thermal hydrothermal system. Mineral assemblage in the paleothermal vents consists of several generations of quartz, barite, fluorite, galena and pyrite.

Epithermal rejuvenation in the Pine Creek Inlier occurs at the present day as hot thermal springs with low temperature alteration associated with brecciation and quartz veining. Some economic uranium mineralisation around and east of the Cullen Batholith may be also taken in account as a part of the epithermal rejuvenation system. Mineralisation related to continuing thermal events has occurred throughout the geological history of the Pine Creek Geosyncline and it is suggested that this is related to the production of heat by the HHP granites of the Cullen Batholith. Such long lived hydrothermal systems have been documented from elsewhere and are commonly associated with similar HHP producing granites.

8. Timing of Magmatic and Hydrothermal Events of the Cullen Batholith

The Cullen Batholith is a part of the much larger Pine Creek Plutonic Complex. The Batholith is located within the border zone of two cratonic plates. Towards the north, the batholith is thinner and at the surface is represented by isolated, deep rooted satellite intrusions. The Cullen magma source was generated from an underplated layer at 2 200 Ma, with a short crustal residence time (400 Ma), Sheppard (1992).

The batholith consists of twenty-three plutons representing several magma pulses. They are almost tabular intrusions with subhorizontal (ethmolitic) bottoms and roofs. Outward and inward-dipping contacts have been recognised in the geometry of the batholith roof. Inward-dipping contacts of granites are indicated by overlaps of magnetic anomalies and the narrow width of their thermal aureole.

The zonation of the shallow plutons (Stuart-Smith et al., 1993) mostly shows cryptic layering and ghost stratigraphy within their shallow-unroofed tops.

The Early and Transitional Suites comprise dominant parts of the major plutons. The Early Igneous Suite is usually intruded by the Transitional Igneous Suite and represents the sub-horizontally stratified roof of the batholith. The Transitional Suite outcrops either as independent younger intrusions (Tabletop and Umbrawarra granites) or occupies the internal parts of the batholith usually underneath the Early Suite. The Young Igneous Suite is represented by an independent group of plutons which are intruding either the Early and Transitional Igneous Suites, or as satellite bodies further in the northern periphery of the Batholith. The Young Igneous Suite intrudes both earlier Igneous Suites and shows differences in composition and fractionation patterns.

Early Igneous Suite granites are mesocratic hornblende-biotite or biotite, undifferentiated, late-orogenic, tin-barren ± metaluminous, and monzogranodiorite.

Transitional Igneous Suite granites are biotite, coarse equigranular, poorly differentiated, late-orogenic, stanniferous peraluminous, and monzogranite.

Young Igneous Suite granites are medium to fine grained, equigranular, moderately differentiated, post-orogenic, stanniferous, peraluminous, monzosyenogranite.

According to data presented by Stuart-Smith et al., (1993), the emplacement age of the Early Igneous Suite (I) is at 1 835 Ma (Fingerpost Granodiorite), the Transitional Igneous Suite (II) is at 1 818–1 825 Ma, and the Young Igneous Suite (III) at 1 800 Ma (Burnside Granite). Magmatism spanned an interval up to 35 Ma.

As stated by Stuart-Smith et al. (1993) the pooled Cullen Batholith Rb-Sr age is about 40 million years younger than the U-Pb zircon age. This time difference may indicate the cessation of magmatic consolidation of the Cullen Batholith was not until 1 770–1 780 Ma. The K-Ar biotite ages (1 650–1 700 Ma, Hurley et al., 1961) of some of these rocks suggest that final cooling below 300 °C was not attained until some 100 million years later (Stuart-Smith et al., 1993). Such time differences between closing temperatures of the individual isotope systems indicate prolonged cooling of the Cullen Batholith from 540 °C to below 300 °C. This slow cooling may have some implications to the age and the extent of the thermal aureole and the age of hydrothermal mineralisation spatially and temporally related to the Cullen Batholith.

A broad scale of hydrothermal deposits shows contrasts in spatial distribution, style, temperature and timing. Tin mineralisation is genetically related to the late-post-orogenic granites as their post-magmatic continuum, showing a definite distribution patterns along their endo- and exo-contact. On a regional scale the gold mineralisation shows similar zonation, more distal from the granite roof and/or contact, but in detail more controlled by depositional "traps". A model of gold mineralisation related to granite acting as a heat source is proposed in the next section. Topography of the roof and/or granite contacts is critical for regional and detailed distribution of tin and gold mineralisation.

This relationship of deposits with the granites and their thermal aureole suggests that the deposits were formed after the emplacement of the batholith (tin mineralisation) and the following cooling stages (gold mineralisation).

The age of the gold mineralisation has been isotopically analysed on zircon, xenotime and monazite extracted from a gold bearing quartz sulphide veins in Goodall deposit. According to Compston & Matthai (1994), the largest group of zircon has a mean age of 1 863 ± 7 Ma, which is interpreted by Compston and Matthai (1994) as the maximum depositional age. About 30 % of the analyses have a younger mean $^{207}Pb/^{206}Pb$ age of 1 817±16 Ma, within the error of the age of the Cullen Batholith. This age of vein formation is supported by $^{207}Pb/^{206}Pb$ ages of xenotime and monazite, which have a mean age of 1 810 ± 10 Ma. In addition, a small number of analyses are much youger with a mean $^{206}Pb/^{238}U$ age of 536 ± 38 Ma indicating the time complexity of mineralisation of the Cullen Batholith.

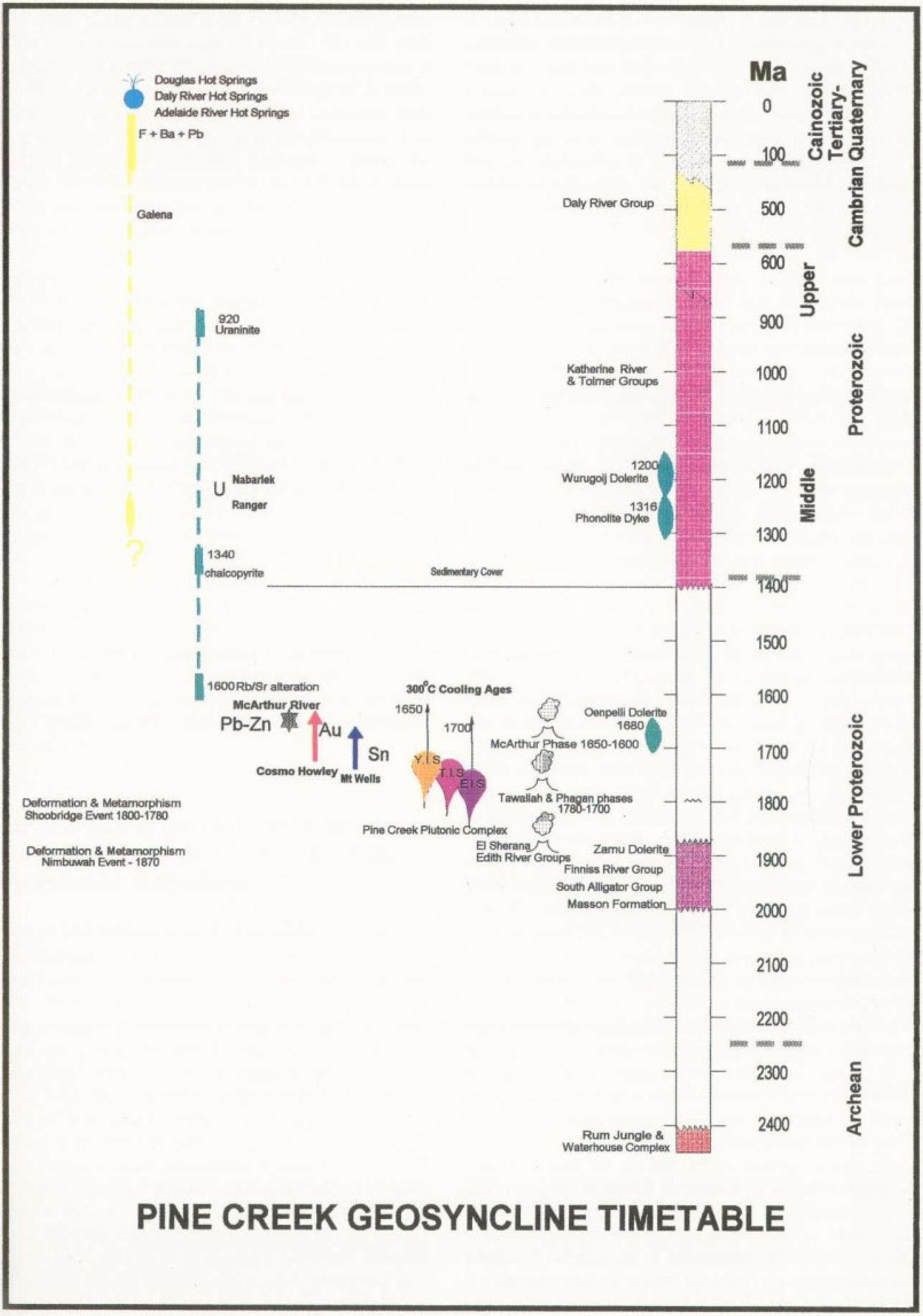

Figure 32. The Pine Creek Province timetable.

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 associ-