Fluid inclusion data indicate high-medium formation temperatures for tin mineralisation (500–300 °C) and gold mineralisation (300–100 °C). The main gold deposition is younger than the high temperature greisen type of tin mineralisation. The age history of the Cullen Batholith fully covers the timing of the tin and gold mineralisation. The age-thermal history of the Cullen Batholith is within the range from 1 835 Ma at about 800 °C, to 1 650 Ma at about 300 °C. It may indicate a time gap between magmatic and hydrothermal temperatures within the Cullen Batholith for tin deposition of about 20 Ma, and for gold deposition of about 40 Ma.

Unconformity-type uranium deposits of the Pine Creek Geosyncline (the East Alligator River districts) were formed in many stages, spanning more than a billion years. They may be used as an example of subsequently remobilised mineralisation between 1 700 and 800 Ma. Pitchblende and galena generally yield discordant U-Pb ages of about 800 to 900 Ma, but some pitchblende and some pyrite from Jabiluka II yield discordant ages of about 1 120 to 1 770 Ma (Hills & Richards, 1976; Gulson & Mizon, 1980).

The long term of high temperature regime within and around the Cullen Batholith can be explained by high heat flow as a result of the high heat production of its granites. The occurrence of thermal ground waters in the Douglas Hot Springs, Daly River and Adelaide River Hot Springs, and palaeothermal vents in the Old Boiler gold deposit (Marshall et al., 1988) suggests that a component of low-temperature hydrothermal convection associated with the Cullen Batholith was not necessarily restricted to the times when the granites intruded and cooled, and it can be traced up to recent times.

## 9. Genetic Model for Gold Mineralisation in the Thermal Aureole of the Lower Proterozoic Batholiths

Structural and microstructural observations indicate that gold mineralisation formed contemporaneously with D4, which appears to be related to the final stage of granite intrusion. Retrogression of contact metamorphic assemblages further suggests that mineralisation post-dates granitoid intrusion and contact metamorphism. Vein mineralisation and associated alteration mineralisation appear to have formed at high fluid pressures in the brittle/ductile regime in zones of contrasting lithological competency such as overturned short limbs of folds.

Mineralisation is either vein-hosted or occurs in both veins and altered wallrock. A simple relationship between higher gold grades and an increasing alteration intensity is noted. Localised lithological competency contrasts are also important. There is a distinctive symmetric alteration zonation within dolerite hosted mineralisation, with increasing alteration intensity towards the centre of the zone which shows a marked depletion in the elements Ca, Mg and Cu, and strong enrichment in the elements K, Fe, S, Ba, Au, As, Bi, W and Sb. Alteration assemblages grade from chlorite and actinolite dominated assemblage surrounding the vein systems, to a bleached albite-rich zone which transgresses into a zone of biotite growth. On the basis of this wallrock alteration zonation and preservation of primary textures and mineralogy away from the central zone, fluid-wallrock ratios are interpreted to increase towards the centre of the system of alteration. Carbonaceous sediment vein-hosted mineralisation shows depletion in K, Rb, Ba and Cu and enrichment in Fe, Ca, Na, S, As, Au, Sb, W, Bi, Pb and Zn. Many of the features of the gold deposits in the Pine Creek Geosyncline suggest that they could not have been formed by syngenetic processes. These data also argue against remobilised syngenetic models for their formation. It is clear that both the dolerite hosted and sediment hosted gold mineralisation have closer affinities with epigenetic gold veining and mineralisation in all styles of gold deposits appear to have occurred after both regional and contact metamorphism. 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 entirely 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. A brief review of other styles of gold deposits and their major and trace element geochemistry suggests gold mineralisation in the Pine Creek geosyncline is closely analogous to Archaean mesothermal syntectonic deposits and Slate Belt styles of gold deposits. The mineralisation has a similar mineralogy and fluid chemistry to both deposit types. There is a closer resemblance to the Archaean style in element enrichment and depletion and with low base metals. It is suggested that the source of a component of the fluids may be from metamorphic dewatering reactions during granite intrusion.It appears that at most prospects early quartz was deposited from overpressured fluids during reactivation of the D2 and D3 structures, possibly ahead of the intrusion of the YIS granites. Passage of subsequent ore fluids was controlled by further reactivation of the earlier structures and structures associated with emplacement of the YIS granites. During crystallisation of the granite, fluids derived from devolatilization of graphitic rocks in the thermal aureole were channelled along faults in the country rock and possibly along the contact between the metasedimentary rocks and the silicified margin of the plutons. Near the top of the pluton along its margin, hot $CO_2$ ± $CH_4$-rich fluids (equivalent Type 1?) mixed with moderately saline, aqueous magmatic fluid (equivalent Type 2?) exsolved from the granite. Fluid mixing, in conjunction with pressure decreases associated with quartz fracturing, induced phase separation and deposition of quartz sulphide veins ± K-feldspar veins at about 450–490 °C. Fluids which consisted increasingly of isotopically exchanged formation or meteoric water in equilibrium with the metasedimentary rocks, were focussed along reactivated thrust faults through the relatively oxidised sedimentary rocks comprising the base of the sedimentary sequence. Phase separation associated with brittle fracture along the ore shoots, deposited gold and sulphides from solution in response to elevated $CH_4$ and/or $CO_2$ contents in the moderately saline fluid (equivalent Type 3?) derived from interaction with wall-rocks away from the site of ore deposition at approximately 320 °C. This fluid would have been trapped by impermeable lithologies in suitable structural sites at various levels along anticlinal crests and at the margins of domal structures thus allowing maximum interaction of the fluid with the wall rocks to occur. With further reactivation of the hosting structure fluid pressures would have increased resulting in hydraulic fracturing of the host lithologies and the subsequent deposition of gold mineralisation. This may account for the apparent formation of saddle type structures at various levels along a fold such as the Howley Anticline. According to Darnley (1982) the Cullen Batholith granites may be classified as uraniferous. The average uranium, thorium and potassium content for the Batholith is 15 ppm U, 40 ppm Th and 4 % K. The Cullen Batholith is more radiothermal than many of the high-heat-producing (HHP) granites in Britain, including the Cornubian Batholith with DHR project (4.0–5.7 $\mu W/m^3$ in Webb et al, 1985). This compares with radiothermal heat production (pre-weathering) of 4.2–12.8 $\mu W/m^3$ for radiogenic Bushveld granites (McNaughton et al., 1993), and 5.7–6.3 $\mu W/m^3$ for radiogenic granites from northern Australia invoked by Solomon & Heinrich (1992) as the heat source for the giant Pb-Zn deposit of the Mount Isa and McArthur River areas. The longevity of intrusion and the HHP potential of the granites of the Cullen Batholith appears to be the key in the generation of sufficient hydrothermal fluid to produce the maximum fluid to rock ratios required to scavenge gold and base-metals from the surrounding sedimentary rocks. These sedimentary rocks were not only the source for the metals but also provide structural and geochemical traps higher in the succession as the hydrothermal systems cooled to form economic mineral deposits.

For the origin of the gold mineralisation in the Pine Creek Geosyncline three a stage model is proposed:

**Stage 1.** Sedimentary preparation

The first step in the complex genesis of these gold deposits seems to require synsedimentary and/or diagenetic preconcentration of gold in sediments. Different gold content in sediments is controlled either by distance from the continent or by their primary chemical composition (carbonaceous and/or iron rich composition).

**Stage 2.** Metamorphic upgrading

In areas of pervasive regional metamorphism a small part of the metallic gold may be dissolved and redistributed by metamorphic fluids containing sulphur compounds. These fluids are produced by prograde dewatering process during formation of metasedimentary rocks water under definite PT conditions (2–3 kb and 550 °C). Gold was precipitated in rock-forming minerals representing greenschist assemblages.

**Stage 3.** Hydrothermal mobilisation

Large granite plutons produced a broad aureole of contact metamorphism which hornfelsed the mineral assemblages of greenschist facies. Magma emplacement has been responsible also for structural modification of the country rocks. These processes have produced the mass expansion and communication (decompression) with the paleosurface (faulting, brecciation, volcanic activity and rock dykes). Duration of the high thermal regime inside and around the batholith has been extended by a considerable contribution of radiothermal heat. This long-lasting cooling of the batholith has been accompanied by circulation of fluids coming from different sources. The poorly mineralised meteoric fluids have been diluted by portions of magmatic and metamorphic waters. Such a mixture of fluids produced hydrothermal alteration of pre-existing greenschist mineral assemblages, leaching of gold from sedimentary rocks and the transport of gold in thio-complexes into a new brittle-ductile (saddle reefs) and/or brittle (array of veins or stockworks) structural environment at the periphery of the thermal aureole of the batholith. Gold precipitation into economic concentration has been controlled by wall-rock interaction and fluid mixing which lowered total dissolved sulfur and changed pH and $fO_2$ of the fluids over a wide range of temperature from 100 to 320 °C within the structurally prepared traps.

According to this model the origin of the gold mineralisation in the Pine Creek Geosyncline is a multistage, long term process which is represented by a number of quartz vein generations. It started prior to the Cullen Batholith emplacement (stage I and II), culminated during the heating and subsequent cooling of the country rock around the batholith (stage III), and ceased after cooling of the batholith roof below 300 °C. The end of the process is documented by late quartz veins containing gold and cutting the Mount Shoobridge Granite.

The scenario which has been recognised for the origin of the gold deposits in the Pine Creek Geosyncline may be generally compatible to that of a number of major styles of gold deposits in Australia (Tanami, The Granites, Tarcoola, Selwyn and Telfer).

## 10. Conclusions and Prospectivity Rankings

The main aims of the study were to assess the role of granites of the Cullen Batholith in the formation of ore deposits in the Pine Creek Geosyncline, especially gold mineralisation. It was hoped that a set of criteria could be developed to prioritise exploration targets in the Pine Creek Geosyncline and possibly in other Precambrian terrains. In summary the main findings from the study are:

1. Economic tin and gold mineralisation is located within the inner zone of the thermal aureole spatially and temporaly related to the 1 800–1 835 Ma Cullen Batholith. Spatial distribution of both deposit types is generally controlled by geometry of the granite contact. The granites show both inward and outward dipping contacts.
2. Generally older tin mineralisation occurs within endo-