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

Table 9. All available Pb isotope data on granites and sulphides (Tom's Gully and Mt Bundey Granite data from Sheppard, 1992)

Sample	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Type
Mt Bundey Initial Pb	15.131	15.146	35.268	LR-AWKF
Burnside Granite Initial Pb	15.604	15.312	35.543	AWKF
Tom's Gully-ore sulphides				
107677B	16.162	15.511	35.712	ore pyrite
107678B+A	16.178	15.481	35.624	ore pyrite
107679B+C	16.215	15.488	35.661	ore pyrite
107679D+E	16.195	15.490	35.651	ore pyrite
107681A+B1	16.116	15.487	35.633	ore pyrite
107681C2	16.109	15.489	35.629	ore pyrite
Douglas Hot Springs	18.184	15.672	38.105	water
GALENAS				
Mineralisation within vein cutting Burnside Granite: listed north to south				
Old prospect trenches	16.267	15.542	36.070	K141 gn
Lead prospect - sth Burnside	21.127	16.074	41.886	K13 gn
Rising Tide	42.457	18.436	53.498	K192 gn
Howley Anticline and nearby areas				
Big Howley	16.044	15.451	35.235	K311 gn
Big Howley	16.580	15.739	35.948	gn from FLINC sample
Bridge Creek	16.186	15.481	35.822	DDH BC6 gn
Brock's Creek				
BKRC 151 - 109.3m	16.480	15.525	36.183	gn from below ore
Cosmo Howley	22.103	16.339	40.405	gn from DDH
Woolwonga	15.924	15.425	35.415	K37 gn
Mt Shoobridge area				
Lead prospect	16.230	15.492	35.888	K61 gn
Barret's Mine	16.222	15.488	35.907	K52 gn
Full Hand Mine	16.211	15.488	35.883	K71 gn
Full Hand Mine	16.160	15.476	35.842	K72 gn
Pyromorphite prospect	16.188	15.494	35.891	K91A gn
Various locations				
Flora Belle #	15.711	15.377	35.444	gn
Evelyn Mine	21.044	16.068	41.279	K201 gn@
Evelyn Mine	16.096	15.465	35.249	K202 gn@@
Evelyn Mine	16.094	15.466	35.248	K203 gn@@
Woodcutters	16.758	15.817	36.187	gn
Pickfords	16.170	15.441	35.929	gn
Rum Jungle Ck South	16.554	15.595	36.388	K321 gn

LR- = least radiogenic; AWKF = acid-washed K-feldspar

gn = galena

deposit within Pine Creek Shear Zone

@crosscutting cpy-gn-sphal vein

@@ more massive mineralisation

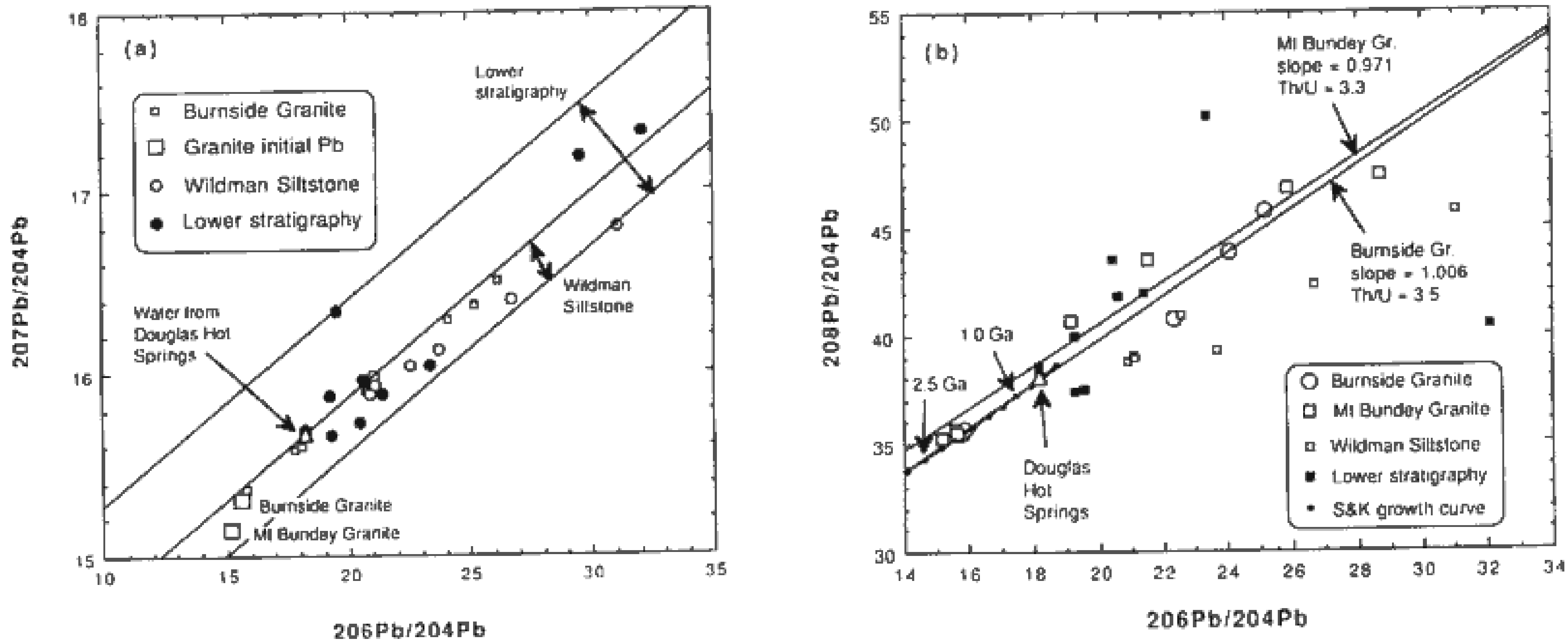

Figure 26. Common Pb isotopic diagrams comparing data for the Burnside and Mt Bundey Granites with metasedimentary and metavolcanic rocks: (a) $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, and (b) $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$. Data for the Mt Bundey Granite and rocks from the Proterozoic succession from Sheppard (1992). S&K is the lithospheric growth curve of Stacey and Kramers (1975).

distinguish between the basement rocks and the sedimentary rocks which are probably derived from the basement.

The Th/U of the Wildman Siltstone is lower than both the granites and Stacey & Kramers (1975) average crustal growth curve, and is mostly lower than the rocks of the lower succession (Fig. 26b). The rocks of the lower succession have variable Th/U and overlap other rock suites.

6.1.2. Douglas Hot Springs

Lead was extracted from water collected from the Douglas Hot Springs. The Pb isotope composition (Fig. 26) is broadly similar to the modern composition of the Burnside Granite as well as metasedimentary and metavolcanic rocks from the region. The Pb in the spring water is unlikely to have been derived from modern volcanic rocks, as these would be expected to contain Pb similar to the modern Stacey and Kramers (1975) composition. From this observation, it is concluded that the hot springs are probably related to HHP granites at depth, rather than recent igneous activity.

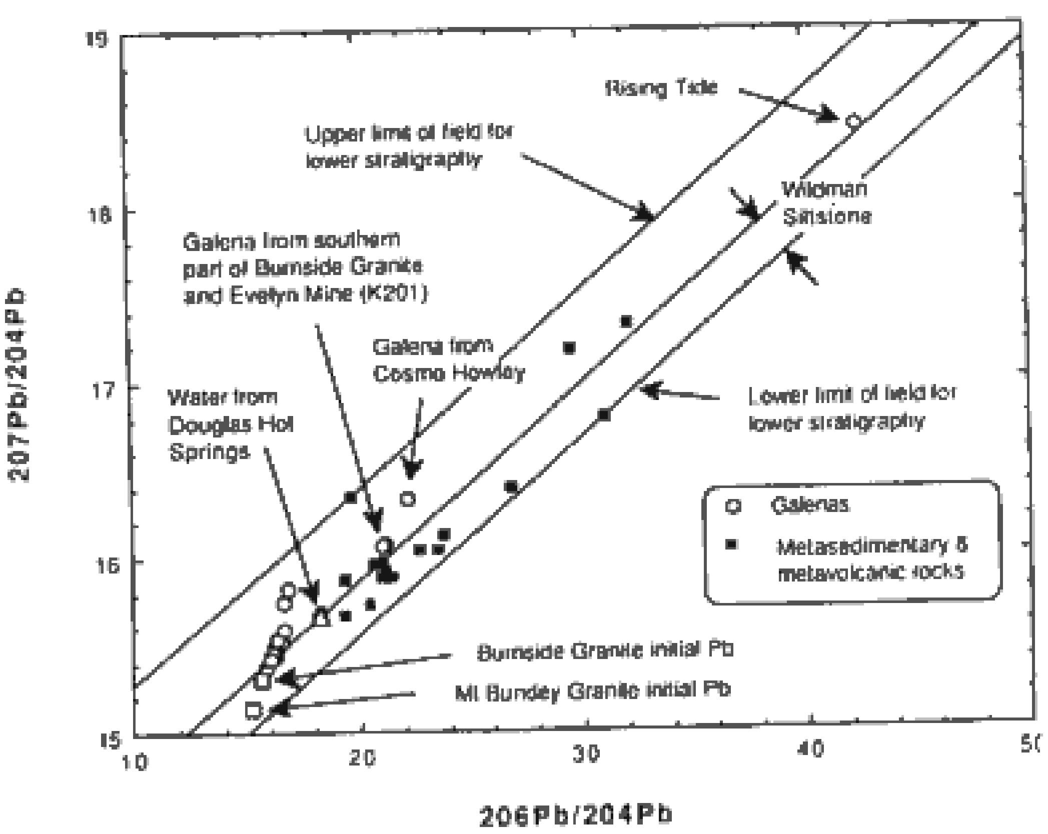

Figure 27. Common Pb isotopic comparison of sulphide data from ore deposits with the Proterozoic succession and the initial Pb from the Burnside and Mt Bundey Granites on a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram. Data for the Mt Bundey Granite and rocks from the Proterozoic succession from Sheppard (1992).

6.1.3. Galenas related to Ore Deposits and Prospects

The galena data show two main features: a small number of analyses are extremely radiogenic (e.g. Figs 27 & 28), whereas most fall in a cluster or on a steep trend which appears to include the granite initial Pb compositions (Fig. 29). These are discussed in more detail below. All of the galena data fall within the field for the Proterozoic succession at the time of granite activity (Fig. 27).

6.1.4. Burnside Granite: Galena in a crosscutting Quartz Vein

A prominant N-S quartz vein crosscuts the middle of the Burnside Granite and contains a number of galena occurrences. Three samples ranging from near the middle of the granite (sample K141) to near the southern margin of the granite (sample K13) to a mineralisation at Rising Tide just south of the granite margin, show progressively greater radiogenic compositions to the south (Table 9; Fig. 28). The unusual aspect of this correlated isotopic and spatial trend is that the most radiogenic Pb from Rising Tide is more radiogenic than any other sample so far analysed and much more radiogenic than the modern Pb in the Burnside Granite or any other rock so far encountered (i.e., galena has $^{206}Pb/^{204}Pb = 42.5$ compared to the granite which has a

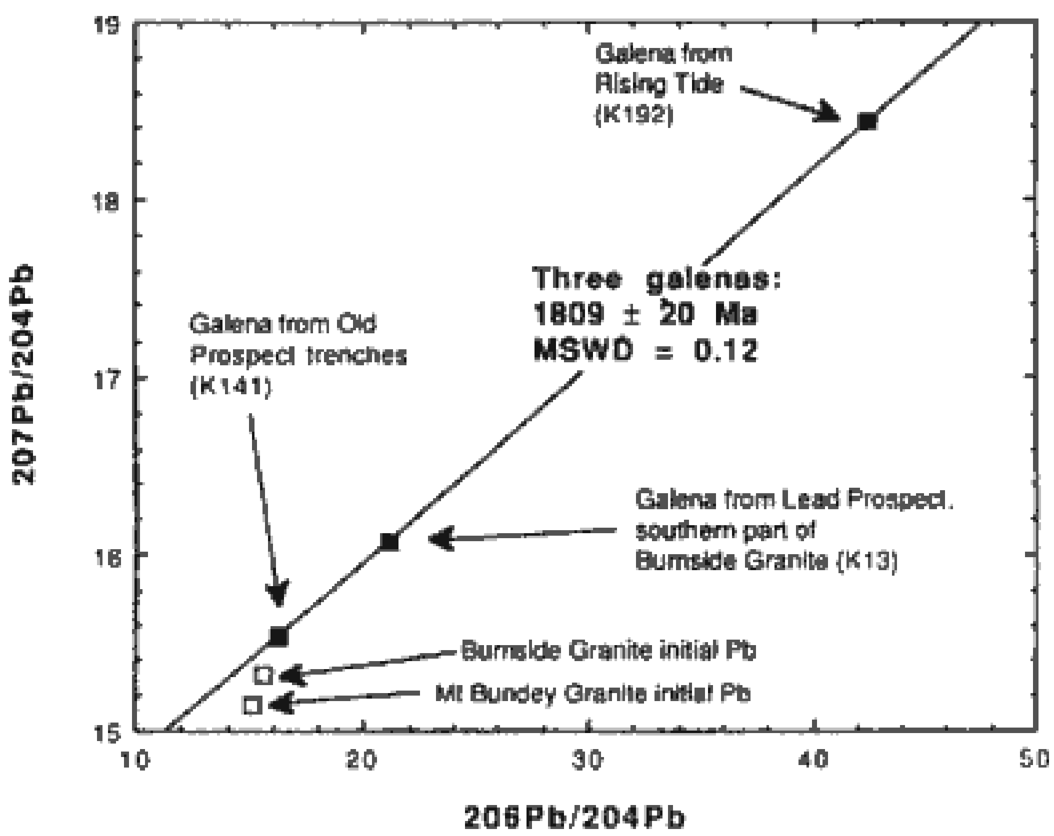

Figure 28. Common Pb isotopic array of galenas from three sites along the N-S dyke which transects the Burnside Granite. Data for the Mt Bundey Granite from Sheppard (1992).

maximum, modern-day $^{206}Pb/^{204}Pb = 25.2$). Further, the linear trend defined by the three galenas is perfectly fitted to a straight line (MSWD = 0.12), and if treated as an isochron yields an age of 1 809±20 Ma (±2σ), which is indistinguishable from the age of granite emplacement. The two-stage model source μ is 8.41±0.01, which is different from the Burnside Granite, and the galena linear array does not pass through the Burnside Granite initial Pb composition (Fig. 28).

The very radiogenic Pb in Rising Tide galena and the Pb-Pb isochron "age" which equates to the age of granite emplacement, can only be reasonably explained by: (i) galena formation in recent times such that the linear array in Fig. 28 is an isochron, and (ii) the source of Pb for all three galenas was the same, but this source was not solely the Burnside Granite.

Such an interpretation of relatively recent galena growth in this vein is compatible with the modern hot spring activity inferred to be related to HHP granites. The two are probably related and the vein may represent the root zone of a relatively recent high-level hydrothermal system. The galena in the vein from Rising Tide is interstitial to barite (calcite) blades, now pseudomorphed by quartz, and is compatible with low temperature formation. In a more regional context, if such mineralisation was driven by the "heater" of an HHP granite, "epithermal" mineralisation could occur at any time during the past ca. 1 810 Ma.

6.1.5. Other galenas with very radiogenic Pb

Two other galenas with radiogenic compositions have been identified (Table 9; Fig. 27). One is from the three samples from the Evelyn Mine (K201, from a crosscutting chalcopyrite-galena-sphalerite vein). Two galena samples from massive sulphide samples from the Evelyn Mine are identical to each other and cluster with a number of other deposits (Fig. 29). It is therefore likely that the radiogenic Evelyn galena does not preserve the initial Pb isotope composition from its formation, and, because it is also on the galena isochron shown in Fig. 28, it is inferred to have received more radiogenic Pb subsequent to the formation of the other two galenas; that is, it probably reflects much younger galena growth due to prolonged hydrothermal activity related to HHP granites.

Similarly, a galena from Big Howley is also significantly more radiogenic than another sample from this deposit (Fig. 29). However in this case, the Pb from the two Big Howley galenas do not fall along a ca. 1 810 Ma isochron and an alternative origin must be proposed to explain the relationship between the two Big Howley galena samples (discussed below).

6.1.6. Main Grouping of Galena Data

The majority of the galena data fall in a linear trend with the granite initial ratios, and most of the data form a distinct cluster (Figs 27 & 29). In Fig. 29, Woodcutters and Big Howley are the most radiogenic, whereas Flora Belle is the least radiogenic and closest to the granite initial Pb compositions. There are a number of important interpretations of the data distribution in Fig. 29.

1. The data for the Tom's Gully and the Bridge Creek deposits, amongst others, have approximately the same initial Pb, whereas their spatially related granites have distinctly different initial Pb from each other and the deposits. This indicates that if the granites contributed Pb to the ore fluids, then this contribution was minor. Further, the relatively homogeneous Pb isotopic composition for a significant group of the deposits and prospects implies coeval

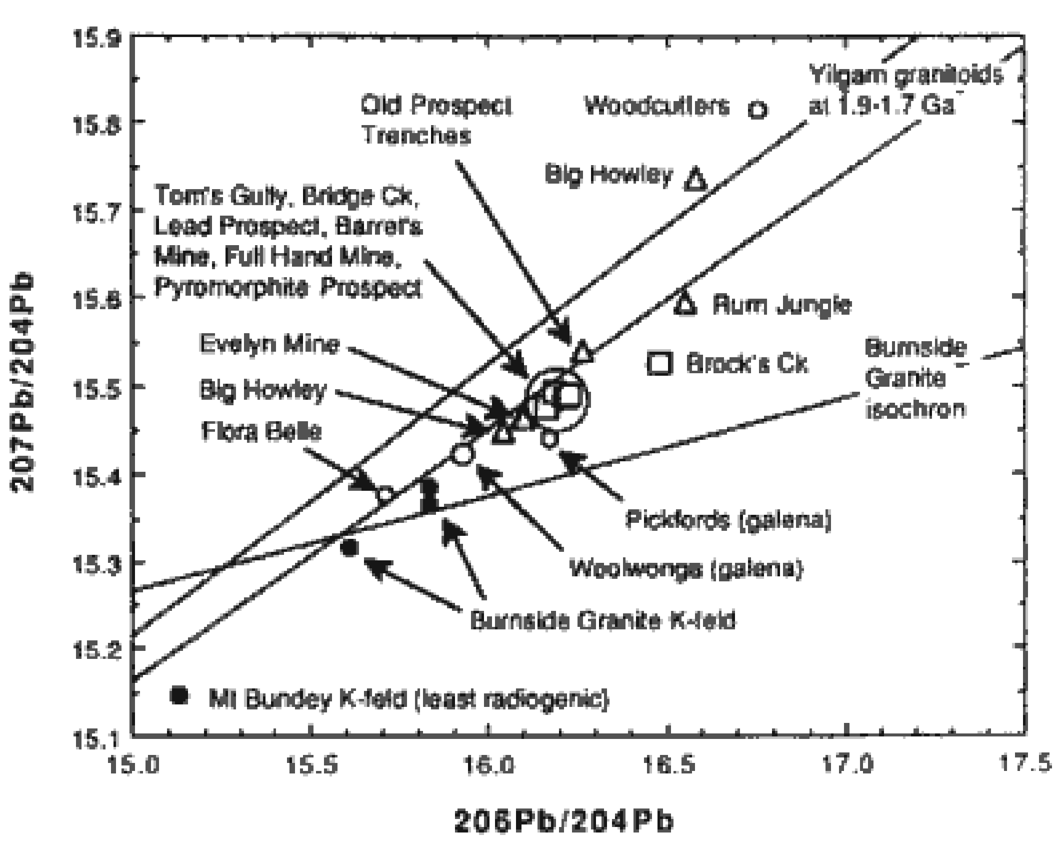

Figure 29. Common Pb isotopic comparison of the less radiogenic sulphide data from ore deposits with the Burnside Granite isochron and the initial Pb from the Burnside and Mt Bundey Granites on a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram. Also shown is the calculated trend for Pb in Archaean granites from the Yilgarn Block at 1.9–1.7 Ga. Data for the Mt Bundey Granite from Sheppard (1992); Yilgarn data from Wang et al. (1993).

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.

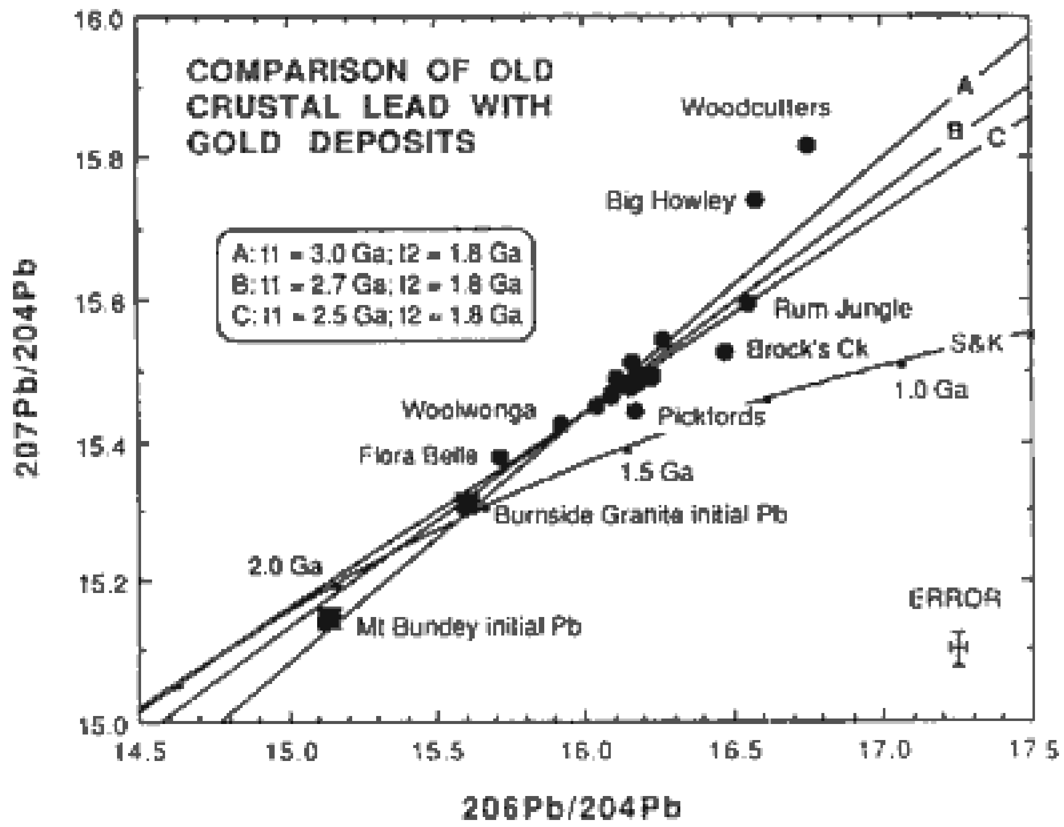

Figure 30. Common Pb isotopic modelling of the Pb from older crust compared to the sulphide data from ore deposits and the initial Pb from the Burnside and Mt Bundey Granites on a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram. t1 is the age of the older crust; t2 is the age of mineralisation. 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 Ade-