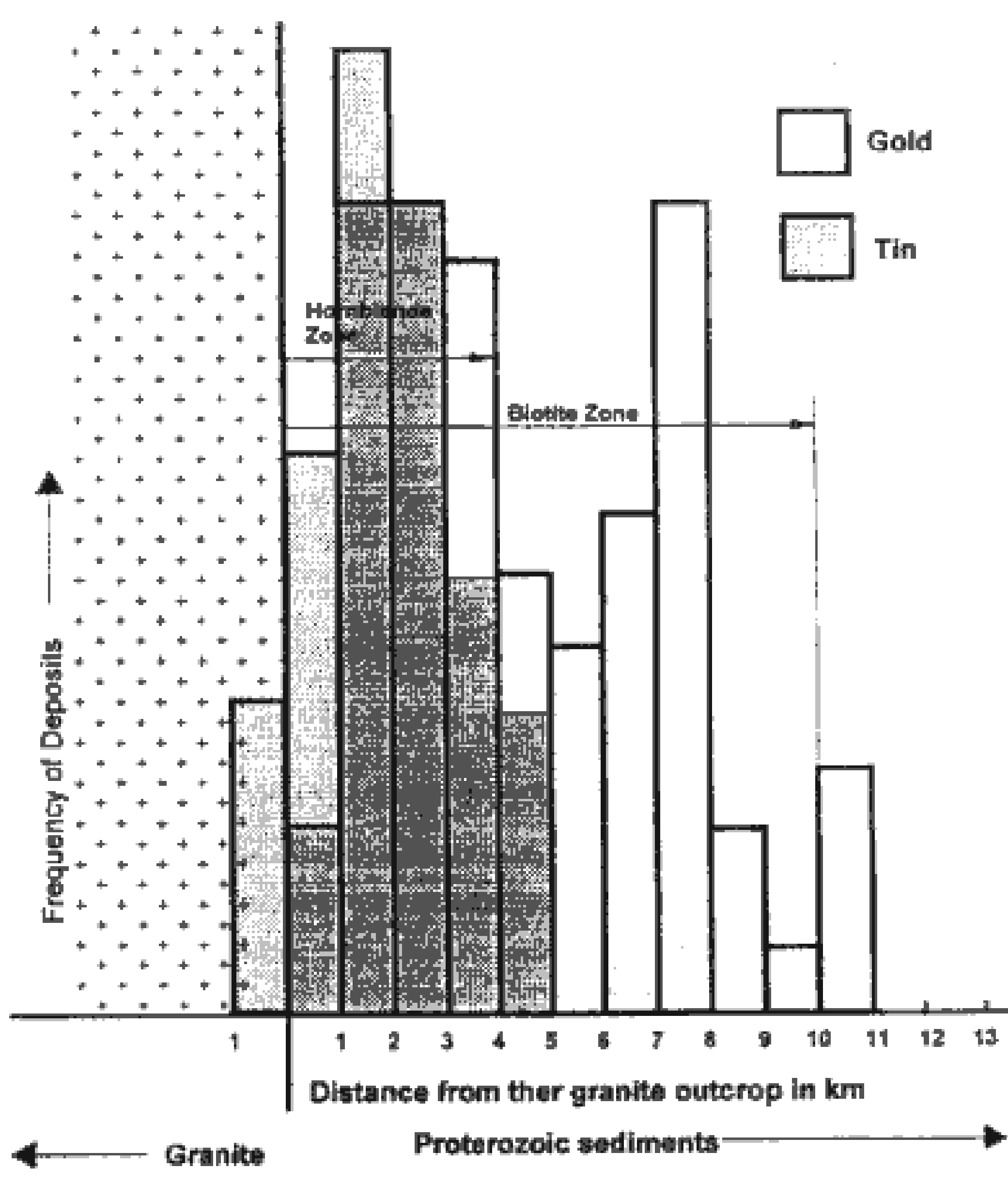

Figure 24. The Cullen Batholith. Lateral distance of gold and tin deposits.

5. Hydrothermal Mineralisation associated with the Cullen Batholith

The geosyncline has been the focus for several phases of mineralisation and contains reserves of gold, base-metals, tin, tantalum, iron, platinum, palladium and uranium (Needham & De Ross, 1990). These resources have been exploited over the past century with periods of major interest during the turn of the century and during the past 20 years. Economically viable resources of predominantly gold, eg., Pine Creek, Cosmo Howley, Goodall and Tom's Gully, and Ag-Pb-Zn, eg., Woodcutters are currently being mined. Gold mineralisation and some base metal mineralisation in the Pine Creek Geosyncline occurs in linear belts up to 20 kilometres in length associated with regional structures eg. the Howley Anticline or the Pine Creek shear zone. No gold mineralisation has been mined to date from the inner thermal aureole of the Batholith. Whereas tin and base-metal mineralisation appear to be exclusively spatially related to the contact aureoles of the Cullen Batholith (Fig. 23 and 24). All of the mineralisation has either a spatial or direct association with D2, D3 or D4 deformation zones, is late in the tectonic sequence mainly related to older reactivated structures. On a regional scale, gold and to some extent base-metal mineralisation has a heterogeneous distribution and is confined to elongate zones associated with regional folds and shear zones suggesting that the dominant control on mineralisation is structural rather than lithological.

The structural controls on mineralisation on a regional scale appear to be dependent on the presence of fluid pathways, and generally reactivated older structures such as the Pine Creek shear zone or the Shoobridge Fault. However, although over 90 % the of mineral deposits lie between the Pine Creek Shear zone and the Shoobridge Fault, no deposits are hosted by these structures. Rather mineralisation appears to be hosted by smaller structures, mainly the D2 and more rarely D3 anticlines and shear zones.

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, and may be related to duplex thrust systems at depth. These thrusts may have acted as feeders for hydrothermal fluids from the larger structures into the anticlines and subsequent trap sites.

In the lower stratigraphy of the Pine Creek Geosyncline the Zamu Dolerite sills (Tab. 1) 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. In many ways the structural controls on many of the gold, and to some extent base-metal deposits in the Pine Creek Geosyncline are very similar to those described by workers in oil exploration. Therefore the style and to some extent size of gold and base metal deposits depends on the competency contrasts of particular packages of rocks, which often depend on the depth of formation of mineralisation, the presence of pre-existing structural heterogeneities or alteration such as silicification or hornfelsing due to granite intrusion.

5.1. Tin Mineralisation

Most tin deposits occur within massive or brecciated quartz lodes either filling faults or within quartz stockwork zones associated with D2 anticlines. The structural control on tin mineralisation is similar to gold mineralisation and will be discussed in more detail in the section on gold mineralisation. Tin generally occurs as finely disseminated or aggregated cassiterite crystals associated with pyrite, arsenopyrite, chalcopyrite, chalcocite, wolframite, scheelite, bismuth minerals, galena, sphalerite, gold, silver and tourmaline. Other forms of tin mineralisation include cassiterite, tourmaline, and muscovite, quartz (greisen) veins, which appear to be transitional to cassiterite, tantalum, lithium bearing pegmatites and also greisenised border vein systems within the roof zones of some plutons. The main production of tin has come from the tin quartz lode deposits at Mt. Wells and from the Hayes Creek field. The tin mineralisation occurs throughout the contact aureole of the Cullen Batholith and is more common where granite contacts appear to be shallow. A small number of deposits lie within greisenised portions of the Cullen Batholith. For example, at the Yeuralba King mine swarms of quartz-tourmaline-topaz veins host the main tin and tungsten mineralisation.

An extensive pegmatite field which has produced the main tantalum and tin mineralisation occurs to the north-west of the Batholith. The pegmatites appear to be related to the Two Sisters Granite south of Darwin Harbour (Fig. 1). More than 90 tin-tantalum-niobium mines have been documented from this area (Crohn,1968). In tin and tantalum pegmatite bodies of the Bynoe area in the contact aureole of the Two Sisters Granite, four types of fluid inclusions are identified in quartz by Ahmad (1994). Type A ($H_2O + CO_2 \pm CH_4$) inclusions were trapped at the H_2O-CO_2 solvus at 5 ~1 kbar, T ~ 300 °C (range 240–328 °C) and salinity ~ 6 wt % eq NaCl. Pressure-salinity corrected temperatures on Type B ($H_2O \pm$ 20 % vapor), C (H_2O + <15 % vapor) and D (H_2O + NaCl + vapor) inclusions also fall within the range of Type A inclusions. Salinity increases systematically with decreasing temperature from 6 % in Type A to about 30 % in Type D inclusions.

A study of tin mineralisation in the Mt. Wells region by Ahmad (1993) recognised two stages of quartz veining. Cassiterite is present in stage I veins while stage II veins composed of minor pyrite and quartz are barren. The contacts between the tin lodes and the wallrock are sharp with weak alteration effects confined to vein selvedges. These consist of sericite, quartz, tourmaline, chlorite, pyrite and minor K-feldspar.

Also four types of fluid inclusions have been recognised: Type A $CO_2 \pm H_2O \pm CH_4$, Type B $H_2O \pm$ 20 % vapour, Type C $H_2O \pm$ < 15 % vapour and Type D H_20 < 15 % vapour + NaCl. Early primary inclusions are represented by type A and B inclusions and have a well defined temperature of formation at 300 °C and a salinity range of 1–20 wt % eq NaCl, whereas the second stage fluid inclusions have a temperature range of 120–160 °C and salinities from about 1 to more than 26 wt % NaCl. The melting sequence of frozen inclusions suggest that the ore fluids were mainly H_2O-CO_2-CH_4-Na-Ca-Cl brines.

Oxygen and sulphur isotope data are consistent with a magmatic origin for the ore fluids with some input from the surrounding carbonaceous sediments. According to Ahmad (1994) the possible mechanisms of ore mineral precipitation are acid neutralisation by feldspar consumption (alteration of feldspar to muscovite) and oxidation due to loss of CH_4. Loss of CO_2 will also result in an increase in pH and provides a possible precipitation mechanism for cassiterite.

It appears that magmatic crystallisation of the TIS and YIS granites ceased at about 600 °C, with crystallisation of pegmatites and the formation of greisens below 600 °C at 1 kbar. This is the upper stability temperature for muscovite + quartz assemblages. Groves & McCarthy (1978) have shown that tin and tungsten mineralisation is related to the most highly fractionated members of a Batholithic series, as indicated particularly by the low levels of Ba and Sr, and high Rb. The incompatible elements Sn, W, Nb, U, Th, Li and Be are also enriched in the residual magmas. The presence of these highly fractionated granites is well documented in the Cullen Batholith eg. in Mount Wells hidden cusp, Wolfram Hill and in the Burnside Granite.

5.2. Gold Mineralisation

5.2.1. Mineralisation Style and Wallrock Alteration

On a regional scale gold mineralisation has a heterogeneous distribution and is confined to elongate zones associated with regional folds and shear zones. Recent mapping suggests that the dominant control on mineralisation is structural rather than lithological. The main regional structural controls in the Howley area are a series of reverse N-trending shear zones which are spatially associated with overturned F2 folds. These shear zones have an en echelon pattern and postdate F2 folding but are deformed by F4 folds. On a deposit scale the mineralisation generally occurs in quartz veins parallel to shear fabrics, in stockwork zones where quartz veins occur as tension fractures which have been formed synchronously with shearing and also parallel to either bedding or an axial planar cleavage or as disseminated gold within sheared alteration zones. The timing of the gold mineralisation can be constrained by using stratigraphic, structural, and geochronological data. The cross-cutting or replacement nature of most of the mineralisation, which may be hosted by Zamu Dolerite suggests 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 shearing, folding and the reactivation of D2 and D3 structures. As none of the gold deposits show evidence of metamorphism, the mineralisation must postdate peak regional metamorphism. Granitoid intrusion and contact metamorphism also appears to have pre-dated the mineralisation as some deposits within the contact aureoles of granites retrogress the high grade contact metamorphic assemblages eg, Goodall, Western Arm and Brocks Creek. 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 sedimentation.

Gold mineralisation occurs in all the units of the South Alligator Group and Burrell Creek Formation and in most areas is related spatially to regional anticlinal structures (eg., Pine Creek, Woolwonga, Brocks Creek, Cosmo Howley). Gold mineralisation occurs as stratiform replacement deposits or as auriferous quartz reefs, 1–4m in width, that fill faults parallel to the axial plane of the anticline, as quartz veins parallel to shear fabrics, in stockwork zones, as veins parallel to either bedding (S0) or the regional axial planar cleavage (S2), and as disseminated gold within silicified alteration zones. The largest gold deposits in the Pine Creek Geosyncline are located on the D2 regional anticlines. The Howley Anticline has a line of deposits along its length that have been the major producers of gold in the Howley District, including Cosmopolitan Howley, Chinese Howley and Big Howley. The cross-cutting or replacement nature of most of the gold mineralisation suggests that mineralisation postdates the deposition of their host rocks. Tension fractures hosting gold mineralisation in shear zones are commonly re-folded, boudinaged and overprinted by further shearing suggesting that mineralisation was synchronous with shearing, and postdates D3 folding.

Geological data from the Mount Shoobridge area (Burke, 1987) indicate that gold mineralisation is younger than tin-bearing pegmatite. The style of gold mineralisation can be subdivided into a continuum between two end member types as shown on Fig. 25. Most gold mineralisation is

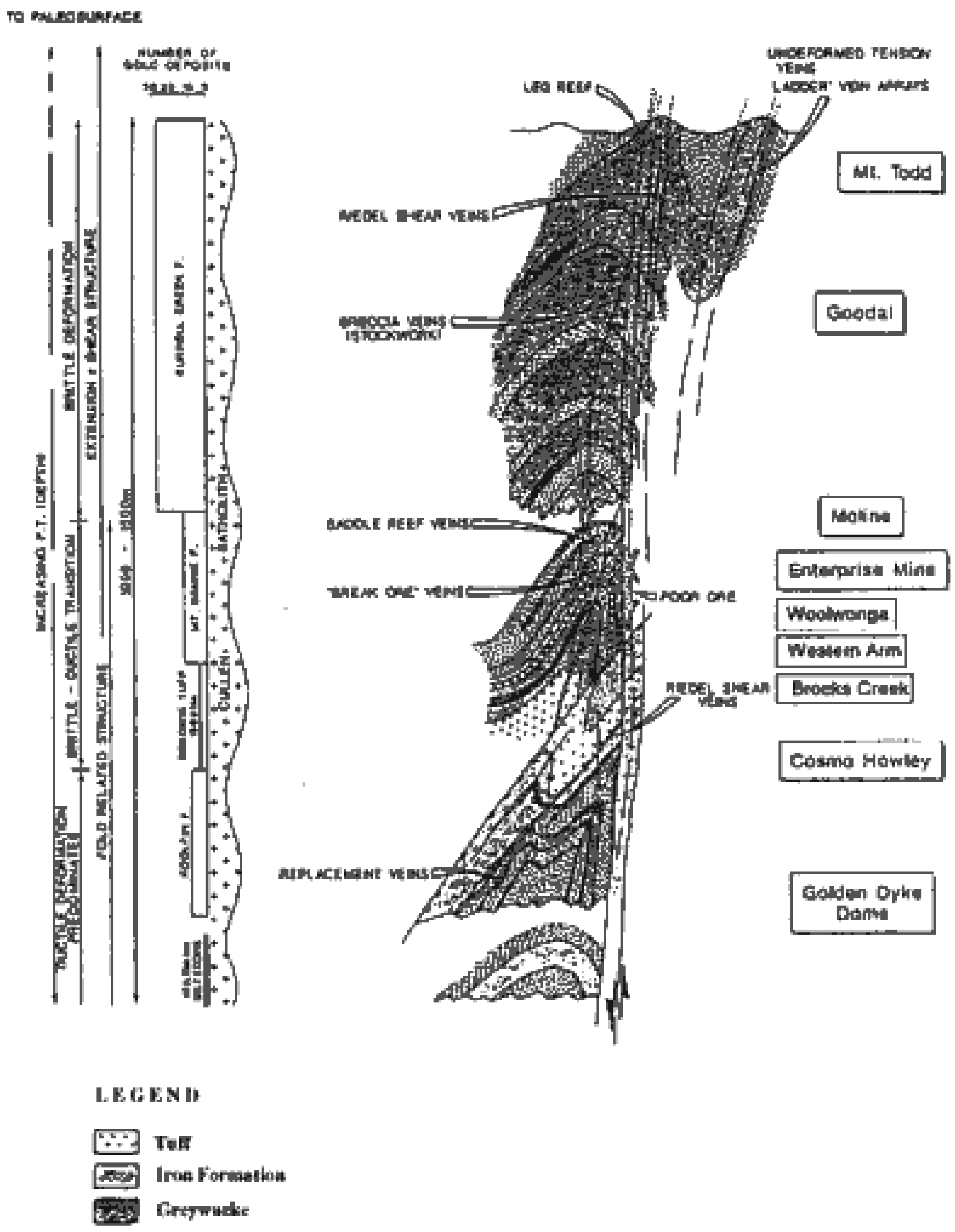

Figure 25. Stratigraphic and structural control of the gold mineralisation around the Cullen Batholith.

located between and adjacent to regional D2 and D4 shear zones such as the Shoobridge Fault and the Pine Creek Shear Zone. The deposit style appears to be directly related to the contrast in host rock competency and geochemistry. Those lithologies, which are brittle with low geochemical contrast, form vein/stockwork mineralisation whereas those with both contrasting competency and geochemistry form vein and replacement deposits. The size of the deposit can also be related to the trapping potential of the host rocks and the size of the controlling structure.

The Bridge Creek and Cosmo Howley deposits are both cited as examples of stratiform syngenetic style mineralisation by Nicholson and Eupene (1994), Nicholson et al. (1994). However, recent work suggests that these type of gold deposits are good examples of the alteration/replacement end member of gold mineralisation.

Cosmo Howley straddles the Howley Anticline and is hosted by carbonaceous mudstone and siltstone of the Middle Koolpin Formation. Gold mineralisation is generally confined to an iron rich sequence of mudstones and silicate Banded Iron formation and is closely associated with pyrite and arsenopyrite. The mineralisation is mainly associated with quartz veins, breccias and shear zones (Alexander et al., 1990), although a syngenetic component of the ore has been postulated due to the stratiform nature of the mineralisation.

Bridge Creek to the north of Big Howley gold mineralisation has also been described as syngenetic by Sanger von Oepen et al. (1988). However, recent work (Partington et al.,1994) has shown that mineralisation at the Bridge Creek prospect can be divided into sediment hosted stratabound mineralisation and dolerite hosted vein-alteration mineralisation. The stratabound style of mineralisation and dolerite hosted mineralisation, although superficially different, has many similarities in alteration and chemistry. Detailed structural studies and fluid inclusion work has shown unequivocally the mineralisation at Bridge Creek to be epigenetic. These deposits are therefore considered to form the replacement/alteration end member of gold deposits in the Pine Creek Geosyncline.

The other end-member types includes Goodall and Mt. Todd, where mineralisation forms as broad stockwork zones located on the limbs of D2 folds. The gold is generally associated with thin 5 to 50 millimetre vein arrays, which form subparallel to earlier structures such as bedding, reactivated shear zones and S2 cleavage. At Mt. Todd the vein system is continuously mineralised over widths of up to 300 metres, a strike extent of 1500 metres and a depth extent of 500 metres. The veins are composed of quartz and variable amounts of pyrite, arsenopyrite, chlorite, K-feldspar and carbonate. The gold is generally late sited in fractures and at grain boundaries.

The range of deposits between these two end-member styles include many of the shear zone hosted and quartz stockwork/saddle reef style of mineralisation ± alteration zones. The Woolwonga deposit lies on the Woolwonga Anticline on the eastern margin of the Burnside Pluton. The main host rocks for the mineralisation are interbedded siltstone, greywacke and mudstones of the Mt. Bonnie Formation. Gold mineralisation is associated with quartz sulphide veins that fill fractures in a folded sequence of greywacke and mudstone. Mineralisation is epigenetic and structurally controlled (Kavanagh and Vooys, 1990). This style of mineralisation is also found at Enterprise, Brocks Creek and the Western Arm. At Tom's Gully the main host to mineralisation is a D2 thrust fault which appears to have been reactivated and cuts an early D2 fold.

The main zones of gold mineralisation in the Pine Creek Geosyncline are associated with quartz vein stock-work zones, which contain silicified wall-rock and are associated with pyrite and arsenopyrite. The higher grade zones (up to 120 g/t Au) are often confined to laminated quartz veins at the margin of carbonaceous lithologies. The gold is often late and forms in crosscutting fractures within veins of K-feldspar, veins of massive pyrite, and haematite and arsenopyrite. This alteration is associated with an increase in K, As, Si, S and Fe. Alteration assemblages coexist and appear to be lithologically controlled. This alteration has caused a depletion in elements such as K, Rb, Ba, and Cu with a corresponding enrichment of Fe, Ca, Na, S, As, Au, Sb, W, Bi, Pb and Zn as the intensity of veining increases (Cooper, 1990). The alteration assemblage overprints metamorphic assemblages and forms a distinct zonation at vein margins away from the shear and fracture zones in the dolerite. The mineralogy is actinolite, albite, chlorite, biotite and carbonate with sulphides and gold as additional integral components of the mineralised alteration assemblage. 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, and free gold is considered to be a more important contributor to mineralisation. Geochemical analyses of wallrocks in the dolerite-hosted mineralisation indicate a depletion of Ca, Mg, Fe and Cu as intensity of alteration increases. Wallrock enrichment of Na, K, S, As, Au, Ag, W, Sb, Bi, Rb, Sr and Ni occurred and the enrichment of W, Sb, Au and As occurred in the veins (Cooper, 1990).

5.2.2. Fluid Inclusions

Preliminary fluid inclusion studies at Tom's Gully, Western Arm, Enterprises and Bridge Creek suggest that the gold bearing quartz veins were deposited from a moderate salinity, methane-rich fluid at about 250 °C to 350 °C and 1 kbar. 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 deposition temperatures slightly lower. Gold mineralisation appears to have been introduced at this time.

Fluid inclusion studies on vein quartz associated with gold mineralisation at the Western Arm and Tom's Gully indicate the presence of an early CO_2-rich fluid prior to the main gold mineralising event which probably contains methane. Moderately saline aqueous fluids are confidently related to the mineralisation process; it is interpreted that a higher temperature (450–490 °C) fluid deposited the quartz veins and some sulphides, and a lower temperature fluid (325–395 °C) was involved in the 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-rich inclusions and high-temperature, moderate-salinity aqueous inclusions could represent end member fluid compositions which were mixed, or resulted from phase separation.

5.2.3. Discussion

Although the various styles of gold mineralisation in the Pine Creek Geosyncline appear to be quite different there are significant similarities between each style and also with mineralisation described from mesothermal gold deposits in Archaean terrains (Groves and Ho, 1990; Partington, 1990).

On a deposit scale, the mineralisation is generally associated with quartz veining parallel to shear fabrics and within pre-existing structures associated with the regional folding. The presence of hydraulic breccias and veining within small scale compressional structures in many deposits argues for high fluid pressures at the time of gold deposition. The timing of the gold mineralisation appears to be similar on the scale of the geosyncline and can be constrained by using stratigraphic and structural data. The cross-cutting or replacement nature of most of the mineralisation, which may be hosted by Zamu Dolerite, suggests that mineralisation postdates the intrusion of the Zamu dolerite. Tension fractures hosting gold mineralisation in shear zones are commonly refolded, boudinaged and overprinted by further shearing suggesting that mineralisation was synchronous with shearing and postdating F2 folding and the formation of a S2 regional cleavage.

As most gold deposits contain evidence for retrogression of higher grade metamorphic assemblages within alteration zones related to gold mineralisation the mineralisation must postdate peak metamorphism, and this also suggests that granitoid intrusion pre-dated the gold mineralisation. However, as evidenced by the preliminary fluid inclusion studies hydrothermal activity associated with granitoid intrusion appears to be synchronous with gold mineralisation.

Geochemical analyses of wallrocks associated with all styles of mineralisation are very similar and are not inconsistent with some contribution from a metamorphic/granitic source. Wallrock enrichment of Na, K, S, As, Au, Ag, W, Sb, Bi, Rb, Sr and Ni occurred and enrichment of W, Sb, Au and As has occurred to some degree in the mineralised zones at both prospects. The veins commonly contain low amounts of base metals and characteristic granite-associated elements such as Hg, Mo and Te, which would be expected to be higher if the fluids were solely magmatically derived. Base metals in the system are characteristically low for all types of alteration and vein sets, with copper actually depleted within both the alteration zone of the dolerite and the carbonaceous sediments.

5.3. Base Metal Mineralisation

The controls on base-metal mineralisation appear to be very similar to those described for gold mineralisation (Fig. 25). Mineralisation is associated with veins, breccias and stockwork zones mostly hosted by carbonaceous and dolomitic metasediments. The vein systems can be up to 5 metres wide and over 1 000 metres in length. The primary ores consist of argentiferous galena, sphalerite, pyrite in a gangue of carbonate and quartz and minor arsenopyrite, marcasite, chalcopyrite and gold.

Base-metal mineralisation at the Evelyn mine is related to a skarn consisting of tremolite, actinolite, anthophyllite, diopside, garnet and serpentine. The ore bodies are small irregular, tabular to lens-shaped lodes en echelon lodes within a northwest trending shear zone. The Rum Jungle Ag-Zn-Pb deposits overlap the zones of uranium mineralisation at Rum Jungle. The Woodcutters deposit occurs within a D2 anticline related to an axial planar fault (Ormsby et al., 1994). The mineralisation occurs as en echelon lenses within the fault zone and as replacement stratiform units within the Coomalie Dolomite.

A sequence of stratiform deposits occur within the Masson Formation, which appear to be confined to a sequence of siltstone, shale with calcarenite and sandstone. The pelitic rocks are carbonaceous and pyritic at a depth. This sequence immediately underlies the Stag Creek mafic volcanics. Base-metal mineralisation, also associated with gold mineralisation occurs as stratiform deposits at the Mt. Bonnie, Golden Dyke and Iron Blow mines. These deposits consist of pyrrhotite, pyrite, sphalerite, galena, arsenopyrite, chalcopyrite and minor silver. These sulphides occur in a gangue of dolomite, chlorite, talc, actinolite and quartz. Goulevitch (1980) proposed that the dewatering of underlying ashstones of the Gerowie Tuff provided saline solutions capable of transporting the ore metals. Devitrification of the ashstones could have provided the heat source and means of liberating the metals to the brine. Sea water in restricted sea floor depressions would have provided the source of reduced sulphur to precipitate the sulphides. An alternative interpretation is that these deposits are related to skarn mineralisation as is described from the Evelyn Mine.

The current belief is that the majority of the base-metal deposits and by definition gold mineralisation associated with the base-metals (eg Mt Bonnie) are most probably syngenetic (Goulevitch, 1980; Nicholson & Eupene, 1993) with the metals derived from the pyroclastic or carbonaceous pelites in the South Alligator Group. Mineralisation at Woodcutters, which is demonstrably epigenetic, is thought to represent a feeder zone for the syngenetic mineralisation on the surface (Nicholson et al., 1994, Butler et al., 1994; Ormsby et al., 1994).

5.4. Uranium/Gold/Platinoid Mineralisation

The Rum Jungle and Alligator River Uranium Fields accounted for 96 % of the total value production of uranium and for 97 % of reserves (Needham & Roarty, 1980). The majority of these deposits are located in breccia zones in partly or wholly carbonaceous pelitic rocks, adjacent to crystalline carbonate rocks. The ore bodies are generally tabular to basin shaped and conformable to some degree.

At Rum Jungle, the deposits lie on, or close to, the contact between massive crystalline dolomite/magnesite of the Coomalie Dolomite, and the overlying calcareous carbonaceous shales of the Masson Formation. They occur in the northern limb of a syncline between two granite complexes (the Archaean Waterhouse and Rum Jungle Complexes), along shear zones on, or near, the crest of a subsidiary anticline on this structure. The Rum Jungle deposits are 'best developments' of mineralisation within a series of overlapping mineral zones (Fraser, 1975), and grade from uranium alone in the north at Dysons, through U-Co-Cu-Pb-Ag at Whites and Cu at Intermediate, to Ag-Pb-Zn at

Browns. The primary ore minerals in the base metal deposits were sulphides, but significant amounts of production came from secondary minerals in some of the deposits, mainly malachite and cerussite. Secondary uranium minerals included torbernite, autunite, phosphuranylite, 'gummite' and saleeite.

In the Alligator Rivers region, most of the U and U-Au deposits are near the base of the Cahill Formation and adjacent to lenses of massive dolomite and/or magnesite. This common proximity between uranium deposits and carbonate rocks may be relevant to ore genesis. All the deposits are located in zones of chloritisation, ranging from minor in the Rum Jungle deposits, to massive and pervasive in the Alligator Rivers deposits. In each the chloritisation is localised around the deposit; for example, at Jabiluka the alteration halo extends 200 m from the uranium deposits. The ore zones consist mainly of uraninite, mostly as disseminated and massive (colloidal and vein-type) pitchblende, and as 'paint' on fractures. The Alligator Rivers deposits contain gold, but only Jabiluka Two contains economically recoverable quantities. Minor chalcopyrite, galena and pyrite and also arsenopyrite are also present. Secondary uranium minerals include sklodowskite, saleeite, gummite and metatorbernite.

Some uranium deposits occur as massive mineralisation in planar dislocation or crush structures which extend beyond the outer limits of the ore body. They are vein-type deposits, and include the Adelaide River and George Creek mines in the west of the Pine Creek Geosyncline, and the Nabarlek deposit in the northeast of the Alligator Rivers Uranium Field. The Adelaide River and George Creek mines, together with minor vein and disseminated patchy uranium in the south of the Cullen Granite near Edith River, are probably magmatic in origin.

There are significant gold ± platinum and palladium occurrences associated with uranium mineralisation. Visible gold veins crosscut uraninite-bearing veins in the South Alligator deposits. Recent exploration has discovered disseminated gold adjacent to some of the uranium mines eg. Jabiluka II and Coronation Hill. The relationship between the two styles of deposits is not clearly understood. However recent work by Wyborn et al. (1994) suggests that this mineralisation is a variant of the unconformity style uranium mineralisation discussed above.

Evidence from fluid inclusion work suggests that U, Au, Pt, and Pd were transported in the same highly oxidised, low pH and very calcium-rich brine, probably as oxy-chloride complexes, at temperatures around 140 °C. Isotopic data indicate that the ore bearing fluids were derived from meteoric ground waters from well above the deposits. All known deposits are close to major strike-slip fault systems, eg the Giants Reef Fault or the Coronet Fault that were active after the deposition of the cover sequence. As the fluids originate above the deposits, a thick neutral to oxidised cover sequence acts as a thermal blanket so that meteoric fluids can reach temperatures of 120 °C to 150 °C. This heating may have been instigated by added thermal input from the HHP granites that are peripheral to most uranium deposits. A thick neutral to oxidised cover is also required to maintain and concentrate the fluids in an oxidised metal-saturated state without causing precipitation. Modelling has shown that Au+Pt+Pd ores may be precipitated with a moderate decrease in fO_2 and an increase in pH due to interaction with feldspar-rich lithologies. Greater reduction is required to precipitate U and this can occur when the metal rich fluids interact with carbonaceous sediments, iron-rich lithologies or methane bearing fluids derived from the basement.

6. Isotopes Studies

Sulphur and oxygen isotopic data which are presented by Golding et al. (1990) and Wygralak & Ahmad (1990) suggest a mixed magmatic and metamorphic source for the fluids responsible for gold mineralisation, which is also proposed by Sheppard (1992) based on lead isotopic data and reconnaissance stable isotope data.

6.1. Lead Isotopes

Lead isotope studies were undertaken to determine the age of the Burnside Granite, and the initial Pb isotope composition of this granite and gold deposits of the Pine Creek Geosyncline. These data are compared with similar data collected from the Mt Bundey Granite and Tom's Gully deposit by Sheppard (1992). The aim of this part of the overall study is to establish the relationship, if any, between the magmatic Pb in the granites at the time of emplacement, and the Pb in the ore deposits at the time of mineralisation. New Pb isotope data on samples of the Burnside Granite were presented in Tables 7 and 8, and Fig. 18, whereas galena data from a number of deposits are presented in Table 9.

6.1.1. Metasedimentary, Metavolcanic and Plutonic Rocks of the Pine Creek Geosyncline

Sheppard (1992) analysed the Pb isotopic composition of a number of rocks from the Proterozoic succession. These data are modern day compositions and are shown with granite data in Fig. 26. At the time of granite emplacement, ca. 1810 Ma ago, the Pb in these rocks would be less radiogenic and fall in the fields shown in Fig. 26a. The field for the Wildman Siltstone is well constrained, and overlaps the initial Pb from the two granites. The remainder of the succession below the Wildman Siltstone is represented by few data, and shows considerably more variation, particularly tending to higher $^{207}Pb/^{204}Pb$ compositions compared to the Wildman Siltstone. The lower succession could also be a source for the granites as their field overlaps the granite initial Pb compositions, although this would be unlikely based on P-T constraints. However, Pb isotope data may not