

SHRIMP U–Pb analyses of detrital zircon: a window to understanding the Paleoproterozoic development of the Tanami Region, northern Australia

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Abstract Poorly exposed Paleoproterozoic turbiditic to shallow marine sedimentary rocks of the Tanami Basin, NT, Australia are largely the erosional products of either the ~1.87–1.85 Hooper Orogeny and/or magmatism associated with the ~1.87 Ga Nimbuwah Event. Dating of detrital zircon from six of the principal sedimentary units shows that deposition spanned at least the period ~1.84–1.77 Ga. Collectively, the detrital zircon ages reveal a progression in provenance that is a record of the development of the orogen. The basal Dead Bullock Formation contains only zircon derived from Archean basement and no contemporaneous products of orogeny. Its deposition age is inferred to be ~1.87–1.84 Ga. Orogenic ~1.86 Ga zircon appears in the overlying Killi Killi Formation, deposited between ~1.84–1.82 Ga and persists, probably due to recycling in all overlying units except one, the Mount Charles Formation. The accepted stratigraphic position of this unit might be incorrect.

Keywords Geochronology · SHRIMP · Detrital zircon · Provenance · Tanami · North Australia

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Introduction

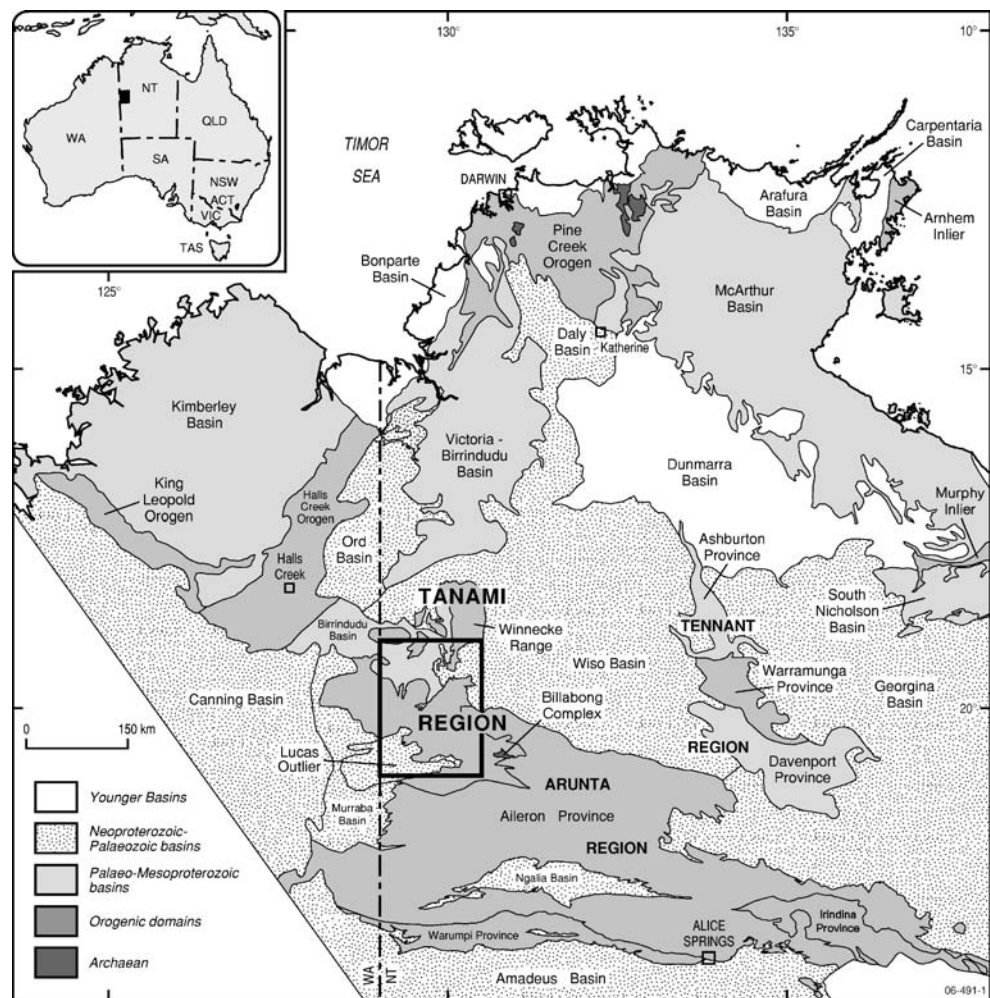
The Tanami Region in NW central Australia is one of the richest gold-bearing Proterozoic regions in Australia. Gold production from the major mines (e.g. Callie, Tanami, The Granites) over the last 20 years has exceeded 4.8 Moz, with proven reserves of over 7.7 Moz (Wygralak et al. 2005). The province is a part of the North Australia Craton (NAC; Fig. 1) and has similarities with other north Australian Paleoproterozoic terranes such as the Halls Creek Orogen, the Pine Creek Orogen and the northern Arunta Inlier. However, because much of the Tanami Region is covered by regolith, its geology remains poorly understood.

The stratigraphy of Paleoproterozoic sequences of the Tanami Region has been established principally on the basis of drill core logging and mine exposures. The studied areas are widely scattered, however, and the paucity of intervening surface outcrop has made correlations tenuous. The only direct information about deposition ages has been provided by geochronology of felsic volcanic units that have yielded zircon U–Pb ages of approximately 1.82 Ga (Smith 2001).

Poor knowledge of the stratigraphy and basin architecture has been a major hindrance to effective exploitation of the Tanami Region's mineral potential. Therefore, in 1998, a geochronological study of the region was included in the joint Northern Territory Geological Survey—Australian Geological Survey Organisation (now Geoscience Australia) age determination program. The aims of the study were to document the history of sedimentation and igneous activity in the Tanami Region, providing a time framework for basin development and improved basin-wide correlations.

In this paper, we report the results of a SHRIMP U–Pb isotopic study of detrital zircon from 12 sedimentary rocks representing each of the major stratigraphic units from the

Fig. 1 Location of the Tanami Region



Tanami Region. These age determinations provide direct information both on the provenances of the sediments and their maximum deposition ages. An additional constraint on the deposition age of the Dead Bullock Formation was obtained by dating igneous zircon from an intercalated felsic tuff. This study has established that deposition occurred at least between the period 1.84 to 1.77 Ga, and that the sediments were probably eroded from sources to the north (Pine Creek Orogen) and northwest (Halls Creek Orogen) in response to uplift before ~1.84 Ma.

Geology

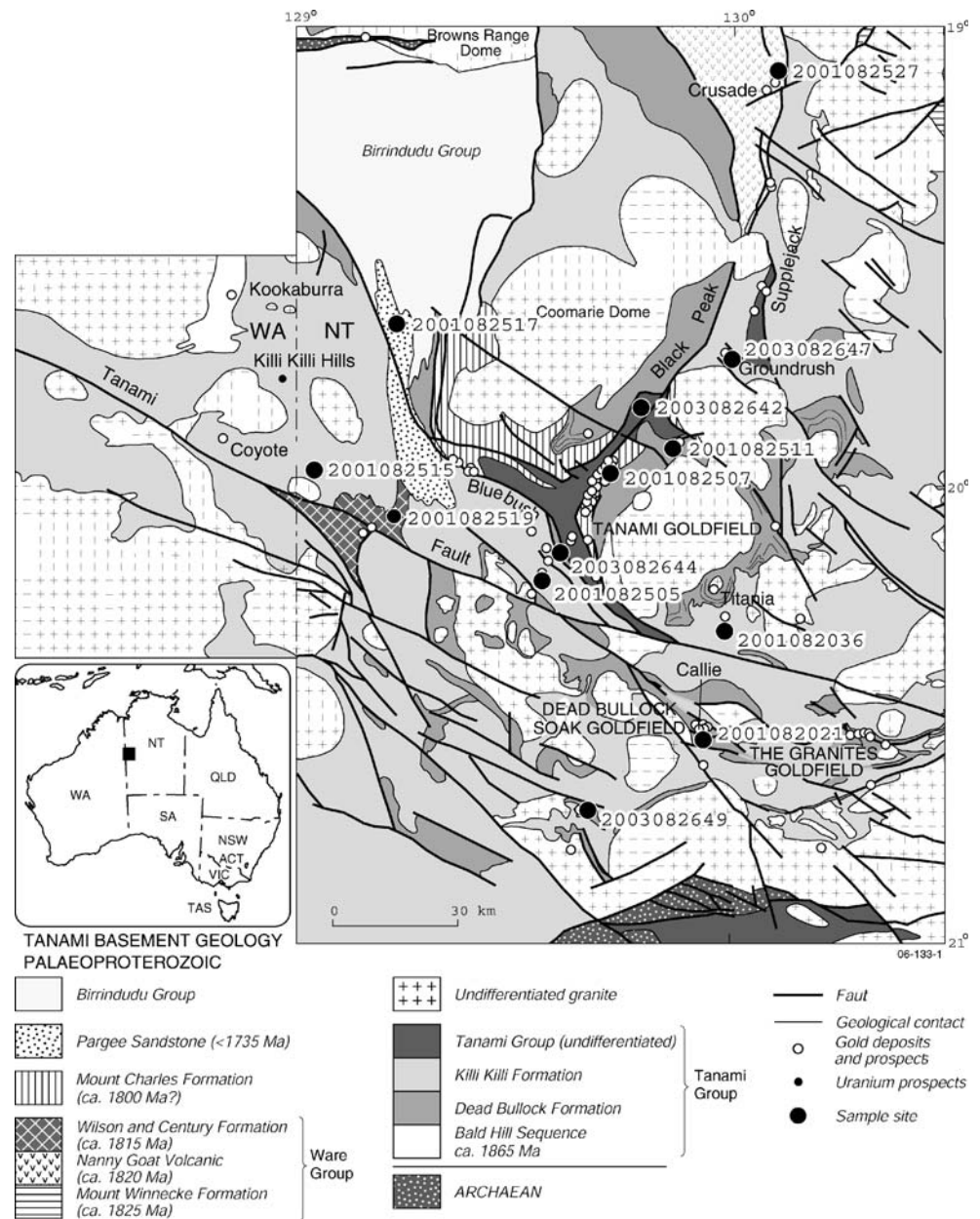
The following is a brief summary of the major geological features of the Tanami region. The reader is referred to Crispe et al. (2006) for a more complete discussion. Figure 2 is a generalized geological map of the Tanami region showing SHRIMP U–Pb zircon geochronology sample sites discussed in this paper, and Fig. 3 is a generalized time–event column for the Tanami region.

The Tanami province consists of a thick sequence of predominantly low grade Paleoproterozoic marine sedimen-

tary rocks and rare volcanic rocks deposited on late Archean granitic gneiss and intruded by granite mostly at ~1.82–1.79 Ga (Hendrickx et al. 2000; Page et al. 1995). Recent unpublished work suggests that the oldest known Paleoproterozoic rocks occur in the Bald Hill sequence in Western Australia. A high level rhyodacite in this unit has an interpreted zircon U–Pb SHRIMP crystallization age of ~1,864 Ma (cited in Huston et al. 2006). The sedimentary sequence has been subdivided into six main units. These, from base to top, are: the Dead Bullock Formation (lower sandstone, upper carbonaceous siltstone with lesser iron formation); the Killi Killi Formation (turbidite) of the Tanami Group; the Ware Group (coarse sandstone, felsic volcanic rocks); the Mount Charles Formation (predominantly turbidite, arkosic sedimentary rocks with interlayered basalt); the Pargee Sandstone (sandstone and conglomerate); and the Birrindudu Group (marine to fluvial sandstone, conglomerate, and calcareous sedimentary rocks). There is a progression within the sequence from deeper to shallower water facies. The principal hosts for Au mineralization are the Dead Bullock and Mount Charles Formations.

Rocks of the Tanami Group were intruded by doleritic sills and subsequently deformed by the ~1,830 Ma Tanami

Fig. 2 Generalised geology map of the Tanami Region, showing sample locations

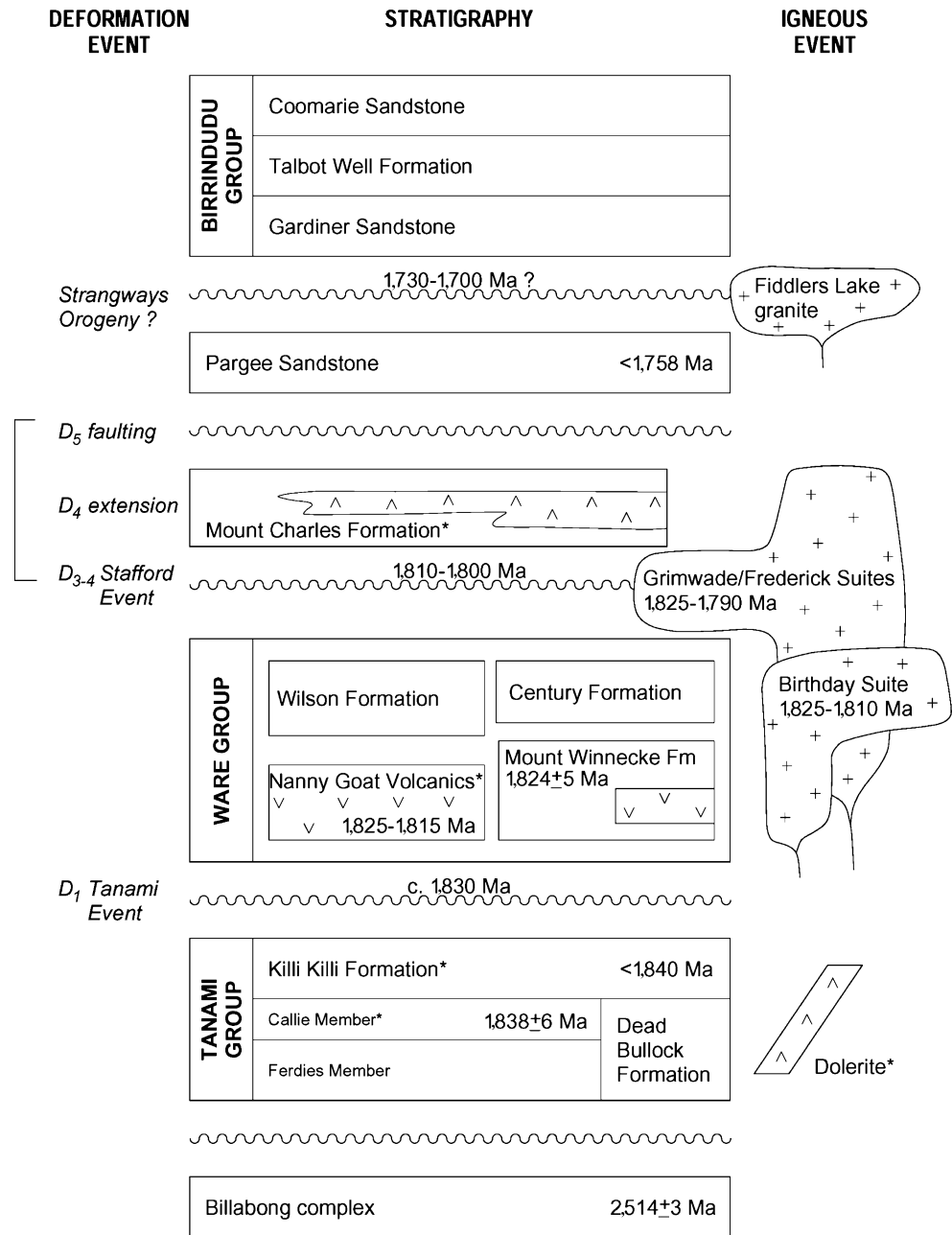


Event (D_1 – M_1). This event locally caused meso- and macroscopic disharmonic folds and greenschist facies metamorphism. A second period of compressional deformation (D_2) is broadly synchronous with ~1.82–1.79 Ga granite intrusion and is the first event to affect Ware Group rocks. A further compressional event (D_3) is interpreted to have affected rocks of the Ware Group. An extensional event is interpreted, resulting in the deposition of sediments and basalts of the Mount Charles Formation before D_4 , a SSE-directed shortening event. D_5 transpression resulted in the development of shear zones and faults. Many of the Au deposits in the Tanami region are associated with D_5 structures (Huston et al. 2006).

Materials and methods

Zircon separates were obtained using magnetic and density techniques from crushed samples. Detrital zircons were not handpicked, but sprinkled onto the mount surface to ensure an unbiased range of zircon grains. Zircons were mounted in epoxy resin, together with standard zircons SL13 (U abundance zircon) and QGNG (Pb/U age standard). The epoxy mount was polished to reveal zircon interiors and photomicrographs were taken in transmitted and reflected light. Cathodoluminescence (CL) images were taken using a Hitachi S 2250-N SEM at the ANU-RSBS Electron Microscopy Unit.

Fig. 3 Generalised time–event column for the Tanami Region. Asterisks denote units hosting significant gold mineralisation



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Isotopic analyses reported in this study were carried out on the SHRIMP I, SHRIMP II and SHRIMP-RG ion microprobes at the Australian National University, Canberra and SHRIMP B at the Curtin University of Technology in Perth, Western Australia. Analytical procedures are described in Compston et al. (1984), Williams and Claesson (1987) and Claoué-Long et al. (1995).

The primary oxygen ion beam ranged between ~2 to ~6 nA in intensity for a spot diameter of between ~20 to ~40 μm . Ionized particles were extracted into the mass spectrometer with a 10 kV potential and counted by a single electron multiplier. Ions were focussed into the collector by a cyclic stepping of the magnet. Each analysis represents

the average of five to seven scans through the different mass stations.

Calibration of Pb/U ratios was by comparison to the zircon standard QGNG and the power law relationship of Pb^+/U^+ and UO^+/U^+ (Claoué-Long et al. 1995). The Pb/U ratios were normalized to an assumed value for QGNG of 0.3324 (equivalent to 1,850 Ma). Uranium and thorium abundances have been calculated with reference to SL13 (238 ppm U) and are subject to uncertainty of at least $\pm 20\%$, this being the range of U abundance within that reference material. Common Pb corrections were based on individual measured ^{204}Pb abundances and assuming crustal common Pb of the same age in the zircon as

modelled by Stacey and Kramers (1975). Data reduction was carried out using the SQUID 1 and ISOPLOT 3 Microsoft Excel-based macros of Ludwig (2001, 2003).

Individual analyses reported in this paper have uncertainties listed in the tables and plotted on concordia diagrams as shaded ellipses at the 1σ level; unfilled ellipses represent compositions that are greater than 10% discordant. Final ages are quoted in the text with 95% confidence limits. Analyses of the QGNG standard were interspersed with the unknowns at the rate of approximately one in four.

Detrital zircon maximum deposition age calculation

Detrital zircon U–Pb age studies by either ion microprobe or laser ablation ICPMS routinely provide a large number of age determinations on individual zircon grains recovered from clastic sedimentary rocks. The zircon age distributions generated by these methods can be used to infer sediment provenance, and to make correlations between discontinuous sedimentary sequences. In addition, the youngest zircon(s) can be used to estimate the maximum deposition age of a sedimentary unit. Maximum deposition age estimates obtained in this way have the potential to provide important stratigraphic constraints for siliclastic sequences, especially those from Proterozoic basins where interlayered felsic volcanics are rare and fossil control absent.

There are two broad approaches in estimating a maximum deposition age from the isotopic ages of the youngest detrital zircon grains in a population. These are to use the age determination from the youngest zircon grain analyzed (Cross et al. 2003), or to determine a pooled age from the youngest statistically coherent zircon age population (Williams 2001; Black et al. 2004).

Maximum deposition ages derived from the age of the youngest zircon grain(s) from a detrital population are based on a number of assumptions. First, the analyzed zircon grains are assumed to have experienced no Pb loss. Second, all zircon grains are considered as individuals. Finally, in the absence of any morphological or chemical similarities, no assumption of age-group membership is made. Using this approach, the age and uncertainty of the youngest zircon is used as an estimate for the maximum deposition age. The uncertainty of this age estimate can be improved by calculating a pooled age from the youngest few analyses.

The above approach can involve sampling of individual zircon ages from the younger tail of a Gaussian, near-Gaussian or composite age distribution. Individual ages may be statistically indistinguishable from older members of the population. In addition, when the youngest few apparent ages are pooled to increase the precision of the age estimate, the resulting mean squared weighted deviation (MSWD) can be well below unity, and therefore indicate biased sampling of the detrital zircon population (e.g. Cross et al. 2003).

In the circumstance where the youngest detrital zircon from an age distribution is statistically distinguishable from older grains, multiple analyses will improve the precision of the age and should be performed to ensure that Pb loss has not occurred. Nelson (2001) was able to show that in some situations, the youngest grains can be a reliable estimate of the depositional age of a clastic unit. However, the possibility of contamination during sample processing must be borne in mind when interpreting the significance of a maximum depositional age based on the presence of a single zircon.

Many researchers (e.g. Black et al. 2004; Williams 2001; Smithies et al. 2001; Trendall et al. 2004) establish the age of the youngest detrital zircon component in an age distribution, using the age and uncertainty of the youngest statistically coherent zircon age population. This approach involves an iterative process of culling individual zircon ages (points) from the older analyses in an age distribution, until the age of the youngest grouping of zircon grains has an MSWD value that approaches the upper 95% confidence interval boundary for a given number of points (i.e. degrees of freedom). This method of defining a statistically coherent population from either a Gaussian, near-Gaussian or composite population is treated on a sample-by-sample basis and is an entirely appropriate method to use when a morphological and/or chemical similarity between zircon grains is recognised. However, when no such similarity is observed, the youngest statistically defined population of zircon grains is assumed to have originated from a single crystallization event, even though it could represent a mix of different protolith sources with a range of overlapping zircon crystallization ages. This is an important point to consider, as most detrital zircon analyses on SHRIMP typically use four to five scans. The relatively reduced count rates have lower precisions in comparison to six to seven scan analyses which are typically used for SHRIMP U–Pb dating of igneous rocks.

Maximum deposition age estimates calculated from the youngest zircon(s) on the younger tail of a larger distribution may result in an under-estimation of the true deposition age, whereas maximum deposition age estimates calculated from the youngest statistically coherent population may result in an over-estimation of the true depositional age.

A crucial difference between the two approaches is that by calculating the age of the youngest statistically coherent zircon component, the researcher acknowledges that the age and uncertainties of the analyses on the younger tail of a larger distribution cannot be statistically separated from older zircon in the same distribution. We believe this to be the conservative approach and have adopted it in this contribution.

Sample selection

Samples were selected from the Tanami basin sequence with the aim of constraining the deposition age of each of the major stratigraphic units. To maximize the recovery of detrital heavy minerals, sandstone samples were chosen wherever possible in preference to shale samples. The samples collected included: (1) an arkose and feldspathic arenite from the Ferdies Member of the Dead Bullock Formation, (2) a graywacke, quartz arenite and two quartz wackes from the Killi Killi Formation, (3) a lithic arenite and graywacke from the Ware Group, (4) two arkoses from the Mount Charles Formation, (5) a quartz arenite from the Pargee Sandstone and (6) a quartz arenite from the Gardiner Sandstone. Most of the samples were collected from outcrop or mine exposures; four samples were selected from drill core provided by Newmont Mining. At each outcrop sampled, the material collected was the most coherent, least altered and least weathered available. Particular care was taken to avoid veining and obvious alteration. Veining and mineralization were also avoided when selecting samples from drill core.

Results

Dead Bullock formation—Tanami group

Ferdies Member; arkose (2003082647)

Sample 2003082647 was collected from a massive bed of immature, poorly sorted arkosic conglomerate exposed in the southern extension of the Groundrush Pit on the eastern wall about 60 m below ground level (Table 1). The arkose

consists of coarse-grained microcline, quartz and plagioclase in a quartz–biotite matrix. The zircon grains recovered are a mixed population with a range of sizes (30–200 μm diameter), shapes and colours, consistent with derivation from a variety of sources. Most are clear, colourless, relatively equant, subhedral to anhedral grains with few fractures or inclusions. Many are angular crystal fragments and a few have pitted surfaces resulting from sedimentary transport and reworking. Rare grains are more prismatic with sharply euhedral terminations. Some of the more equant grains also have some well-preserved crystal faces, and about 20% of the grains have faint internal zoning visible in transmitted light. CL imaging shows the zoning patterns more clearly, although the luminescence in most cases is dark. Concentric oscillatory and sector zoning predominates. Relatively few grains have obvious textural cores. Some grains have thin, irregular, very weakly luminescent overgrowths.

One hundred and twenty grains were analyzed (S1, Fig. 4). With two exceptions, U contents are moderate to low (28–500 ppm) and Th/U moderate to high (0.2–1.9, median 0.9). Most of the analyzed areas, although appearing clear, glassy and free of fractures or inclusions, contain significant amounts of common Pb. These range from just detectable (~ 0.15 ppm) to very high (300 ppm), median 2.5 ppm. There is, however, no systematic correlation between the common Pb content and radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ or Pb/U. The great majority of ages are concordant or near concordant within analytical uncertainty, although the uncertainties on the analyses with large common Pb corrections are much higher than normal. Four exceptions are more than 20% discordant (A100.1, A63.1, A71.1 and A19.1) and are not considered further in the age assessment (Fig. 4). Five other analyses (A53.1, A42.1,

Table 1 Location and other information for samples analysed as a part of this study

Unit	Lithology	OZCHRON number	Location GDA 94		Analyses >90% concordant
Ferdies Member	Arkose	2003082647	604082	7819984	112
Ferdies Member	Feldspathic arenite ^a	2003082649	571390	7710386	87
Callie Member	Tuff	2001082511	590477	7798371	27 ^b
Killi Killi Formation	Quartz wacke ^a	2001082021	599116	7730736	58
Killi Killi Formation	Quartz arenite	2001082505	560827	7767424	55
Killi Killi Formation	Quartz wacke	2001082515	507360	7790816	69
Killi Killi Formation	Greywacke ^a	2001082036	600796	7756265	56
Ware Group	Lithic arenite	2001082519	523028	7782433	82
Ware Group	Greywacke	2001082527	615954	7884346	66
Mount Charles Formation	Arkose	2003082644	564775	7770935	91
Mount Charles Formation	Arkose	2001082507	574953	7792871	32
Pargee Sandstone	Quartz arenite	2001082517	525686	7826720	66
Gardiner Sandstone	Quartz arenite	2003082642	580942	7804774	74

^aDrill core sample

^bMagmatic zircon

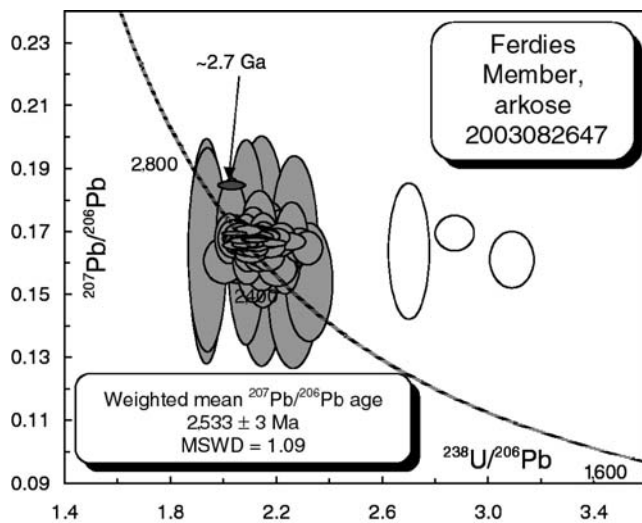


Fig. 4 Concordia plot of detrital zircon U–Pb analyses for arkose sample 2003082647 from the Ferdies Member of the Dead Bullock Formation

A75.1, A119C.1 and A12.1) have very large uncertainties in $^{207}\text{Pb}/^{206}\text{Pb}$ (>15%). These are not plotted in Fig. 4 and are not considered further.

The remaining 112 analyses scatter in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ more than expected from the analytical uncertainties (MSWD=4.6). The entire excess scatter is due to one analysis higher than the rest (A11.1). Omitting this analysis leaves 111 determinations that form a single population (MSWD=1.1). The weighted mean radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (0.16750 ± 0.00030) is equivalent to an age of $2,533 \pm 3$ Ma. Taking into account uncertainty in decay constants (Ludwig 2000), the uncertainty in the age is ± 7 Ma.

Ferdies Member, feldspathic arenite (2003082649)

Sample 2003082649 was a section of half core from Officer Hill (OHD002, 217.5–225.7 m) (Table 1). The arenite selected is the coarsest unit within an otherwise fine-grained sequence of carbonaceous siltstone. The sample is a fine- to medium-grained, grey-green, feldspathic arenite with a pronounced foliation defined by anastomosing chlorite. The zircon grains recovered are a mixed population of sizes (100–400 μm diameter) and shapes consistent with derivation from a variety of sources. The majority of the grains are subhedral, rounded to subrounded, stubby prismatic crystals with few or no preserved crystal faces. Rare grains are euhedral. Most grains are clear and weakly coloured, with relatively few inclusions or fractures. Some larger grains are highly fractured and discoloured. About 20% of the grains have faintly visible internal zoning and/or cores and rims in transmitted light. Some zircons have surface pitting but in most grains, the surfaces are covered

by a thin (<5 μm) layer of younger zircon that partially obscures this texture. There is a wide range in luminescence from dark to light with the average CL much stronger than that seen in the zircon grains from sample 2003082647. Many of the grains (~30%) have little or no obvious growth zoning. Zoning in the remainder ranges from broad banding to fine oscillatory zones. Truncation of the zones by the grain margins shows that most grains are fragments of larger crystals. The thin late overgrowths are dark in CL, a feature often typical of zircon rims.

One hundred and four grains were analyzed, eight in duplicate and two in triplicate (S2, Fig. 5). There is a very wide range in U content (24–2,135 ppm), but low U contents predominate (median 100 ppm). This range is skewed only to a small extent by the decision not to analyse those grains that are in poor crystallographic condition. Th/U is mostly moderate (0.1–1.5) with just a few grains lower (0.01–0.05) and higher (1.8–3.1). In contrast to those from sample 2003082647, the zircon grains have a very wide range of isotopic compositions; many (~20%) are significantly discordant. $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages range from ~3.24 to ~1.57 Ga. The main clusters of ages are at ~3.20 and ~2.70 Ga. There are very few grains with apparent ages less than 2.20 Ga. With four exceptions, the 31 grains in the ~3.20 Ga group are concordant within analytical uncertainty, but there is a significant range in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (MSWD=46). The population is broadly bimodal with a main group at ~3.20 Ga and minor group at ~3.05 Ga. Considering only the concordant analyses, the 11 oldest grains have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ within analytical uncertainty yielding a weighted mean age of $3,219 \pm 7$ Ma. With four exceptions, the 16 younger grains also form a coherent group with a weighted mean age $3,169 \pm 10$ Ma.

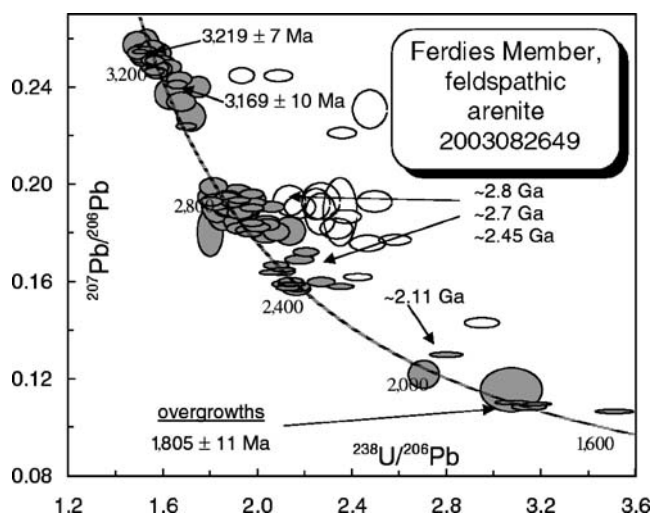


Fig. 5 Concordia plot of detrital zircon U–Pb analyses for feldspathic arenite sample 2003082649 from the Ferdies Member of the Dead Bullock Formation

Twelve of the 50 grains in the ~2.70 Ga group are more than 10% discordant and are not considered further. The remaining 38 grains have a broadly trimodal age distribution, with peaks at ~2.78, ~2.70 and ~2.45 Ga. Each of these groups is composite. There are only four grains with an age similar to that of the 2.53 Ga zircon, which is dominant in sample 2003082647.

Due to their possible importance in placing a limit on the deposition age of the arenite, the six grains on which apparent ages less than ~2.20 Ga were analyzed mostly in duplicate or triplicate. With one exception (grain 82), these crystals are subhedral prisms with distinct cores and euhedrally zoned overgrowths. It is the overgrowths that give the grains their prismatic form and crystal faces. The cores of these grains, in shape and size, closely resemble the bulk of the rounded zircon grains in the rock. It is possible that these overgrowths are the same material that forms a very thin coating on those rounded grains. The overgrowths are rich in U (555–2,135 ppm) and mostly have high to very high (~2–25 ppm) common Pb contents. It is the overgrowths that yield the younger ages but there is no direct correlation between discordance and either U or common Pb contents. Three of the eight overgrowths are less than 5% discordant and combine to give a $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1,805 \pm 11$ Ma. The other two analyses in the younger group both come from cores. One has a large analytical uncertainty (± 93 Ma), but the other is relatively precise and, if there has been no Pb loss from the grain, places an upper limit of $2,109 \pm 10$ Ma on the deposition age of the arenite. Thus, the deposition age for this unit must be between $2,109 \pm 10$ and $1,805 \pm 11$ Ma.

Callie Member, tuff (2001082511)

Sample 2001082511 was collected from a thin oxidized, feldspathic layer within a low lying outcrop of more mature sandstone in the Black Hills region, located about 15 km northeast of the Hurricane-Repulse Pit (Table 1). The tuff is friable, fine- to medium-grained, bleached orange, weakly foliated and deeply weathered. It consists of quartz and altered feldspar in a clay-rich matrix. The foliation is defined by weathered chlorite. The zircon grains recovered are a homogeneous population of fine (~40–80 μm diameter), predominantly euhedral, clear, colourless, prismatic grains with aspect ratios of 1–6. Considering the highly weathered state of the rock, the zircon grains are remarkably unaltered, coherent, and free from iron oxide discolouration. Many (~20%) have the irregular axial cavities commonly found in zircons from volcanic rocks (Nutman et al. 1997). Very few have faint visible internal zoning or cores in transmitted light. The grains have a moderate to bright luminescence, which reveal that the population is dominated by broad oscillatory growth

zoning. Texturally discordant cores are very rare. All these features are consistent with the zircon grains being derived from a single igneous source rock.

Thirty-two grains were analyzed (S3, Fig. 6), each selected to be a best possible example of igneous growth. No attempt was made to analyse inherited cores. The analyzed areas have moderate U contents (~70–200 ppm) and Th/U ratios (~0.4–1.15, median 0.55). Two grains have higher Th/U ratios of ~1.71 (A14.1) and ~1.74 (A29.1). Common Pb contents are low (<0.5 ppm) and all but one of the ages are concordant to near concordant. The discordant grain (A6.1) was not included in the pooled age calculation. The remaining 31 grains have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ within analytical uncertainty (MSWD=1.2), yielding a weighted mean age of $1,834.9 \pm 6.9$ Ma. However, there is a general trend towards grains with higher measured ^{204}Pb having lower radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$, implying a small isobaric interference at mass ^{204}Pb . The four analyses with the highest mass 204 counts are the most affected. Omitting these, the weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age becomes $1,838.4 \pm 6.4$ Ma (MSWD=0.99), which is our best estimate of the crystallization age of the tuff.

Killi Killi Formation, quartz wacke (2001082021)

Sample 2001082021 was collected from diamond drill core in the Dead Bullock Soak goldfield (DBD 422, 170.95–178.5; Table 1). The sample was selected from a long section of monotonous nonmineralized mature quartz wacke. It consists of sub-rounded to sub-angular, moderately sorted quartz, and rare feldspar in a sericitised clay matrix. Zircons are a mixed population of sizes, shapes and colours consistent with derivation from a range of sources. Most (~70%) of the grains are of relatively uniform size (80–100 μm diameter).

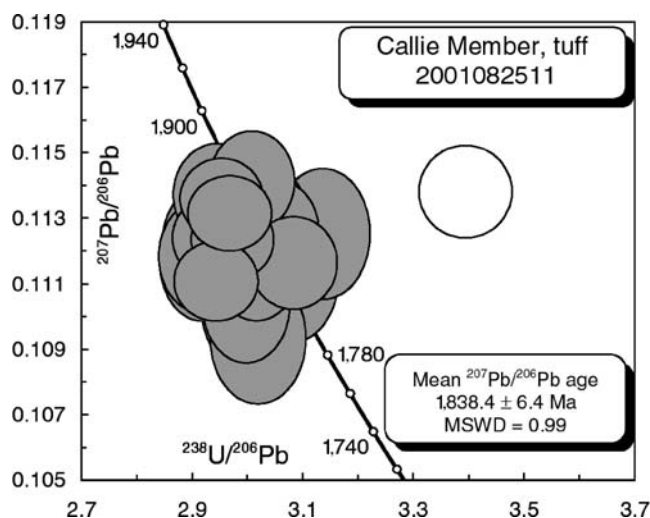


Fig. 6 Concordia plot of zircon U–Pb analyses for tuffaceous rock sample 2001082511 from the Callie Member of the Dead Bullock Formation

The full size range is 40–200 μm in diameter, and equant sub-rounded grains predominate. About 10% of these have surfaces pitted presumably by mechanical sedimentary abrasion. Approximately 5% of the grains are subhedral to euhedral, with some well-preserved crystal faces. The zircon grains are colourless to pale-brown, clear, with relatively few fractures and inclusions. Many of the grains have visible concentric growth zoning in transmitted light. With very few exceptions, the CL is uniformly dark and provides little information on the internal zoning textures.

The 94 zircon grains analyzed have, with few exceptions, a very limited range of U content (100–400 ppm) and normal felsic igneous Th/U (0.2–0.9) (S4, Fig. 7). Common Pb contents are uniformly low, but about 30% of the analyses are moderately to strongly discordant (Fig. 7). Most of the analyses (67%) define a discordance line with an upper concordia intercept of ~ 1.86 Ga. The remaining analyses have $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages in the range 3.2–2.0 Ga, with a cluster at ~ 2.50 Ga. The discordance line defined by the 63 analyses in the youngest group is moderately well defined MSWD=4, with concordia intercept ages of $1,868.6 \pm 6.5$ and 99 ± 71 Ma, indicating that most of the Pb loss has taken place very recently. The best estimate of the zircon crystallization age is given by the radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ of the least discordant analyses. The 38 analyses that are less than 10% discordant have a range of radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ that is slightly greater than expected from the analytical uncertainties (MSWD=2.6). Even omitting the analysis with the lowest $^{207}\text{Pb}/^{206}\text{Pb}$, which has the highest common Pb correction, some scatter remains (MSWD=2.2). There are, however, no remaining identifiable outliers. The $^{207}\text{Pb}/^{206}\text{Pb}$ robust median age (Ludwig 2001) of the remaining 37 analyses is $1,865.6 \pm 3/-7.5$ Ma, with the asymmetric uncertainties reflecting the asymmetric distribution of the data.

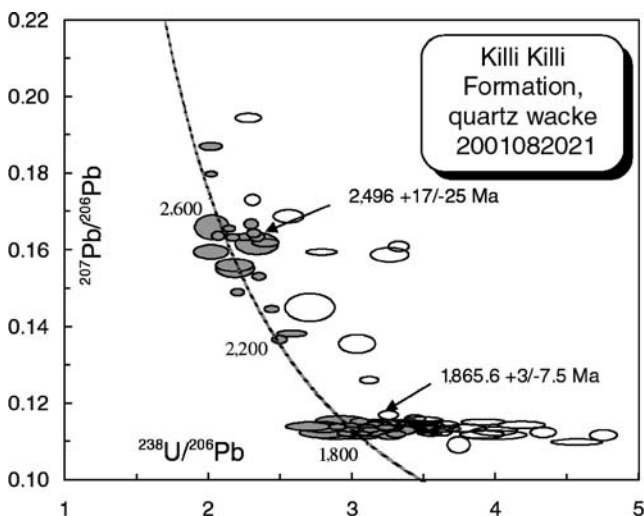


Fig. 7 Concordia plot of detrital zircon U–Pb analyses for quartz wacke sample 2001082021 from the Killi Killi Formation

A loose cluster of 18 analyses dominates the older group at ~ 2.50 Ga. Five of these are more than 10% discordant. Although there is no correlation between discordance and radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ because the age of the Pb loss is not known, these analyses are of no value in assessing the age distribution. The 13 remaining grains have $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages in the range ~ 2.53 – 2.41 Ga and are dispersed beyond analytical uncertainty (MSWD=10). Most of the analyses (11) cluster at ~ 2.50 Ga but are still scattered (MSWD=4.8). This scatter can be reduced, but not eliminated, by omitting one other low analysis (MSWD=3.8). No other omissions can be justified. The median age of the remaining grains is $2,496 \pm 17/-25$ Ma, the large uncertainty reflecting the residual scatter.

Killi Killi Formation, quartz arenite (2001082505)

Sample 2001082505 was collected from outcrop in the Turkey Bore region, approximately 5 km southwest of Jims Pit (Table 1). The sample is a moderately sorted quartz arenite with rounded to sub-rounded quartz grains and sericitised matrix. The zircon grains recovered are a mixture of sizes, shapes and colours consistent with derivation from a range of sources. The grains range in diameter from ~ 40 to $200 \mu\text{m}$ and the majority are equant and sub-rounded. Less than 5% of the grains are subhedral with some retaining well preserved crystal faces. Approximately 50% of grains have pitted surfaces indicative of mechanical sedimentary abrasion and $\sim 20\%$ have what is predominantly faintly visible growth zones in transmitted light. The zircon grains are mainly clear, colourless to pale brown and many grains have fractures that are stained by iron oxides. Most grains have a dark to moderate luminescence. Two contrasting types of zoning, finely oscillatory and broadly diffuse, are about equally represented.

The 64 zircon grains analyzed have a limited range of ages. U contents are mostly 100–350 ppm (S5, Fig. 8). The full range is 25–615 ppm. Th/U is 0.14 to 1.8, with most values in the range 0.3–1.0. Common Pb contents are consistently low. Most of the analyses ($\sim 80\%$) are concordant or near concordant. The grains have a wide range of $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages. The main cluster is at ~ 1.85 Ga and there are smaller groups at ~ 2.50 and ~ 2.10 – 1.90 Ga. Most of the discordant grains are included in the youngest group. The 29 analyses in the youngest group plot almost within error on a single discordance line (MSWD=1.8). Omitting one concordant low value (C22.1) reduces the scatter (MSWD=1.5). The resulting line has concordia intercept ages of $1,870.2 \pm 6.1$ and 210 ± 88 Ma. The 24 analyses that are concordant or near concordant have a range in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ that is barely larger than expected from the analytical uncertainties (MSWD=1.9). Omitting the same low value

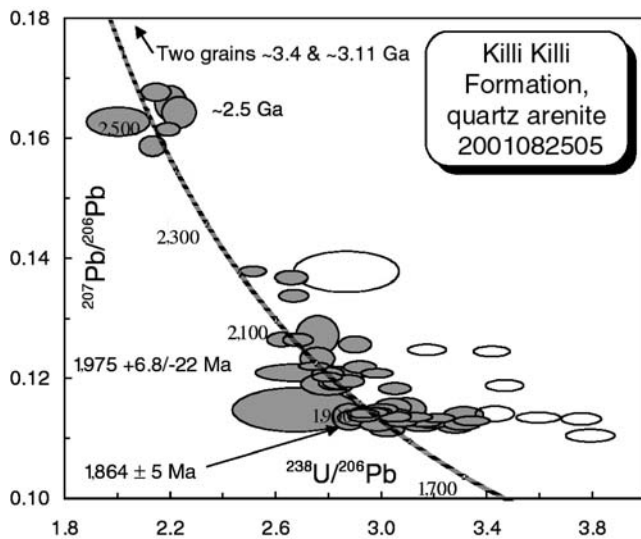


Fig. 8 Concordia plot of detrital zircon U–Pb analyses for quartz arenite sample 2001082505 from the Killi Killi Formation

that was an outlier in the regression reduces the scatter (MSWD=1.6), yielding a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1,864.4 \pm 5.3$ Ma.

The remaining analyses cluster at ~ 2.50 , ~ 2.0 and ~ 1.97 Ga. The 1.97 Ga cluster consists of 14 grains that have a range in $^{207}\text{Pb}/^{206}\text{Pb}$ ages of ~ 1.99 to 1.94 Ga. One analysis is significantly discordant and is not included in assessing the age distribution. The remaining 13 analyses are dispersed beyond analytical uncertainty (MSWD=3.4). Omitting the youngest grain reduces the scatter (MSWD=2.3), but does not eliminate it and no other omissions can be justified. The robust median $^{207}\text{Pb}/^{206}\text{Pb}$ age of the remaining grains is $1,975 \pm 6.8/-22$ Ma, the large uncertainty reflecting the residual scatter. The ~ 2.03 Ga group consists of seven analyses with a range of discordance that plot within error (MSWD=1.09) on a single discordance line with concordia intercept ages at $2,050 \pm 12$ and 174 ± 130 Ma. The lower intercept indicates very recent Pb loss. The ~ 2.50 Ga group consists of six grains that range in age from ~ 2.54 to ~ 2.44 Ga.

Killi Killi Formation, quartz wacke (2001082515)

Sample (2001082515) was collected about 5 km northeast of the Maverick granite. The quartz wacke consists of well sorted, sub-rounded to sub-angular quartz grains in a sericitised, fine-grained matrix. The zircon grains recovered range in size from ~ 30 to $200 \mu\text{m}$ in diameter. They are mostly equant, rounded to sub-rounded, clear and colourless. Surface abrasion is common, but a few grains still preserve some crystal faces. Relatively few grains ($<5\%$) have faintly visible growth zoning in transmitted light. Dark CL and faint oscillatory growth zoning predominate. Most grains are

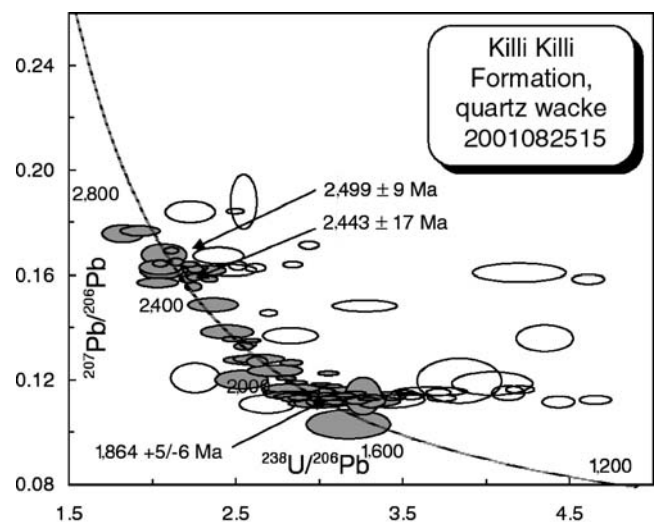


Fig. 9 Concordia plot of detrital zircon U–Pb analyses for quartz wacke sample 2001082515 from the Killi Killi Formation

fragments of larger crystals. A few grains ($\sim 10\%$) have stronger CL and in some the zoning is weak or absent.

One hundred and twelve analyses are listed in S6 and plotted in Fig. 9. The zircon grains have mostly low to moderate U contents (50–500 ppm), with a full range of 20–1,000 ppm. Th/U is mostly moderate to high (0.1–3.1), and an unusually large fraction of the grains (50%) have values in the range 1–3. More than 30% of the analyses are greater than 10% discordant. The $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages are dispersed over the range ~ 3.50 to ~ 1.70 Ga, with prominent groups at ~ 2.50 and 1.86 Ga. The 58 analyses in the youngest group are very poorly fitted to a discordance line (MSWD=11) consistent with dominantly recent Pb loss. Considering only the 38 least discordant analyses, there is nevertheless a significant range in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (MSWD=17). The scatter is mainly due to a group of seven analyses with ages significantly higher than the main population. Omitting these, the scatter is not eliminated (MSWD=2.2). Omitting the lowest value ($1,696 \pm 63$ Ma) makes little difference because of its large analytical uncertainty (MSWD=2.0) and there are no other obvious outliers. The median $^{207}\text{Pb}/^{206}\text{Pb}$ age for the remaining 30 values is $1,868 \pm 5.3/-6.1$ Ma. The seven older grains are dispersed over the range ~ 1.98 – 1.90 Ga and do not form a discrete age group.

The 26 analyses in the ~ 2.50 Ga group do not even loosely define a discordance line. Considering just the 16 least discordant points, there is a significant range in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (MSWD=16). This group can be divided into three subgroups. Nine of the analyses have equal $^{207}\text{Pb}/^{206}\text{Pb}$ within error (MSWD=1.3), with a weighted mean age of $2,499 \pm 9$ Ma. Five of the grains are younger, with a weighted mean age of $2,443 \pm 17$ Ma (MSWD=2.4) and two grains are older with ages of ~ 2.55 Ga.

Killi Killi Formation quartz wacke (2001082036)

Sample 2001082036 was a section of half core from the Titania Au prospect (TDH01, 110.6–116.6 m), located about 40 km northwest of The Granites Goldfield (Table 1). The sample was a piece of vein-free quartz wacke from a long section of monotonous non-mineralised quartz wacke. It consists of moderately sorted, sub-rounded to sub-angular quartz grains and minor feldspar in a sericitised, fine-grained matrix. The zircon grains recovered range from 40 to 180 μm in diameter. Most are sub-rounded equant grains, ~5% are elongate prisms with aspect ratios of 2–3. Approximately 5% of the grains are subhedral to euhedral with some preserved crystal faces. The majority (60%) have predominantly well-defined visible growth zones in transmitted light and many (~40%) have pitted abraded surfaces. Many of the growth zones are metamict. The zircon grains are clear, colourless to brown and many have fractures that are iron oxide stained. They predominantly show faint oscillatory growth zones in CL.

Seventy-nine analyses are listed in S7 and plotted in Fig. 10. The zircon grains have low to moderate U contents (50–500 ppm) with a full range of 9–2,383 ppm. Th/U ranges from 0.06–1.60, with most values in the range 0.2–1.1. Common Pb contents are mostly low (<0.6 ppm) but about 30% of the isotopic compositions are moderately to strongly discordant. Most analyses cluster at ~1.86 Ga, with smaller groups between ~2.50 and 1.90 Ga. The 37 analyses in the dominant 1.86 Ga group do not define a discordance line. Considering only the 27 concordant and near-concordant analyses, the data are slightly dispersed in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (MSWD=2.0). This scatter can be reduced, but not eliminated by omitting the two highest values (MSWD=1.7). No other omissions can be justified.

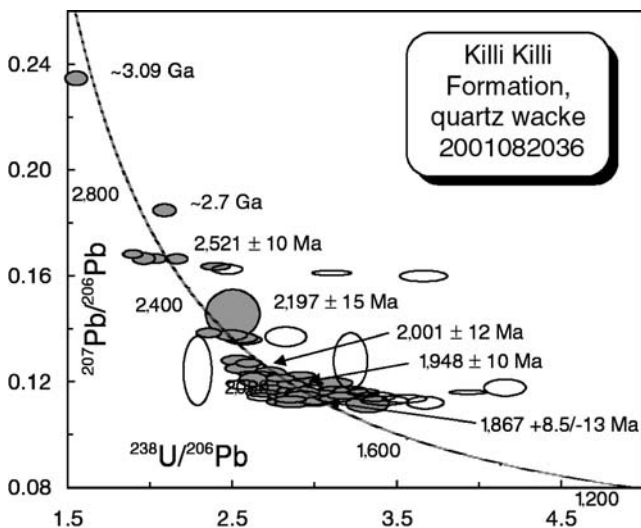


Fig. 10 Concordia plot of detrital zircon U–Pb analyses for quartz wacke sample 2001082036 from the Killi Killi Formation

The median $^{207}\text{Pb}/^{206}\text{Pb}$ age of the remaining grains is $1,867.2 \pm 8.5/-13$ Ma.

The other age clusters are at ~2.50, ~2.20, ~2.00 and ~1.95 Ga. The ~1.95 Ga group consists of 15 grains that have a constant $^{207}\text{Pb}/^{206}\text{Pb}$ within error (MSWD=1.6), giving a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1,948 \pm 10$ Ma. The ~2.0 Ga group consists of 10 grains that have a significant range in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (MSWD=3.2). By omitting two of the highest values, the scatter is eliminated (MSWD=0.57) leaving eight analyses which give a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2,001 \pm 12$ Ma. The ~2.20 Ga cluster comprises six analyses that have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ within analytical uncertainty (MSWD=0.98) giving a weighted mean age of $2,197 \pm 15$ Ma. The eight analyses in the ~2.50 Ga group lie within error (MSWD=0.92) on a discordance line, with concordia intercept ages of $2,521 \pm 10$ and 250 ± 66 Ma.

*Ware group**Century Formation, lithic arenite (2001082519)*

Sample 2001082519 was collected from a low lying, isolated outcrop of silicified, medium to coarse grained sandstone, located about 15 km southwest of the Pendragon deposits (Table 1). The rock comprises approximately 70% moderately sorted rounded to sub-rounded quartz grains in a matrix of poorly sorted mostly angular lithic fragments. Zircon grains recovered range in diameter from 50–200 μm . They are mostly sub-rounded to rounded equant grains but ~30% are euhedral to subhedral crystals or crystal fragments with some well preserved faces. The zircon grains are clear, colourless to pink with few fractures or inclusions. Less than ~5% have faintly visible growth zones in transmitted light, and ~10% have abraded surfaces. The majority are dull in CL, and well-developed oscillatory growth zones predominate over lesser sector zoning and diffuse banding.

The 99 zircon grains analyzed have uniformly low U contents (14–290 ppm, median 115) and low to moderate Th/U (0.11–1.75, median 0.57, S8, Fig. 11). Common Pb contents are also low, and about 17% of the analyses are more than 10% discordant. The $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages are scattered through the range of ~3.50–1.80 Ga. There is a major group at ~1.83 Ga, a secondary group at ~1.88 Ga, and minor clusters at ~2.50 and ~3.40 Ga. Euhedral to subhedral grains and fragments with preserved crystal faces predominate in the ~1.83 Ga group. Two analyses are more than 10% discordant and have not been used in assessing the age distribution. The remaining 38 concordant and near-concordant analyses have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ within analytical uncertainty (MSWD=0.96) and yield a weighted mean age of $1,823.2 \pm 3.7$ Ma. The 1.88 Ga group consists of 20 analyses, six of which are more than 10%

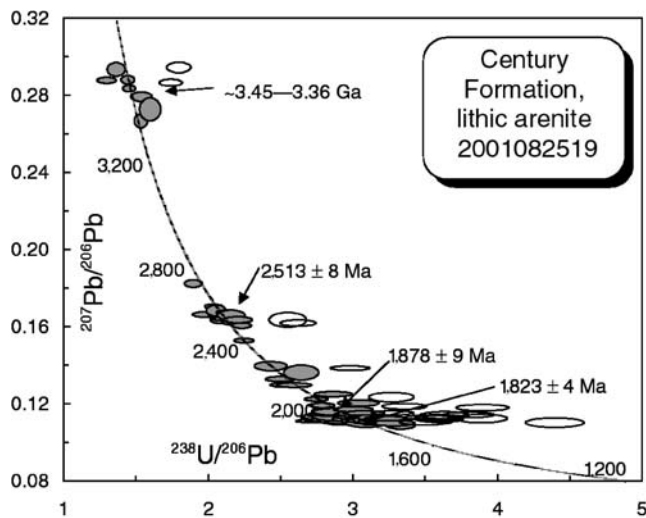


Fig. 11 Concordia plot of detrital zircon U–Pb analyses for lithic arenite sample 2001082519 from the Century Formation

discordant but all have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ within error (MSWD=1.4). The weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of the 14 near-concordant analyses is $1,877.8 \pm 9.3$ Ma.

The ~2.50 Ga group consists of a loose cluster of 14 analyses. Two of these are more than 15% discordant and are not considered further. The remaining 12 analyses are dispersed in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ beyond analytical error (MSWD=2.4). The scatter is eliminated by removing the two lowest values (MSWD=1.5) leaving 10 that give a weighted mean age of $2,512.6 \pm 8.3$ Ma. The ~3.40 Ga group consists of seven grains that range in apparent age from ~3.45 to 3.36 Ga.

Wilson Formation, graywacke (2001082527)

Sample 2001082527 was collected from a low lying outcrop of tightly folded, thick-bedded, graded, granular conglomerate and graywacke located about 2 km east of the Crusade Au prospect (Table 1). This graywacke is poorly sorted, consisting of rounded to sub-rounded monocrystalline quartz grains with lesser lithic fragments, polycrystalline quartz and feldspars ~4 mm in diameter, in a matrix of finer grained angular feldspars and quartz grains in a sericitic groundmass. The zircon grains recovered range in diameter from 40 to 150 μm . Most are sub-rounded to rounded, turbid, fractured and metamict with well-defined visible growth zones in transmitted light. Approximately 20% of the grains are subhedral to euhedral, clear and colourless with some well-preserved crystal faces. There is also a minor population (~10%) of rounded to sub-rounded clear, colourless grains that have abraded surfaces.

One hundred and twenty grains were analyzed (S9, Fig. 12). U contents are mostly low to moderate, (60–550 ppm, median 180), with the full range being 29–

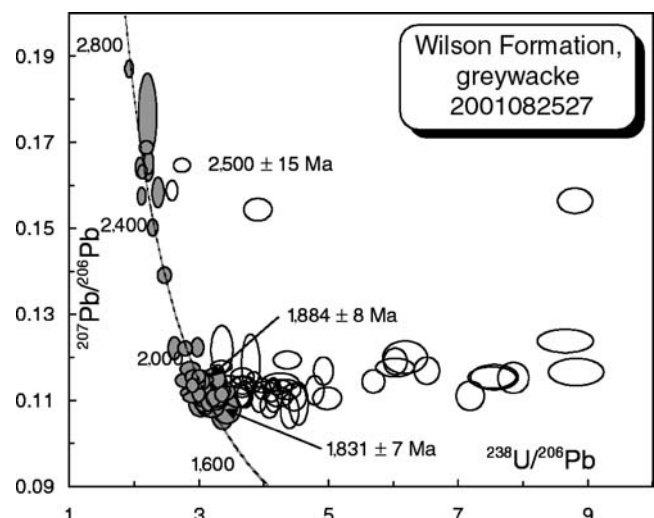


Fig. 12 Concordia plot of detrital zircon U–Pb analyses for graywacke sample 2001082527 from the Wilson Formation

2,664 ppm. Th/U is moderate to very high (0.3–7, median 1.14). Common Pb contents are moderate to high (~0.05–6 ppm) and ~45% of the grains are moderately to strongly discordant. Most of the grains (~80%) have $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages that cluster between ~1.98 and ~1.76 Ga. There is a minor group at 2.50 Ga and scattering of ages between ~2.44 and ~1.99 Ga. Three grains have $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages less than 1.72 Ga but none give a reliable estimate on the primary age. Two of the grains (B27.2, B40.1) are U-rich and their ages are extremely discordant (~80%), the third (B42.1) has a high common Pb content.

The dominant grouping consists of 93 analyses that are dispersed beyond analytical uncertainty (MSWD=3.1). This population is bimodal with a dominant cluster at ~1.83 Ga and a minor cluster at ~1.89 Ga. The ~1.83 Ga cluster consists of 57 analyses ~35% of which are greater than 10% discordant. All analyzed compositions in this group, plot within error on a single discordance line (MSWD=0.97) with concordia intercept ages at $1,831.7 \pm 6.1$ and 3 ± 40 Ma. The lower concordia intercept age indicates that Pb loss has taken place very recently. In that case, the best estimate of the zircon crystallization age can be obtained from the radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ of the least discordant analyses. The 36 analyses that are less than 10% discordant are within analytical error (MSWD=1.08) and give a weighted mean age of $1,830.9 \pm 6.5$ Ma.

The 1.89 Ga cluster comprises of 36 analyses, ~55% of which are greater than 10% discordant. The 16 concordant and near concordant analyses from this group have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ within analytical uncertainty (MSWD=0.48) and yield a weighted mean age of $1,883.8 \pm 8.4$ Ma. The older ~2.50 Ga group consists of four concordant and near concordant analyses that have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (MSWD=0.39) and give a weighted mean age of $2,500 \pm 15$ Ma.

Mount charles formation, arkose (2003082644)

Sample 2003082644 was collected from a massive bed of medium-grained arkose exposed in the western side of Jims Pit located about 30 m below ground level (Table 1). The sample is a dark grey medium-grained arkose with rare rounded chert and/or siltstone intraclasts up to 8 mm in diameter. It is very strongly sericitised, containing a poorly sorted matrix of angular and sub-angular altered feldspars, quartz, lithic grains, rounded polycrystalline quartz and 20–30% opaque Fe–Ti oxides.

Zircon grains recovered comprise a range of shapes and sizes, in the range of ~40 to ~200 μm in diameter. The majority are stubby, subhedral to euhedral, clear, colourless prisms and crystal fragments with few fractures or inclusions. About 30% of the grains have abraded surfaces and almost all have some preserved crystal faces. Less than 5% have faintly visible growth zones in transmitted light. Luminescence ranges from dull to bright, but most are moderately luminescent. Fine oscillatory and broadly diffuse growth zones predominate.

One hundred and two grains were analyzed (S10, Fig. 13). U contents are low to moderate (18–250 ppm), with one value higher (B24.2, 390 ppm), and Th/U moderate to high (0.14–2.8, median 0.6). Common Pb contents are uniformly low (<0.01–0.8 ppm) and 10% of the analyses are moderately to strongly discordant. The sample comprises three distinct age clusters, a dominant grouping at ~2.50 Ga and two minor groups at ~3.50–3.32 and ~1.91 Ga. The dominant grouping consists of 80 analyses, nine of which are greater than 10% discordant and are not considered further. The concordant and near-concordant grains scatter in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ more than expected from the analytical uncertainties (MSWD=2.9). This scatter can be reduced but not eliminated by omitting

two of the highest values (MSWD=1.8). No other omissions can be justified. The median age for the remaining grains is $2,503.6 \pm 4.4/-5.8$ Ma. The oldest zircon grains in this sample comprise seven grains that have apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages between 3.50 and 3.32 Ga. Four of these grains are within analytical uncertainty (MSWD=0.66) and have a weighted mean age of $3,421.6 \pm 6.4$ Ma. The ~1.91 Ga group is made up of euhedral crystals and crystal fragments with preserved faces. Zircon grains from this group generally has Th/U>1. Nine analyses on eight grains have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ within analytical uncertainty (MSWD=1.7), and give a weighted mean age of $1,913 \pm 18$ Ma.

Mount Charles formation, arkose (2001082507)

Sample 2001082507 was collected from a massive bed of coarse-grained arkose exposed in the western side of the Hurricane-Repulse Pit approximately 20 m below ground level (Table 1). Petrographically, it is similar to sample 2003082644. The sample consists of angular and sub-angular quartz, feldspar and rounded polycrystalline quartz grains in a matrix of strongly sericitised, mostly angular lithic fragments.

Zircon grains recovered comprise a mixed population of shapes with a wide range in size (20–200 μm diameter). The majority (~70%) are sub-rounded, optically turbid, metamict, highly fractured with well-defined visible growth zones in transmitted light and abraded surfaces. Other zircon grains are clear, colourless and subhedral to euhedral, many have preserved crystal faces and only rarely do they show signs of abrasion. The CL response from the turbid, metamict zircon grains is dark and provides little information on the internal zoning characteristics of these grains. The clear, colourless zircon grains however, are dull to brightly luminescent and reveal a predominance of fine concentric growth zoning over sector-zoned crystals.

Sixty analyses were made on zircon grains from this sample (S11, Fig. 14). There is a large range in U content (36–2281, median 150) and, with one exception, moderate to high Th/U (0.42–4.2). Common Pb contents are moderate to high (~0.05–6 ppm) and ~50% of the grains analyzed are moderately to strongly discordant. These analyses show no correlation between radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ and discordance, and because the age of the Pb loss is not known, they have been excluded from the age assessment for this sample. The remaining 30 concordant and near concordant analyses principally cluster at ~3.42 and ~1.91 Ga. The older grouping consists of eight grains that have constant radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ within analytical uncertainty and give a weighted mean age of $3,419.2 \pm 3.6$ Ma. Zircon grains in the youngest ~1.91 Ga grouping consists of euhedral to subhedral grains with preserved crystal faces and Th/U generally >1. These 10 analyses have the same radiogenic

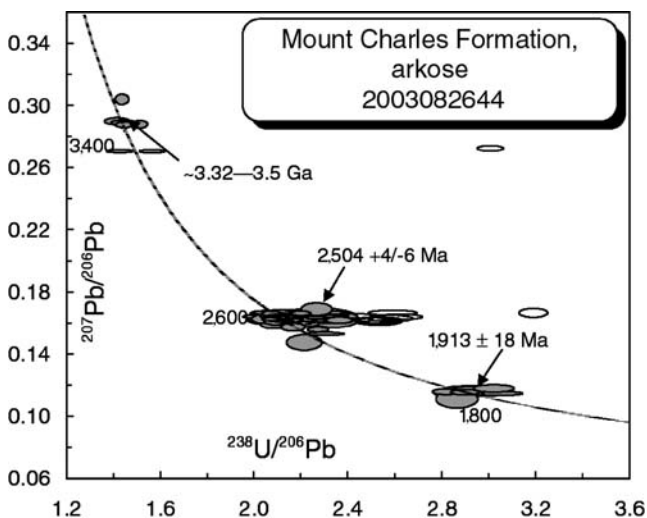


Fig. 13 Concordia plot of detrital zircon U–Pb analyses for arkose sample 2003082644 from the Mount Charles Formation

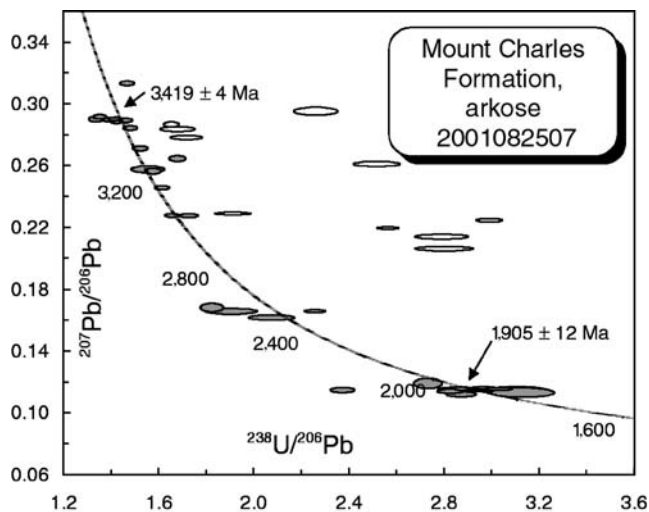


Fig. 14 Concordia plot of detrital zircon U–Pb analyses for arkose sample 2001082507 from the Mount Charles Formation

$^{207}\text{Pb}/^{206}\text{Pb}$ within analytical uncertainty (MSWD=1.8) and give a weighted mean age of $1,905 \pm 12$ Ma.

Pargee Sandstone, quartz arenite (2001082517)

Sample 2001082517 was collected in the Pargee Hills area, from a low lying sequence of thickly bedded medium to coarse grained sandstone and conglomerate, located about 250 m south of the contact with the unconformably overlying Gardiner Sandstone (Table 1). The sample is a red, medium-grained, moderately well-sorted quartz arenite, with rounded to sub-rounded quartz grains and rare sub-rounded lithic fragments. The zircon grains recovered comprise a wide range of shapes, colours and sizes that range from ~50 to 150 μm in diameter. The vast majority are equant, sub-rounded to rounded grains and range from turbid and brown in colour to clear and colourless. Many grains are highly fractured which in the majority of cases made SHRIMP-spot overlaps onto these fractures unavoidable. The zircon grains have well-defined visible growth zones in transmitted light and almost all have abraded surfaces. Most grains have a moderate to bright CL with oscillatory growth zones, and ~20% have rounded cores. Approximately 20% are dull in CL and give little or no information on their internal growth zones.

One hundred and eleven grains were analysed from this sample (S12, Fig. 15). Many of these analyses (~40%) are moderately to strongly discordant which is consistent with the highly fractured nature of many of the zircon grains in this sample. Forty-five analyses that are greater than 10% discordant are not considered further. The remaining 66 analyses have low to moderate U contents (27–250 ppm), moderate Th/U (0.4–1.4), and low to moderate common Pb contents (<0.01–2 ppm). The $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages are scattered between ~3.37 and 1.73 Ga with clusters at ~2.53

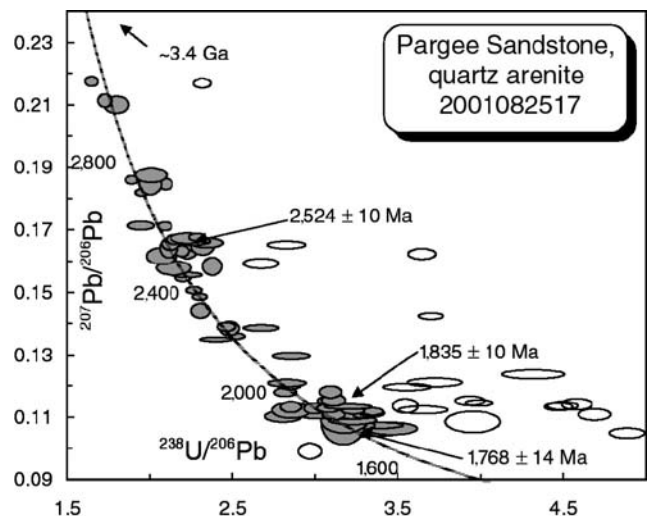


Fig. 15 Concordia plot of detrital zircon U–Pb analyses for quartz arenite sample 2001082517 from the Pargee Sandstone

and ~1.80 Ga. The youngest cluster comprises 25 analyses that are dispersed in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages (MSWD=8). This population is bimodal with a dominant grouping at ~1.83 Ga and a minor one at ~1.77 Ga. The dominant grouping consists of 13 analyses that are dispersed in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (MSWD=2.1). This scatter can be eliminated by removing the highest value (MSWD=1.3), the remaining analyses combine to give a weighted mean age of $1,835.4 \pm 9.8$ Ma. The minor group is made up of 12 analyses that all have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (MSWD=1.7), and combine to yield an age of $1,768 \pm 14$ Ma. The oldest grouping comprises nine analyses that have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (MSWD=1.6) and combine to give a weighted mean age of $2,524 \pm 10$ Ma. There are also minor peaks at ~2.70 and ~2.21 Ga.

Gardiner Sandstone, sublitharenite (2003082642)

Sample 2003082642 was collected from an outcrop of thickly bedded, massive, purple sandstone in the Coomarie Range (Table 1). The sample is well sorted and consists of about 80% sub-angular to sub-rounded quartz and about 15% fine-grained sedimentary and meta-sedimentary lithic clasts. The zircon grains recovered are remarkably uniform in diameter (~70–100 μm). They are clear and colourless, with relatively few fractures or inclusions. The majority are equant, rounded to sub-rounded, and 70–80% have abraded surfaces. Rare grains (<5%) have some preserved crystal faces. CL imaging shows that most grains have fine oscillatory growth zones. There is also a lesser population of crystals that show diffuse banding and sector zoning.

Ninety-three analyses are listed in S13 and plotted in Fig. 16. The analyzed zircon grains have low to moderate U contents (~30–270 ppm, median 130) and Th/U (0.15–1.68, median 0.51). Common Pb contents are uniformly low

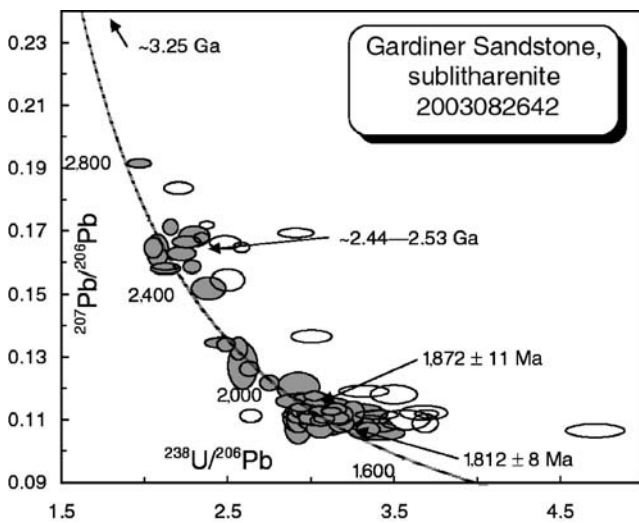


Fig. 16 Concordia plot of detrital zircon U–Pb analyses for sublitharenite sample 2003082642 from the Gardiner Sandstone

(<0.01–0.6 ppm) and approximately 20% of the analyses are moderately discordant. The $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages range between ~3.25 and ~1.74 Ga with a dominant cluster at ~1.83 Ga (70%) and a minor cluster at ~2.50 Ga. The 65 analyses in the youngest grouping do not define a single discordance line. Considering only the analyses that are less than 10% discordant, there is significant dispersion in radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (MSWD=4.1). This population is bimodal, forming a dominant group at ~1.81 Ga and a subordinate one at ~1.87 Ga. The dominant group comprises 36 analyses that have equal $^{207}\text{Pb}/^{206}\text{Pb}$ within error

(MSWD=1.4) and combine to give a weighted mean age of $1,812.2 \pm 7.9$ Ma. The subordinate group comprises 18 analyses that have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ (MSWD=1.7) and combine to give a weighted mean age of $1,872 \pm 11$ Ma. The 2.50 Ga group comprises six analyses that range in apparent $^{207}\text{Pb}/^{206}\text{Pb}$ age between 2.53 and 2.44 Ga.

Discussion

The detrital zircon age distributions displayed in Fig. 17 comprise 12 samples from the six principal sedimentary units in the Tanami Region, and the depositional age estimates for these units are shown in Table 2. The data in Fig. 17 demonstrate that all units contain zircons with an age mode of ~2.50 Ga. In addition, with the exception of the Mount Charles Formation, all units younger than the Ferdies Member of the Dead Bullock Formation are dominated by Paleoproterozoic detritus with an age mode between ~1.89 and ~1.84 Ga. The Ware Group samples contain a youngest zircon component between ~1.83 and ~1.82 Ga and only in the youngest Pargee and Gardiner Sandstone do ~1.80 Ga zircon components appear. The Ferdies Member contains zircon grains with age groups of ~3.20, ~2.70 and ~2.50 Ga (Fig. 17). These ages contrast markedly with younger sedimentary units in the Tanami Region. The Mount Charles Formation is also dominated by zircons with Archean ages but in addition, contains a youngest detrital component at ~1.91 Ga, which is about 100 Ma older than its depositional age as suggested by Crispe et al. (2006).

Table 2 Depositional age estimates for the principal sedimentary sequences in the Tanami Region

Unit	OZCHRON Number	Max. age (Ma) (detrital zircon)	Max. Age (Ga)	Min. age (Ga)
Ferdies Member	2003082647	2,533±3	~2.11 ^a	~1.84 Ga ^b
Ferdies Member	2003082649	2,109±20	~2.11 ^a	~1.84 Ga ^b
Killi Killi Formation	2001082021	1,866+3/–8	~1.84 ^b	~1.82 Ga ^c
Killi Killi Formation	2001082505	1,864±5	~1.84 ^b	~1.82 Ga ^c
Killi Killi Formation	2001082515	1,868+5/–6	~1.84 ^b	~1.82 Ga ^c
Killi Killi Formation	2001082036	1,867+9/–13	~1.84 ^b	~1.82 Ga ^c
Ware Group	2001082519	1,823±4	~1.82 ^c	~1.80 Ga ^f
Ware Group	2001082527	1,831±7	~1.82 ^c	~1.80 Ga ^f
Mount Charles Formation	2003082644	1,913±18	~1.82 ^c	~1.80 Ga ^f
Mount Charles Formation	2001082507	1,905±12	~1.82 ^c	~1.80 Ga ^f
Pargee Sandstone	2001082517	1,768±14	~1.77 ^d	~1.64 Ga ^{g, h}
Gardiner Sandstone	2003082642	1,812±8	~1.77 ^d	~1.64 Ga ^{g, h}

^a Age of youngest detrital zircon in Ferdies Member sample 2003082649 (this study)

^b Crystallisation age for sample of tuff in Callie Member (this study)

^c Contemporaneous felsic volcanism in Ware Group

^d Age of youngest detrital zircon population from Pargee Sandstone, sample 2001082517 (this study)

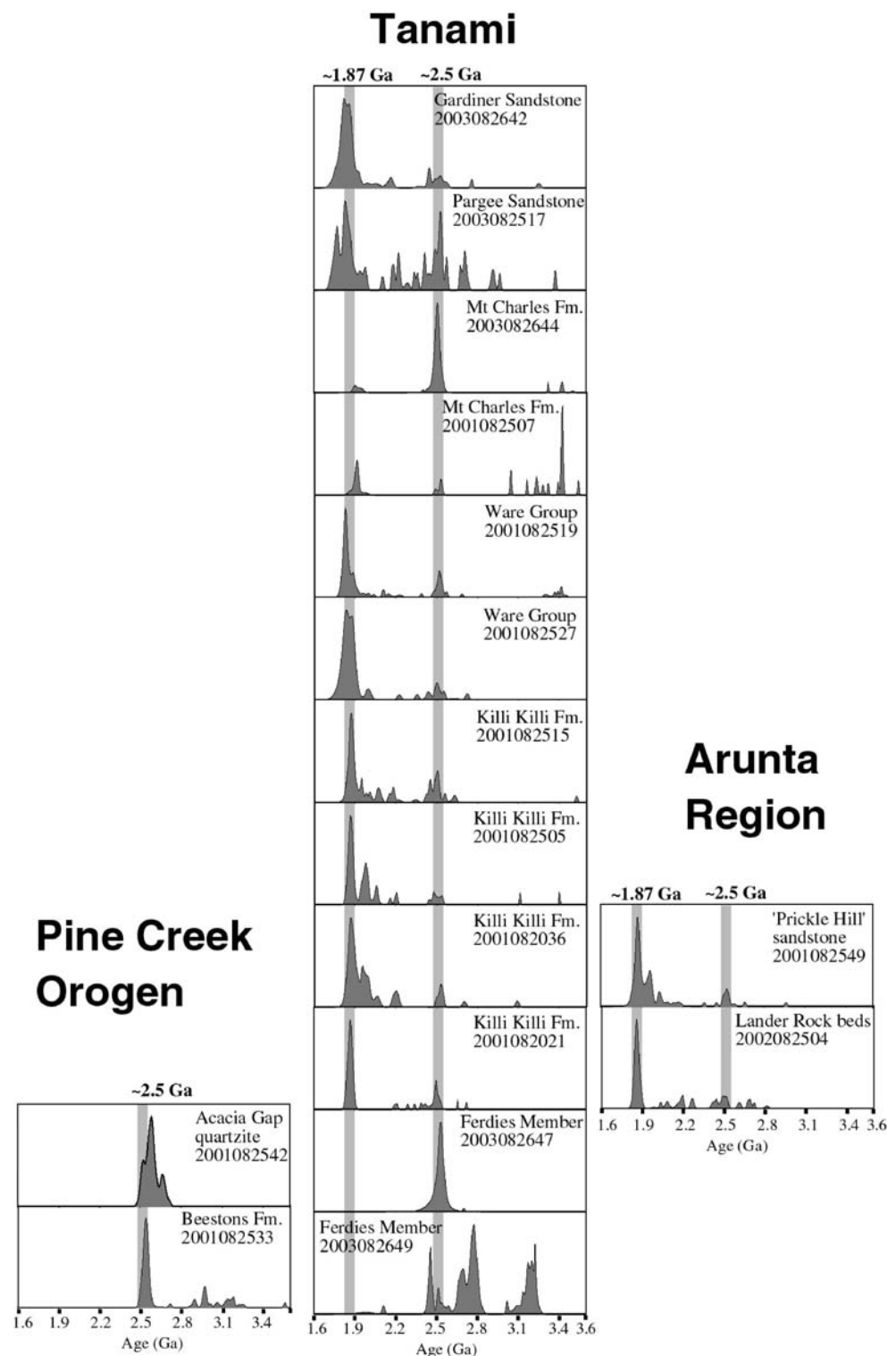
^e Age of cross cutting igneous intrusion (Crispe et al. this volume)

^f Inference from ages of cross cutting igneous intrusions (Crispe et al. this volume)

^g SHRIMP U–Pb dating of diagenetic xenotime from Gardiner Sandstone (Vallini et al. this volume)

^h Correlation of Gardiner Sandstone with rocks in the Victoria River Basin which are overlain by the ~1.64 Ga Limbanya Group (Cutovinos et al. 2002).

Fig. 17 Probability density distribution diagrams comparing detrital zircon U–Pb ages for analyzed samples from this study with data from: Cross et al. (2005b) for the Lander Rock beds (2002082504); Cross et al. (2005c) for the ‘Prickle Hill’ sandstone (2001082549); Cross et al. (2005a) for the Acacia Gap Quartzite (2001082542) and Beestons Formation (2001082533). Grey vertical lines are common major age peaks at ~2.50 and ~1.87 Ga



The tuffaceous sample from the Callie Member of the Dead Bullock Formation (2001082511) represents the only volcanic rock to have been isotopically dated from the Tanami Group. Rare angular and euhedral grains of quartz, feldspar and zircon indicate a tuffaceous origin. The zoned zircons strengthen this interpretation. Isotopically, they

record a single U–Pb age. Morphologically they are homogenous, pristine, euhedral zircon grains with axial inclusions a feature typical of volcanic zircon. Features that would indicate an intrusive origin for this unit, such as contact metamorphism in local rocks, or chilled margins with adjacent units were not observed at the sample site. It

is for the above reasons that we interpret this sample as tuffaceous in origin and likely to have been deposited contemporaneously with sediments of the Callie Member. The SHRIMP U–Pb age for this unit of $1,838 \pm 6$ Ma provides an important constraint for the depositional chronology of the rocks included in the Tanami Group and early basin development.

Detrital zircon depositional age estimates

Ferdies member of the dead bullock formation

Zircon grains from the Ferdies Member arkose (2003082647) sampled from the Groundrush region define a maximum deposition age of $2,533 \pm 3$ Ma, whereas a feldspathic arenite (2003082649) from the same unit at Dead Bullock Soak contains zircon grains that imply a deposition age after ~ 2.11 Ga. A minimum age of sedimentation for the Ferdies Member is provided by the overlying Callie Member felsic tuff (2001082511), which contains zircons that crystallized at $1,838 \pm 6$ Ma (Table 2).

The timing of deposition for the Ferdies Member is poorly constrained between ~ 2.11 – 1.84 Ga. Therefore, estimates of the true age of deposition remain speculative. Two alternatives are possible. Firstly that there may be an extended depositional hiatus (i.e. cryptic unconformity) between the Ferdies and Callie Members of the Dead Bullock Formation lasting up to a maximum of approximately 270 Ma. A similar scenario to this has been detected in the Paleoproterozoic Hurwitz Group in the western Churchill Province of northern Canada. Using U–Pb dates from baddeleyite and detrital zircon, Aspler et al. (2001) detected a previously unrecognized time break of approximately 200 Ma across an internal cryptic unconformity. The second alternative is that the Archean detrital zircons found in the Ferdies Member were derived from the uplift of either Archean basement rocks or sedimentary rocks derived from Archean source rocks. In this scenario, uplift of these sources before ~ 1.84 Ga, during either the ~ 1.87 – 1.85 Hooper Orogeny, the ~ 1.87 Ga Nimbuwah Event or the early stages of the ~ 1.83 Ga Tanami Event shed detritus into the proto-Tanami basin. If this model is adopted, Ferdies Member sedimentation would have occurred between ~ 1.86 and 1.84 Ga. Of the two models presented in this study, we prefer the latter as the most likely as the Dead Bullock and Killi Killi Formations share a similar structural history and have been interpreted as conformable in numerous drill core intersections (see Crispe et al. 2006).

Killi killi formation

The youngest zircon component in all four samples from the Killi Killi Formation, provide a consistent maximum

depositional age estimate of between ~ 1.87 – 1.86 Ga. However, this unit is well constrained between the conformably underlying $1,838 \pm 6$ Ma, Callie tuff (2001082511), and an intrusive contact with the 1.82 Ga Water Tower Tonalite (Crispe et al. 2006). Therefore, the Killi Killi Formation was deposited at least 20 Ma after the age indicated by its youngest detrital zircon component.

Ware group

The youngest detrital zircon component in the Century Formation (Ware Group), lithic arenite (2001082519) indicates a maximum deposition age of $1,823 \pm 4$ Ma, whereas a graywacke from the Wilson Formation (2001082527) contains a youngest zircon component at $1,831 \pm 7$ Ma. Similar ages have been measured in felsic volcanic units within the Ware Group. For example, a sample of rhyolite from the Mount Winnecke Formation has a SHRIMP U–Pb age of $1,824 \pm 5$ Ma (Page 1995) and a dacite and felsic volcanic from the Nanny Goat Volcanic Complex have SHRIMP U–Pb ages of $1,816 \pm 7$ and $1,821 \pm 5$ Ma, respectively (Smith 2001). Crispe et al. (2006) suggest that minimum age constraints for sedimentation in the Ware Group can be inferred from the ~ 1.82 – 1.79 Ga, age of D_2 deformation, and the intrusion of the $1,815 \pm 5$ Winnecke Granophyre.

For the two samples of sedimentary units in the Ware Group considered in this study, the youngest zircon grains constitute a minor population of euhedral and unabraded grains. Given their relatively pristine state, we consider them to be first-cycle sediments, and to have probably been derived from either one or a combination of nearby ca. ~ 1.82 Ga felsic volcanic rocks and granites. This indicates that sedimentation and volcanism associated with this group was broadly contemporaneous. Accordingly, we consider the maximum deposition age estimates for the two Ware Group sedimentary rocks analyzed for this study to be good approximations for their true depositional age.

Mount Charles formation

The ages of the youngest zircon component in both samples from the Mount Charles Formation are indistinguishable. Sample 2003082644 has a youngest component at $1,913 \pm 18$ Ma, while the youngest grains analyzed from 2001082507 crystallized at $1,905 \pm 12$ Ma. Page (1998) obtained similar results to these in another detrital zircon SHRIMP U–Pb study of a sediment from the Mount Charles Formation. In this study, Page (1998) calculated a maximum deposition age of $1,916 \pm 8$ Ma, (MSWD=1.66) from the youngest 14 grains analyzed.

The ~ 1.91 Ga detrital zircon from our Mount Charles samples and that of Page (1998) share similar morphological

and chemical characteristics. They all have preserved crystal faces with no signs of sedimentary abrasion and have $\text{Th/U} > 1$. The youngest component from all three samples have the same radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ within analytical uncertainty ($\text{MSWD}=1.16$) and combine to give an age of $1,913 \pm 6$ Ma.

The absence of D_1 – D_3 deformation in rocks included in the Mount Charles Formation, aplite dyke intrusions, and also contact metamorphism associated with Grimwade suite granites have led Crispe et al. (2006) to suggest a depositional age for the Mount Charles Formation at ~ 1.80 Ga. This is 100 Ma younger than the ~ 1.91 Ga age of the youngest zircon grains in the three samples examined in this study.

Pargee Sandstone and Gardiner Sandstone

The youngest detrital zircon component analyzed from the Pargee Sandstone (2001082517) crystallized at $1,768 \pm 14$ Ma. In contrast, the youngest zircons from the unconformably overlying Gardiner Sandstone (2003082644) records an age of $1,812 \pm 8$ Ma, about 45 Ma older than zircons from the Pargee Sandstone. Clearly, the detrital zircon maximum deposition age estimate for the Gardiner Sandstone does not approximate the true age of sedimentation.

There are no direct minimum age constraints for the deposition of the Pargee Sandstone. Therefore, controls on the timing of sedimentation for the Gardiner Sandstone offer the only geological constraints for the minimum age of deposition for the Pargee Sandstone. The upper limit for sedimentation in the Gardiner Sandstone is constrained by diagenetic xenotime growth at $1,632 \pm 3$ Ma (Vallini et al. 2006) and the ~ 1.64 Ga age of Limbunya Group rocks, which were interpreted in drill core by Cutovinos et al. (2002) to overlie Birrindudu rocks in the Victoria River Basin, north of the Tanami Region. Therefore, the timing of sedimentation for both the Pargee Sandstone and Gardiner Sandstone is currently loosely constrained to between ~ 1.77 and ~ 1.64 Ga. The depositional age constraints from the six principal sedimentary units from the Tanami Region outlined above show that sedimentation occurred at least between the period ~ 1.84 – 1.77 Ga.

The above examples emphasize the importance of isotope studies of intercalated volcanic units to reliably determine the deposition age of non-fossiliferous sedimentary rocks. An alternative to this approach, is to date diagenetic minerals (such as monazite and xenotime) (see Vallini et al. 2006).

Source of detrital zircon

Ferdies member—dead bullock formation

The detrital zircon age distributions in the basal Ferdies Member samples discussed in this study are remarkably

different compared to other Tanami sedimentary units. Ferdies Member samples are almost entirely composed of Archean aged detritus and lack the ~ 1.86 Ga zircon that is a principal component in most younger samples (Fig. 17).

Detrital zircon grains from the Ferdies Member arkose 2003082647 constitute a unimodal age peak at ~ 2.53 Ga. This rock is clearly derived from a restricted late Archean source. Known rocks of this age in the NAC occur in the nearby Billabong Complex, where Page et al. (1995) have interpreted an age of $2,514 \pm 3$ Ma, and in the Rum Jungle Complex where the earliest phase of granite intrusion occurred at ~ 2.53 Ga (Cross et al. 2005a). The wide range in morphology of these zircon grains (euhedral to rounded and sometimes pitted) probably reflects both proximal and more distal sources. Therefore, we consider it possible that these zircon grains could have been derived from either of the above regions, a combination of both or an exotic source. Detrital zircon SHRIMP studies from two sedimentary rocks from the Pine Creek Orogen share similar zircon age distributions to the Ferdies Member arkose 2003082647. The Acacia gap Quartzite Member of the Wildman Siltstone, and the Beestons Formation which rests unconformably on the Archean Rum Jungle Complex are both dominated by detrital zircon approximately 2.50 Ga old (Fig. 17; Cross et al. 2005a). This could indicate the once widespread occurrence of NeoArchean crust across much of northern Australia.

Feldspathic arenite (2003082649) from the Ferdies Member has age modes at ~ 3.20 , ~ 2.78 , ~ 2.70 and ~ 2.45 Ga. It is possible that a large percentage of these zircon grains are derived from the Pilbara Craton in Western Australia. The ~ 3.20 Ga zircon grains can be correlated with the ~ 3.27 to 3.23 Ga Cleland Supersuite of the western part of the Pilbara Craton (Van Kranendonk et al. 2004) and the ~ 2.78 age mode with magmatism associated with the Fortescue Group (Nelson 1999). The ~ 2.45 Ga age mode may in part be derived from the Pine Creek Orogen, or alternatively from magmatism in the Pilbara region between ~ 2.60 and 2.45 Ga that was associated with the Hamersley Group (Thorne and Trendall 2001).

Killi killi formation

Detrital zircon age distributions from four samples of Killi Killi Formation are remarkably similar. Each is dominated by a zircon population that crystallized at ~ 1.87 Ga, with a subordinate age group at ~ 2.50 Ga (Fig. 17). The dominant zircon component could have been derived from one or a combination of similarly aged rocks in Northern Australia. These include magmatic rocks from the Pine Creek and Litchfield provinces (Worden et al. 2004; Needham et al. 1988), the Halls Creek Orogen (Blake et al. 2000) and Tennant Creek Region (Compston 1995 and Smith 2001).

The dominant ~1.87–1.86 Ga zircon grains from the four samples of Killi Killi Formation are likely to represent first-cycle sedimentary components because they are typically equant subrounded prisms with ~5% having retained their crystal faces. Furthermore, when sedimentary pitting on zircon exteriors is present, it is usually faint. This is in contrast to the NeoArchean zircon grains that are typically well rounded and have a marked pitting on grain exteriors, which is indicative of a longer history of sedimentary transport and/or recycling. The Archean zircon grains in the Killi Killi Formation samples were probably recycled from underlying units such as the Ferdies Member, which contain a high percentage of zircons of this age. Alternatively, these zircon grains may have been derived from similarly aged granites and also clastic units that are dominated by late Archean zircon grains from the Pine Creek Orogen (see Cross et al. 2005a).

The detrital zircon age distributions in the four Killi Killi samples (this study) share close similarities to detrital zircons from the Lander Rock beds, southern Arunta (Cross et al. 2005b) and the ‘Prickle Hill’ sandstone, northern Arunta (Cross et al. 2005c) (Fig. 17). The similarities in the detrital zircon age distributions between these widely separated samples indicates that the Killi Killi Formation may have once been a part of a much larger depositional system.

Ware group

Detrital zircon grains from two samples of sedimentary rocks from the Ware Group have similar age distributions. Both are dominated by ~1.83 Ga detrital zircons, and like other units analyzed in this study, have a minor age population at ~2.50 Ga (Fig. 17). The detrital zircon age distributions for the Ware Group samples 2001082527 and 2001082519 are broadly similar to that of the Killi Killi Formation samples discussed above. Like the samples from the Killi Killi Formation, samples from the Ware Group contain a significant proportion of ~1.86 Ga detrital zircon. These zircon grains are characteristically mature with rounded to well-rounded morphologies. Only the younger, ~1.82 Ga, euhedral, non-abraded zircon grains present in samples from the group can be used to isotopically distinguish between sedimentary rocks in the Killi Killi Formation and Ware Group. We interpret that the similarity of detrital zircon age patterns in these samples indicates that the younger Ware Group may be largely derived from the recycling of the underlying, Tanami Group. The abraded morphology of the ~1.86 Ga, and Archean-aged zircon grains in the samples from the Ware Group supports this interpretation. Therefore, we consider that the Ware Group has mostly been derived from the recycling of sedimentary rocks in the Tanami Group with a relatively minor input of ~1.83–1.82 Ga volcanics and granites derived from local sources.

Mount Charles formation

Detrital zircon age distributions from two samples of arkose from the Mount Charles Formation are distinctive. Both are largely comprised of Archean-aged zircons. Sample 2003082644 is dominated by ~2.50 Ga zircons, while 2001082507 contains only a minor age group at ~2.50 Ga and is dominated by zircons that crystallized at ~3.40 Ga. Both samples also have a youngest component at ~1.91 Ga (Fig. 17). The older Archean-aged zircon grains in these rocks are rounded with pitted surfaces. The ~2.50 Ga zircon grains may have been derived from similarly aged granites in the Pine Creek Orogen or recycled from underlying units such as the Ferdies Member. The well-rounded morphology of Archean zircons from these two samples probably excludes a local granitic protolith such as the Billabong Complex as a source. The ~3.40 Ga zircon grains from sample 2001082507 represents the oldest zircon component measured during this study. These zircon grains may indicate a provenance from similarly aged rocks in the Pilbara Craton (Nelson 1999).

A possible source for the 1.91 Ga zircon component common to all Mount Charles samples examined is the Ding Dong Downs Volcanics. These rocks are comprised of mainly mafic and also felsic volcanics and form the basement to the eastern zone of the Halls Creek Orogen. The Ding Dong Downs Volcanics have a SHRIMP U–Pb age of $1,907 \pm 6$ Ma and a granophyre from the same unit has a SHRIMP U–Pb age of $1,912 \pm 3$ Ma (Blake et al. 1999). Zircons from the Ding Dong Downs Volcanics have Th/U ratios that are distinctively high and are often >1 . Given that the youngest Mount Charles detrital zircon grains crystallized at ~1.91 Ga and also have Th/U ratios >1 , we suggest that they may have been derived from the Ding Dong Downs Volcanics in the Halls Creek Orogen.

In contrast to the rounded and pitted surface textures of the Archean-aged zircon grains in the Mount Charles Formation, zircons from the 1.91 Ga population have retained crystal faces with no signs of sedimentary abrasion. The grains are therefore likely to represent first-cycle sedimentary detritus. Their pristine condition and presence in three samples from the Mount Charles Formation suggests that they may record the true age of sediment deposition, either representing the products of source region uplift and coeval magmatism, or contemporaneous volcanism. In addition, Archean zircon age distributions from the Mount Charles Formation, in particular sample 2003082644, are similar to the basal Ferdies Member arkose (2003082647) (Fig. 17). Significant also is the lack of any ~1.87 Ga zircon component in sedimentary rocks analyzed from the Mount Charles Formation. As pointed out earlier, this component is a major feature of the Killi Killi Formation, Ware Group,

Pargee Sandstone and Gardiner Sandstone. We interpret the presence of ~1.87 Ga zircon in sedimentary rocks younger than the Killi Killi Formation to be the result of reworking of underlying clastic units. Given that Crispe et al. (2006) place the Mount Charles Formation as overlying the Ware group and deposited at ~1.80 Ga, the apparent absence of ~1.87 Ga zircon grains in this unit is puzzling. If the Mount Charles Formation was deposited at ~1.91 Ga, it would require that this unit was in some way partitioned from the effects of three significant deformational events (D_1 to D_3) in the Tanami Region. The inference that the Mount Charles Formation may have been deposited before ~1.88 Ga has obvious implications for exploration. That is, that the Au-rich Mount Charles Formation may in fact underlie either the Callie Member, Killi Killi Formation or Ware Group.

An alternative explanation for the 1.91 Ga detrital zircon component in the Mount Charles samples is that they do not approximate the age of sediment deposition and were derived from a very restricted catchment that only eroded rocks of the Ding Dong Downs Volcanics, or age equivalents, together with older basement endowed with Archean zircons. Clearly further studies of the Mount Charles Formation are required to establish its true depositional age and stratigraphic position.

Pargee Sandstone and Gardiner Sandstone

Principal age groups in samples from the Pargee Sandstone (2001082517) and Gardiner Sandstone (2003082644) occur at ~2.70, ~2.0 and ~1.80 Ga. A younger population at ~1.76 Ga was only detected in the Pargee Sandstone sample. Scrimgeour (2003) has suggested that this component was probably related to magmatic events associated with the Late Strangways Orogeny in the Arunta Region.

Older zircon grains from the Pargee and Gardiner Sandstones are predominantly well rounded with pitted surfaces indicative of a long history of sedimentary transport and reworking. These grains were probably derived from underlying sedimentary rocks in the Tanami Group.

Considered collectively, detrital zircon grains from the Killi Killi Formation, Ware Group, Pargee Sandstone and Gardiner Sandstone are characterized by a high percentage of ~1.86 Ga grains with a minor component at ~2.50 Ga. The ~1.86 Ga component from these samples shows a progression in zircon rounding from their appearance in the Killi Killi Formation to the top of the sequence in the Gardiner Sandstone. Detrital zircons in the Killi Killi Formation is predominantly sub-rounded with rare signs of surface abrasion, whereas zircon grains from the Gardiner Sandstone is predominantly rounded and 70–80% of grains have abraded surfaces. We interpret the presence of the ~1.86 Ga and ~2.50 Ga age populations in all of these units, and the successive rounding of the ~1.86 Ga zircon

component from older to younger units, to indicate that recycling of underlying sediments has played a major role in supplying detritus to younger sequences.

Early development of the Tanami Basin

Reassessment of Browns Range Dome granite sample 88495008

A sample of granite (88495008) from the Browns Range Dome in the north west of the Tanami Region was interpreted from a SHRIMP U–Pb zircon study by Page et al. (1995) to have crystallized at $2,510 \pm 22$ Ma and to have undergone high-grade metamorphism at either ~1.97 or ~1.88 Ga. The latter (~1.88 Ga) age interpretation for this sample has been used by Hendrickx et al. (2000) as evidence for the initial extension associated with the early development of the Tanami Basin. To access the evidence for this proposed ~1.88 Ga metamorphism, the original SHRIMP mount with zircon from the granite sampled from the Browns Range Dome was re-examined using CL imaging, a technique unavailable to the original researchers.

Zircons from this sample have a diverse array of sizes and shapes. They dominantly constitute rounded to well-rounded concentrically and sector-zoned zircon cores that are overgrown by highly metamict, dark luminescence response overgrowths up to 100 μ m in thickness. Concordant and near-concordant compositions range in apparent age between ~3.42 to ~1.87 Ga and fall into three loosely defined groups of ~3.15 to 3.04 Ga ($n=6$), ~2.67 to 2.44 Ga ($n=8$) and ~1.99 to 1.87 Ga ($n=9$). There are also two zircon grains at ~2.31 and ~2.26 Ga and two older grains at ~3.42 and ~3.24 Ga (Fig. 18). The nine concordant and near-concordant compositions that range in $^{207}\text{Pb}/^{206}\text{Pb}$ age

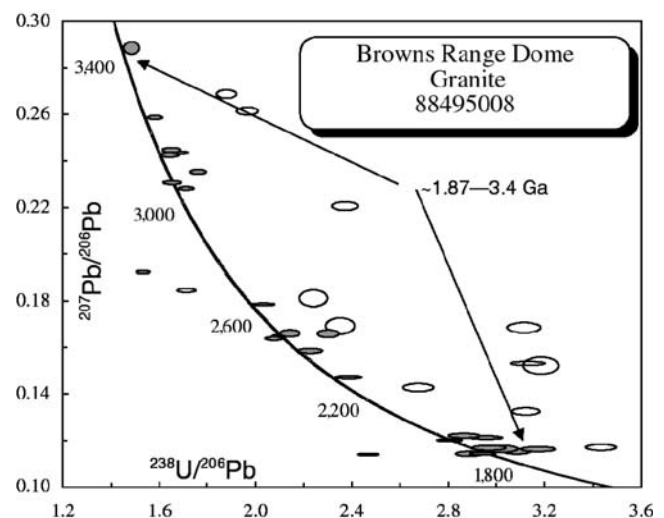


Fig. 18 Concordia plot of zircon U–Pb analyses for Browns range Dome granite sample 88495008

between ~1.99 and ~1.87 Ga (Table 3) were interpreted by Page et al. (1995) as recording the age of metamorphism in Browns Range Dome.

The precise location of each SHRIMP spot for analyses that ranged between ~1.99 and ~1.87 Ga were examined with reference to the new CL images. These images showed that each SHRIMP spot was entirely centred on concentrically or sector zoned, luminescent, rounded to well-rounded zircon cores (for example, Fig. 19). We interpret these internal zoning features and high degree of rounding of these cores to be more characteristic of zircon grains that have crystallized from an igneous melt and later rounded during sedimentary transport, rather than zircon that has grown and/or re-crystallized under metamorphic conditions.

Zircons that have grown or re-crystallized under metamorphic conditions generally has Th/U<1 (Hoskin and Black 2000; Williams 2001) and is often very poorly luminescent. Regions in zircons that have been re-crystallized can appear as lobate, poorly luminescent patches discordant to the primary growth zones (e.g. Hoskin and Black 2000). In contrast, new zircon growth under metamorphic conditions usually forms poorly luminescent new crystals (Williams 2001) or precipitates as an overgrowth onto a protolith zircon core (Williams 2001; Tyler et al. 1999). Although almost all zircon grains from this sample have thick, poorly luminescent overgrowths, these are highly metamict and when targeted with the SHRIMP, yielded grossly discordant ages.

Th/U ratios for the nine analyses between ~1.99–1.88 Ga, are generally low, ranging from 0.19–0.02. Four analyses have Th/U less than 0.1, and the remaining five range between 0.13 and 0.19. Although some of these Th/U ratios are <0.1, by themselves, they cannot be used to diagnose a metamorphic origin. The majority remain within the normal range for zircons from felsic igneous rocks (1–0.1:Williams 2001). Furthermore, Th/U ratios for the older, Archean

zircons in this sample vary widely between 0.04 and 1.66 with no apparent pattern.

The morphological characteristics of these zircon grains, as seen in the CL images, is thought to be diagnostic of their origins. The interpretation of Page et al. (1995) that these zircon grains formed by metamorphic processes within their host granite is inconsistent with these new observations. They are better interpreted to represent inherited components possibly from a meta-sedimentary protolith. By inference therefore, the Archean crystallization age attributed to this granite must also represent an inherited component. The youngest three analyses from this sample combine to give a weighted mean age of $1,874 \pm 10$ Ma, and can be used as a maximum emplacement age for this rock.

Proposed model for the early evolution of the Tanami Basin

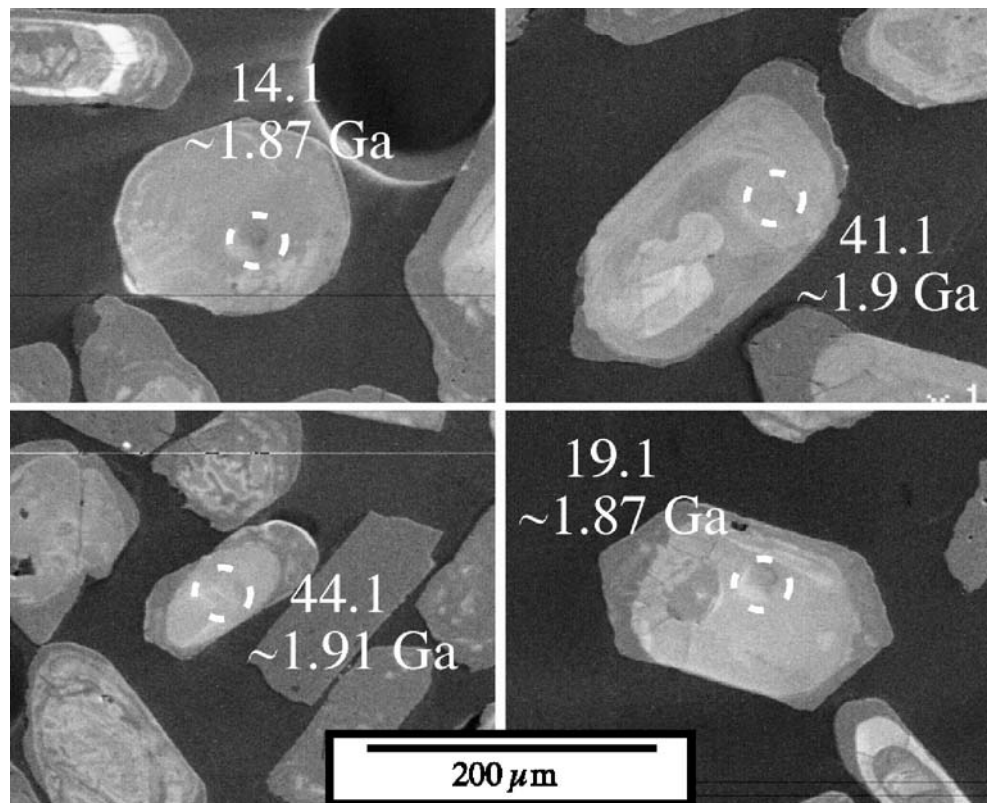
With the removal of the evidence for a ~1.88 Ga event to have affected Tanami rocks in the Browns Range Dome, the model for the early evolution of the Tanami Basin can be revised. To do this, understanding the timing of the earliest sediment deposition of the Ferdies Member is crucial. However, there are no direct constraints on the timing of sedimentation for this unit. The oldest direct constraint for the minimum age of sedimentation for the Ferdies Member is the $1,838 \pm 6$ Ma age of the overlying Callie tuff (2001082511). Therefore any ideas regarding the true deposition age of this sequence are speculative. However, as previously stated, we believe that the early development of the Tanami basin to have occurred between ~1.87 and 1.84 Ga. This interpretation is partly supported by the ~1,864 Ma age of the Bald Hill sequence in Western Australia (cited in Huston et al. 2006). This unit may represent one of the earliest sedimentary units in the Tanami Region.

Table 3 SHRIMP U–Pb isotopic data for zircons (~1.87–1.99 Ga) from granite in Browns Range Dome (88495008)

Spot name	U (ppm)	Th (ppm)	Th/U	²⁰⁶ Pb (ppb)	²³⁸ U/ ²⁰⁶ Pb (±1σ %)	²⁰⁷ Pb/ ²⁰⁶ Pb (±1σ %)	²⁰⁷ Pb/ ²⁰⁶ Pb age (Ma±1σ)	Discordance (%)			
19.1	240	45	0.19	138	0.3469	0.0043	0.1143	0.0007	1,869	11	−3
14.1	611	106	0.17	352	0.3401	0.0041	0.1145	0.0004	1,871	7	−1
17.1	415	55	0.13	858	0.3245	0.0040	0.1155	0.0008	1,888	12	4
28.1	890	43	0.05	2085	0.3154	0.0047	0.1163	0.0007	1,900	10	7
41.1	211	37	0.18	204	0.3316	0.0051	0.1165	0.0010	1,903	16	3
44.1	200	27	0.14	43	0.3372	0.0052	0.1169	0.0007	1,910	11	2
8.1	800	33	0.04	101	0.3572	0.0043	0.1202	0.0003	1,960	5	0
27.1	979	23	0.02	1074	0.3385	0.0051	0.1213	0.0005	1,975	7	5
31.1	1,003	28	0.03	2846	0.3496	0.0052	0.1222	0.0006	1,988	9	3

Isotope ratios are corrected for common Pb by reference to the measured abundance of ^{204}Pb
 ^{206}Pb denotes the amount of common ^{206}Pb measured

Fig. 19 Cathodoluminescence images of zircons from sample 88495008, which Page et al. (1995) used to interpret metamorphic events at ~1.99 or ~1.87 Ga. The SHRIMP spot locations are shown to have targeted rounded zircon cores (see text for discussion)



Initial uplift caused by either the ~1.87–1.85 Ga Hooper Orogeny (Halls Creek Orogen) and/or the Nimbuwah Event (Pine Creek Orogen) or alternatively, the very early stages of the ~1.83 Ga Tanami Event caused Archean basement rocks or sedimentary rocks derived from Archean sources to be shed into the Tanami basin forming the basal Ferdies Member of the Dead Bullock Formation. Between ~1.84–1.82 Ga the ~1.86 Ga voluminous products of the Hooper Orogeny and magmatism associated with the Nimbuwah Event were exposed, eroded and transported to form turbidite of the Killi Killi Formation. A similar significant age contrast in detrital zircons between basal and overlying sediments shed from an orogen has been observed by McLennan et al. (2001) in the lower Paleozoic rocks in the New England region of North America. These researchers also reported that the oldest sedimentary sequences do not record contemporaneous orogenic activity, but rather reflected older recycled continental margin rocks. Detrital zircon studies thus suggest that the first sediments shed from an emerging orogen might not record contemporaneous magmatism, but rather represent the eroded products of uplifted basement rocks.

Conclusions

The Paleoproterozoic Tanami basin probably developed between ~1.87–1.84 Ga in response to either the Hooper

Orogeny (Halls Creek Orogen), Nimbuwah Event (Pine Creek Orogen) or very early stages of the Tanami Event. Initial uplift and erosion of Archean basement probably occurred between ~1.87–1.84 Ga and produced sediments now represented by the Ferdies Member of the Dead Bullock Formation. Its deposition age is loosely constrained between ~2.11 and 1.84 Ga. The extensive turbiditic sandstone units of the Killi Killi Formation can be correlated with the Lander Rock beds in the adjacent Arunta region. Killi Killi Formation turbidite was largely derived from the erosion of ~1.86 Ga orogenic granites and deposited at ~1.84 Ga. Detrital zircon ~2.50 Ga old, appears in all Tanami sediments investigated and with the possible exception of the Mount Charles Formation, ~1.86 Ga zircon components are present in all sediments younger than the Killi Killi Formation. The persistence of these age modes throughout the various units shows that recycling has played a major role in the development of the sedimentary successions of the Tanami basin.

Based primarily on structural grounds, the Mount Charles Formation is interpreted by Crispe et al. (2006) to have been deposited at ~1.80 Ga. However, this unit lacks the ~1.86 Ga component so prominent in sequences younger than the Killi Killi Formation and is dominated by Archean detritus with a youngest zircon component defining a maximum deposition age of ~1.91 Ga. One possible source for this component is the similarly aged Ding Dong Downs Volcanics in the eastern part of the Halls Creek Orogen. The

unabraded nature and preserved crystal faces of this zircon component indicate that they are first-cycle sediments and may record the timing of contemporaneous volcanism and by inference the depositional age of this unit. Alternatively, the youngest 1.91 Ga detrital zircon component in the Mount Charles Formation may not approximate the timing of sedimentation, but represent a derivation from a restricted catchment, that only eroded rocks endowed with Archean and ~1.91 Ga zircon components.

Detrital zircon grains from the Pargee Sandstone define a maximum deposition age of $1,768 \pm 14$ Ma, whereas the youngest zircons from the overlying Gardiner Sandstone are ~40 Ma older, and crystallized at $1,812 \pm 8$ Ma. Therefore, detrital zircons from the Gardiner Sandstone do not approximate its depositional age. There are no minimum age constraints for the deposition of the Pargee Sandstone other than the ~1.64 Ga constraint provided by the Gardiner Sandstone (Vallini et al. 2006; Cutovinos et al. 2002). Hence, timing controls for sedimentation of the Pargee Sandstone currently span ~40 Ma. Without firm minimum age controls for the deposition of this unit, the accuracy of the ~1.77 Ga, detrital zircon max deposition age cannot be determined. Clearly, further isotopic and field studies focussing on locating intercalated volcanic units and/or diagenetic minerals are needed to establish the depositional age and stratigraphic setting of the Mount Charles and Gardiner Sandstone units.

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