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An assessment of the determination of depositional ages for precambrian clastic sedimentary rocks by U–Pb dating of detrital zircons

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Abstract

Methodologies for the determination of depositional ages for clastic sedimentary rocks by ion microprobe U–Pb analysis of their detrital zircon populations are described. Provided there has been no sample contamination or disturbance of the U–Pb system, the youngest igneous crystallization dates obtained on detrital zircons from a sedimentary rock sample will provide a maximum age for sediment deposition. Maximum depositional ages so obtained are comparable to minimum ages determined from the dating of cross-cutting dykes, or of metamorphic or diagenetic minerals, but a significant advantage of this approach is that detrital zircons are virtually ubiquitous in clastic sedimentary rocks. The advantages and limitations of this approach are demonstrated in case studies of sedimentary rocks from the Archaean Yilgarn Craton, the Mesoproterozoic Albany–Fraser Orogen and the Neoproterozoic Officer Basin of Australia. These examples demonstrate that the probability that maximum deposition ages based on the dating of detrital zircons are close to the time of sediment deposition is influenced by the lithological characteristics of the sediment samples, with the best results obtained from lithologies with the widest possible provenance range represented in their detrital zircon populations. Due to difficulties in matching wide provenance ranges to particular source areas, lithologies that are suited to maximum depositional age determinations are not necessarily suited to provenance studies. The approach will find applications particularly in studies of sedimentary basins that lack volcanic or intrusive rocks amenable to radiometric dating. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Determination of the time of deposition of the commonly unfossiliferous sedimentary rocks of the Precambrian can be a difficult task. A preferred approach is to date interbedded volcanic horizons using radiometric dating methods, such as ^{40}Ar–^{40}Ar of high-K_2O minerals, or by U–Pb dating of high-U minerals such as zircon. Unfortunately, in many Archaean and Proterozoic basins, suitable well-preserved volcanic horizons amenable to radiometric dating are uncommon. Minimum ages for sediment deposition may be obtained by the radiometric dating of cross-cutting intrusive rocks, by the dating of metamorphic minerals such as monazite, apatite and other phosphates, by the Pb–Pb isochron method on carbonates or banded iron-formation, or by Rb–Sr or K–Ar dating of metamorphic micas. However, these approaches are also dependent on the availability of

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suitable cross-cutting intrusive rocks, of well-preserved chemical sedimentary rocks or of dateable metamorphic minerals. Moreover, such minimum ages may be considerably younger than, and therefore provide few useful constraints on, the time of sediment deposition.

One promising approach is offered by the dating, by the U–Pb method, of suitable diagenetic minerals, such as high-U phosphates. Sub-micron sized phosphate minerals with high U contents, particularly REE-phosphates such as xenotime, have been described as common in marine sedimentary rocks and are believed to have been precipitated within the zone of sulphate reduction and methanogenesis following burial (Rasmussen, 1996). One difficulty with this approach arises from the interpretation of the significance of the dates obtained. This is dependent on the determination of the time at which such minerals form, relative to the time of host sediment deposition for each case. Furthermore, as these phosphates form at low temperatures, they might also be expected to form, possibly episodically, over a geologically significant time interval, and to be susceptible to recrystallization at low temperatures. These complexities may limit the potential usefulness of these U-rich phosphates for the dating of deposition of sedimentary rocks.

A further alternative approach to the dating of deposition of sedimentary rocks, whose potential has yet to be fully realized, is by the U–Pb dating of detrital zircons using an ion microprobe. Detrital zircons significantly larger than the size of the ion microprobe analysis spot (ca. 20 μm diameter) are virtually ubiquitous in clastic sedimentary rocks. The ion microprobe Sensitive High-Resolution Ion MicroProbe (SHRIMP) can date more than 50 zircons in a 24 h session, so the analysis of sufficient zircons to enable determination of the age structure of a zircon population from a clastic sedimentary rock can be achieved during a single analysis session. Provided there has been no disturbance of the U–Pb system, the youngest igneous crystallization dates obtained on detrital zircons from a sedimentary rock sample will provide a maximum age for sediment deposition. The precision of the maximum depositional age may be improved by pooling of multiple analyses obtained on the youngest detrital grain or grains. In most circumstances, maximum depositional ages so obtained are comparable, in terms of their geological value, to minimum ages determined from the dating of cross-cutting dykes, or of metamorphic or diagenetic minerals.

A useful adjunct to the determination of maximum depositional ages of sedimentary rocks by the dating of detrital zircons is the provenance information provided for the host sediment. U–Pb dating of detrital zircons can make an important contribution to sediment provenance studies, particularly when combined with detailed field sedimentological investigations. In a recent study of placer deposits, Sircombe and Freeman (1999) demonstrated that the provenance of detrital minerals need not relate to present proximity, but is instead strongly influenced by the history of uplift, tectonism, recycling and transport mechanisms before and during sediment deposition. Dating of detrital zircons therefore represents a useful tool in basin analysis studies, both for the determination of the time of sediment deposition, and for the provenance information for sedimentary rocks offered by this method.

This contribution documents new methodologies for the determination of depositional ages for sedimentary rocks, by U–Pb analysis of detrital zircon populations using SHRIMP. The advantages and limitations of this approach are demonstrated by case studies, documented herein, of the application of ion microprobe detrital zircon analysis to the dating of deposition of a range of sediment lithologies from different tectonic settings. Case studies include analysis of metasedimentary rock samples from the western part of Australia; from the same unit of the Jack Hills metasedimentary belt that contains ≥4 Ga detrital zircons, from the greenstones of the Southern Cross and Eastern Goldfields Provinces of the Yilgarn Craton, from the Mesoproterozoic Albany–Fraser Orogen, and from a Neoproterozoic diamictite of the Officer Basin. Approximate positions of the sampling sites are shown on Fig. 1. Photomicrographs of some detrital zircons from the samples examined are shown in Figs. 2 and 3.

The case studies demonstrate that the lithological characteristics of sediment samples will influence the probability that maximum deposition ages based on the dating of detrital zircons are close to the time of sediment deposition, and that the best results are obtained from sample lithologies having the widest

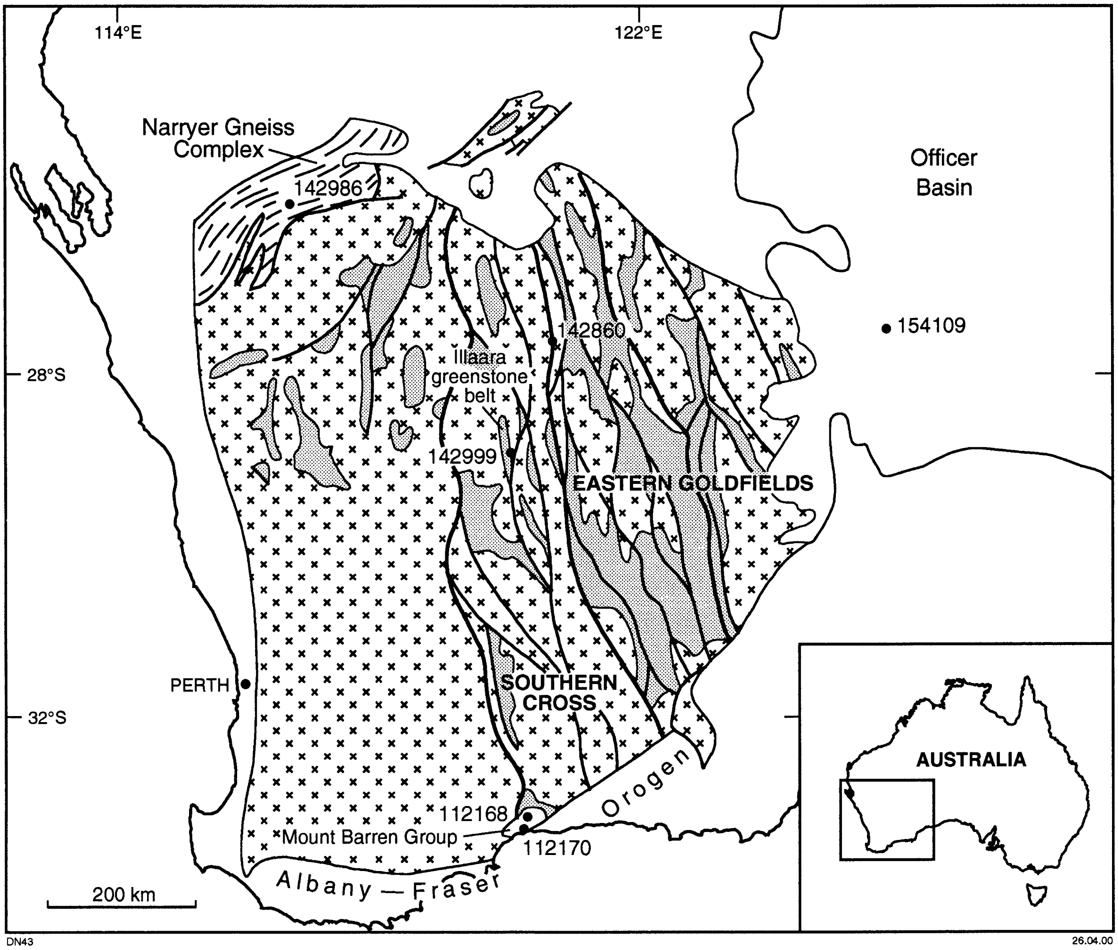


Fig. 1. Map of the southwestern part of Australia showing main tectonic components of the Yilgarn Craton (granitic rocks shown as '×', greenstones shown shaded) and adjacent tectonic units, and sampling sites for clastic sedimentary rock samples investigated in this study.

possible provenance range represented in their detrital zircon populations. The case studies also show that lithologies which are better suited for maximum depositional age determinations are not necessarily suited to provenance studies, due to difficulties in matching wide provenance ranges to particular source areas.

2. Methodology

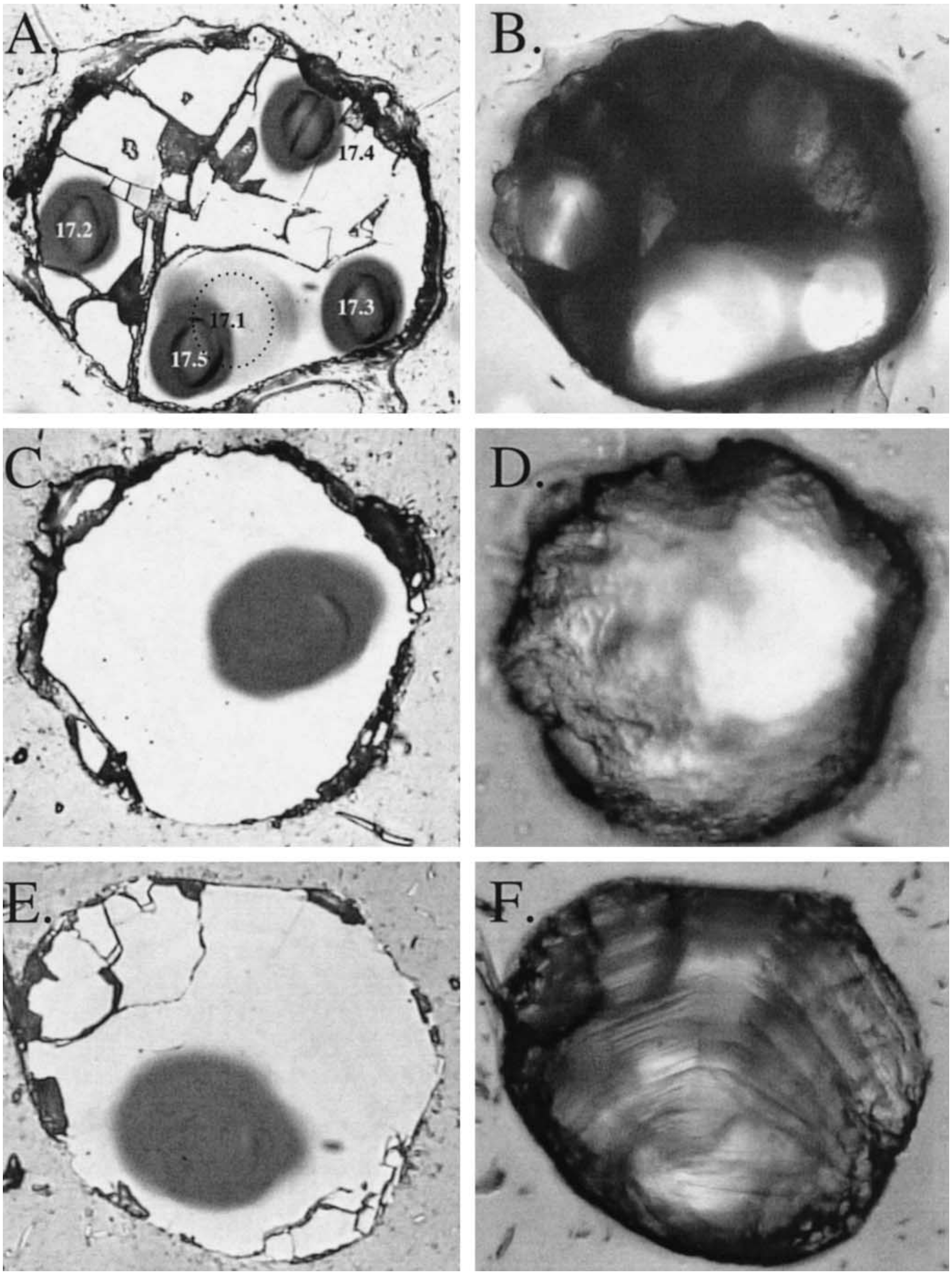
2.1. Background

Maximum deposition ages determined by U–Pb isotopic dating of detrital minerals using an ion microprobe rely on the pooling of the comparatively small number of analyses that indicate the youngest crystallization dates obtained. They may be based on analyses obtained from a few grains, a single grain, or even on a single analysis. This imposes strict requirements on the analytical methodology:

1. Sediment samples must be free of veins and melt patches, as these are potential sources of mineral contaminants younger than the time of sediment deposition. Although it is often possible to infer a detrital origin for zircons based on their morphological features, metamorphic zircons may be

rounded in shape and have textured surfaces, and may thus (in rare cases) be difficult to distinguish from detrital grains. Consequently, samples should preferably be at relatively low metamorphic grade.

2. There must be no possibility of sample contamination by foreign zircons. Accidental inclusion of any zircons younger than those within the sample from sources other than the sample — during sample collection or processing, for example — may result in erroneous maximum age determinations.



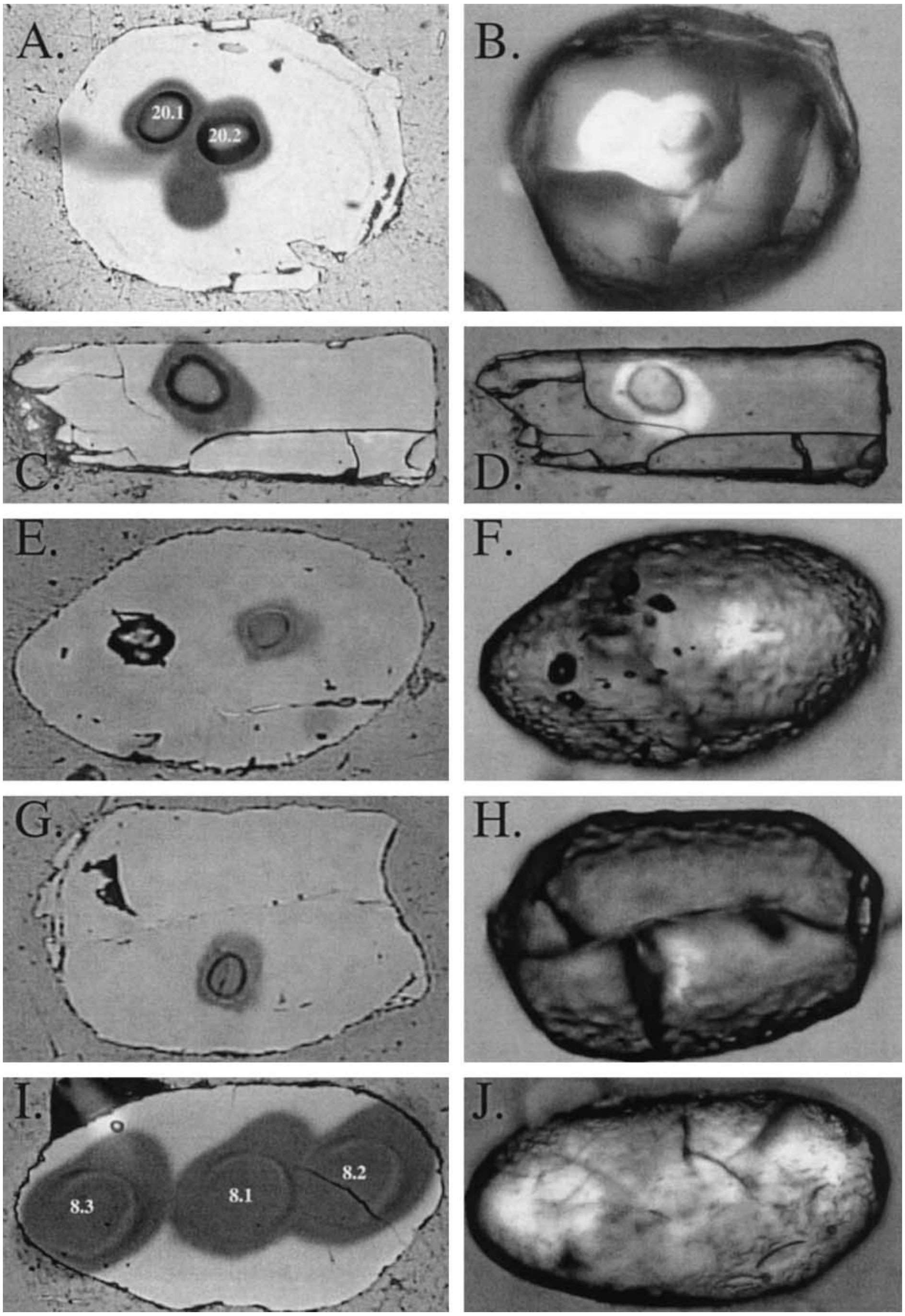
3. Whereas dating of igneous rocks commonly results in comparatively simple age populations enabling post-crystallization disturbance to be readily assessed, this is rarely the case for sedimentary rocks. The complex age patterns of detrital zircon populations make assessment of the effects of secondary disturbance difficult. Due to the progressive accumulation of radiation damage within their crystal structures, the U–Pb system within high-U minerals such as zircon becomes increasingly more susceptible to post-crystallization disturbance with age. Analyses of metamict zircons commonly indicate recent redistribution or loss of radiogenic-Pb within the crystals, attributable to secondary alteration processes following recent exhumation. Therefore, lithologically fresh samples, with minimal evidence of post-depositional weathering or alteration, are essential, in order to minimize interpretation ambiguities arising from post-crystallization isotopic disturbance.

Dates on igneous rocks by ion microprobe are commonly based on the pooling of a number of statistically indistinguishable analyses. As the crystallization of igneous minerals typically occurs over a time interval that is significantly less than the analytical error obtained from pooled analyses, the precision of dates so obtained for igneous mineral populations is limited principally by analytical error. However, for analyses obtained on a population of detrital zircons, it cannot be assumed that a sub-population of analyses, which are analytically indistinguishable, was derived from a common (single-aged) source. It is therefore essential that analytical and ‘geological’ sources of error (such as those arising from inclusion of analyses of zircons derived from sources of different age or that may have lost small amounts of radiogenic Pb) are independently quantifiable. Fortunately, all sources of analytical error such as counting statistics, common-Pb corrections and inter-element ratio (Pb/U) calibration error components, for individual analyses obtained using the ion-probe are readily quantifiable. The validity of the pooling of a sub-population of ion-microprobe analyses obtained from detrital zircons may be assessed using a chi-square test. This test can ascertain whether the scatter displayed by the analyses of the sub-population about a single weighted mean value can be accounted for entirely by analytical sources of error. Chi-square values for grouped analyses of less than or equal to unity indicate that scatter about the weighted mean value determined for the grouped analyses can be accounted for by analytical sources of error alone. A chi-square value significantly greater than unity indicates that other (geological) sources of error are present within the grouped population. A chi-squared test will only be meaningful, however, if there is a sufficiently large number of analyses within the sub-population to be tested.

Investigation of depositional ages using detrital zircons may be facilitated by employing sampling strategies based on a sound understanding of the sedimentological and tectonic processes that have influenced sediment deposition. There is a greater probability of incorporation of detrital zircons close in age to the time of sediment deposition in cases in which sedimentary basins form as a result of active tectonism accompanied by copious magmatism, or by unroofing and erosion of nearby and recently emplaced granitoid rocks, than in those cases where

Fig. 2. Photomicrographs of detrital zircons from the samples examined in this study. (A) Reflected light image of grain 17 from sample 142986: metasandstone from the Jack Hills metasedimentary belt of the Yilgarn Craton. The grain is 158 μm in diameter. SHRIMP analysis pits, surrounded by dark haloes caused by pre-analysis rastering of the surface with the primary beam, are clearly visible. Analysis 17.1 and the remaining analyses of this grain were obtained during different analysis sessions. (B) Transmitted light image of grain 17 from sample 142986: metasandstone from the Jack Hills metasedimentary belt of the Yilgarn Craton. Although this zircon is dark in color, pitting due to abrasion during detrital transport is evident on its surface. (C) Reflected light image, showing the ion microprobe analysis pit, of grain 32 of Group 1, sample 142999: metasandstone from the base of the Illaara greenstone belt, Southern Cross Province of the Yilgarn Craton. The grain is 120 μm in diameter. (D) Transmitted light image of grain 32 of Group 1, sample 142999: metasandstone from the base of the Illaara greenstone belt, Southern Cross Province of the Yilgarn Craton. Pitting due to abrasion during detrital transport is evident on the surface of this grain. (E) Reflected light image of grain 20 of Group 1, sample 142999: metasandstone from the base of the Illaara greenstone belt, Southern Cross Province of the Yilgarn Craton. The grain is 129 μm in diameter. (F) Transmitted light image of grain 20 of Group 1, sample 142999: metasandstone from the base of the Illaara greenstone belt, Southern Cross Province of the Yilgarn Craton. Euhedral zonation is truncated and the surface of this grain is pitted due to abrasion during detrital transport.

basins form as a result of passive subsidence. However, as emphasized by Eriksson et al. (2001), the processes operating during the formation of most Archaean and many Proterozoic sedimentary basins are generally not well understood. In addition, the stratigraphies of many Archaean greenstone-related basins have been influenced by both syn- and post-depositional deformation, whereas many Proterozoic



sedimentary basins, particularly those within intracratonic settings, apparently formed with little or no accompanying igneous activity. Under these circumstances, depositional ages should be based on the investigation of a substantial number of samples taken from coherent parts of the stratigraphic section. A range of other factors, including sample lithologies and their stratigraphic contexts, and the possibility that the provenance of the sedimentary rocks within the basin may have progressively changed as the basin developed, should also be considered during both sampling and interpretation of the results.

How closely a maximum age based on the analysis of a detrital zircon population approximates the depositional age of the host sedimentary rock will depend on both the age structure of the provenance region and the number of analyses obtained. As discussed above, it is usually not possible to be confident in advance that a source of newly-crystallized zircon was present nearby and contributed detritus during the deposition of Archaean or Proterozoic sedimentary rocks. Furthermore, ion microprobe analytical time is costly and usually strictly limited, and in terms of constraints on the time of host sediment deposition, there is little advantage in obtaining multiple analyses for an age group of detrital zircons if that age group is not the youngest identified. Therefore, in the absence of any evidence that sediment deposition was accompanied by contemporaneous igneous activity, sedimentary rocks containing detrital zircon populations derived from the widest possible provenance range are preferred to those derived from a restricted provenance range and with a small number of local, and possibly old, sources of zircon. This is because in the general case, the number of different age groups represented within a detrital zircon population, and thus the probability of detecting any zircons that crystallized close to the time of deposition of the host sedimentary rock in a randomly chosen sample of the population, will increase with increasing provenance area.

As will be demonstrated in the case studies documented herein, the probability that a maximum age based on analyses obtained for a detrital zircon population will closely approach the depositional age of the host sediment may be improved by careful sample selection. In the absence of sedimentary rocks having a volcanigenic component, in practice the best outcomes have been obtained from coarse-grained, highly mature, siliceous sandstones, such as those formed in high-energy depositional environments. The more extensive mechanical sorting and mineral reworking required to form mature clastic sedimentary rocks promotes the mixing of detrital grains from a generally wider range of source components and consequently, potentially offers a wider range of provenance ages than will be obtained from texturally and compositionally immature sedimentary rocks. There is therefore a low probability that a small number of locally derived, and possibly old, age components will dominate the zircon population and a greater probability of the incorporation of zircons from sources closer in age to that of the time of deposition of the host sedimentary rock. An additional important advantage is that the detrital zircons from such lithologies commonly have low U (typically ≤400 ppm), as high-U grains are preferentially mechanically destroyed in high-energy depositional

Fig. 3. Photomicrographs of detrital zircons from the samples examined in this study. (A) Reflected light image of grain 20 of Group 1, sample 142860: conglomeratic metasandstone from the Kaulweerie Conglomerate, Eastern Goldfields Province of the Yilgarn Craton. The ion microprobe analysis sites are clearly visible. The grain is 163 μm long. (B) Transmitted light image of grain 20 of Group 1, sample 142860: Conglomeratic metasandstone from the Kaulweerie Conglomerate, Eastern Goldfields Province of the Yilgarn Craton. The grain is rounded and surface pitting is evident, consistent with detrital transport. (C) Reflected light image of grain 10 of sample 112168: metasandstone, Mount Barren Group, No Tree Hill. The grain is 360 μm long. (D) Transmitted light image of grain 10 of sample 112168: Metasandstone, Mount Barren Group, No Tree Hill. Pitting of the surface is evident on the edges near the ends of this grain. (E) Reflected light image of grain 7 of Group 1, sample 112170: metasandstone, Mount Barren Group, Barrens Beach. The grain is 237 μm long. (F) Transmitted light image of grain 7 of Group 1, sample 112170: metasandstone, Mount Barren Group, Barrens Beach. The surface is extensively pitted, due to detrital transport. (G) Reflected light image of grain 10 of Group 1, sample 112170: metasandstone, Mount Barren Group, Barrens Beach. The grain is 180 μm long. (H) Transmitted light image of grain 10 of Group 1, sample 112170: Metasandstone, Mount Barren Group, Barrens Beach. The surface is extensively pitted, due to detrital transport. (I) Reflected light image of grain 8 of sample 154109: quartz-carbonate diamictite from the Officer Basin. The ion microprobe analysis sites are clearly visible. The grain is 163 μm long. (J) Transmitted light image of grain 8 of sample 154109: Quartz-carbonate diamictite from the Officer Basin. The grain is rounded and surface pitting is clearly evident.

environments. Provided a wide provenance range is represented, the U contents of detrital zircons will be independent of their age, so preferential removal of high-U grains will not systematically bias the age populations obtained. Moreover, low-U grains are generally less susceptible to post-deposition disturbance and radiogenic-Pb loss. Dates obtained on such low-U zircons will generally be comparatively imprecise due to low count rates, but this disadvantage is more than offset by their better structural preservation and consequent lower susceptibility to post-crystallization disturbance. Furthermore, detrital zircons from such lithologies are typically large, clear and structureless (see Figs. 2 and 3) and are readily identifiable as detrital in origin as they are commonly well rounded, with pitted and abraded surfaces. The larger size of these zircons facilitates the acquisition of multiple analyses on individual grains should this prove necessary. Such structureless, clear, low-U zircons generally provide highly reliable and concordant U–Pb dates.

How representative the age structure based on ion microprobe analyses is of the provenance of the entire detrital zircon population will depend on the number of analyses obtained on the detrital zircons within the sediment sample. As outlined by Dodson et al. (1988), for a number (n) of analyses obtained at random on a zircon population, the probability (P) of missing an age population is related to its frequency (f) within the population by:

$$P = (1 - f)^n.$$

For a typical analysis session during which 50 analyses are obtained, there is an even chance ($P = 0.5$) that sub-populations with a frequency of 1.4% will be detected.

The likelihood of detecting a zircon or zircons providing a crystallization date close to that of the time of deposition of the host sediment is highly dependent on the provenance range which (as outlined above) should be as large as possible. As the provenance may vary within a stratigraphic sequence, it is a preferable strategy to analyse a smaller number of detrital zircons from several samples from the same stratigraphic package, rather than a large number from a single sample. How closely a maximum age based on analyses obtained from a detrital zircon population approaches the depositional age of the host sediments may be assessed by the analysis of detrital zircons from a series of samples which have well-understood stratigraphic relationships. Maximum depositional ages based on analyses of the detrital zircon populations determined for these samples can then be compared with those anticipated from the stratigraphic order. However, the time range over which the sedimentary package was deposited must be large enough to be resolvable. Identification of suitable samples with both suitable lithologies and having a resolvable range of depositional ages within a single stratigraphic package for this exercise is often difficult in practice.

2.2. Analytical procedures

Following crushing and screening, heavy minerals were isolated from at least 0.5 kg (typically 2 kg) of sample using modified heavy-liquid and magnetic techniques. Representative zircons were mounted in epoxy and sectioned approximately in half, and the mount surface polished to expose the grain interiors. U, Th and Pb isotopic measurements were made using the Perth Consortium SHRIMP-2. Full details of sample processing, operating and data processing procedures are given elsewhere (Nelson 1997a, 1999). Pb/U ratios were determined relative to that of the standard Sri Lanka zircon CZ3, which has been assigned a $^{206}\mathrm{Pb}/^{238}\mathrm{U}$ value of 0.0914, corresponding to an age of 564 Ma. For pooled analyses, individual analyses have been weighted according to the inverse square of the individual analytical error of the analysis to give a weighted mean value. All errors cited in the text and figures are at $\pm t\sigma$ (corresponding to 95% confidence, where t is Fisher's t) unless otherwise indicated; error boxes shown in the Concordia plots (Figs. 4–7 and in Fig. 9) are at the $\pm 1\sigma$ level.

In addition to presentation on a Wetherill concordia plot, data obtained on detrital zircon populations from sedimentary rock samples are displayed herein on Gaussian Summation probability density plots. This plot presents a probability density curve for concordant analyses (i.e. those analyses for which the $^{206}\mathrm{Pb}/^{238}\mathrm{U}$ date is within error of $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ date at the $\pm 2\sigma$ error level) only. Where two or more analyses indicating analytically indistinguishable dates (at the $\pm 1\sigma$ error level) have been obtained on a single zircon, a single weighted mean date and

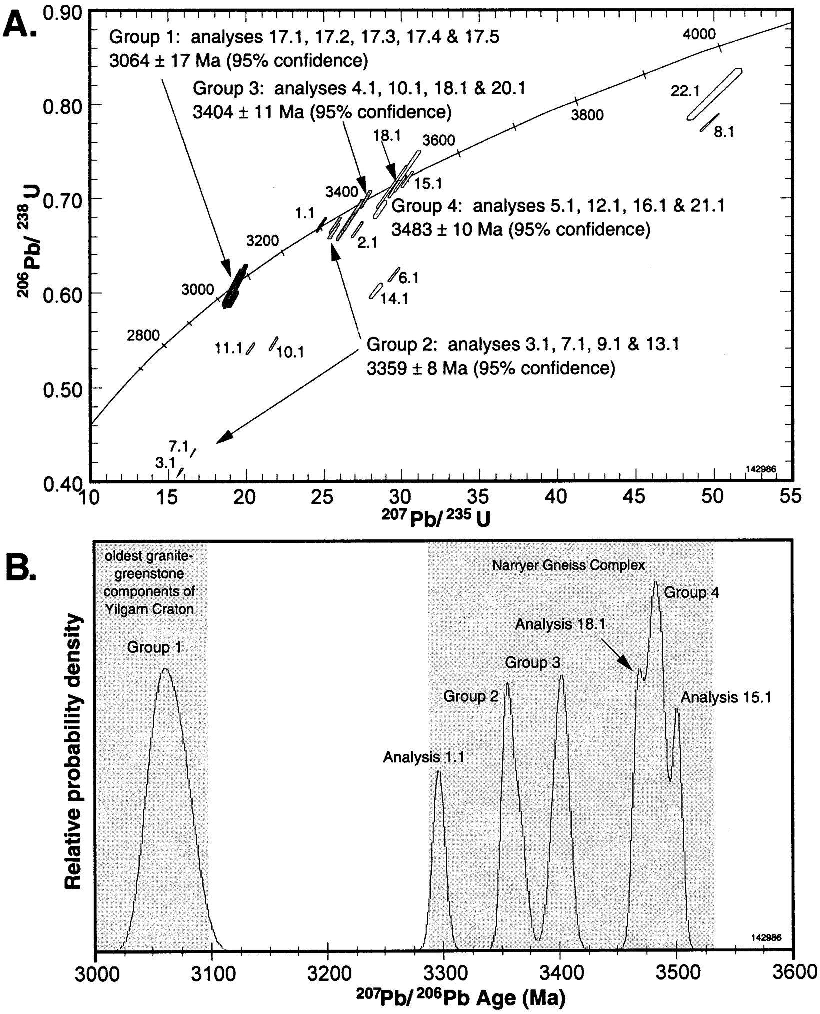


Fig. 4. (A) Concordia plot for analyses obtained for detrital zircons within sample 142986: metasandstone from the Jack Hills metasedimentary belt, Narryer Complex of the Yilgarn Craton. Full analytical data are given in Nelson (2000). (B) Gaussian Summation probability density plot of ^{207}Pb/^{206}Pb dates obtained from detrital zircons within sample 142986: metasandstone from the Jack Hills metasedimentary belt, Narryer Complex of the Yilgarn Craton.

error has been substituted in generating the probability density curve.

3. Case studies

The case studies documented below are not intended to represent completed investigations of the dating of deposition of sedimentary rocks using detrital zircons. Some of these examples were undertaken for other (unrelated) reasons, on samples that are not ideally suited for detrital zircon dating. Nevertheless, they have been selected for inclusion here principally to illustrate aspects of the strengths and weaknesses of this approach encountered in practice.

3.1. Jack Hills metasedimentary belt, northwestern Yilgarn Craton

In the northwestern part of the Yilgarn Craton, rocks of the Narryer and Jack Hills metasedimentary belts were tectonically interleaved with heterogeneous

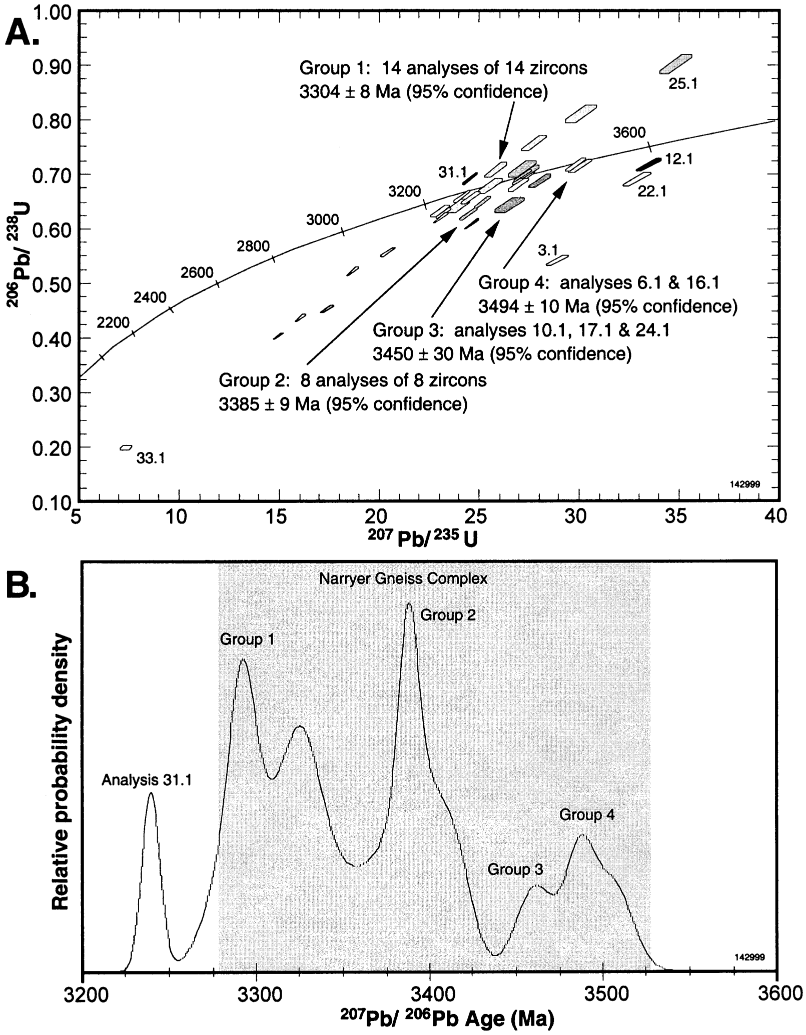


Fig. 5. (A) Concordia plot for analyses obtained for detrital zircons within sample 142999: metasandstone from the base of the Illaara greenstone belt, Southern Cross Province of the Yilgarn Craton. Full analytical data are given in Nelson (2000). (B) Gaussian Summation probability density plot of ^{207}Pb/^{206}Pb dates obtained from detrital zircons within 142999: metasandstone from the base of the Illaara greenstone belt, Southern Cross Province of the Yilgarn Craton.

gneisses derived from 3730 to 3600, 3480 to 3460, and 3370 to 3300 Ma granitic precursors and were deformed a number of times between 2740 and 2620 Ma. Granites were emplaced throughout the northwestern part of the craton during these events and were also heterogeneously deformed. The discovery of detrital zircons older than 4.0 Ga within the Narryer and Jack Hills metasedimentary rocks (Froude et al., 1983; Compston and Pidgeon, 1986) has attracted considerable international interest, yet the timing of deposition of the host metasedimentary rocks has remained poorly constrained. Kinny et al. (1990) state that the maximum age for deposition of the sedimentary precursors to the quartzites at Mount Narryer is '…3280 Ma, or by association with other sequences possibly 3100 Ma'. A quartzite unit of the Jack Hills metasedimentary belt was therefore sampled in order to better constrain the time of deposition of its sedimentary precursor.

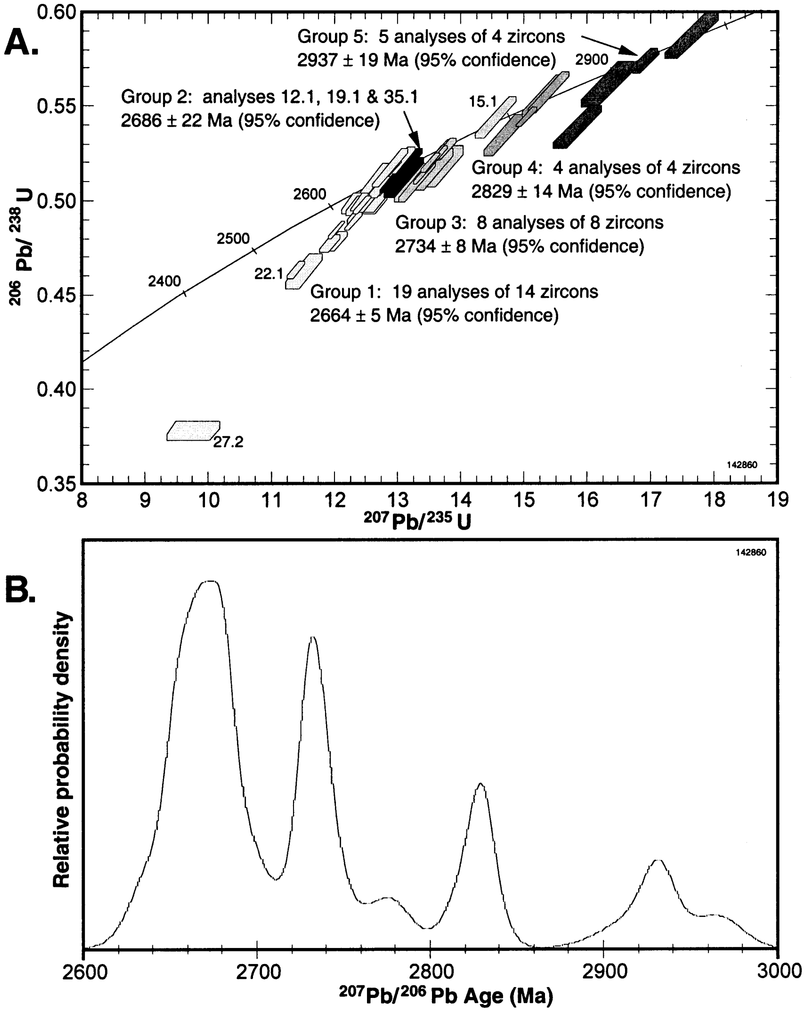


Fig. 6. (A) Concordia plot for analyses obtained for detrital zircons within sample 142860: conglomeratic metasandstone from the Kaulweerie Conglomerate, Eastern Goldfields Province of the Yilgarn Craton. Full analytical data are given in Nelson (1998). (B) Gaussian Summation probability density plot of ^{207}Pb/^{206}Pb dates obtained from detrital zircons within 142860: conglomeratic metasandstone from the Kaulweerie Conglomerate, Eastern Goldfields Province of the Yilgarn Craton.

A sample of metasandstone (142986) from a cross-bedded feldspathic sedimentary unit of the Jack Hills metasedimentary belt was taken from a site (Byro SG 50-10 1:250,000 map-sheet, 116°59′34″E 26°10′06″S) located 5 m north of the site of Compston and Pidgeon (1986) and about 6 km east of Eranondoo Hill (see Fig. 1). It is a sericitic, weakly schistose quartzite with accessory leucoxene and rutile, derived from a medium to coarse sandstone. In thin section, the sample consists of a massive metamorphic quartz mosaic ≤1.5 mm in grain size, incorporating minor irregularly anastomosing lenses and lamellae of schistose muscovite or sericite (≤5 vol.%). The quartz is finer grained in areas of more abundant mica as the grain boundaries have been trapped against mica flakes. Rare patches of leucoxene occur locally and relict detrital rutile occurs as grains ≤100 μm in diameter. Zircons having a wide range of morphologies, from euhedral grains to spherical and irregular-shaped fragments between 100 × 100 and 150 × 500 μm, were extracted from this sample. The majority are black and metamict,

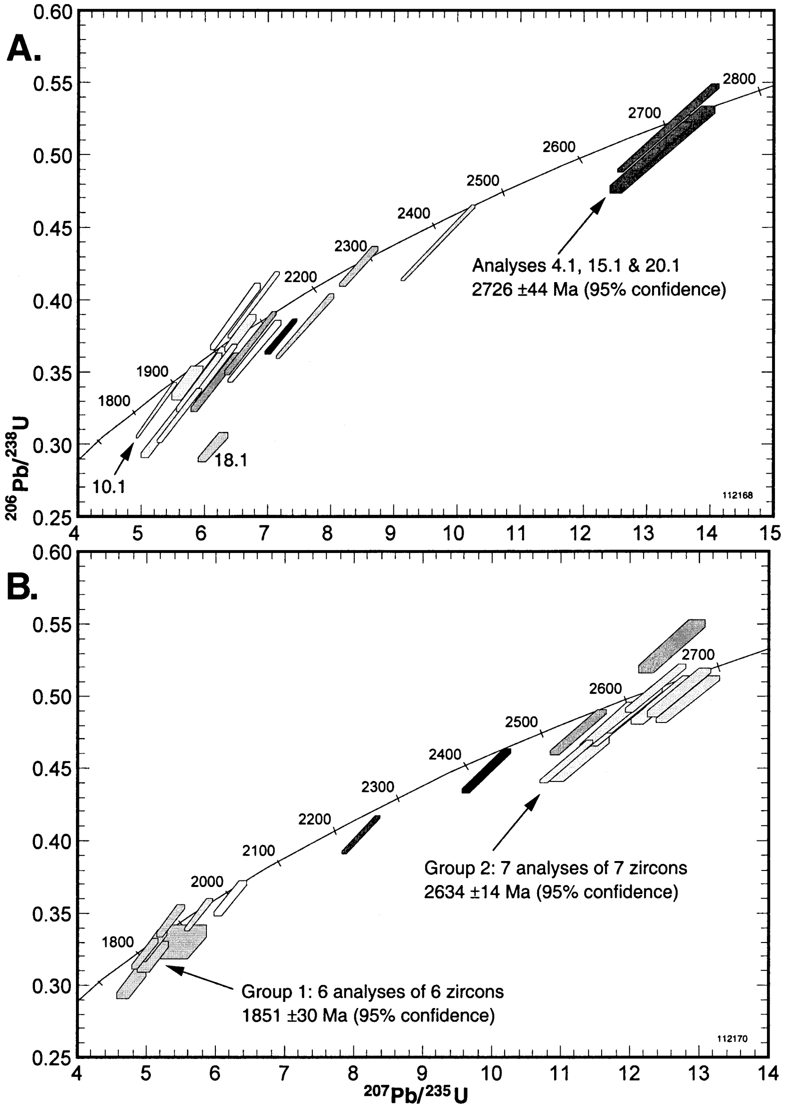


Fig. 7. Concordia plots for analyses obtained for detrital zircons within Mount Barren Group. (A) Sample 112168: metasandstone, No Tree Hill. (B) Sample 112170: metasandstone, Barrens Beach. Full analytical data are given in Nelson (1996).

but a minority of grains, particularly those that are rounded in shape, are yellow-brown and dark brown in color. Igneous zonation and small fluid inclusions may be seen in many crystals. The surfaces of many grains show evidence of surface pitting or abrasion.

Twenty-six analyses were obtained from 22 zircons. Results are shown on concordia and Gaussian Summation probability density plots in Fig. 4. Many analyses are discordant, with the discordance patterns consistent with either a single recent episode, or several recent episodes, of radiogenic-Pb redistribution. The patterns of discordance from the analysis of detrital zircon populations cannot always be interpreted with certainty, but the ratio $^{207}Pb/^{206}Pb$ is not affected by recent redistribution of radiogenic Pb within the zircon crystals, as has been the case in this example. On the basis of their $^{207}Pb/^{206}Pb$ ratios, most analyses may be assigned to four groups. Grain

17 is dark in color and fractured, but is highly spherical and has a pitted surface (see Fig. 2A and B). Five analyses were obtained from grain 17, of which four were concordant. All five analyses obtained from grain 17, assigned to Group 1, have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 1.82) and indicating a weighted mean date of 3064 ± 17 Ma. Deletion of slightly discordant analysis 17.1 and pooling of the remaining four concordant analyses obtained from grain 17 results in a slightly lower chi-squared value of 1.15 and a weighted mean date of 3060 ± 17 Ma. Discordant analyses 3.1, 7.1, 9.1 and 13.1, assigned to Group 2, have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 0.59) and indicating a weighted mean date of 3359 ± 8 Ma. Analyses 4.1, 10.1, 18.1 and 20.1, assigned to Group 3, have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 1.30) and indicating a weighted mean date of 3404 ± 11 Ma. Analyses 5.1, 12.1, 16.1 and 21.1, assigned to Group 4, have $^{207}Pb/^{206}Pb$ ratios defining a single population and indicating a weighted mean date of 3483 ± 10 Ma. The remaining analyses (1.1, 2.1, 6.1, 8.1, 11.1, 14.1, 15.1, 19.1 and 22.1) cannot be assigned to the above groups. Analyses 8.1 and 22.1 are highly discordant but indicate $^{207}Pb/^{206}Pb$ dates of 4126 ± 3 and 4080 ± 10 Ma ($\pm 1\sigma$ errors), respectively.

Grain 17 is a dark yellow-brown, spherical, fractured grain that lacks evidence of internal structure but has a pitted surface and is clearly of detrital origin (see Fig. 2A and B). As this grain is clearly detrital, the date of 3064 ± 17 Ma indicated by the pooling of all five analyses obtained on this grain is interpreted as a maximum age for deposition of the host precursor sandstone. Apart from the analyses on grains older than 4.0 Ga (analyses 8.1 and 22.1), the remaining analyses obtained for the detrital zircons can be closely matched with dates obtained for the Dugal (3300–3380 Ma), Eurada (3460–3480 Ma) and Meeberrie (3300–3730 Ma, with resolvable components at 3600, 3620 and 3670 Ma; Kinny and Nutman, 1996) gneiss associations within the Narryer Complex, consistent with a local provenance for the metasandstone.

In a detailed microstructural investigation of two ≥4.0 Ga zircons recently discovered as xenocrysts within two samples of late Archaean granitic gneiss from the Narryer and Murchison terranes of the Yilgarn Craton, Nelson et al. (2000) argued that all ≥4.0 Ga grains so far identified from the northwestern part of the Yilgarn Craton were derived from a composite terrane comprised of a range of age components, including ca. 4276, 4185, 4150, 4005, 3978, 3945 and 3874 Ma igneous and high-grade metamorphic rocks. The results of this study indicate that remnants of this composite terrane may have been united with the Narryer Complex by ca. 3064 Ma, the maximum time at which the Jack Hills and Narryer metasedimentary rocks were deposited.

3.2. Quartzites at the base of the greenstones of the Southern Cross Province, central Yilgarn Craton

The Southern Cross Province of the Yilgarn Craton comprises narrow and arcuate, north–northwest-trending greenstone belts separated by extensive, heterogeneously deformed monzogranite plutons. The greenstones have been subdivided into three components. A lower sequence consists mainly of basaltic and ultramafic units. Due largely to an absence of readily dateable volcanic rocks, the age of this lower sequence is unknown, but a date determined for a porphyry within the lower sequence indicates that this sequence is older than 3023 ± 10 Ma (Nelson, 1999). Deformed and metamorphosed quartzites, quartz–muscovite schists, pelitic phyllites and chert conglomerates occur at the base of, and within, the mafic and ultramafic units of the lower greenstone sequence at scattered localities across the province. Two upper greenstone sequences consist of felsic volcanic and clastic sedimentary rocks, components of which have been dated at 2813 ± 3 Ma (Nelson, 2001) and 2732 ± 3 Ma (Nelson, 2000). Monzogranitic plutons were mostly emplaced between 2770 and 2630 Ma (Wang et al., 1998; Nelson 1999, 2000).

Wherever it is exposed, the base of the greenstones has been strongly tectonised and rocks that may have formed basement to the lower greenstone sequence have yet to be recognized. Deformed quartz–mica schists and quartzites at low or medium metamorphic grade occur at the base of the lower greenstone sequence. The quartzites are lithologically similar to the quartz arenites described from the Superior and Churchill provinces of the Canadian Shield, for which Donaldson and Kemp (1998) ascribed deposition during a period of intense chemical weathering in a setting of crustal stability. In order to investigate the nature of the basement to the greenstone sequences of the Southern Cross Province and to provide constraints for the maximum depositional age of the lower greenstone sequence, a basal quartzite unit was sampled and its detrital zircon populations analysed.

A metasandstone sample (142999) was taken from a 5 m thick rocky ridge on the north side of, and about 10 m from, a small creek bed, about 5 km south–southeast of Walling Rock (Menzies SG 51-5 1:250,000 map sheet, AMG 51, 222530E 6747430N; see Fig. 1), near the stratigraphic base of the Illaara greenstone belt. The outcrop here consists of pink-white, flaggy, fine- to medium-grained, recrystallized micaceous quartzite. At the sampling site, 2–5 m thick layering was interpreted to be bedding. The sample consists of ≥99 vol.% quartz, with minor sericite, limonite/hematite, apatite and tourmaline representing ≤1 vol.% of the sample. Sericite and limonite or hematite as plates, mostly ≤0.2 mm long, define a foliation. Grain boundaries are partly locked onto inclusions. The original lithology was fine-grained quartz sandstone. The zircons isolated from this sample are pale yellow or dark yellow-brown to black, generally between 40 × 60 and 100 × 250 μm in size and subhedral, oval or irregular in shape. Many are black and metamict, and some have patches of gold-yellow discoloration. Many grains are internally structureless but most show traces of internal growth zoning.

Thirty-three analyses were obtained from 33 zircons. Results are shown on concordia and Gaussian Summation probability density plots in Fig. 5. Analyses are concordant or slightly to highly normally and reversely discordant, with the discordance pattern generally consistent with a single recent episode of radiogenic-Pb redistribution. On the basis of their $^{207}Pb/^{206}Pb$ ratios, most analyses may be assigned to four groups. Fourteen analyses of 14 zircons (1.1, 2.1, 5.1, 7.1, 8.1, 11.1, 14.1, 19.1, 20.1, 27.1, 30.1, 32.1 and 33.1), assigned to Group 1, have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 1.63) and indicating a weighted mean date of 3304 ± 8 Ma. Eight analyses of eight zircons (4.1, 9.1, 13.1, 15.1, 21.1, 25.1, 28.1 and 29.1), assigned to Group 2, have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 1.13) and indicating a weighted mean date of 3385 ± 9 Ma. Analyses 10.1, 17.1 and 24.1, assigned to Group 3, have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 1.19) and indicating a weighted mean date of 3450 ± 29 Ma. Analyses 6.1 and 16.1, assigned to Group 4, have $^{207}Pb/^{206}Pb$ ratios defining a single population and indicating a weighted mean date of 3494 ± 10 Ma. The remaining analyses (3.1, 18.1, 21.1, 22.1, 26.1 and 31.1) cannot be grouped.

Zircons of Group 1 are typically highly spherical and have pitted surfaces (see, for example, grain 32 shown in Fig. 2C and D, and grain 20 in Fig. 2E and F) and have clearly undergone detrital transport. The date of 3304 ± 8 Ma indicated by the fourteen analyses of Group 1 is interpreted as a maximum time for deposition of the sandstone precursor to the quartzite. Analysis 31.1 indicated a lower $^{207}Pb/^{206}Pb$ date of 3240 ± 5 Ma ($\pm 1\sigma$ error) but is discordant. The lower greenstone sequence was therefore deposited later than 3304 ± 8 Ma, based on analysis of the detrital zircons within quartzite sample 142999, but before 3023 ± 10 Ma, the date obtained on a felsic porphyry that has intruded rocks of the lower sequence.

The date of 3023 ± 10 Ma obtained for the porphyry that has intruded the lower sequence represents the oldest date determined so far from the Southern Cross Province, yet there are no detrital zircons younger than 3200 Ma within the metasandstone. Possible source rocks having ages matching those of the detrital zircons within this sample are not known from the central or eastern part of the Yilgarn Craton. However, possible source rocks occur within the Narryer Complex of the northwestern part of the Yilgarn Craton, as can be seen by comparing the probability density plot obtained for the Jack Hills metasandstone (Fig. 4B) with that of the Southern Cross metasandstone (Fig. 5B). The dates obtained for the detrital zircons of the Southern Cross sample closely match those of the orthogneiss components of the Narryer Complex (see Section 3.1). Comparison of the probability density plots obtained for the Jack Hills (Fig. 4B) and Southern Cross (Fig. 5B) metasandstones reveals that there are peaks in both samples at 3300, 3400 and 3480 Ma. A local derivation was inferred for the Jack Hills metasandstone, with the peak at 3300 Ma attributed to a contribution from the Dugal gneiss component of the Narryer Complex, whereas the 3400 and 3480 Ma peaks were attributed to input from the Eurada gneiss. This suggests that the sedimentary precursors to the basal quartzites of the Southern Cross Province were derived by erosion of granitic basement rocks similar to those of the pre-3300 Ma components of the Narryer Complex of the distant northwestern part of the Yilgarn Craton.

There are no detrital zircons within the basal quartzite sample from the Illaara greenstone belt with ages that can be matched with any known dates for rocks of the Southern Cross Province. If the sandstone precursor to the quartzite was deposited close to 3023 Ma, the minimum age of the lower sequence based on the date obtained for the porphyry, it is surprising that the quartzite apparently contains no detrital zircons that crystallized during magmatic events between 3200 and 3025 Ma, including those associated with deposition of the lower greenstone sequence itself. One possible explanation that is consistent with its stratigraphic position at the base of the lower greenstone sequence is that the quartzite represents the oldest lithology preserved within the Southern Cross Province. Either the quartzite unit is allochthonous, or the pre-3200 Ma granitic source rocks from which the detrital zircons in the basal quartzite were derived have been destroyed by incorporation into the sources of, and subsequent remelting to generate, the younger (mainly 2770–2630 Ma) monzogranitic rocks that presently dominate the province. Alternatively, the absence of any 3200–3025 Ma detrital zircons in the quartzite may be explained by the under-representation of regions of subsidence or of low topography, such as is likely to be the case for those rocks forming the basement to a sedimentary basin, compared to regions undergoing active uplift and erosion. Detailed studies of additional samples of the quartzite unit are presently underway to assess these alternatives.

3.3. Conglomerates overlying the greenstones, eastern Yilgarn Craton

In the Eastern Goldfields Province of the Yilgarn Craton, greenstone belts consisting mainly of ultramafic to mafic and dacitic volcanic rocks were deposited between 2713 and 2672 Ma, onto ca. 2960 to 2920,2800,2760 and 2735 Ma basement rocks (Nelson, 1997b). Locally, clastic sedimentary rocks were deposited onto the greenstone sequences, commonly within northerly trending synclinal basins adjacent to major shear zones (see Fig. 1). Polymict conglomerates containing clasts of locally derived felsic porphyry, granite, chert and mafic rock overlie the greenstones at widespread localities throughout the eastern part of the Yilgarn Craton. Examples include the Penny Dam conglomerate (Swager, 1994a; Ahmat, 1995), the Merougil beds (Griffin, 1990), the Kurrawang Formation (Witt, 1994) and the Yilgangi conglomerate (Swager, 1994b). These conglomerates were deposited later than ca. 2670 Ma, the youngest date obtained for the underlying felsic volcanic rocks within the greenstones of the Eastern Goldfields. A minimum estimate for the time of deposition for the conglomerate at Yilgangi is provided by a U–Pb zircon date of 2662 ± 5 Ma determined for a monzodiorite dyke that has intruded these conglomerates (Nelson, 1996). The monzodiorite has intruded the clastic sequence parallel to the trend of the regional foliation and is heterogeneously foliated parallel to D_2, suggesting that it was emplaced during D_2 deformation. However, some isolated occurrences of these clastic metasedimentary rocks are apparently undeformed and unmetamorphosed, and have been correlated with lithologically similar sediments of the Proterozoic basins that overlie the northern and eastern parts of the Yilgarn Craton. One such outlier of polymict conglomerate and lithic arenite, the Kaluweerie Conglomerate (see Fig. 1), was considered by Allchurch and Bunting (1976) to be Proterozoic in age.

A sample (142860) from a conglomeratic metasandstone unit of the Kaluweerie Conglomerate was taken from a 0.5 m diameter boulder situated about 0.5 km north of a prominent east-trending quartz vein at Kaluweerie (Sir Samuel SG 51-13 1:250,000 map sheet, AMG 51 229120E 6918580N; see Fig. 1). The sample is of a coarse, poorly sorted pebbly sandstone with indistinct sedimentary bedding, although lenses of coarser polymict conglomerate are present. Thin-section examination reveals that the sample consists of angular to platy quartz and feldspar, largely sodic plagioclase, and lesser amounts of pale to light-green detrital amphibole. Accessory detrital minerals include tourmaline, titanite, apatite, zircon and epidote. Lithic fragments of fine-grained quartz–feldspar chert with strongly-oriented grains of pale-green amphibole, fine-grained mafic metavolcanic rock, strongly foliated quartzite and fine-grained actinolite schist are also recognizable. The clasts are typically angular and range in size from 0.7 mm to an unresolvable intergranular crystal hash, although much of the quartz and feldspar has a size of about 0.3 mm. Platy quartz and elongate mineral and lithic clasts are oriented and thin phyllosilicate flakes have been deformed around quartz and feldspar grains during compaction, but there is no evidence of a tectonic foliation. Low-grade metamorphism is indicated by the albitic composition of the plagioclase, the detrital epidote and actinolitic amphibole, and the foliated chert clasts where these include metamorphic actinolitic amphibole. The zircons extracted from this sample have a wide range of morphologies. Most grains are euhedral with rounded and abraded terminations, between $150 \times 200\ \mu m$ but ranging up to $250 \times 350\ \mu m$, and are light yellow-brown to pink-brown in color. Equant, structureless grains are also present.

Forty-one analyses were obtained from 35 zircons. Results are shown on concordia and Gaussian Summation probability density plots in Fig. 6. The analyses are concordant or slightly discordant, with the discordance pattern consistent with a single recent episode of radiogenic-Pb loss. On the basis of their $^{207}Pb/^{206}Pb$ ratios, most analyses may be assigned to five groups. Group 1 consists of 19 analyses of 14 zircons (1.1, 4.1, 4.2, 9.1, 10.1, 17.1, 20.1, 20.2, 21.1, 22.1, 23.1, 25.1, 25.2, 27.1, 27.2, 30.1, 30.2, 32.1, 33.1, 34.1 and 35.1) which have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 0.94) and indicating a weighted mean date of 2664 ± 5 Ma. Analysis 22.1 indicates a slightly younger $^{207}Pb/^{206}Pb$ date of 2637 ±10 Ma ($\pm 1\sigma$ error), but this analysis is highly discordant. Many of the zircons of Group 1 have rounded terminations and pitted surfaces (see, for example, grain 20 shown in Fig. 3A and B) and have clearly undergone detrital transport. The date indicated by the analyses of Group 1 is therefore interpreted as providing a maximum age for deposition of the host sediment. Group 2, consisting of analyses 12.1, 19.1 and 35.1, have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 0.94) and indicating a weighted mean date of 2686 ± 22 Ma. Group 3, consisting of 8 analyses of 8 zircons (3.1, 6.1, 7.1, 8.1, 11.1, 24.1, 29.1 and 31.1), have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 0.21) indicating a weighted mean date of 2734 ± 8 Ma. Group 4, consisting of four analyses of 4 zircons (13.1, 14.1, 18.1 and 28.1) with $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 0.11), indicates a weighted mean date of 2829 ± 14 Ma. Group 5, consisting of 5 analyses of 4 zircons (2.1, 5.1, 16.1, 26.1 and 26.2), have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 1.49), corresponding to a weighted mean date of 2937 ± 19 Ma.

As might be anticipated from the texturally and compositionally immature nature of the sample, the detrital zircons within the Kaluweerie Conglomerate sample have a limited provenance range that closely matches that of the known local geology. Apart from analysis 15.1, which indicates a date of ca. 2779 Ma, and the analyses of Group 4, which indicate a date of 2829 ± 14 Ma, all of the remaining detrital zircons analyzed provide dates that can be matched with those obtained for monzogranitic rocks in the region. A maximum depositional age of 2664 ± 5 Ma for the Kaluweerie Conglomerate is provided by the nineteen analyses of Group 1. If the Kaluweerie Conglomerate is a correlative of the other lithologically similar polymict conglomerate units within the upper parts of the greenstone sequences, such as those at Yilgangi, deposition of these conglomerates is constrained to between 2669 Ma, based on the maximum age of 2664 ± 5 Ma for the Kaluweerie Conglomerate, and 2557 Ma, from the minimum age of 2662 ± 5 Ma provided by the monzodiorite dyke at Yilgangi. The absence of any detrital zircons of Proterozoic age is consistent with deposition of the Kaluweerie Conglomerate shortly after cessation of greenstone volcanism. However, a restricted provenance has been inferred for the conglomerate, based on the lithologies of the clasts. The detrital zircons represented within the Kaluweerie Conglomerate sample also indicate a limited provenance range, so the absence of Proterozoic detrital zircons may be due to the absence of source rocks of this age within the restricted provenance area sampled by the conglomerate.

The results obtained from the Kaluweerie Conglomerate emphasize the importance of ensuring that the widest possible provenance range is represented within the detrital zircon populations if maximum age determinations based on dating of detrital zircons are to be close to the time of deposition of the host sedimentary rock. As discussed earlier, in the absence of an understanding of the history of magmatism within the provenance area at the time of sediment deposition, sediment samples having a wider provenance range are preferable for maximum depositional age determinations using detrital zircons than those from a restricted provenance, due to the greater probability of the incorporation of detrital zircons having crystallization ages closer to the time of deposition. Little or no additional information on the depositional age of a sedimentary rock is provided by the analysis of detrital zircons of the same age, so costly instrument time will be wasted analyzing large numbers of detrital zircons belonging to a small number of age groups. The distribution of U–Pb analyses along the concordia curve offers a way of qualitatively assessing the provenance range and thus, the reliability of a maximum age determined by the U–Pb dating of detrital zircons. In general terms, a restricted provenance range will be indicated by ‘clumping’ of analyses into a small number of discrete age groups, as is the case for the Kaluweerie Conglomerate sample (see Fig. 6). In contrast, a scatter of analyses along the concordia curve suggests that the detrital zircons have been derived from a wide provenance range.

3.4. Allochthonous metasedimentary rocks of the Mount Barren Group

The mid-Proterozoic Albany–Fraser Orogen extends along the southern and southeastern margin of the Yilgarn Craton (Fig. 1). The orogen consists mainly of orthogneiss and granite, with large sheets and dykes of metagabbro, and scattered remnants of metasedimentary rocks. Within the orogen, four major plutonic episodes, at ca. 2630, 1700–1600 Ma, ca. 1300 and 1180 Ma, have been identified (Nelson et al., 1995). Orthogneiss derived from late Archaean and early and middle Proterozoic granitoid rocks, and metasedimentary rocks, were deformed and metamorphosed in the granulite facies at ca. 1300 Ma. Following rapid exhumation and westward transport of these gneisses along low-angle thrust faults over the southeastern margin of the Yilgarn Craton, granites were emplaced throughout the orogen between 1190 and 1100 Ma.

Sedimentary rocks within the orogen are at low to medium metamorphic grade and are inferred to have been deposited prior to the regional ca. 1300 Ma metamorphic episode, but their depositional ages and origins are unknown. Quartzites, quartz–mica schists and phyllites of the Mount Barren Group are found near Hopetoun (Fig. 1). Few studies of the metasedimentary rocks of the Mount Barren Group have been undertaken. An imprecise whole-rock Rb–Sr isochron date of 1791 ± 184 Ma was obtained by Thom et al. (1980) on pelitic schists from the Mount Barren Group, but the geological significance of this date remained unclear. Mount Barren Group sediments may have been deposited on the Yilgarn Craton, or onto Proterozoic basement rocks that occur within, but that predate, the orogen. Alternatively, as the ca. 1300 Ma deformation and metamorphism episode has been attributed to collision of the Yilgarn Craton with an ‘east Antarctic–Gawler’ continent (Nelson et al., 1995), sediments of the Mount Barren Group may have been deposited along the margins of either continent, or possibly on an east Antarctic–Gawler continent, prior to the collision event. In order to investigate the depositional ages and provenance of these metasedimentary rocks, detrital zircons from two samples of Kundip Quartzite (Witt, 1997) of the Mount Barren Group were analyzed.

Sample 112168, from a site near No Tree Hill (Ravensthorpe SI 51-5 1:250,000 map sheet, AMG 51 228200E 6259100N; see Fig. 1), consists of fine-grained (0.1–0.2 mm) angular grains of quartz with accessory tourmaline, opaque minerals, biotite, rutile, and zircon, cemented by minor sericite. It has undergone low or medium grade metamorphism. Most zircons are 100–200 μm long, light yellow-brown, rounded and pitted, and clearly detrital in origin. A few are elongate (≥250 μm), thin and needle-like, but the terminations of these are also rounded and pitted (see Fig. 3C and D), and these grains are also inferred to be of detrital origin. Cores and rims were not discernible in any of the grains examined.

Twenty-one analyses were obtained from 21 zircons. Results are shown on a concordia plot in Fig. 7A. Apart from discordant analysis 18.1, the remaining analyses are concordant or slightly discordant and indicate $^{207}Pb/^{206}Pb$ dates of from ca. 1917 to 2730 Ma. The youngest $^{207}Pb/^{206}Pb$ date of

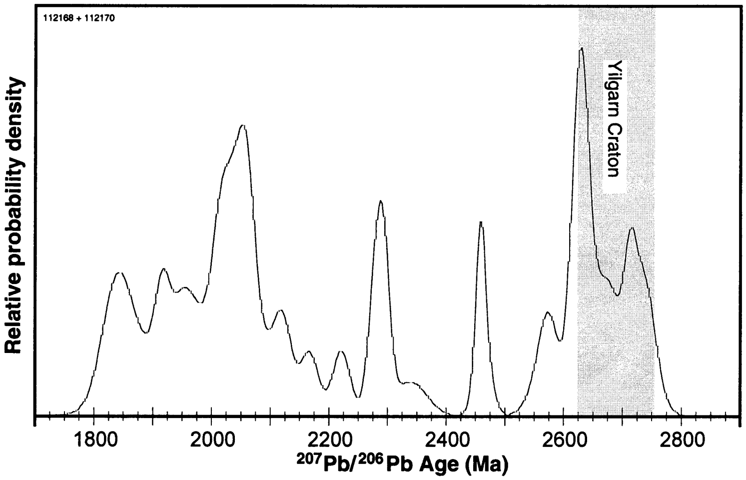


Fig. 8. Gaussian Summation probability density plot of $^{207}Pb/^{206}Pb$ dates obtained from detrital zircons within Mount Barren Group metasandstone samples 112168, No Tree Hill and 112170, Barrens Beach.

1917 ± 13 Ma (±1σ error), indicated by analysis 10.1 on a clear and internally structureless, irregular fragment that is of detrital origin (see Fig. 3C and D), provides a maximum deposition age for the host sandstone. Measured $^{207}Pb/^{206}Pb$ ratios of three analyses (4.1, 15.1, and 20.1) define a single population with little excess scatter (chi-squared = 1.24) indicating a weighted mean date of 2726 ± 44 Ma.

Sample 112170 was collected from a scree slope on the west side of Barrens Beach (Ravensthorpe SI 51-5 1:250,000 map sheet, AMG 51 225300E 6242100N; see Fig. 1). It consists of a coarse-grained, slightly oriented mosaic of quartz, with accessory, strongly oriented small flakes of muscovite, and rare tourmaline. The precursor was a coarse grained sandstone, but the rock has undergone low-grade metamorphism and sedimentary textures are not preserved. Most zircons within this sample are between 100 and 600 μm long, ovoid in shape, rounded and pitted, and clearly detrital in origin. Cores and rims cannot be distinguished in any of the grains examined.

Twenty-one analyses were obtained from 21 zircons. Results are shown on a concordia plot in Fig. 7B. All analyses are concordant or near-concordant, and indicate $^{207}Pb/^{206}Pb$ dates between ca. 1830 and 2700 Ma. On the basis of their $^{207}Pb/^{206}Pb$ ratios, many analyses may be assigned to two main groups. Group 1 contains six analyses (1.1, 3.1, 7.1, 9.1, 10.1, and 17.1) that have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 0.64) and indicating a weighted mean date of 1851 ± 30 Ma. This population, on zircons of detrital origin (see, for example, grains 7 and 10 shown in Fig. 3E–H), provides a maximum age for deposition of the sandstone precursor. Measured $^{207}Pb/^{206}Pb$ ratios of a further seven analyses (2.1, 5.1, 6.1, 12.1, 14.1, 18.1, and 21.1), assigned to Group 2, define a single population (chi-squared = 0.84) indicating a weighted mean date of 2634 ± 14 Ma.

For the fine-grained sandstone at No Tree Hill (112168), an analysis on a single clear, irregular zircon fragment of detrital origin (Fig. 3C and D) provides a maximum deposition age for the sandstone of 1917 ± 13 Ma (±1σ error). For the metasandstone from Barrens Beach (112170), six analyses of six detrital zircons provide a maximum deposition age of 1851 ± 30 Ma. The metasedimentary rocks of the Mount Barren Group were therefore deposited later than ca. 1930 Ma. Zircons derived from the 1700 to 1160 Ma orthogneisses and granitic rocks of the Albany–Fraser Orogen (Nelson et al., 1995) were not identified in either metasedimentary rock sample, consistent with the deposition of the Mount Barren Group metasedimentary rocks prior to the time of the Albany–Fraser Orogen at ca. 1300 Ma.

A Gaussian Summation probability density plot for analyses obtained from both Mount Barren Group samples is shown in Fig. 8. The Archaean dates can be matched with dates obtained for components within the Yilgarn Craton, but the provenance of the Proterozoic detrital zircons does not closely match the known dates of rocks of the Albany–Fraser Orogen, or of any other region within southwestern Australia. Possible late Archaean to middle Proterozoic source regions for the detrital zircons include the Gawler Craton, basement presently buried beneath the Eucla Basin northeast of Israelite Bay, or east Antarctica.

The rounded and highly pitted, internally structureless, low-U detrital zircons extracted from the two metasandstone samples from the Mount Barren Group have a range of ages that scatter along the concordia curve, rather than clustering in a low number of discrete age groups (Fig. 7), characteristics that suggest these zircons were derived from a wide provenance range. These mature coarse, quartz-rich lithologies are therefore well suited for maximum depositional age determinations by this approach. Additional ion-microprobe analytical work on the detrital zircons from these two samples is likely to identify further young detrital zircons and may decrease their maximum possible depositional ages. These and the contrasting results obtained for the Kaluweerie Conglomerate also emphasize that those lithologies giving the best maximum depositional age results are not necessarily ideally suited for provenance investigations. Whereas lithologies having a wider provenance range are better suited for maximum depositional age determinations, it is commonly difficult to match such wide provenance ranges with the regional geology of potential source regions.

This case study is preliminary and limited in scope, and further analytical work on the detrital zircons within metasedimentary rocks of the Mount Barren Group may enable the maximum depositional age determinations for these metasedimentary rocks to be lowered and their provenance regions to be identified.

3.5. Neoproterozoic diamictite of the Officer Basin

The Officer Basin covers an area of 375,000 km^2 of the southwestern part of central Australia. The basin contains up to 7 km of siliciclastic, evaporitic, carbonate, aeolian and glacigene sedimentary rocks and volumetrically minor basaltic rocks, which range in age from Neoproterozoic to Cretaceous (Iasky, 1990). It forms part of the more extensive Centralian Superbasin, which covers much of the central part of the Australian continent (Walter et al., 1995). In order to investigate the suitability of glacial sedimentary rocks for detrital zircon maximum age determinations and to examine the provenance of the rocks of the basin, detrital zircons isolated from a diamictite of the Officer Basin have been investigated.

A sample (154109) of diamictite was taken from 457.5 m depth of GSWA stratigraphic drillhole Empress 1A (Westwood SG 51-16 1:250,000 map sheet, 125°09′24″E 27°03′13″S; see Fig. 1). K–Ar dates of 1058 ± 26 and 484 ± 8 Ma ($\pm 2\sigma$ errors) have been obtained on basalt flows at 1602 and 216 m depth, respectively, from Empress 1A (Nelson, 1999). Although interpreted as minimum ages for the basalts, these dates are considered to provide reliable upper and lower age constraints for the time of deposition of the diamictite unit under investigation. Sample 154109 is a poorly-sorted, quartz–microcline-carbonate diamictite with a ferruginous, micritic carbonate matrix. It was taken from near the base of a 170 m thick diamictite, mudstone and sandstone unit that has been correlated with similar lithologies within the Lupton Formation of the Officer Basin (Grey et al., 1999). The sample consists of angular to moderately rounded clasts set in a matrix dominantly of ferruginous carbonate. The clasts are mainly of quartz, but other clast types include tourmaline, chert, carbonated chert, micritic carbonate clasts encrusted with crystalline carbonate, quartz clasts encrusted with carbonate, opaque material intergrown with euhedral grains that have apparently been replaced with chlorite or serpentine, grains solely composed of material with low birefringence such as chlorite or serpentine, and rare clear grains with strong positive relief that may be garnet. Microcline and micritic carbonate constitute 1 vol.% of the sand fraction. The prominence of carbonate among the clasts suggests that some of the groundmass carbonate may also be primary, rather than a late replacement of clay. The rock is interpreted to be a product of glacial abrasion of a dominantly carbonate terrain, with the glacial flour and some of the clasts derived from the carbonate. The zircons isolated from this sample are commonly colorless to light yellow-brown, between 100 × 150 and 250 × 350 μm in size and are generally internally structureless or weakly zoned. Most are rounded and have pitted and abraded surfaces, consistent with

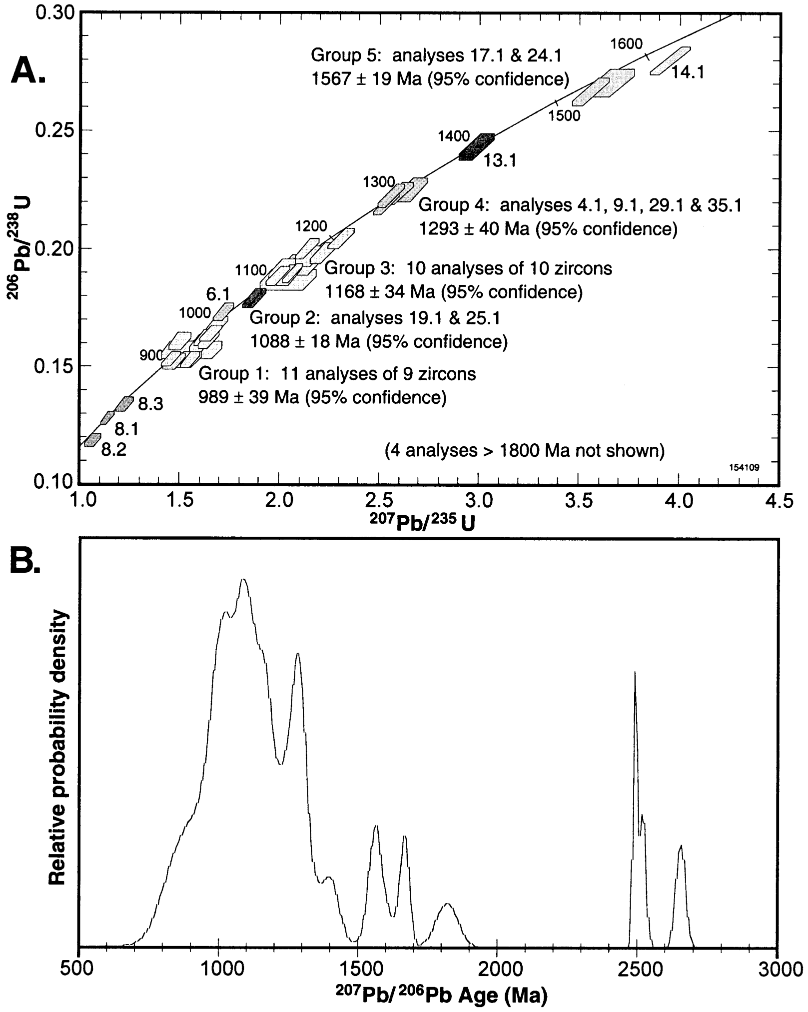


Fig. 9. (A) Concordia plot for analyses obtained for detrital zircons within sample 154109: quartz-carbonate diamictite from the Officer Basin. Full analytical data are given in Nelson (1999). (B) Gaussian Summation probability density plot of ^{207}Pb/^{206}Pb dates obtained from detrital zircons within 154109: quartz-carbonate diamictite from the Officer Basin.

detrital transport. Many contain mineral or fluid inclusions.

Thirty-nine analyses were obtained from 35 zircons. Results are shown on concordia and Gaussian Summation probability density plots in Fig. 9. Most analyses are concordant and many may be assigned to five groups on the basis of their ^{207}Pb/^{206}Pb ratios. Eleven analyses of 9 zircons (3.1, 5.1, 7.1, 7.2, 10.1, 15.1, 21.1, 23.1, 23.2, 26.1 and 28.1), assigned to Group 1, have ^{207}Pb/^{206}Pb ratios defining a single population (chi-squared = 1.39) and indicating a weighted mean date of 989 ± 39 Ma. The weighted mean ^{206}Pb/^{238}U date indicated by this group is 947 ± 24 Ma, but a high chi-squared value of 2.08 suggests that there is scatter beyond that anticipated from analytical uncertainty, attributed to recent redistribution of radiogenic Pb within the analysis sites. Analyses 19.1 and 25.1, assigned to Group 2, have ^{207}Pb/^{206}Pb ratios defining a single population and indicating a weighted mean date of 1088 ± 18 Ma. Ten analyses of 10 zircons (1.1, 2.1, 12.1, 18.1, 22.1, 27.1, 30.1, 31.1, 32.1 and 34.1), assigned to Group 3, have ^{207}Pb/^{206}Pb ratios defining a single population (chi-squared = 1.81) and indicating a weighted mean date of 1168 ± 34 Ma. Analyses 4.1, 9.1, 29.1 and 35.1, assigned to Group 4, have $^{207}Pb/^{206}Pb$ ratios defining a single population (chi-squared = 0.42) and indicating a weighted mean date of 1293 ± 40 Ma. Nine analyses (6.1, 11.1, 13.1, 14.1, 16.1, 17.1, 20.1, 24.1 and 33.1) do not define discrete groups.

Grain 8 is a 100×50 μm, clear, structureless and elliptical grain that has an extensively pitted surface (see Fig. 3I and J), consistent with detrital transport. This grain may have been incorporated into the diamictite following glacial erosion of a host clastic sedimentary rock. Three analyses (8.1, 8.2 and 8.3) were obtained on this grain. All three analyses have $^{207}Pb/^{206}Pb$ ratios define a single population (chi-squared = 0.33) and indicating an imprecise weighted mean date of 788 ± 110 Ma. The discordance pattern of these three analyses is consistent with some recent loss of radiogenic Pb from the site of analysis 8.2. The latter analysis was undertaken on a site that included a prominent fracture (evident in Fig. 3I). Following deletion of analysis 8.2, a weighted mean $^{206}Pb/^{238}U$ date of 791 ± 18 Ma is indicated by the pooling of analyses 8.1 and 8.3.

The weighted mean $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ dates obtained on grain 8 are interpreted as providing maximum possible times for deposition of the host diamictite. The remaining analyses are interpreted to be of detrital grains, with the age groups consistent largely with an origin from either the Musgrave Complex, located to the east and north-east, or from the Albany–Fraser Orogen located to the south of the site of the Empress 1A drillhole.

4. Discussion

4.1. Strengths and limitations of the detrital zircon approach

The case studies documented above demonstrate some of the strengths and limitations of the determination of the maximum time of deposition and provenance of sedimentary rocks by the U–Pb dating of detrital zircons. In most of the instances described (the exception being sample 154109, the diamictite from the Officer Basin), the sedimentary rock samples investigated are from unfossiliferous clastic sedimentary sequences with poorly constrained stratigraphic relations and that lack interbedded volcanic or intrusive rocks suitable for radiometric dating. Maximum depositional dates obtained from the analysis of detrital zircon populations therefore offer the only means available of constraining the timing of deposition of these sequences. As most clastic sedimentary rocks contain detrital zircons, the approach is particularly useful in instances where an absence of suitable lithologies rules out the use of other methods. This probably applies for a substantial proportion of Archaean, Palaeoproterozoic and Mesoproterozoic intracratonic sedimentary basins whose formation was unrelated to greenstone-belt volcanism.

The case studies also emphasize that most of the ion-microprobe analysis time is devoted to the identification of the youngest grain or grains within the detrital zircon population. Once identified, the geological significance of the dates obtained on the youngest grain or grains must be understood before the date can be confidently interpreted as corresponding to a maximum depositional age. This will commonly involve detailed microstructural investigation of the individual grain or grains, to ensure that each grain has morphological features consistent with a detrital transport cycle and that the date obtained predates the time that each grain underwent this detrital transport. The problem therefore then reduces to correct interpretation of the life histories of individual zircon grains. Although detrital zircons may consist of older cores and younger overgrowths, dates obtained on such cores or rims, or even on parts of both of these, will still be older than the time of detrital transport provided that the outer surfaces of the grains show evidence of such transport. Such internal complexity does not compromise the integrity of the technique, and detailed cathodoluminescence or back-scattered electron investigations of the internal microstructures of the detrital zircons are generally not required. Provided there has been no sample contamination or post-crystallization disturbance, a U–Pb date corresponding to the time of igneous crystallization of a detrital zircon, or of part of the grain, will provide a maximum time for host sediment deposition. The analytical precision of the maximum depositional date may be improved by the pooling of multiple analyses obtained on the youngest grain or grains (see for example, the results obtained herein for samples 142986 and 154109).

Two main limitations of this approach are evident from the documented case studies. One limitation is that a maximum depositional age based on dates obtained from the youngest zircon or zircons identified may still be substantially older than the time of sediment deposition. To minimise this possibility it is essential that the detrital zircons within the sedimentary rock sample have a wide range of different ages. For clastic sedimentary rocks, petrographic examination to assess the textural and compositional maturity of the sample offers a first-order means of assessing the suitability of sediment samples for dating by analysis of their detrital zircon populations. Analysis of detrital zircons from texturally immature clastic sedimentary rocks may result in the identification of a low number of discrete age groups, each having a high frequency within the detrital zircon population (for example, the locally-derived and texturally immature Kaluweerie Conglomerate), whereas there is a greater likelihood of generating analyses that scatter along the concordia by analysis of texturally and compositionally mature sedimentary rock samples (for example, the dispersed analyses of the highly mature Mount Barren Group samples). However, a wide provenance range was also represented by the detrital zircons from the texturally and compositionally immature Officer Basin diamictite, probably because the detrital zircons within the diamictite were derived largely by the glacial erosion of mature clastic sedimentary rocks. Examination of the morphologies of the detrital zircons for evidence of prolonged detrital abrasion offers a more reliable, if less convenient, means of assessing the likelihood of a wide provenance range being represented, than the composition and texture of the host sedimentary rock. The distribution of U–Pb analyses along the concordia provides a means of assessing the reliability of a maximum age determined by the U–Pb dating of detrital zircons. Lower confidence can be placed in a maximum depositional age if the analyses clump into a small number of discrete age groups than for cases where the analyses scatter along the concordia. Although sufficient analyses to determine the age distribution of the zircon population must be obtained, costly instrument time will be wasted if most of the analyses fall into a small number of discrete age groups, and the success of the approach is more critically dependent on the provenance range of the detrital zircons within the sample than on the number of analyses obtained. It is also apparent from the case studies that lithologies which are better suited for maximum depositional age determinations are not necessarily ideally suited to provenance studies, due to the difficulties in matching wide provenance ranges to particular source areas.

A second limitation evident from the case studies arises from the effects of post-depositional redistribution of radiogenic Pb within individual zircon grains. It is conceivable that, due to ancient radiogenic-Pb loss, a concordant ion-microprobe date on a zircon grain may be younger than the time of its detrital transport and incorporation into the host sediment. It is, however, highly improbable that analyses of different sites within the same grain that have undergone ancient radiogenic-Pb loss will show the same proportion of such loss and give analytically indistinguishable $^{207}Pb/^{206}Pb$ dates, unless the grain has completely recrystallized. Complete recrystallization of zircon is unlikely to occur unless the host sedimentary rock has undergone relatively high-grade metamorphism. Therefore, in order to minimize the possible effects of post-depositional radiogenic-Pb redistribution, sedimentary rocks samples investigated using the detrital zircon approach should be at relatively low metamorphic grade, and multiple and concordant analyses should be obtained on each of the youngest grain or grains wherever this is possible.

5. Summary

The range of techniques available for the determination of depositional ages for sedimentary rocks of the largely unfossiliferous sedimentary basins of the Archaean and Early Proterozoic is limited. A new approach, using ion-microprobe U–Pb analysis of detrital zircons, has been documented herein. The strengths and limitations of this approach have been illustrated by case studies of sedimentary rocks from Archaean and Proterozoic basins of Australia. The method requires only that sedimentary lithologies free of veins and melt patches and that have undergone only low grade metamorphism are available for sampling, and that sample processing be undertaken with no possibility of contamination by foreign zircons. Although sufficient analyses to establish the age distribution of the detrital zircon population must be obtained, the success of this approach is critically dependent on the provenance range of the sample. As detrital zircons from coarse-grained, highly mature, siliceous lithologies deposited in high-energy environments will typically be derived from a large sampling area, there is a greater probability of the incorporation and detection of detrital zircons from source regions closer in age to the depositional age of the sediment. Furthermore, the detrital zircons from such lithologies are typically large, clear and internally structureless, are commonly well rounded, with pitted and abraded surfaces and thus are readily identifiable as detrital in origin, and have generally low U contents. Their size, lack of internal structural complexity and low U contents facilitates the acquisition of reliable and concordant U–Pb dates. The effects of post-depositional redistribution of radiogenic Pb within individual zircon grains may be assessed by obtaining multiple analyses on the youngest detrital grain or grains. Analysis of detrital zircons from a series of samples which have well-understood stratigraphic relationships will enable comparison of maximum depositional ages based on analyses of the detrital zircon populations with those anticipated from the stratigraphic order of the samples. It is envisaged that this approach to the determination of the depositional ages of sedimentary rocks will find wide applicability within many Archaean and Proterozoic sedimentary basins.

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