mineralisation (to ± 50 Ma) and an unusually homogeneous Pb source on a scale of the order of 100 km (ie, from Tom's Gully to Bridge Creek). This Pb source is not the granites but is present on the scale of the distribution of the deposits.
2. The linear trend between the deposits and granite initial Pb ratios may be explained by the modelling of potential Pb source regions. Modelling data for Yilgarn granitoids shows a subparallel trend to the linear array for most deposits and the two granite initial Pb compositions (Fig. 29). If the basement has an age of 2.5, 2.7 or 3.0 Ga and mineralisation was about 1.8 Ga, the basement rocks would be expected to show a linear trend with a slope of 0.28, 0.31 and 0.36, respectively, as shown on Fig. 30. A linear trend of these slopes does link the granite initial Pb isotope compositions and most of the galena data, but one sample from Big Howley and the Woodcutters galena are significantly off this trend (Fig. 30). The Pb in these two galenas could either come from a different source than the other deposits, or be from the same source but formed earlier.

Alternatively, the slope of the basement trend does depend on the age of the basement. If the hidden basement were significantly older than 3.0 Ga, the slope of the trend would be steeper and could be compatible with a link between the granite and the radiogenic galena data from Woodcutters and Big Howley. Notwithstanding this possibility, it is more likely that the data for Woodcutters and Big Howley are anomalous and require a different Pb source than other deposits. This may well be the case for Woodcutters but is not easily accepted for Big Howley when other data from the deposit are consistent with the main cluster of data. The origin of the Big Howley galena data remains uncertain.

In detail, the data in the cluster of deposits on Fig. 29 are slightly heterogeneous and may reflect a slightly heterogeneous source, local fluid-rock interactions, and/or different ages of mineralisation. These alternatives cannot be resolved from the current data.

3. If the linear trend of data in Figures 29 and 30 relates to variable contributions from granite Pb and Pb from another reservoir, then it follows that Woodcutters and Big Howey may be the deposits which are the most distal to a granite, and Flora Belle is the most proximal to a source of granite Pb. This appears to be compatible with their location, but may require further testing of deposits which are known to be proximal or distal to granites. This could include other deposits, or additional samples from the deposits already analysed. Woolwonga (Fig. 29) is considered more proximal to the Burnside Granite by this model: this may be verifyable by a more detailed study.

A number of deposits such as Brock's Creek, Pickfords and Rum Jungle show significant offsets relative to the observed cluster or trend of data (Figs 29 & 30). The reason for this might relate to the samples (e.g. Brock's Creek galena is not related to an ore zone; Rum Jungle galena may not be related to mineralisation), differences in the source region or timing of the galena formation in each sample, or later galena growth as inferred for the more radiogenic compositions. Further work would be needed to resolve the origin of these offsets.

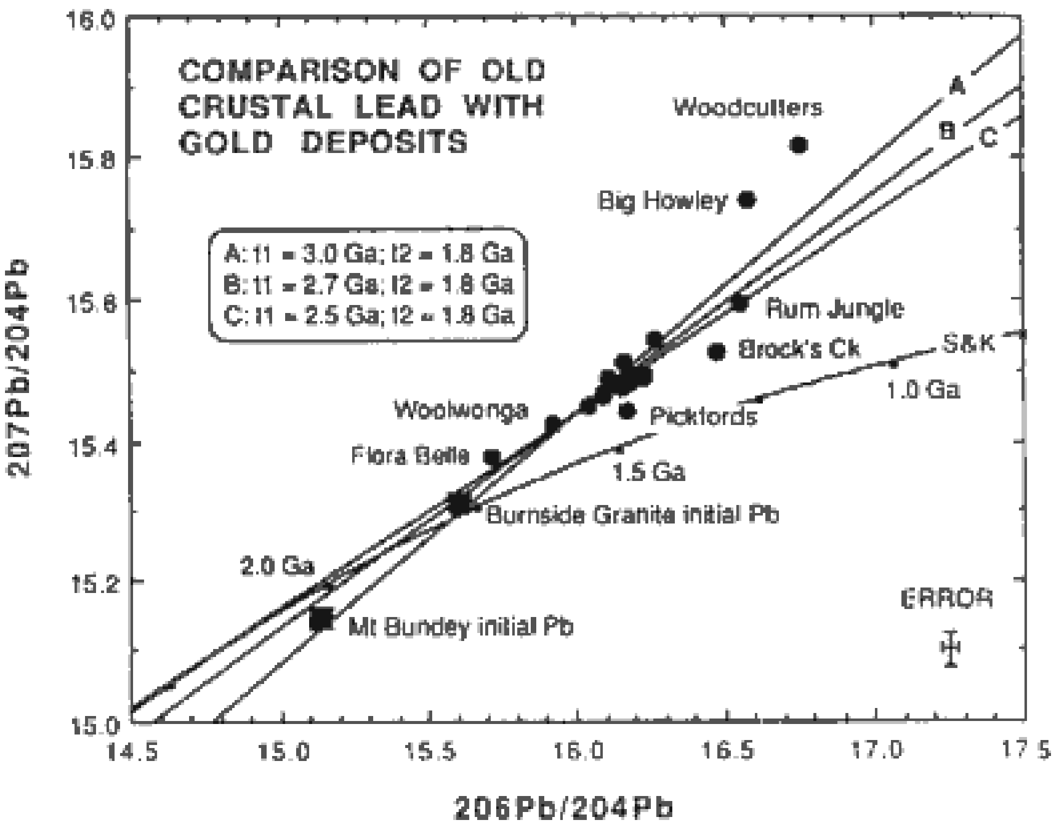

Figure 30. Common Pb isotopic modelling of the Pb from older crust compared to the sulphide data from ore deposits and the initial Pb from the Burnside and Mt Bundey Granites on a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram. t1 is the age of the older crust; t2 is the age of mineralisation. Data for the Mt Bundey Granite from Sheppard (1992). S&K is the lithospheric growth curve of Stacey and Kramers (1975).

4. The deposits to the SE of the Shoobridge Granite (see Table 9) all have similar Pb isotope compositions and cluster more tightly in Fig. 29 than galenas from the Howley Anticline area. The association of pegmatites and gold deposits in the area SE of the Shoobridge Granite suggests there may be a granite directly below the mineralised area. As such, the difference with the Howley Anticline area may be one of more direct input of magmatic Pb near the Shoobridge Granite, to more heterogeneous mixing along the Howley Anticline. The area near the Shoobridge Granite might be one area where K-feldspars from pegmatites may have the same initial Pb as the galenas and hence prove a relationship between magmatism and mineralisation. This would be important to test with further work.

7. Phanerozoic and Recent Hydrothermal Activity

As it was already recognised by Marshall et al. (1988) the Pine Creek Inlier contains products of high-level epithermal activity up to the present time. The most obvious products of this recent thermal activity are hot mineral springs (eg. Douglas Hot Springs, Daly River Hot Springs and Adelaide River Thermal Springs). These are generally located on the regional strike slip faults (see Fig. 31) and their water production, composition and temperature have not been measured. Metal content was tested in the Douglas Hot Springs thermal water with results: 0.045 ppb Au, 0.3 ppb Sn and 10 ppb B. According to Hamilton et al., (1983) a common upper limit of gold concentrations in fresh waters is 140 to 200 parts per trillion (0.14–0.20 ppb). The Adelaide River Thermal Springs are located within the Adelaide River Fault, which is represented by strongly brecciated Cambrian sandstone. Water output estimation is in the order of 10 million litres per day. The temperature of the water is about 35 °C with 0.1 mg/l fluorine content and gold content under the detection limit (0.05 ppt).

The Douglas Hot Springs are located within the sandstones and siltstones of the Waterbag Creek Formation (Middle Proterozoic Tolmer Group), along a north-west trending fault, which is sub-parallel to the Pine Creek Shear zone. The springs join in a central pool on the banks of the Douglas River. Their temperature has been recorded at over 60 °C. Carbonate precipitate from the bicarbonate-rich water contains 1 ppb Au and 4 ppb Pb and cements a breccia consisting of country rock fragments with 154 ppb Pb, 30 ppb Zn and 59 ppb Cu. Fluoride concentrations are between 0.3 and 0.4 mg/l (McCowan, 1989) in the ground water to the west of Douglas Hot Springs within of the Tindal Limestone (Cambrian age).

The Daly River Hot Springs (Surveyor Creek Springs and Daly River Crossing Springs) are known to be spatially associated with barite, galena and fluorite mineralisation in brecciated Cambrian limestone.

Fossil hot springs were identified by Blake (see Marshall et al., 1988) at the Old Boiler locality 15 kilometres south-west of the Mount Bundey granite (Fig. 31). A fossil hot spring vent is a part of quartz vein stockwork, which crops out over about 250 metres and is 5 metres wide. The structure contains encrusting siliceous sinter and concretions (geyser eggs). The vent forms part of a three kilometre long fault system.

Epithermal mineralisation was identified in the Lead and Full Hand prospects south-east of the Shoobridge Granite and in an unnamed prospect at the Burnside Granite. The Lead prospect consists of vein of comb-textured quartz with galena, sphalerite, amethyst and barite. The Full Hand prospect includes two lodes. Lead (galena) mineralisation is found in narrow quartz veins with multi-phase zonal textures. The unnamed prospect cuts the Burnside Granite and consists of a quartz vein, several kilometres long and 1 to 5 metres wide. At least two old prospects contain galena in brecciated and altered granite. The vein consists of comb-textured multi-zoned quartz.

The Sundance Gold Mine near Batchelor has been studied by Simpson (1994). There are some indications of low temperature pipe-like epithermal mineralisation consisting of a siliceous breccia cemented by massive auriferous pyrite. According to Simpson (1994) the age of mineralisation is probably Middle-Upper Proterozoic (the paleogossan is buried under the Upper Proterozoic Depot Creek Sandstone). At Sundance the mineralisation also contains anomalous tin.

The Clonmara Creek fluorite and barite prospects are located north and south of Daly River Hot Springs (see Fig. 31). Fluorite veins occur within altered stromatilitic Tindal Limestone (Lau, 1977), indicating the presence of an epi-

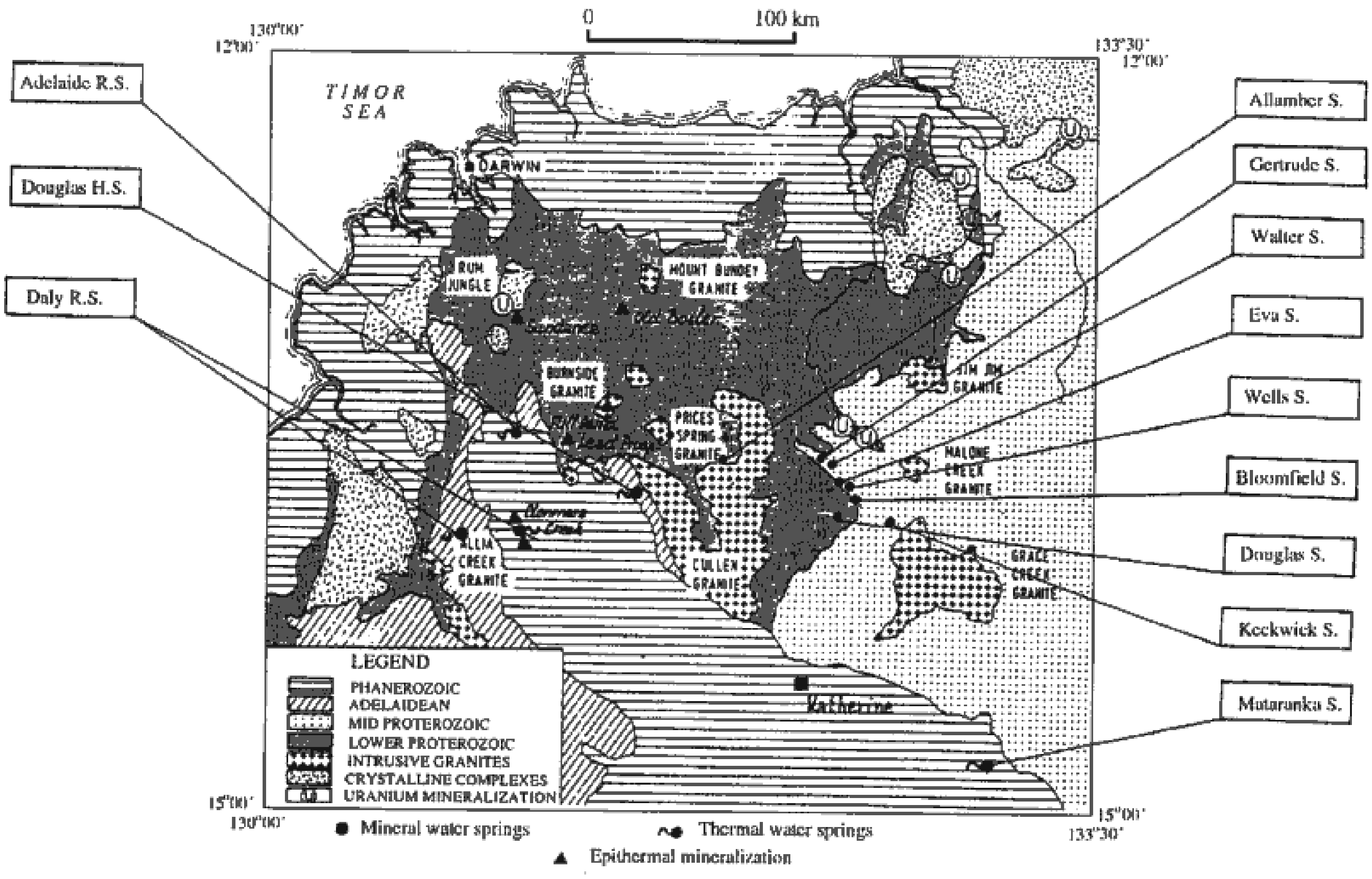

Figure 31. Epithermal mineralisation and mineral water springs in the Pine Creek Province.

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.