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U–Pb ages and source composition by Hf-isotope and trace-element analysis of detrital zircons in Permian sandstone and modern sand from southwestern Australia and a review of the paleogeographical and denudational history of the Yilgarn Craton☆

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Abstract

Detrital zircons from the Permian Collie Coal Measures and modern sands on the northern part of the Albany Province have been analysed for U–Pb ages by a laser ablation microprobe-inductively coupled plasma mass spectrometer (LAM-ICPMS) and for Hf-isotope compositions by a laser ablation microprobe multi-collector inductively coupled plasma mass spectrometer (LAM-MC-ICPMS). Trace elements were determined by analysis on the electron microprobe (EMP) and the ICPMS's. This combination of techniques makes it possible to determine for each grain not only the age but the nature and source of the host magma, whether crustal or juvenile mantle, and a model age (T_{DM}) based on a depleted-mantle source, which gives a minimum age for the source material of the magma from which the zircon crystallised. The integrated analysis, applied to suites of detrital zircon, gives a more distinctive, and more easily interpreted, picture of crustal evolution in the provenance area than age data alone. Zircons from Permian and Triassic sediments already analysed for U–Pb ages by a sensitive high-resolution ion microprobe (SHRIMP) were also analysed for Hf isotopes and trace elements.

Zircons from Collie and Permian and Early Triassic rocks of the northern Perth Basin have an age spectrum with a peak at about 1200 Ma that can be traced to the Albany Province. Differences, however, in Hf-isotope composition indicate that the Collie Coal Measures and the northern Perth Basin sandstones were not derived from the northern part of the Albany Province or from the coastal strip of felsic granitoids. The Perth Basin samples have a second peak age of 600–500 Ma that can be traced to the Leeuwin Block. One of the modern sands has a major peak at 2616 Ma that can be traced to the Yilgarn Craton.

Compiled with previously published U–Pb zircon age spectra, the analyses provide insights into the paleogeographical history. The Yilgarn Craton sloped from the north at 1700 Ma, from the southeast at 1350–1140 and 490 Ma, its eastern part to the east at 300 Ma, and the southern part to the northwest from the Albany Province at 300–255 Ma. Denudational data from apatite fission-track analysis and vitrinite-reflectance studies suggest that the Yilgarn Craton was covered by a ~5-km-thick blanket of Permian and Mesozoic sedimentary rock that was almost entirely removed by the Cenozoic, possibly because the craton was situated between the shoulders of rift systems that grew into the eastern and southeastern Indian Ocean.

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Ordovician, Permian, Early Triassic, and Quaternary sediment of the Perth Basin came from Proterozoic orogens. Only the Late Permian sample contains significant populations of Archean (Yilgarn) zircons but whether they came direct from the craton or were recycled from the postulated sedimentary cover is not known. The increased influx of sediment during the Jurassic matched by a peak in the denudation rate would seem to require a primary supply from the craton. This question could be resolved by dating zircon from the rapidly accumulated Jurassic formations.

Keywords: Australia; Yilgarn Craton; Perth Basin; U–Pb ages; Hf-isotopes; Permian sandstone; Modern sand; Source composition; Detrital zircons; Paleogeographical and denudational history

1. Introduction

Detailed geochronology, especially the U–Pb dating of single zircon grains using SHRIMP ion microprobes, has been essential to paleogeographical reconstructions and an understanding of the tectonic history of Australia and its neighbours in Gondwanaland (Veevers, 2000). Recently published data on zircon age populations from modern strandline deposits (Sircombe and Freeman, 1999) and Permian and Triassic sandstones of the the Perth Basin (Cawood and Nemchin, 2000) indicate that only a few zircons were derived from the neighbouring Archean Yilgarn Craton. This matches the present state whereby the craton supplies zircons to the southern coastal drainage (Cawood et al., 2003) but only a few Archean grains reach the west coast (Sircombe and Freeman, 1999).

However, age data alone give a one-dimensional picture of provenance, and cannot distinguish between two provenances of similar age but different geological history. Recent developments in microanalytical technology now make it possible to obtain U–Pb ages, trace-element data, and Hf-isotope measurements from single grains of zircon (Knudsen et al., 2001; Belousova et al., 2001, 2002; Griffin et al., 2000, 2002). This combination of techniques makes it possible to determine for each grain not only the age but the nature and source of the host magma, whether crustal or juvenile mantle, and model age (T_{DM}). The integrated analysis, applied to suites of detrital zircon, gives a more distinctive, and more easily interpreted, picture of crustal evolution in the provenance area than age data alone. We apply these techniques to zircons from Permian and Triassic sandstones, including three dated samples from the Perth Basin (Cawood and Nemchin, 2000), and modern sands from southwestern Australia (Figs. 1–3).

After comparing these and other detrital spectra with those of potential provenances (Figs. 4–6), we integrate the chronological and sedimentological data in maps of southwestern Australia from 1700 Ma to the present (Figs. 7 and 8), and finally focus on the denudational history of the Yilgarn Craton (Fig. 9).

T_{DM} model ages are expressed in Ga (e.g., 2.0–1.8 Ga), and signify the level of precision. U–Pb zircon ages are given in Ma (e.g., 1068 Ma) except where space considerations, as in some figures, require abbreviation (e.g., 1.07 Ga).

The analytical data are available in archived data tables (Tables A–K; Background Online Dataset[1]).

2. New analyses of zircons from the Permian Collie Coal Measures and modern sands on the Albany province

2.1. Methods

Zircon separates were prepared from crushed samples and alluvial sediments using standard techniques. Zircon grains were picked under the binocular microscope (with UV light attachment), mounted in epoxy blocks, and polished for further analysis. The selection of grains was designed to include all visually recognised populations in approximate proportion to their abundance in the sample, without attempting a statistically representative selection. It is our view that such "statistical representation" is unlikely to be geologically meaningful in any case, given the wide abundance of zircon in different rocks, coupled with the vagaries of transport survival.

[1] See the online version of this article.

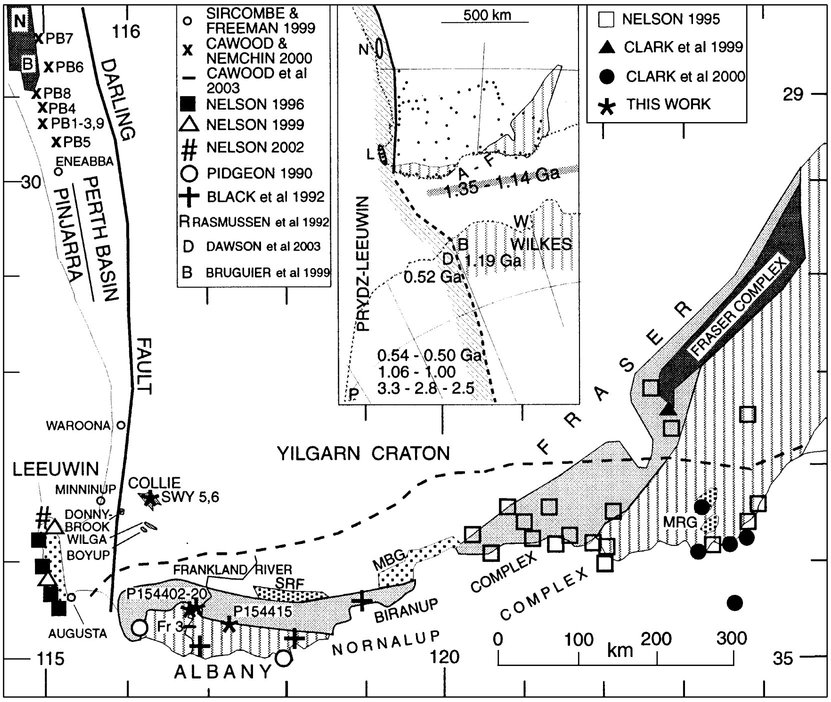


Fig. 1. Southwestern Australia, showing location of dated sediment samples (keyed to source publications), including those dated here (*) from the Permian Collie Basin and modern sands (two: P154402-20, pooled from samples 9 km apart, and P154415), and of the surrounding Proterozoic Albany-Fraser Orogen, comprising the Biranup, Fraser, and Nornalup Complexes and the adjoining Stirling Range Formation and Mount Barren Group, and the Pinjarra Orogen, including the Leeuwin and Northampton Blocks. Fr3 is sand from the lower reaches of the Frankland River. Geology after Dawson et al. (2003). The broken line is the divide between the modern southern external drainage and the internal, largely uncoordinated drainage, much of it inherited from past ages (Hocking and Cockbain, 1990; Morgan, 1993; Freeman, 2001). MBG = Mount Barren Group; MRG = Mount Ragged Group; NB = Northampton Block; SRF = Stirling Range Formation. *Inset:* regional context before extension and breakup in the Mesozoic, from Veevers (2000, Fig. 304), with additions from Fitzsimons (2003), in particular the common (1.35–1.14 Ga) age of the Wilkes Province and the Albany-Fraser Orogen, and location (dots) of southwestern Australian samples for apatite fission-track analysis (AFTA) (Kohn et al., 2002). A-F = Albany-Fraser Orogen; B = Bunger Hills; D = Denman Glacier; L = Leeuwin Block; N = Northampton Block; P = Prydz Bay; W = Windmill Islands.

Following Sircombe (1999) and Cawood and Nemchin (2000), we aimed to analyse at least 50–60 grains of zircon from each sample; analysis of 60 grains provides a 95% probability of finding a population comprising 5% of the total (Dodson et al., 1988). In our case, the attempt to include all recognisable populations would improve the probability that such minor populations have been included. Internal structure (inherited cores, resorption events, metamorphic rims) was revealed by cathodoluminescence (CL) microscopy and back-scattered electron (BSE) imaging on the electron microprobe (EMP). The electron microprobe was also used for precise analysis of Hf and Y in individual grains. The Hf data allow Yb/Hf and Lu/Hf ratios collected during Hf isotope analysis (see below) to be converted to concentrations. These elements, together with U and Th data collected during the U–Pb analysis, provide discriminants that can be used to recognise broad categories of magmatic rocks from which the zircons crystallised. The viability of such discriminants has been debated (Hoskin and Ireland, 2000) but has been demonstrated by statistical analysis of larger databases; see discussion by Belousova et al. (2002).

U–Pb analysis was carried out using a New Wave Research 213 nm laser-ablation microprobe (LAM) attached to a Hewlett Packard 4500 inductively coupled plasma mass spectrometer (LAM-ICPMS). A well-characterised zircon standard (GEMOC GJ-1; 608 Ma with near-concordant Pb) is ablated under

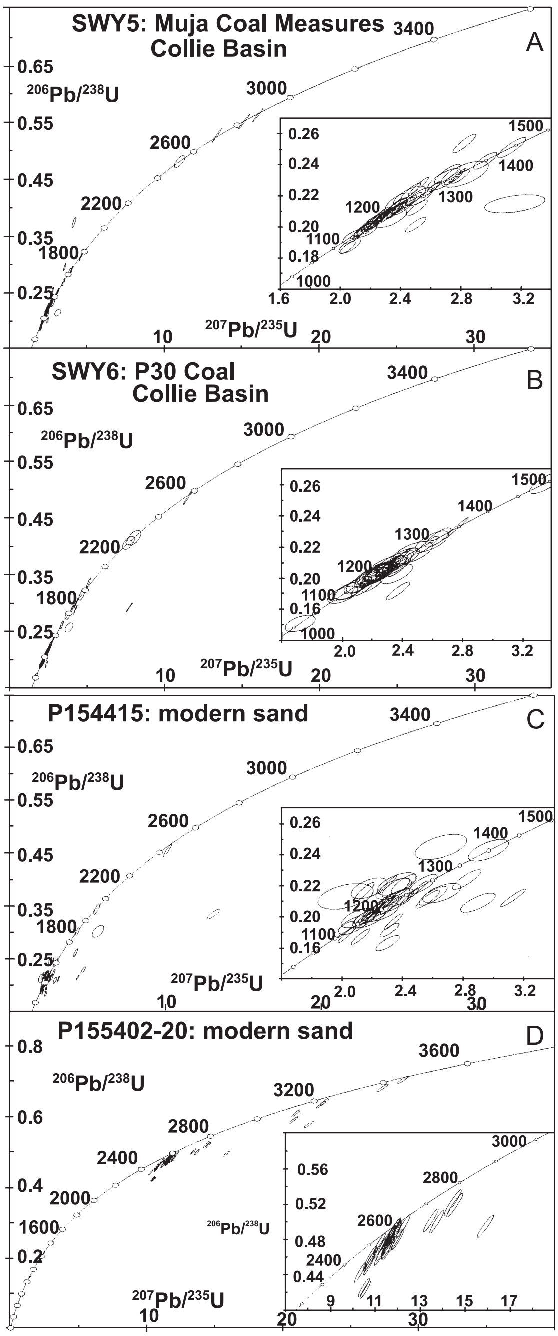


Fig. 2. Concordia diagrams for the analysed samples.

the same conditions. Spatial resolution is 30–40 μm. This method gives U–Pb ages with precision (1% or less) comparable to those of ion-probe data; accuracy has been demonstrated by repeated analyses of standard zircons from several sources (Belousova et al., 2001; Andersen et al., in press; Jackson et al., in press). Comparison of count rates between sample and standard also yields concentration values for U and Th. We have used the more precise $^{206}Pb/^{238}U$ ages for grains with $^{207}Pb/^{206}Pb$ ages < 1000 Ma, and $^{207}Pb/^{206}Pb$ ages for older grains. Because most grains were concordant as analysed, no common-lead corrections have been applied (e.g., Andersen, 2002). We have discarded grains that are discordant by more than 20% (i.e., where the $^{206}Pb/^{238}U$ age is less than 80% of the $^{207}Pb/^{206}$ Pb age). This cutoff is more generous than is typically applied in dating individual rock samples. However, in the study of detrital samples, where one aim is to pick up small populations, the exclusion of mildly discordant grains risks the loss of information on the age structure of the sample. Some reversely discordant grains with unusually low $^{208}Pb/^{232}Th$ ages imply multistage disturbance of the U–Pb systematics and also have been discarded. The age spectra described in the text have been deconvoluted using an in-house program that models the data as a series of Gaussian distributions; the associated uncertainties are given as the full width half maximum of each peak.

In-situ Hf-isotope analyses were carried out by a New Wave Research 213 nm LAM attached to a Nu Plasma multicollector (MC) inductively coupled plasma mass spectrometer (ICPMS); techniques are described by Griffin et al. (2000, 2002). Interferences of ^{176}Yb and ^{176}Lu on ^{176}Hf are corrected using $^{176}Yb/^{172}Yb$ and $^{176}Lu/^{175}Lu$ ratios determined by analysis of mixed Yb–Hf and Lu–Hf solutions. The technique provides individual analyses of spots 50–80 μm across with precision and accuracy equivalent to conventional mass-spectrometric analysis of zircon composites.

For the calculation of ε_{Hf} values, which give the difference between the sample and a chondritic reservoir in parts/10^4, we have adopted the chondritic values of Blichert-Toft et al. (1997). To calculate model ages (T_{DM}) based on a depleted-mantle source, we have adopted a model with $(^{176}Hf/^{177}Hf)_i = 0.279718$ and $^{176}Lu/^{177}Hf = 0.0384$ to produce a value of $^{176}Hf/^{177}Hf$ (0.28325) similar to that of average MORB over 4.56 Ga. There are currently three proposed values of the decay constant for ^{176}Lu. ε_{Hf} values and model ages used in the figures were calculated using the value 1.93×10^{-11} year^{-1} proposed by Blichert-Toft et al. (1997); values for ε_{Hf} and model ages calculated using this value lie between other proposed values of the decay constant (1.865×10^{-11} year^{-1}, Scherer et al., 2001; 1.983×10^{-11} year^{-1}, Bizzarro et al., 2003).

T_{DM} model ages, which are calculated using the measured $^{176}Lu/^{177}Hf$ of the zircon, can only give a minimum age for the source material of the magma from which the zircon crystallised. Therefore we also have calculated, for each zircon, a "crustal" model age (T_{DM}^{C}) which assumes that its parental magma was produced from an average continental crust ($^{176}Lu/^{177}Hf = 0.015$) that originally was derived from the depleted mantle. Nd model ages recalculated relative to a depleted mantle (T_{DM}), and interpreted as the age of extraction of crustal material from the mantle, are given for Proterozoic rocks by Fitzsimons (2003), and for the Archean Yilgarn Craton by Fletcher et al. (1994) augmented by Nd data from the Eastern Goldfields (Champion and Sheraton, 1997) and Hf-isotope data from the northern Yilgarn Craton (Griffin et al., 2004).

The analytical data for our samples are given in Tables A–H and new data for Cawood and Nemchin's zircons from the Perth Basin in Tables I–K of the Background Online Dataset.

2.2. Sample description and data

Fig. 1 shows the location of samples from the potential proximal provenances and the sedimentary samples from southwestern Australia, including those from Collie and the Albany Province analysed here. Altogether, 227 grains were analysed from four samples: two from the Permian Collie Basin and two sands (P154402-20, pooled from samples 9 km apart, and P154415) from modern surface sands on the Albany Province.

2.3. Collie Coal Measures

The remnant Collie Basin of Permian sediment nonconformably overlies and is downfaulted into the Yilgarn Craton. The total sedimentary thickness of 1350 m comprises 330 m of a basal tillite and overlying bluish-grey shale (Stockton Formation), and a 1120-m-thick succession of 5- to 15-m-thick cycles of sandstone, siltstone, claystone, and coal (Collie Coal Measures)(Wilson, 1990).

Samples come from the Collie Coal Measures (Table 1). SWY-5 is a subarkosic grit between the Galatea and Hebe Coals, at the base of the *Protohaploxypinus rugatus* zone in the ?Kungurian-Ufimian (Le Blanc Smith, 1993), calibrated as 260 Ma (Veevers, 2000). SWY-6 is another subarkosic grit within the P-30 coal, also known as the Unicorn Seam or Premier No. 3, in the lower part of the Premier Coal Measures, in the lower part of the *Microbaculispora villosa* zone (Le Blanc Smith, 1993), equivalent to Upper Stage 4b of eastern Australia, in turn equivalent to the Baigendzinian Sub-Stage of the Artinskian Stage, or 275 Ma (Veevers, 2000).

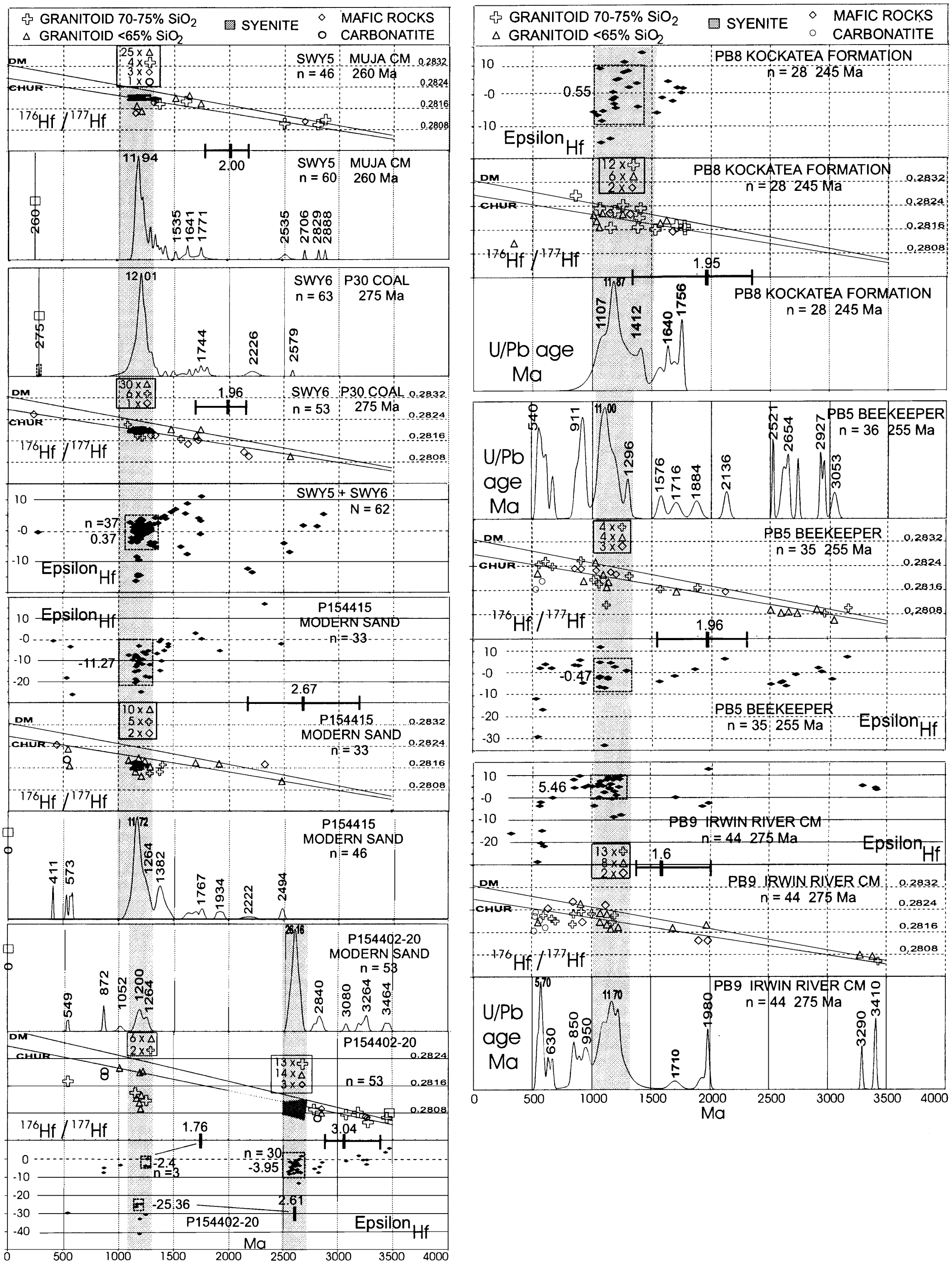
Dr Barry Kohn, University of Melbourne, collected the samples for apatite fission-track analysis. The samples were crushed, minerals separated on a Wifley table, paramagnetic phases removed using a Frantz separator, and the residue separated in heavy liquids.

According to Glover (1952), zircon, with rutile and garnet, is ubiquitous and, in some samples, is the most abundant of the non-opaque heavy minerals. Many zircons are extensively fractured. Subhedral zoned colourless grains are common; perfectly euhedral grains constitute 5%. Purple zircons found at Collie occur also in the coeval Irwin River Coal Measures and other sediments in the region.

According to Wilson (1989), "The palaeocurrent mean for the Collie Coal Measures trends to the northwest [341°] and this represents the palaeoslope dip direction. There is no evidence that the Collie Basin acted as a depocentre surrounded by inwardly dipping palaeoslopes." From this work, Veevers (2000, p. 122) inferred that the source of the zircons lay along the reciprocal bearing of 161° or SSE, and ranged from the proximal Albany Province to the distal Gamburtsev region of East Antarctica.

2.3.1. U–Pb age spectrum, Hf-isotope data and rock type classification

The U–Pb data are shown on a concordia plot for each sample in Fig. 2 and the age distribution, the Hf-isotope data and the rock-type classification are shown in Fig. 3. The analytical data are given in Tables A–D. SWY5 has 11 mildly discordant grains, and SWY6 has 4. The age spectrum of SWY5 has a major peak at 1194 Ma and small populations at 1535, 1641, and



GRANITOID 70-75% SiO2
GRANITOID <65% SiO2
SYENITE
MAFIC ROCKS
CARBONATITE
SWY5 MUJA CM n = 46 260 Ma
SWY5 MUJA CM n = 60 260 Ma
SWY6 P30 COAL n = 63 275 Ma
SWY6 P30 COAL n = 53 275 Ma
SWY5 + SWY6 N = 62
P154415 MODERN SAND n = 33
P154415 MODERN SAND n = 46
P154402-20 MODERN SAND n = 53
P154402-20 n = 53
PB8 KOCKATEA FORMATION n = 28 245 Ma
PB5 BEEKEEPER n = 36 255 Ma
PB5 BEEKEEPER n = 35 255 Ma
PB9 IRWIN RIVER CM n = 44 275 Ma
U/Pb age Ma
Epsilon Hf
176Hf / 177Hf
DM
CHUR
Ma

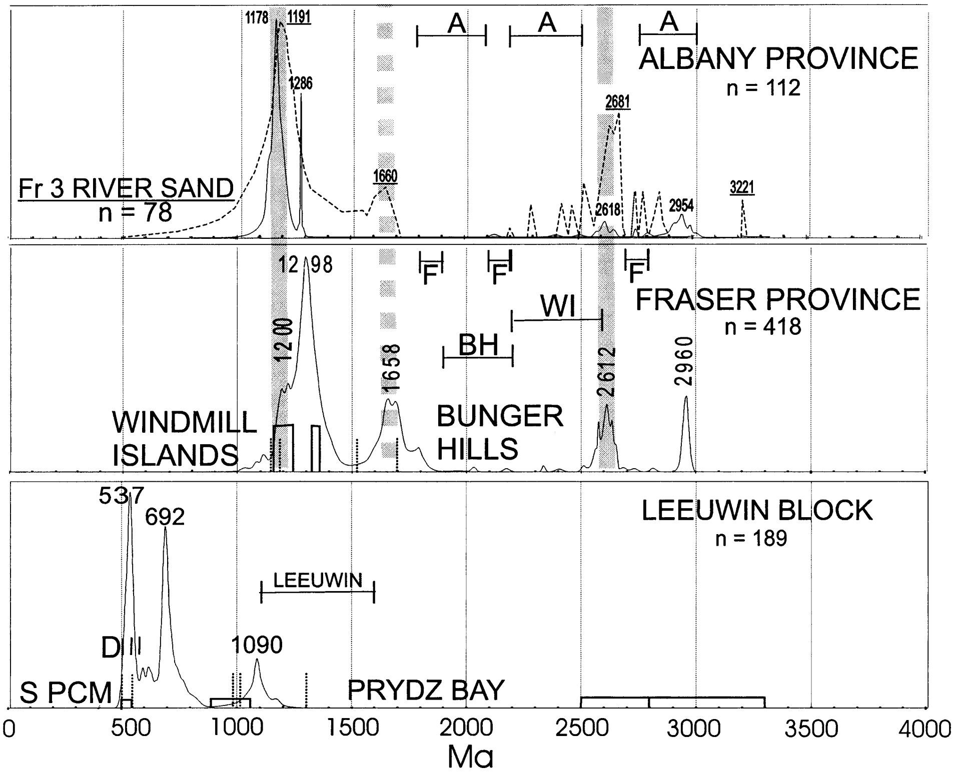
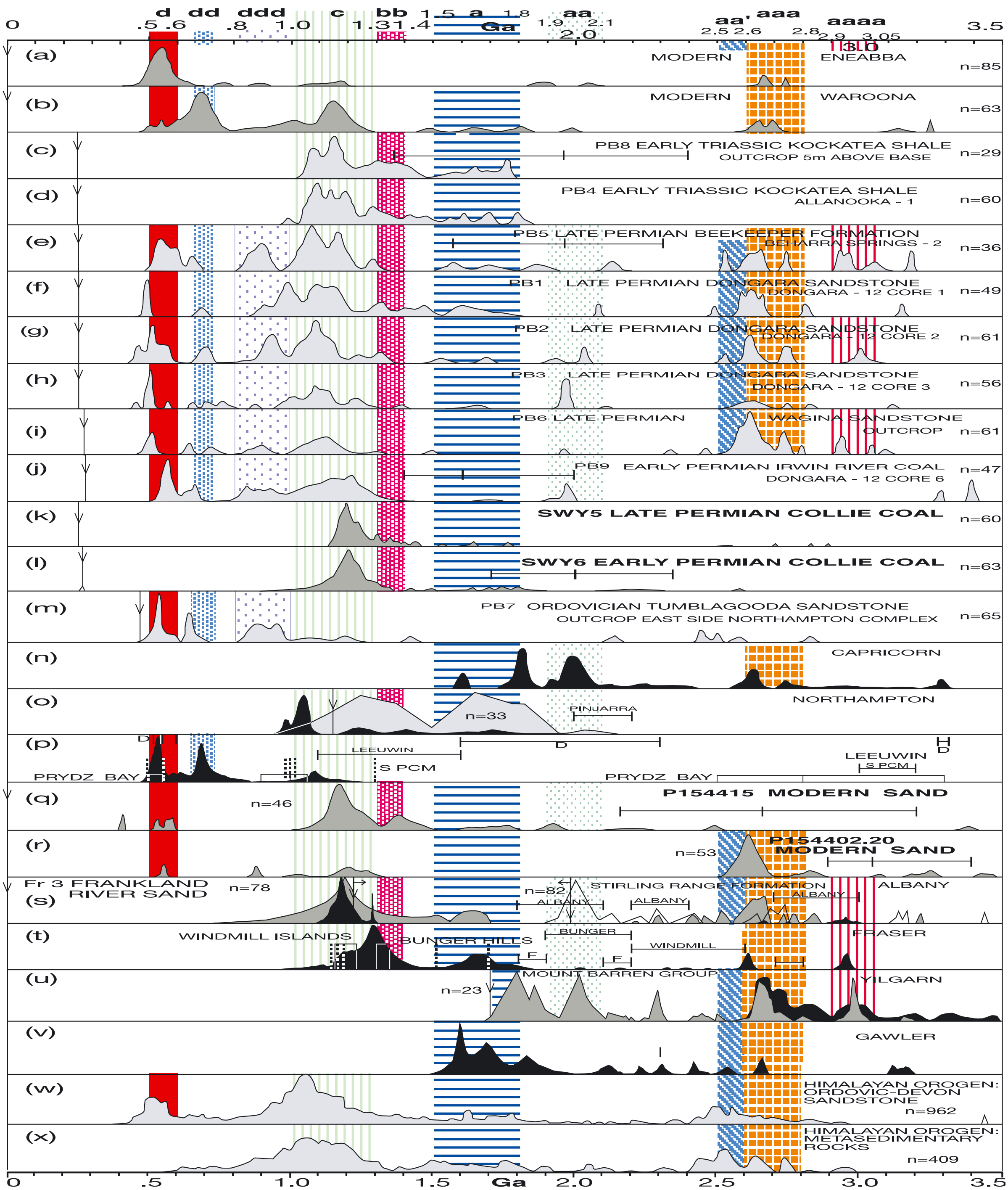


Fig. 4. Probability densities for U–Pb SHRIMP age measurements of individual zircons in potential provenances, with Nd model ages (bars) from Fitzsimons (2003). Albany Province (A) compiled from Pidgeon (1990) and Black et al. (1992), with peaks at 1178 Ma, 1286 Ma, 2618 Ma, and 2954 Ma and corresponding spectrum of Fr3 Frankland River sand (broken line)(Cawood et al., 2003), with peaks (underlined) at 1191, 1660, 2681, and 3221 Ma. Fraser Province (F) compiled from Nelson (1995), Nelson et al. (1995), and Clark et al. (1999, 2000), with Wilkes Province localities at Windmill Islands (WI) (full-line boxes) and Bunger Hills (BH) (broken line). Leeuwin Block compiled from Nelson (1996, 1999, 2002) and Collins (2003), with Denman Glacier (D) (elevated line), Prydz Bay (black outline), and southern Prince Charles Mountains (S PCM) (broken line), all from Fitzsimons (2003).

1771 Ma; a few grains scatter between 2500 and 2900 Ma. SWY6 shows essentially the same pattern, with the major peak at 1201 Ma. The youngest grain (boxed) is 275 Ma, the same as the age of deposition, shown by the vertical line with open rectangle.

In both samples the zircons with ages in the range 1300–1000 Ma (grey band) are derived predominantly from relatively mafic granitoids, with few from felsic granitoids and mafic rocks. The Hf isotope patterns are similar, and all of the data

Fig. 3. Hf–isotopic ratio versus U–Pb ages, host-rock composition, model ages of peak zircons (bars), and Epsilon$_{Hf}$ of detrital zircons from (left-hand column) Permian Collie Coal Measures samples SWY5 and SWY6, and modern sands P154415 and P154402-20 (age of deposition shown by the vertical line with open rectangle); and (right-hand column) Perth Basin, U–Pb in zircon SHRIMP ages from Cawood and Nemchin (2000), and host-rock composition, and Epsilon$_{Hf}$ of the same detrital zircons done here from PB8 Early Triassic Kockatea Shale, PB5 Late Permian Beekeeper Formation, and PB9 Early Permian Irwin River Coal Measures. Probability density plots of U–Pb ages (Ludwig, 2001) and $^{176}Hf/^{177}Hf$ plots with discriminant lines marked CHUR (chondritic unfractionated reservoir) and DM (depleted mantle), and Epsilon$_{Hf}$ (Griffin et al., 2000, 2002) and trace-element classification of source igneous rock (Belousova et al., 2002). The components of the dense concentrations about 1200 Ma (2600 Ma in P154402-20) are given in the box immediately above. The age plots are the accumulation of individual Gaussian curves of each age measurement normalized to a value of one. n is the number of individual ages in each plot. The Perth Basin ages were re-calculated so that ages by $^{207}Pb/^{206}Pb$ were used for >1000 Ma, and $^{206}Pb/^{238}U$ for <1000 Ma, to allow direct comparison with our data.


d dd ddd c bb a aa aa' aaa aaaa
0 .5 .6 .8 1.0 1.3 1.4 1.5 1.8 Ga 1.9 2.0 2.1 2.5 2.6 2.8 2.9 3.0 3.05 3.5
(a) MODERN ENEABBA n=85
(b) MODERN WAROONA n=63
(c) PB8 EARLY TRIASSIC KOCKATEA SHALE OUTCROP 5m ABOVE BASE n=29
(d) PB4 EARLY TRIASSIC KOCKATEA SHALE ALLANOOKA - 1 n=60
(e) PB5 LATE PERMIAN BEEKEEPER FORMATION BEHARRA SPRINGS - 2 n=36
(f) PB1 LATE PERMIAN DONGARA SANDSTONE DONGARA - 12 CORE 1 n=49
(g) PB2 LATE PERMIAN DONGARA SANDSTONE DONGARA - 12 CORE 2 n=61
(h) PB3 LATE PERMIAN DONGARA SANDSTONE DONGARA - 12 CORE 3 n=56
(i) PB6 LATE PERMIAN WAGINA SANDSTONE OUTCROP n=61
(j) PB9 EARLY PERMIAN IRWIN RIVER COAL DONGARA - 12 CORE 6 n=47
(k) SWY5 LATE PERMIAN COLLIE COAL n=60
(l) SWY6 EARLY PERMIAN COLLIE COAL n=63
(m) PB7 ORDOVICIAN TUMBLAGOODA SANDSTONE OUTCROP EAST SIDE NORTHAMPTON COMPLEX n=65
(n) CAPRICORN
(o) NORTHAMPTON n=33 PINJARRA
(p) D LEEUWIN S PCM PRYDZ BAY D PRYDZ BAY LEEUWIN S PCM H D
(q) n=46 P154415 MODERN SAND
(r) n=53 P154402.20 MODERN SAND
(s) Fr 3 FRANKLAND RIVER SAND n=78 n=82 STIRLING RANGE FORMATION ALBANY ALBANY ALBANY ALBANY
(t) WINDMILL ISLANDS BUNGER HILLS BUNGER F F WINDMILL FRASER
(u) n=23 MOUNT BARREN GROUP YILGARN
(v) GAWLER
(w) HIMALAYAN OROGEN: ORDOVIC-DEVON SANDSTONE n=962
(x) HIMALAYAN OROGEN: METASEDIMENTARY ROCKS n=409
0 .5 1.0 1.5 Ga 2.0 2.5 3.0 3.5

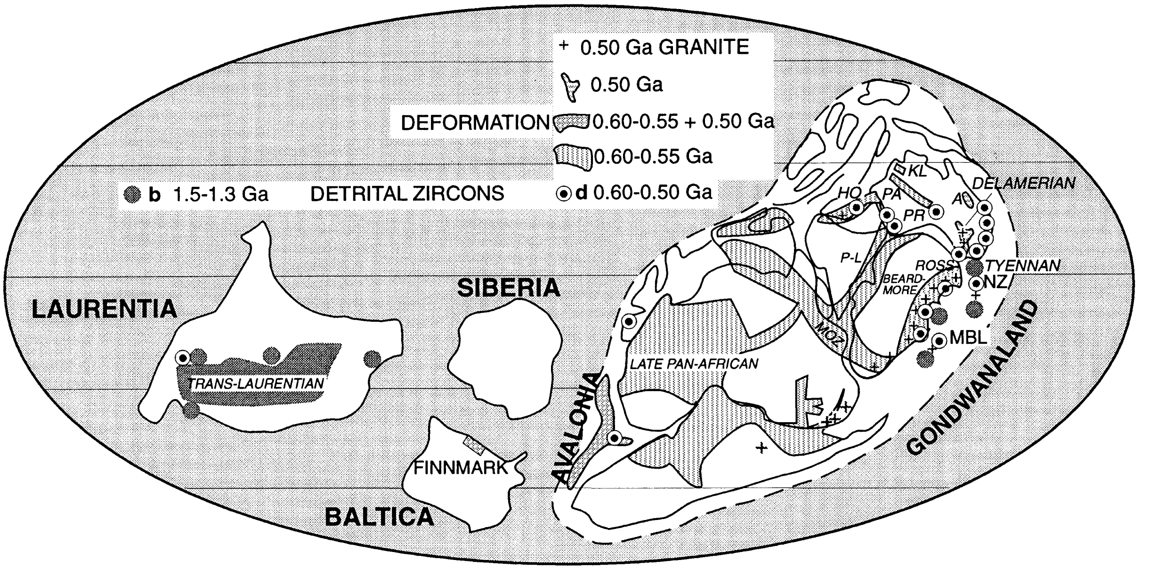


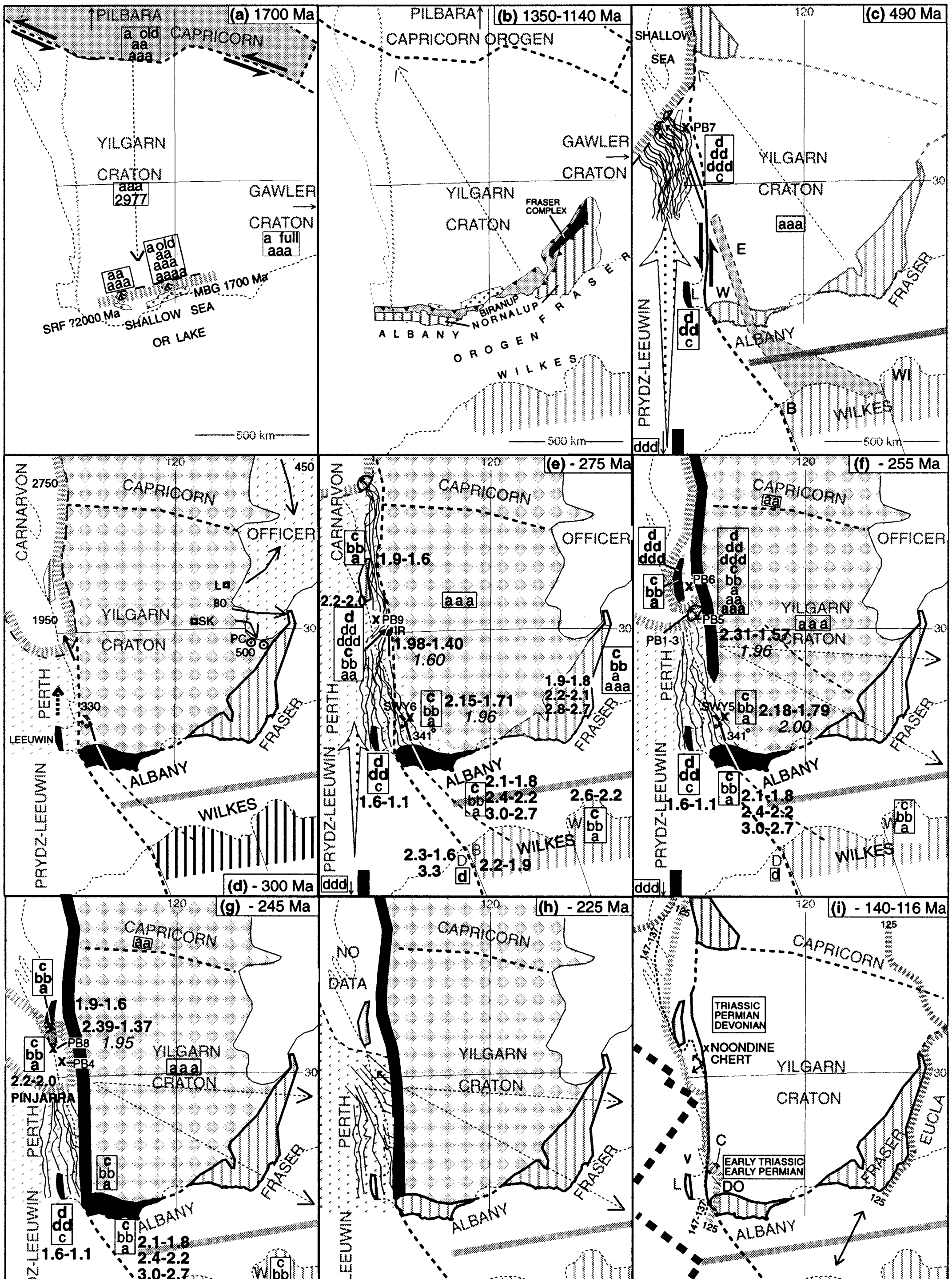
Fig. 6. Neoproterozoic-Cambrian reconstruction showing concentration of (a) 0.6–0.5 Ga deformation, granite, and detrital zircon in Gondwanaland, from Florida and northwest Spain to Antarctica and Australia, and (b) 1.5–1.3 Ga igneous terrane and detrital zircon in Laurentia, Marie Byrd Land (MBL), New Zealand (NZ), and Tasmania. *A* = Anakie; *KL* = King Leopold; *MOZ* = Mozambique belt; *PA* = Paterson; *P–L* = Prydz–Leeuwin belt; *HO* = Himalaya Orogen; *PR* = Petermann. From Veevers (2004, Fig. 5), with addition of data from the Himalayan orogen (Gehrels et al., 2003).

suggest that both samples have drained the same area. The zircons in the main age peak have a mean ε_{Hf} = 0.37. With the assumption that the source rocks for these magmas had a typical crustal value of $^{176}Lu/^{177}Hf$ (0.015; Griffin et al., 2000), the model age (T_{DM}^{C}) of the source is 2.18 to 1.71 Ga, with means of 2.00 and 1.96 Ga. These values correspond with the youngest range (T_{DM} = 2.1–1.8 Ga) of the Albany Province (Fitzsimons, 2003).

2.4. Surface sand in the Albany Province

Fluvial sand was collected by Anglo American Exploration (Aust) Ltd., Perth in an area of little

Fig. 5. Probability density plots of ages of zircons and ranges (and means) of model ages of zircons based on a depleted mantle source, arranged vertically so that similar ages are grouped. Correlation of peaks indicated by coloured patterns. Added to Veevers (2000, Fig. 130) are new spectra from Figs. 3 and 4 and model ages from above and (of bedrock) from Fitzsimons (2003). (a) to (m), (w) and (x): ages of detrital zircon (*n* = number of grains) arranged in approximate order of increasing age of the enclosing sedimentary rock, shown on the left by the vertical line with a V. (a) and (b) are from Sircombe and Freeman (1999), (c) to (j) from Cawood and Nemchin (2000), (k) and (l), SWY5 and SWY6, from Fig. 3, and (m) from Cawood and Nemchin (2000), (w) and (x), from the Himalaya (Gehrels et al., 2003). The remaining plots of probability densities for U–Pb SHRIMP age measurements of individual zircons include those in black from bedrock (potential provenances) from Pell et al. (1997). Nd model ages (bars) are from Fitzsimons (2003). (n) Capricorn Orogen and (o) Northampton Block (both black) from Cawood and Nemchin (2000), detrital zircon (grey) in Northampton paragneiss from Bruguier et al. (1999). (p) Leeuwin Block compiled from Nelson (1996, 1999, 2002) and Collins (2003), with Denman Glacier (D) (bar), Prydz Bay in outline, and southern Prince Charles Mountains (S PCM) by broken lines. (q) and (r): plots of detrital zircons (grey) in the Albany Province from surface sands (samples P154415 and P154402-20, Fig. 3). (s) Albany Province (black) compiled from Pidgeon (1990) and Black et al. (1992), with Fr3 Frankland River sand (grey) from Cawood et al. (2003) and Stirling Range Formation (outline) from Rasmussen et al. (2002). (t) Fraser Province (black) compiled from Nelson (1995) and Clark et al. (1999, 2000), with Wilkes Province localities at Windmill Islands (full-line box) and Bunger Hills (broken line). (u) Yilgarn Craton (black) from Cawood and Nemchin (2000), Paleoproterozoic Mount Barren Group (grey) from Dawson et al. (2002) and Vallini et al. (2002). (v) Gawler Craton from Camacho et al. (2002). (w) Himalayan Orogen, Ordovician–Devonian sandstones of the Tethyan sequence and crystalline thrust sheets (Gehrels et al., 2003), and (x) Himalayan Orogen, pre-Ordovician metasedimentary strata and crystalline thrust sheets, which together with Cambro-Ordovician granites supplied detritus to the Ordovician–Devonian sediments (Gehrels et al., 2003).


(a) 1700 Ma
PILBARA
CAPRICORN
a old
aa
aaa
YILGARN
CRATON
aaa
2977
GAWLER
CRATON
a full
aaa
MBG 1700 Ma
SRF ?2000 Ma
SHALLOW SEA
OR LAKE
500 km
(b) 1350-1140 Ma
PILBARA
CAPRICORN OROGEN
GAWLER
CRATON
YILGARN
CRATON
FRASER COMPLEX
BIRANUP
NORNALUP
ALBANY
FRASER
OROGEN
WILKES
500 km
(c) 490 Ma
SHALLOW
SEA
PB7
YILGARN
CRATON
aaa
E
W
L
FRASER
ALBANY
WI
B
WILKES
PRYDZ-LEEUWIN
ddd
500 km
(d) - 300 Ma
CARNARVON
2750
CAPRICORN
450
OFFICER
YILGARN
CRATON
1950
SK
PC
500
PERTH
330
LEEUWIN
ALBANY
FRASER
WILKES
PRYDZ-LEEUWIN
(e) - 275 Ma
CARNARVON
CAPRICORN
OFFICER
1.9-1.6
2.2-2.0
PB9
IR
1.98-1.40
1.60
SWY6
2.15-1.71
1.96
341
1.9-1.8
2.2-2.1
2.8-2.7
FRASER
PERTH
PRYDZ-LEEUWIN
1.6-1.1
ALBANY
2.1-1.8
2.4-2.2
3.0-2.7
2.6-2.2
WILKES
2.3-1.6
3.3
2.2-1.9
ddd
(f) - 255 Ma
CAPRICORN
OFFICER
PB6
PB5
PB1-3
YILGARN
CRATON
2.31-1.57
1.96
SWY5
2.18-1.79
2.00
341
PERTH
FRASER
PRYDZ-LEEUWIN
1.6-1.1
ALBANY
2.1-1.8
2.4-2.2
3.0-2.7
WILKES
ddd
(g) - 245 Ma
CAPRICORN
1.9-1.6
2.39-1.37
1.95
PB8
PB4
YILGARN
CRATON
2.2-2.0
PINJARRA
PERTH
FRASER
PRYDZ-LEEUWIN
1.6-1.1
ALBANY
2.1-1.8
2.4-2.2
3.0-2.7
WILKES
ddd
(h) - 225 Ma
NO
DATA
CAPRICORN
YILGARN
CRATON
PERTH
FRASER
PRYDZ-LEEUWIN
ALBANY
WILKES
(i) - 140-116 Ma
CAPRICORN
125
147-137
TRIASSIC
PERMIAN
DEVONIAN
NOONDINE
CHERT
YILGARN
CRATON
EARLY TRIASSIC
EARLY PERMIAN
DO
EUCLA
FRASER
ALBANY
WILKES

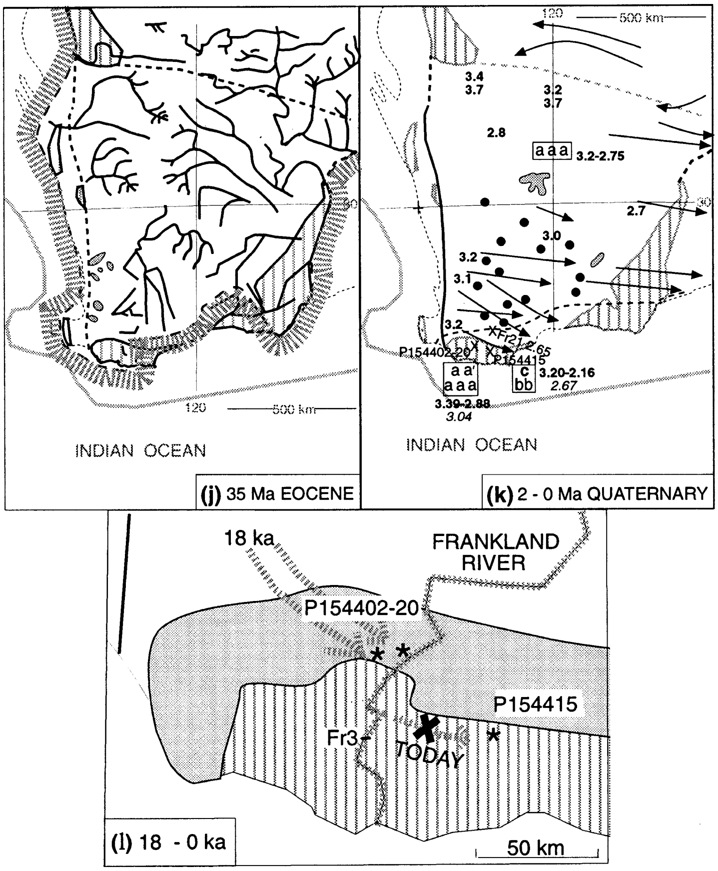


Fig. 7. Paleogeographical maps of southwestern Australia. Shoreline denoted by grey broken line, inferred provenance by solid black, ages of zircons by boxed letters, with peak ages (Ga) and model ages in bold, with means in italics. Present coastline, Darling Fault line, and latitude and longitude lines for reference only. (a) 1700 Ma, "showing indentation of a formerly continuous Pilbara-Gawler continental margin by the Yilgarn Craton, such that the Pilbara-Yilgarn boundary is a transcurrent megashear" (Dawson et al., 2002). The Pilbara and Gawler Cratons lie outside the frame. Ground to the west and south unknown. MBG = Mount Barren Group; SRF = Stirling Range Formation. (b) Collision 1350–1140 Ma on the southeastern margin of the Yilgarn Craton (Fitzsimons, 2003). Western part of Albany Province restored to its pre-550 Ma position. Ground to the west unknown. (c) 490 Ma, Cambrian/Ordovician. The wavy lines signify anastomosing drainage.The transition zone (grey) between the Western (W) biotite domain and Eastern (E) biotite domain extended to between the Bunger Hills (B) and Windmill Islands (WI) (Libby and De Laeter, 1998). The grey line between Australia and Antarctica marks the line of mid-Cretaceous breakup. Prydz Bay is situated 800 km outside the frame. (d) 300 Ma, latest Carboniferous. Glacial and post-glacial paleogeography. Numerals indicate the thickness (m) of glacigenic sediment, solid black concomitant uplift, and the diamond pattern the postulated area of glacigenic cover on the Yilgarn Craton. L = Laverton; PC = Ponton Creek; SK = Sand King. (e) 275 Ma, Early Permian. The Nd model ages (in Ga) of the Pinjarra Orogen, Leeuwin Complex, Albany Province, Fraser Province, Denman Glacier area, Bunger Hills, and Windmill Islands, are from Fitzsimons (2003), and T_{DM}^{C} of SWY6 and PB9 from above. The diamond pattern denotes the postulated area of glacigenic cover on the Yilgarn Craton including the stippled area about Collie. (f) 255 Ma, Late Permian. The dotted arrowed line denotes the long dip-slope away from the rim above the Darling Fault scarp. (g) 245 Ma, Early Triassic. Shoreline and uplift of the Yilgarn Craton along the Darling Fault are from Cockbain (1990). (h) 225 Ma, Late Triassic, from Cockbain (1990) and Mory and Iasky (1996). (i) 140–116 Ma, Early Cretaceous. On the west, the shoreline in the Jurassic–Cretaceous (broken line 147–137) lapped the Darling Fault in the south and by the Barremian (wide broken line 125) had advanced up valleys past Donnybrook (DO) almost to Collie (C). In the east, the 125 Ma shoreline lapped the Precambrian basement in the Eucla and Officer Basins. V, Vlaming Basin. (j) 35 Ma, Eocene. Fluvial (line) and lacustrine (grey) deposits and shoreline (wide grey broken line) from Hocking and Cockbain (1990). (k) 2–0 Ma, Quaternary. The broken line is the divide between the modern external drainage and the internal, largely uncoordinated drainage, much of it inherited from past ages (Hocking and Cockbain, 1990; Morgan, 1993; Freeman, 2001). Other information, from Williams (2000), relates to events at the Last Glacial Maximum (18 ka): eolian dune orientation (arrows), active lunettes (filled circles), and playas (grey). (l) Albany area enlarged from (k) to show distribution of Archean zircons (grey broken-line pattern).

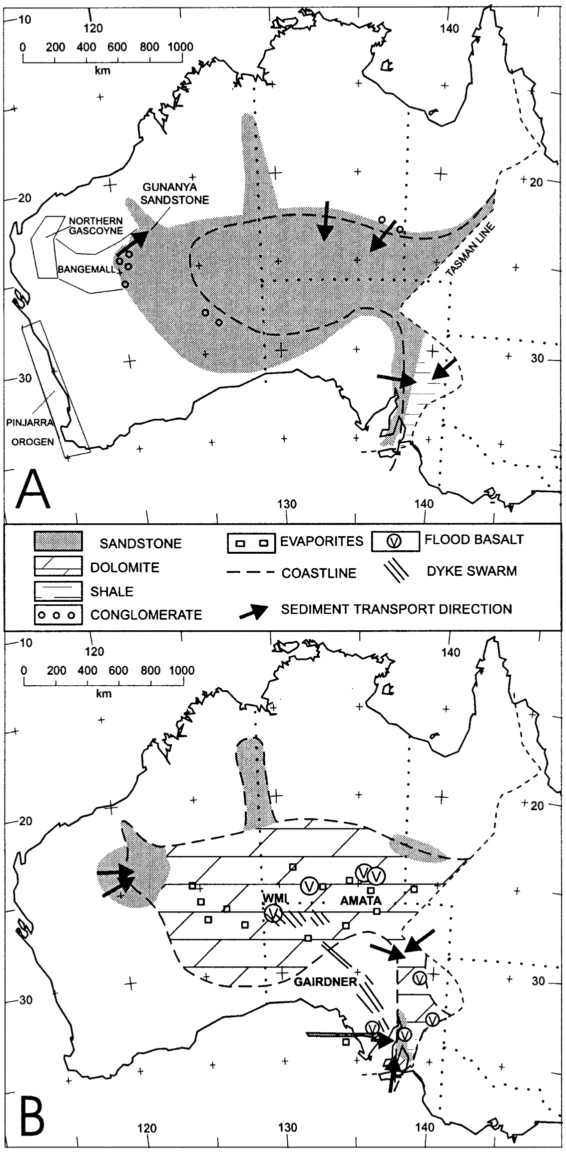


Fig. 8. Neoproterozoic paleogeography, modified from Walter and Veevers (2000, Figs. 157 and 159). (A) At 840 Ma during initial deposition of a sheet of quartz sand at the base of the Centralian Superbasin. The fluvial Gunanya Sandstone was deposited from paleocurrents that flowed down a paleoslope across the zircon provenances of the northern Gascoyne Complex, Bangemall Supergroup, and Pinjarra Orogen, without picking up zircons from the Yilgarn craton. (B) At 830 Ma, the western provenance continued to provide detrital sand to the edge of an epeiric sea that filled with carbonate and evaporites interleaved with basalt fed from dyke swarms, including dolerite in the western Musgrave Inlier (WMI).

outcrop with deep partially dissected laterite profiles. Samples of 15–20 kg of −2 mm material were taken from natural heavy-mineral traps in the current drainage. Zircons were separated by Wifley table, heavy liquid, and magnetic methods.

P154415, at 34.70°S, 117.25°E in the Mount Barker (SI 50–11) 1:250 000 Sheet area (Fig. 1), was collected from the Denmark River 1 km upstream from its confluence with Cleerillup Creek. The area is underlain by the Burnside Batholith near its eastern edge (Myers, 1990), but P154415 samples a drainage system that has its headwaters 10 and 15 km distant in quartzo-feldspathic gneiss and granite of the Nornalup Complex.

P154402, at 34.46°S, 116.78°E in the Pemberton SI 50–10 1:250 000 Sheet area, was collected from a dry watercourse near its crossing of the Muir Highway, and 6 km from its head in a 24 km^2 drainage system in the Biranup Complex. P154420, at 34.45°S, 116.89°E, was collected in a similar situation 11 km to the east, and 3 km from the junction with the Frankland River. The area is underlain by the Burnside Batholith near its northern boundary with the Biranup Complex of quartzo-feldspathic gneiss and granite (Myers, 1990). Of the 53 zircons analysed (Tables E, F), 34 from P154402 and 19 from P154420 were pooled as sample P154402-20. This is justified because the age spectra of P154402 and P154420 are identical except that P154420 lacks grains <1100 Ma and the absence of this small population is not statistically significant when only 19 grains could be analysed.

2.4.1. U–Pb age spectrum, Hf-isotope data and rock type classification

All grains except one in P154402-20 and 16 grains in P154415 are concordant (Fig. 2). The analytical data are given in Tables G and H. The age spectrum of P154415 (Fig. 3) has a major peak at 1172 Ma and a shoulder at 1264 Ma, a minor peak at 1382 Ma, and one or two grains at 2494, 2222, 1934, 1767, 573, and 411 Ma. The peak at 1172 Ma matches the SHRIMP U–Pb ages of 1174 ± 12 Ma for the Albany Adamellite and 1177 ± 4 Ma for the Burnside Batholith (Pidgeon, 1990). These bedrock samples and those from Black et al. (1992) contribute to the 1178 Ma peak in the Albany Province (Fig. 4). The shoulder at 1264 Ma approximates the second peak at 1286 Ma in the Albany Province, from the 1289 ± 10 Ma enderbitic gneiss near Albany (Pidgeon, 1990). Zircon rims with ages of 1356 Ma (#56) and 1126 Ma (#67) suggest that this span also represents a major high-grade metamorphic episode.

More than a third of the analysed grains show oscillatory or laminar zoning together with euhedral crystal forms that indicate magmatic crystallization. Nearly all of these have ages >1190 Ma, including several of those in the 1264 Ma shoulder and most of the grains in the 1450–1350 Ma range. The four zircons with ages < 1000 Ma and those at 1934 ± 26 and 2494 ± 17 Ma are very rounded, suggesting abrasion during transport, most effectively by the eolian processes that pertained during the Last Glacial Maximum, between 25 and 13 ka (Williams, 2000). Anand and Paine (2002) describe the mantle of locally derived eolian silt and fine sand across the Yilgarn landscape in dunes partly stabilised by spinifex and scattered mulga.

The zircons with ages in the range 1300–1000 Ma are derived largely from relatively mafic granitoids, with fewer from felsic granitoids and mafic rocks. They have a mean $\varepsilon_{Hf} = -11.27$ and the model age (T_{DM}^{C}) of the source is 3.20–2.16 Ga, with a mean of 2.67. This older model age distinguishes P154415 from the Collie samples with a mean age of 1.96 Ga.

Unique among our samples, P154402-20 has a major peak at 2616 Ma, a minor peak at 1200 Ma with a shoulder at 1264 Ma, and a few grains at 3464, 3264, 3080, 2840, 1052, 872, and 549 Ma. Half the grains are structureless under BSE/CL. About one-third of the grains show oscillatory zoning, indicating magmatic crystallization, but few have sharp euhedral forms. Many of the >3000 Ma grains are rounded, possibly because they were inherited and partly resorbed in the younger magmas or abraded during eolian transport, or both. The minor peak at 1200 Ma with a shoulder at 1264 Ma mimics the 1178 and 1286 Ma peaks of the Albany Province (Fig. 4) and the main peak at 1172 Ma of sample P154415. The main peak at 2616 Ma matches the 2612 minor peak in the Fraser Province (Fig. 4), and the youngest age (2620 Ma) of the Yilgarn Craton (Nelson et al., 1995) (Fig. 5). Cawood et al.'s (2003) sample Fr21 from the headwaters of the Frankland River wholly within the southern Yilgarn Craton yielded a unimodal age distribution of 2653 ± 15 Ma. Downstream 250 km at Fr3, the contribution from the Yilgarn Craton (2681 ± 39 Ma) comprises only 22% of the sample. We interpret the 2616 Ma peak of the P154402-20 spectrum as derived likewise from the southern Yilgarn Craton, not transported by water—P154402-20 lies in a dry watercourse above the river—but blown in by northwesterly winds directly from the Yilgarn Craton during and after the intensely arid Last Glacial Maximum 18 000 years ago (Williams, 2000). The correspondence of the T_{DM} model ages of 3.39–2.88 Ga (mean 3.04 Ga) with the U–Pb in zircon ages of 3.2–3.0 Ga in the southwestern Yilgarn Craton (Fig. 7k) confirms the correlation. The prevailing westerly wind also eliminates the possibility of Yilgarn Craton zircons being blown westward from the Frankland River to P154402-20. P154415, 50 km downwind from the Frankland River, lacks 2.8–2.6 Ga zircons, indicating the weakness of the present wind to transport sand from the river in today's environment, totally covered with vegetation.

Several 3500–3200 Ma zircons have Hf-isotope compositions indicating derivation from a Depleted Mantle (DM) source, whereas nearly all younger zircons plot below the Chondritic Unfractionated Reservoir (CHUR) reference line, indicating that their host magmas were derived in part from older crustal material. The 1300–1100 Ma zircons have ε_{Hf} values ranging down to -41, with a cluster (boxed) with a mean of -2.4 and $T_{DM} = 1.76$ Ga, and another with a mean of -25.36 and $T_{DM} = 2.61$ Ga. This is identical to the peak U–Pb age (2616 Ma), and reflects derivation from the Yilgarn Craton. The grains with the lowest ε_{Hf} values give unreasonably high T_{DM}^{C}, indicating that the source rocks for their host magmas were more felsic (lower Lu/Hf) than the mean continental crust. These zircons give minimum T_{DM} model ages equivalent to the U–Pb ages of the oldest zircons in the sample (ca. 3.5 Ga), confirming an ancient Archean crustal input to 1.0–1.2 Ga magmatism in the Albany province. The 2700–2500 Ma zircons have a mean $\varepsilon_{Hf} = -3.95$ with T_{DM} model ages of 3.4–2.9 Ga, and a mean of 3.04 Ga. In three grains (2598, 1169, 549 Ma), rims containing more radiogenic Hf than that of the core were intersected as the laser drilled through the grain, indicating mixing between magmas derived from different sources.

The grains in the 2616 Ma peak are classified as derived equally from granitoids with 70–75% SiO_2

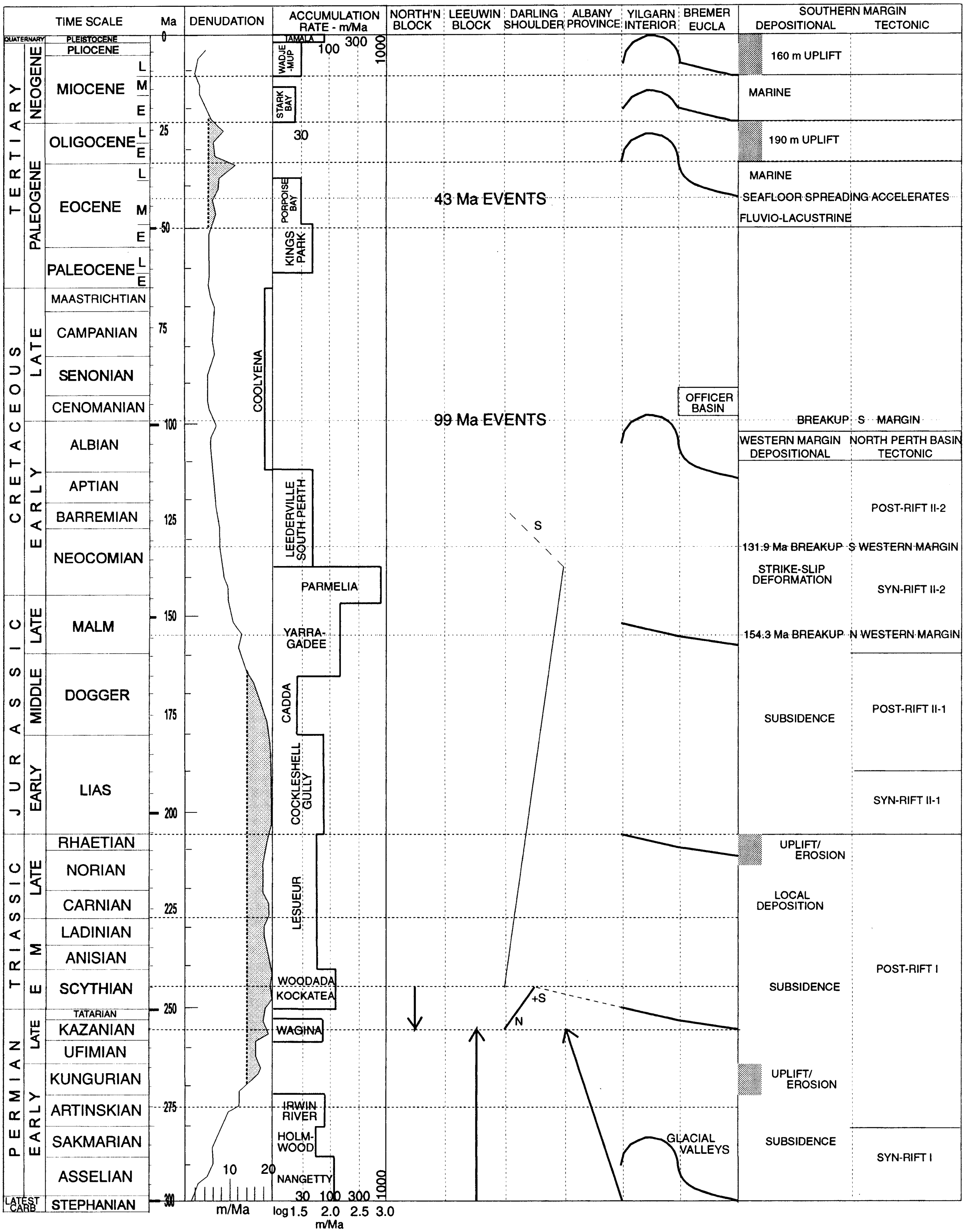

TIME SCALE
Ma
DENUDATION
ACCUMULATION RATE - m/Ma
NORTH'N BLOCK
LEEUWIN BLOCK
DARLING SHOULDER
ALBANY PROVINCE
YILGARN INTERIOR
BREMER EUCLA
SOUTHERN MARGIN
DEPOSITIONAL
TECTONIC
QUATERNARY
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
TERTIARY
NEOGENE
PALEOGENE
MAASTRICHTIAN
CAMPANIAN
SENONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
NEOCOMIAN
CRETACEOUS
LATE
EARLY
MALM
DOGGER
LIAS
JURASSIC
MIDDLE
RHAETIAN
NORIAN
CARNIAN
LADINIAN
ANISIAN
SCYTHIAN
TRIASSIC
TATARIAN
KAZANIAN
UFIMIAN
KUNGURIAN
ARTINSKIAN
SAKMARIAN
ASSELIAN
PERMIAN
LATEST CARB
STEPHANIAN
0
25
50
75
100
125
150
175
200
225
250
275
300
10
20
m/Ma
TAMALA
WADJE-MUP
STARK BAY
PORPOISE BAY
KINGS PARK
COOLYENA
LEEDERVILLE SOUTH PERTH
PARMELIA
YARRAGADEE
CADDA
COCKLESHELL GULLY
LESUEUR
WOODADA
KOCKATEA
WAGINA
IRWIN RIVER
HOLMWOOD
NANGETTY
30
100
300
1000
log1.5
2.0
2.5
3.0
m/Ma
43 Ma EVENTS
99 Ma EVENTS
S
N
+S
OFFICER BASIN
GLACIAL VALLEYS
160 m UPLIFT
MARINE
190 m UPLIFT
MARINE
SEAFLOOR SPREADING ACCELERATES
FLUVIO-LACUSTRINE
BREAKUP S MARGIN
WESTERN MARGIN DEPOSITIONAL
NORTH PERTH BASIN TECTONIC
POST-RIFT II-2
131.9 Ma BREAKUP S WESTERN MARGIN
STRIKE-SLIP DEFORMATION
SYN-RIFT II-2
154.3 Ma BREAKUP N WESTERN MARGIN
SUBSIDENCE
POST-RIFT II-1
SYN-RIFT II-1
UPLIFT/ EROSION
LOCAL DEPOSITION
POST-RIFT I
SUBSIDENCE
UPLIFT/ EROSION
SUBSIDENCE
SYN-RIFT I

Table 1
Details of samples SWY5 and SWY6 from the Permian Collie Coal Measures, Premier Sub-Basin, Collie Basin

Serial	Location	Lat/Long	Formation	Age	X-dip
Rock type	Open Cut		Coal		Azimuth
SWY-5	Muja	33.43°S	Muja CM	Ufimian	NW-ward
subarkosic grit		116.31°E	Hebe-Galatea	260 Ma	(Wilson, 1989)
SWY-6	Ewington-2	33.37°S	P30 coal	Artinskian	NW-ward
subarkosic grit		116.25°E	Unicorn/Premier 3	275 Ma	(Wilson, 1989)

CM = coal measures.

and < 65% SiO_2. This represents another difference from the 1500–1000 Ma zircons of samples SWY5 and SWY6, which are classified as derived predominantly from granitoids with < 65% SiO_2, and of P154415, which has twice as many zircons derived from granitoids with < 65% SiO_2 as those with 70–75% SiO_2.

With a higher proportion of zircons from high-silica granitoids than the others, sample P154402-20 is further discriminated as reflected in its Hf isotope composition, which indicates a greater proportion of older material in the magma sources.

The difference in Hf-isotope composition between the 1300–1100 Ma grains in the two sand samples and those of the Collie Coal Measures indicates that the latter were not derived from the (northern) part of the Albany-Fraser Province sampled by P154415 and P154402-20. The Collie zircons were presumably derived from a coeval provenance to the south, in the southern Albany Province or, at an extreme, in the Wilkes Province.

2.5. Permian and Triassic samples from the northern Perth Basin

Three sets of zircons from the Perth Basin, previously dated by SHRIMP techniques and inferred to have come by longitudinal supply from the south (Cawood and Nemchin, 2000) were analysed for Hf-isotope data and rock type classification (Fig. 3).

2.5.1. Early Permian Irwin River Coal Measures sample PB9

In the Early Permian Irwin River Coal Measures (sample PB9), the zircons with ages in the range 1300–1000 Ma are derived largely from relatively felsic and mafic granitoids, with a few from mafic rocks. The zircons in the main age peak have a mean $\varepsilon_{Hf} = 5.46$, within a range of -0.39 to 9.84. Assuming that the source rocks for these magmas have a typical crustal value of $^{176}Lu/^{177}Hf$ (0.015; Griffin et al., 2000), the model age (T^{C}_{DM}) of the source is 1.40 to 1.98 Ga, with a mean of 1.60 Ga.

Compared with the equivalent Collie Coal Measures (SWY5, SWY6), the Irwin River Coal Measures have a peak age 30 million years younger, and are derived from more felsic granitoids. The model age (T^{C}_{DM}) of the source (1.40–1.98 Ga, mean 1.60 Ga) overlaps that of the Collie samples (1.71–2.34 Ga, mean 2.02 Ga). The differences are small, and may reflect minor variations in the provenance or downstream differentiation of uniform material. As mentioned above, purple zircons are common in the coeval Collie and Irwin River Coal Measures (Glover, 1952).

2.5.2. Late Permian Beekeeper Formation sample PB5

In the 1300–1000 Ma peak of sample PB5, mean $\varepsilon_{Hf} = -0.47$, T^{C}_{DM} ranges from 2.31 to 1.57 Ga, with a mean of 1.96 Ga, and the zircons were derived from equal numbers of felsic and mafic granitoids and

Fig. 9. Timetable of denudation in southwestern Australia, accumulation rate of sedimentary rock in the northern Perth Basin, paleoslopes (north is up) of the Northampton (North'n) Block, Leeuwin Block, Darling shoulder at the western edge of the Yilgarn Craton (N = northern part, S = southern part), Albany Province, interior of the Yilgarn Craton, Bremer Basin, Eucla Basin (Officer Basin, below), and depositional-tectonic events on the southern margin (above) and on the western margin—northern Perth Basin (below). The long-term denudation chronology of southwestern Australia (essentially the Precambrian terranes of the Yilgarn Craton, Albany-Fraser Orogen, and Leeuwin Block) is based on an initial track length of 14.5 μm and constant heat flow (from Fig. 6 of Kohn et al., 2002). The accumulation rate (m/Ma) of sediment in the northern Perth Basin (Cockbain, 1990; Mory and Iasky, 1996) (Table 4) is given on a log scale. The tectonic events in the northern Perth Basin are from Song and Cawood (2000). The time-scale, breakup times, and events at 43 and 99 Ma, are from Veevers (2000, pp. 4, 18–28, 102–109).

mafic rocks. These indicators are similar to those in the nearby sample PB8 from the Early Triassic Kockatea Shale, and to the coeval sample SWY5 Muja Coal Measures of the Collie Basin, which has mean $\varepsilon_{Hf}=0.46$ (Table B), and T^{C}_{DM} ranges from 2.18 to 1.79 Ga, with a mean of 2.00 Ga. The only difference is that the SWY5 zircons came predominantly from mafic granitoids.

2.5.3. Early Triassic Kockatea Formation sample PB8

The zircons in the 1300–1000 Ma peak of PB8 have mean $\varepsilon_{Hf}=0.55$, T^{C}_{DM} from 2.39 to 1.37 Ga, with a mean of 1.95 Ga, and the zircons were derived from twice as many felsic granitoids as mafic granitoids. The mix of granitoid sources is similar to that in the nearby sample PB9 from the Early Permian Irwin River Coal Measures but T^{C}_{DM} is some 0.4 billion years older, which we interpret as reflecting input from the Pinjarra Orogen ($T_{DM}=2.2–2.0$ Ga) and Northampton Block ($T_{DM}=1.9–1.6$ Ga). The Collie samples have similar T^{C}_{DM} means (1.96, 2.00) but a source of predominantly mafic granitoids.

3. Ages of potential provenances

The age spectra and Hf-isotopic geochemistry of the Collie zircons and modern sands from the Albany region (Fig. 3) are now compared with the age spectra of potential provenances in the immediate vicinity (Fig. 4); and with the age spectra of other Permian (and Triassic) sedimentary rocks and modern sands from southwestern Australia, and of potential provenances (Fig. 5). The analyses of modern sands in the Albany Province contribute to the range of age and composition of zircons in the modern provenances.

Individual zircons from the region have been dated by the U–Pb method using the SHRIMP ion microprobe. The data sets of Nelson (1995, 1996, 1999, 2002) were the principal source for compiling the age spectra of the potential provenances.

3.1. Albany Province

The Albany-Fraser orogen (Fig. 1) comprises the northern Biranup Complex of granulite-facies felsic orthogneiss and the southern Nornalup Complex of less deformed orthogneiss and paragneiss, both intruded by the granite of the Burnside Batholith (Myers, 1990). Sufficient data are available to compile an age spectrum for each province.

The U–Pb SHRIMP ages of zircons from bedrock of the Albany Province (Fig. 4, full line) peak at 1178 Ma, representing the ages of the Burnside Batholith and metamorphics (Black et al., 1992; Pidgeon, 1990); a satellite at 1286 Ma is derived from a 1289 ± 10 Ma enderbite (Pidgeon, 1990). Inherited grains give ages of 2618 and 2954 Ma. The bedrock spectrum is complemented by the spectrum of Fr3 sand from the lower reaches of the Frankland River (Fig. 4, broken line) which sampled the western part of the province as well as the Yilgarn Craton. The main peak at 1191 Ma, encloses the 1178 Ma peak from the bedrock, and is flanked by a low peak at 1660 Ma. Ages scattered between 2000 and 3250 Ma peak at 2681 Ma, derived from the Yilgarn Craton, that towers over the bedrock ages about 2618 Ma. Cawood and Nemchin (2000) reported a tectonothermal peak of 1215–1140 Ma in the Albany-Fraser Orogen, represented in Fig. 4 by the 1178 Ma peak in the Albany area and a shoulder in the Fraser area. The main peak age of ~1200 Ma (wide grey line), represented by a shoulder in the Fraser Province, is faithfully reflected in the modern sands and Permian sandstones analysed here. The second peak at 1286 Ma matches the main peak of 1298 Ma in the Fraser Province. The minor peak of 1658 Ma (wide grey broken line) in the Fraser Province is found as a peak at 1660 Ma in the Fr3 river sand from the Albany Province and less distinctly in the P154415 modern sand and Permian sandstones. Nd model ages of orthogneisses and granitoids are 3.0–2.75, 2.5–2.2, and 2.1–1.8 Ga (Fitzsimons, 2003).

3.2. Fraser Province

The U–Pb SHRIMP ages have a major peak at 1298 Ma with a shoulder at 1200 Ma, and minor peaks at 1658, 2612, and 2960 Ma. Clark et al. (1999, 2000) proposed a tectonic model involving oblique Stage I collision (1350–1260 Ma, mean 1305 Ma), indicated by the Fraser (ultramafic) Complex, and reflected (Fig. 4) by the 1298 Ma peak in the Fraser Province. This was followed by regional extension and renewed Stage II compression (1210–1140 Ma, mean 1175 Ma), reflected in the 1178 Ma peak of the Albany Province.

Nd model ages of granitoid gneisses and granitoids are 2.8–2.7, 2.2–2.1, and 1.9–1.8 Ga (Fitzsimons, 2003).

3.3. Wilkes Province (Fitzsimons, 2003)

Outcrops of orthogneiss and paragneiss in the Windmill Islands (Fig. 1, inset, W; Fig. 4, heavy line) contain 1350–1315 Ma amphibolite-facies assemblages with a 1230–1160 Ma granulite-facies overprint, within the main peak of the Fraser Province. In the Bunger Hills (B) (dotted line), 1699 and 1521 Ma orthogneiss underwent granulite-facies metamorphism at 1190 Ma and was intruded by 1170 Ma gabbro and 1151 Ma monzodiorite. Nd model ages of felsic intrusions in the Windmill Islands are 2.6–2.2 Ga, and of granodioritic orthogneiss in the Bunger Hills 2.2–1.9 Ga (Fitzsimons, 2003).

3.4. Leeuwin Block

The Leeuwin Block is the southern exposure of the Pinjarra Orogen. The U–Pb SHRIMP ages of zircons, confined between 1200 and 500 Ma, are dominated by twin peaks at 537 and 692 Ma, with an outlier at 1090 Ma. Collins (2003) added ~750 Ma for gneiss protoliths and 522 ± 5 Ma for granulite/upper amphibolite facies metamorphism, some 100 million years later than previously estimated. Nd model ages are 1.6–1.1 Ga (Fitzsimons, 2003).

3.5. Prydz Bay, Prince Charles Mountains, Denman Glacier (Fitzsimons, 2003)

Zircon ages from eastern Prydz Bay (P, Fig. 1, inset) are from the Rauer Group, with protoliths of 3300–2800 and 1060–1000 Ma, and the 2800–2500 Ma Vestfold Hills Craton, both partially reset at 550–490 Ma. In the south, gneiss was metamorphosed to granulite-facies conditions at 530 Ma and then intruded by A-type granites at 500 Ma. Zircons with ages of 1200–700 Ma within the paragneiss are probably detrital and 1000–900 Ma zircons in mafic units indicate tectonism.

The southern Prince Charles Mountains, 400 km to the southwest, contain 1300 Ma metavolcanics, 1020–980 Ma syenite and granite, 550 Ma orthogneiss, and 510–490 Ma granitic dykes. Nd model ages are 3.2–3.0 Ga.

To the east, the Denman Glacier area, with metamorphics poorly dated 600–550 Ma and a precisely dated syenite at 516 Ma, shows affinity with the Leeuwin Block. Nd model ages are 3.3 and 2.3–1.6 Ga.

This information, copied to Fig. 5, is added to data from other potential provenances.

3.6. Capricorn Orogen

The spectrum of zircon ages from the Gascoyne Complex of the Capricorn Orogen is from Cawood and Nemchin (2000). Further information can be found in Cawood and Tyler (2004).

3.7. Northampton Block

The Northampton Block is the northern exposure of the Pinjarra Orogen. The spectrum of zircon ages from the Northampton Block (black) is from Cawood and Nemchin (2000), and that of ages of detrital zircons in paragneiss (grey) is from Bruguier et al. (1999). The youngest concordant grain (1151 ± 18 Ma) indicates the maximum age of deposition. Fitzsimons (2003) notes a similar age distribution of zircons from psammites in the Mullingarra Complex, 50 km to the southeast. High-grade metamorphics cooled at 1080 Ma, granite at 1068 Ma and pegmatite at 989 Ma.

3.8. Pinjarra Orogen

The age spectrum of the Pinjarra Orogen is given by those of the Northampton and Leeuwin Complexes (Fig. 5o and p). Granitic basement has Nd model ages of 2.2–2.0 Ga (Fitzsimons, 2003).

3.9. Yilgarn Craton

The Yilgarn Craton, from Cawood and Nemchin (2000), has a broad peak between 2.8 and 2.6 Ga that defines **aaa** (Fig. 5), and a tail that stretches past 3.5–3.8 Ga.

3.10. Gawler Craton

The Gawler Craton spectrum is from Camacho et al. (2002).

4. Age spectra of detrital zircons

4.1. Distribution in southwestern Australia and East Antarctica

The ages of zircons in protoliths of southwestern Australian and East Antarctica, including Prydz Bay, can be grouped into ten spans (Fig. 5; Table 2). The spans are modified from the Gondwanaland-wide groups of Veevers (2000, p. 110 *ff*) by comparison with the ages given in Sircombe and Freeman (1999), Cawood and Nemchin (2000), and Cawood et al. (2003). Fig. 5 shows the age spectra of detrital zircons (grey) and primary zircons in adjacent basement (black, with related detrital zircons in grey). Each peak or group of peaks in the detrital zircons can be found in the primary zircons except one, **ddd** (1.0–0.8 Ga), dealt with below.

Table 2
U–Pb ages (Ga) of primary zircons in igneous-metamorphic protoliths (e.g., 0.54–0.52) and of detrital zircons in sedimentary protoliths (e.g., 2.00–1.32)

Region	Sircombe and Freeman (1999)	Cawood and Nemchin (2000)	Cawood et al. (2003)	This paper	
Prydz Bay				**ddd**	1.00–0.80
Leeuwin	0.85–0.50	0.54–0.52		**d**	0.60–0.50
		0.78, 0.68		**dd**	0.725–0.65
		1.20–1.10		**c**	1.30–1.00
Albany	1.35–1.00	1.22–1.14	1.30–1.10	**c**	1.30–1.00
		1.35–1.28			
		1.70–1.60			
		2.40–1.32	2.70–2.00		
Fraser				**c**	1.30–1.00
				bb	1.40–1.30
				a	1.80–1.50
				aa′	2.60–2.50
				aaa	2.80–2.60
Capricorn		1.80, 1.62		**a**	1.80–1.50
		2.05, 1.96		**aa**	2.10–1.90
		3.50–1.70		**aaa**	2.80–2.60
Northampton		1.10–0.99		**c**	1.30–1.00
				bb	1.40–1.30
		2.00–1.15		**a**	1.80–1.50
				aa	2.10–1.90
Yilgarn	2.90–2.50	>2.60	>2.60	**aaa**	2.80–2.60
		4.30–3.00			
E Antarctica		0.55			
		1.00			
		2.80, 2.50			
		3.30			
		2.10–1.80			
		2.80–2.50			

In order of increasing age, the age clusters are as follows.

d (0.6–0.5 Ga), defined locally in the Leeuwin Block, is widespread in Gondwanaland (Veevers, 2003); it is found in all the sedimentary samples except those from Collie and the Triassic of the Perth Basin;

dd (0.725–0.650 Ga) is defined in the Leeuwin Block; it is found in the sedimentary samples except those from Collie and the Triassic of the Perth Basin (again), and the modern Eneabba sand.

ddd (1.0–0.8 Ga) is found in Ordovician and Permian sandstones east and south of the Northampton Block. Primary zircons or zircon-generating events of this age are unknown in the rest of Australia (Myers et al., 1996). The closest sources are the 0.99–0.90 Ga zircons in the conjugate Rayner province of East Antarctica, including Prydz Bay nearly 2000 km distant (Fig. 1, *inset*), and the Eastern Ghats of India (Fitzsimons, 2000, Fig. 3B; Mikhalsky et al., 2001).

c (1.3 –1.0 Ga). Rocks of this age were generated during the collision between proto-Australia and proto-Antarctica (Dawson et al., 2003). A symmetrical peak at ∼ 1.2 Ga is defined from the Albany Province and the related Fr3 Frankland River sand. This is also the age of mafic dykes in the southwestern Yilgarn Craton (Pidgeon and Cook, 2003). The peak is faithfully copied in the Collie sandstones and P154415 modern sand; all other sedimentary samples (except the Tumblagooda Sandstone and Eneabba sand) and the Northampton paragneiss contain abundant zircon ages within the 1.3–1.0 Ga range but with a peak or peaks other than 1.2 Ga. The main peak in the Fraser Province is offset 0.1 billion years to 1.3 Ga within a range of 1.345–1.260 Ga (Dawson et al., 2003), and passes into a saddle between 1.260 and 1.200 Ga that overlaps the Albany peak. Other basement peaks are the main Northampton one at 1.05 Ga and a minor one in the Leeuwin Block at 1.08 Ga. Neither peak at 1.3 Ga nor 1.05 Ga is unequivocally represented in the sedimentary samples. Another event in this range is the emplacement of the 1075 Ma Warkurna large igneous province across west-central Australia (Wingate et al., 2004).

bb (1.4–1.3 Ga) is defined as the older flank of **c** in the Fraser Province; it is found in all the sedimentary samples except the Tumblagooda Sandstone and the Waroona and Eneabba sands.

b (1.5–1.3 Ga) is defined from Trans-Laurentia; it is found in Tasmania but is absent in mainland Australia (Veevers, 2000, pp. 110, 128) except as its younger part (**bb**) in southwest Australia.

a (1.8–1.5 Ga) is defined in the Fraser Province, and reinforced by a 1.6 Ga mound and a 1.8 Ga peak in the Capricorn Orogen. Detrital zircon in this range is found in Frankland River sand, Northampton paragneiss, Permian Dongara Sandstone and Beekeeper Formation, Triassic Kockatea Shale, and modern Waroona sand.

aa (2.1–1.9 Ga) is defined in the Capricorn Orogen, Stirling Range Formation, and Mount Barren Group; it also appears in the Permian Irwin River Coal Measures, and the Wagina and Dongara Sandstones. 2.1–1.8 Ga is the span of global orogens (Zhao et al., 2002).

aa′ (2.6 – 2.5 Ga), not found in any terrane, is defined by detrital zircons in five of the sedimentary rocks in the northern Perth Basin and in the 2.6–2.5 Ga flank of the modern sands P154402-20 and Fr3.

aaa (2.8–2.6 Ga), defined in the Yilgarn Craton and Capricorn Orogen, and a common age in Archean cratons worldwide, is found in the Paleoproterozoic Mount Barren Group, Mesoproterozoic Stirling Range Formation, Permian Wagina and Dongara Sandstones and Beekeeper Formation, and the modern Eneabba, Waroona, P154402-20, and Fr3 sands. Zircons of this age are extremely rare to absent in the Ordovician Tumblagooda Sandstone, Permian Collie and Irwin River Coal Measures, and Triassic Cockatea Shale.

aaaa (3.05–2.90 Ga), defined in the Yilgarn Craton and Albany and Fraser Provinces, is found in the Mount Barren Group (2.977 Ga peak), and in the Wagina and Dongara Sandstones and Beekeeper Formation. Older zircons to a limit of 4.4 Ga (Wilde et al., 2001) are extremely rare.

4.2. Distribution elsewhere

Span **d** (0.60–0.50 Ga), restricted to Gondwanaland (Fig. 6), indicates Pan-Gondwanaland events (Veevers, 2003), and is represented in detrital zircons (Fig. 5w) and granitic bedrock (Fig. 6) of the nearby Himalayan Orogen (HO); span **c** (1.3–1.0 Ga—“Grenvillian”) is common in most continents, including nearby Himalayan India (Figs. 5w, x and 6). The age spectra of the sediments in the Himalaya Orogen (Fig. 5w and x) match those of the Permian sediments of the Perth Basin (Fig. 5e–j) because events of these ages are widespread in Gondwanaland. The matching spectra do not signify a common provenance because, as we show below, the Perth Basin sediments came from the south.

5. Proterozoic setting of southwestern Australia

5.1. Paleoproterozoic–Mesoproterozoic (1700 Ma) successions between the Albany-Fraser Orogen and the Yilgarn Craton (Fig. 7a)

Dawson et al. (2002) sketched a reconstruction of proto-Australia at 1700 Ma, with a formerly contiguous Pilbara-Gawler continental margin indented by the Yilgarn Craton such that the Pilbara-Yilgarn boundary is a sinistral megashear (Fig. 7a).

Fitzsimons (2003) outlined the later Proterozoic geodynamic history of southwestern Australia and conjugate Antarctica, as follows. During two stages of indentation of proto-Australia by a promontory of proto-Antarctica at 1350–1260 and 1210–1140 Ma, the Nornalup Complex collided with the Biranup Complex, Fraser Complex, and Yilgarn Craton to form the Albany-Fraser Orogen, including the coeval Wilkes Province of Antarctica (Fig. 7b). Dawson et al. (2003) point to the possibility that the ~ 1200 Ma stage reflects regional heating rather than collision or orogenic collapse.

The Pinjarra Orogen contains allochthonous 1100–1000 Ma gneissic blocks (Northampton, Mullingarra, Leeuwin) transported along the craton margin during dextral strike-slip at 750 Ma and sinistral strike-slip at 550–500 Ma during oblique collision of Australo-Antarctic and Indo-Antarctic domains, in a final assembly of Gondwanaland (Fitzsimons, 2003; Fig. 7c).

5.1.1. Paleoproterozoic Mount Barren Group

According to Dawson et al. (2002), the Mount Barren Group (MBG), >1250 m of conglomerate, sandstone, mudrock, and dolostone, is a fan delta supplied from locally exposed sedimentary rocks. It rests nonconformably on Yilgarn orthogneiss and was overthrusted by the Albany-Fraser Orogen at ~1300 Ma. Its depositional age of ~1700 Ma is indicated by SHRIMP U–Pb dating of early diagenetic xenotime (Vallini et al., 2002). Detrital zircons indicate a first-cycle provenance of felsic rocks with mean ages of 2977, 2645 (**aaa**), 2448, 2291, 2019 (**aa**), 1860, and 1792 Ma (old part of **a**) (Dawson et al., 2002; Nelson, 2001) (Fig. 5u). The nearest first-cycle provenance of the 2977 Ma (**aaaa**) and 2645 Ma zircons is the Yilgarn Craton itself. Potential first-cycle provenances of the younger zircons are the 1000-km distant Capricorn Orogen, which contains the three main peaks at 2645 Ma (**aaa**), 2019 Ma (**aa**), and 1860–1792 Ma (old part of **a**), and the 800-km distant Gawler Craton, which contains **aaa** and **a** (though with a significantly different full range of 1900–1500 Ga) but lacks **aa**.

The Gawler spectrum given here, from Camacho et al.'s (2002) probability curve of 50 ages, and the Capricorn spectrum, from a curve in Cawood and Nemchin (2000), differ from some of the peak ages given (in tabulated form only) by Dawson et al. (2002). On zircon-age spectra alone, a (now lost) foreland basin succession in the Capricorn Orogen is the preferred provenance of the younger zircons. In terms of contemporaneous tectonics (Dawson et al., 2002), the Yilgarn Craton, on a trajectory to the east-southeast, collided ~1800 Ma (Evans et al., 2003; Cawood and Tyler, 2004) along a sinistral transcurrent megashear with the Pilbara Craton to form the collision zone of the Capricorn Orogen, and at ~1725 Ma indented the rest of proto-Australia in the orthogonal Gawler Craton with the generation of a foreland basin. As advocated by Dawson et al. (2002), sediment recycled from the foreland basin would have supplied the zircons of younger ages, but the Gawler Craton lacks the peak at 2019 Ma.

The range of peak **a** (1.8–1.5 Ga) encompasses also the deformation of the Paterson Orogen (peak 1.8 Ga, Camacho et al., 2002), central Australian terranes, and south and north Australian cratons (Myers et al., 1996), as well as in the neighbouring Antarctic 1.9–1.5 Ga Rayner Province and 1.8–1.7 Ga Ross Province (Condie, 2002), so that zircons of this age are widespread.

5.1.2. Paleoproterozoic–Mesoproterozoic Stirling Range Formation

The Stirling Range Formation (SRF), >1600 m of shallow-water quartz sandstone and shale, probably in tectonic contact with the Yilgarn orthogneiss, has undergone greenschist facies metamorphism and several generations of deformation (Rasmussen et al., 2002). Low-grade metamorphic monazite dated (U–Pb SHRIMP) at 1215 ± 20 Ma (Fig. 5s) was generated during a major tectonothermal event that peaked at 1178 Ma in the Albany Province. The youngest detrital zircons ($n = 82$) are 2016 ± 6 Ma (major peak, **aa**) so that the age of deposition lies between 2016 and 1215 Ma. Other ages of detrital zircons are 2.16, 2.25, 2.30, 2.43, 2.65, 2.70, 2.75 (last three **aaa**), 3.15, 3.18, and 3.46 Ga. The spectrum of the Stirling Range Formation matches those parts of the Capricorn Orogen and the Mount Barren Group spectra older than 1.9 Ga; suggesting (Fig. 7a, arrow) a common provenance in the Capricorn Orogen or a provenance of similar age elsewhere. The main peak between 1.9 and 1.7 Ga in the Mount Barren Group spectrum is lacking in the Stirling Range Formation, possibly indicating that the Stirling Range Formation was deposited at its maximum age of 2.0 Ga.

The deposition on the southern Yilgarn Craton of the shallow-water Mount Barren Group at 1.7 Ga and of the Stirling Range Formation some time between 2.0 and 1.2 Ga means that the Yilgarn Craton at these times was covered by the shallow water of a lake or sea at the foot of a paleoslope that stretched northward through the provenances of the Yilgarn craton and uplifted Capricorn Orogen (grey) along the northern suture zone.

5.2. Albany-Fraser Orogen and the Yilgarn Craton 1350–1140 Ma (Fig. 7b)

The 1700 Ma transpressional collision on the northern margin of the Yilgarn Craton is followed 350 million years later by collisions on the southeast. This is the first appearance of high ground on the southern and southeastern sides of the Yilgarn Craton. No detrital zircon data from contemporaneous sediment are available for this event, and the figure is simply a tectonic reconstruction, with the arrow indicating downslope to the northwest.

5.3. 840 Ma Gunanya Sandstone of the northwestern Officer Basin

High ground appeared again in the northwest during deposition of the 840 Ma Gunanya Sandstone at the base of the Centralian Superbasin (Walter and Veevers, 2000) in the northwestern Officer Basin (Fig. 8A), in the area immediately north of the map area of Fig. 7. As shown by Bagas (2003), the Gunanya Sandstone, deposited from east- to northeast-paleocurrents (arrow), contains detrital zircons whose ages indicate derivation from the northern part of the Paleoproterozoic Gascoyne Complex, Mesoproterozoic Bangemall Supergroup, and Meso- to Neo-Proterozoic Pinjarra Orogen, which lie along reciprocal bearings of the paleoslope to the southwest and west. In the succeeding 830 Ma succession, the westward facies change from detrital sand to carbonate indicates a continuing source of detritus in the west.

The dearth of Archean (**aaa**) zircons suggests that the Yilgarn Craton was subdued.

6. Paleozoic and Mesozoic southwestern Australia

From their study of detrital zircons from the Ordovician and Permian–Triassic sedimentary rocks of the northern Perth Basin, Cawood and Nemchin (2000) found that, as in the modern sands, most zircons from the Ordovician and Permian–Triassic sedimentary rocks were derived from 1.80–0.50 Ga provenances in the south (Leeuwin Block and Albany-Fraser Orogen) and few from the Archean Yilgarn Craton. Zircons from Triassic sandstones have a narrow range of 1.85–0.97 Ga, reflecting a radical change in basin paleogeography that led to cessation of input from the Yilgarn Craton and Leeuwin Block.

6.1. Cambrian–Ordovician (490 Ma) Tumblagooda Sandstone (Fig. 7c)

According to Hocking (1991), the 1200-m-thick Tumblagooda Sandstone of Late Cambrian–Early Ordovician age (Gorter et al., 1994) was deposited on either side of the (then low-lying or covered) Northampton Block in braided rivers and alluvial fans at the foot of a northwestward paleoslope underlain by the Yilgarn Craton. From the dearth of zircons of Yilgarn age in their Tumblagooda sample (PB7), Cawood and Nemchin (2000) inferred a subdued Yilgarn Craton with rivers entrenched in their own alluvium flowing down a northwest-dipping paleoslope (arrow) across an inferred step at the Darling Fault. Direct evidence in this area and time of an upthrown Yilgarn Craton along the Darling Fault is lacking. The braided-river sandstone is succeeded by coastal sandstone with trace fossils and conodonts, so that the depositional structures could be delta (not alluvial) fans prograding down a continuous northwest slope into a shallow sea.

Deposition of the Tumblagooda Sandstone followed the final assembly of this part of Gondwanaland by the oblique collision of Indo-Antarctic and Australo-Antarctic domains. The allochthonous 1100–1000 Ma gneissic blocks (Northampton, Mullingarra, Leeuwin) of the Pinjarra Orogen were transported along the craton margin during sinistral strike-slip at 550–500 Ma, dragging the western part of the Albany Province through 90° (Fitzsimons, 2003). As argued below, the most intense uplift and erosion (solid black) was in the southern part of the system, in the Prydz-Leeuwin Belt.

Evidence of the history of the western Yilgarn Craton south of 32°S comes from Libby and de Laeter (1998). Rb–Sr ages of biotite in the Yilgarn Craton range from 2500 Ma in the east to 430 Ma in the western margin at the Darling Fault. A similar range of ages is found in the Albany Province and conjugate Antarctica. Libby and de Laeter (1998), supported by Nemchin and Pidgeon's (1999) recognition of a 500–400 Ma disturbance of the U–Pb isotopic systems in apatite from the Darling Range Batholith, interpreted the biotite data as indicating a reheating event at 500 Ma that followed tectonic loading by thrusting from the west. Fitzsimons (2003) links the resetting "to the sinistral transcurrent movement that caused pervasive deformation and metamorphism in the Leeuwin Complex and Albany-Fraser margins at 550–500 Ma"; this was part of the terminal heating in the Prydz-Leeuwin Belt during the oblique collision of the Australo-Antarctic and Indian-Antarctic domains. Uplift by erosional rebound caused the biotite dates to be reset at about 430 Ma as the western zone passed upward through the 320°C isotherm representing the blocking temperature of the Rb/Sr isotopic system. The uplifted western domain deflected the interior drainage along a north–northwest axis (arrowed dotted line) which bypassed the locality of sample PB7. Zircons from the erosion of the western domain are also absent in PB7, probably because they were grossly diluted by those from the south.

The main age groups of PB7, **d** and **dd** (both potentially from the Leeuwin Block), and **ddd** (from Prydz Bay), indicate a regional slope from the uplifted Prydz-Leeuwin Belt in the south (black) to the shoreline in the north; northward drainage was deflected (? by the forebears of the NNW-trending Wicherina and Urella Faults) to the northwest to debouch into the sea in a complex of braided rivers and fan deltas.

6.2. Carboniferous–Permian (300 Ma) glacigenic deposits (Fig. 7d)

Widespread glacigenic deposits provide much information on the paleogeography, as outlined below.

The ancestral Great Western Plateau (Veevers, 2000, p. 300), underlain by the Yilgarn and Pilbara Cratons, was covered by ice during the Late Carboniferous Gondwanan glaciation. When the ice melted at the end of the Carboniferous (300 Ma), the glaciated upland (diamond pattern) became strewn with glacial deposits, and the rapidly subsiding peripheral basins on all sides but the south filled with glacial outflow deposits, all as part of the basal Pangean Supersequence (Veevers, 1990). A typical succession is tillite and melt-out conglomerate and sandstone surmounted by bluish-grey or greenish claystone or shale, deposited from suspension in the quiet water of lakes or of the shallow sea on the west.

In the Collie Basin, the Stockton Formation of 330 m of basal tillite and bluish-grey claystone rests on the striated polished surface of the Yilgarn Craton with ~ 200 m topographic relief (Wilson, 1990). The ice vector runs down the paleoslope, indicated by the 341° vector of fluvial transport in the coal-measure sandstone that overlies the glacials (Veevers, 2000, p. 122). In the same area, Backhouse and Wilson (1989) found palynomorphs in a claystone in a drillhole 3 km south of Donnybrook and 1 km east of the Darling Fault with age equivalent to that of the Stockton Formation.

On the eastern margin of the Yilgarn Craton (Eyles and de Broekert, 2001), "open-cut mines [squares] near Kalgoorlie in the Eastern Goldfields region expose a Carboniferous–Permian network of glacially eroded valleys filled with [up to 80 m of] tillite and shale." Drillholes at Ponton Creek (PC) and nearby Cundeelee, within 10 km of the outcropping Yilgarn Craton, penetrated 500 m of Early Permian tillite and sandstone with dropstones overlain by silty shale (Alan Whitaker, Geoscience Australia, pers. comm., 2002), which Eyles and de Broekert (2001) interpret as the fill of valleys overdeepened by glacial flow toward the southeast. The preservation of sediment on a relict Permian glacial topography in the Eastern Goldfields indicates that post-Permian erosion of the region was minimal, though hypothetically much thicker younger Permian sediment could have been removed. The maximum preserved thickness of 500 m suggests that the local bedrock relief was of this magnitude. The valleys fed sediment to outwash fans in the 450-m-thick glacigenic Paterson Formation of the Officer Basin (Iasky, 1990).

The northern Perth Basin contains the 1500-m-thick glacio-marine Nangetty Formation of tillite, sandstone and shale overlain by the 450-m-thick shallow-marine (Sakmarian) Holmwood Shale, with non-marine equivalents in the south (Cockbain, 1990). Erratics in the Nangetty Formation suggest ice movement towards the north-northwest, the same as in the Collie Basin.

In the Carnarvon Basin (Hocking, 1990a), 2750 m of glacially influenced deposits comprise the Lyons Group of diamictites, erratic clasts, and varves, deposited on a rapidly subsiding marine shelf beneath a floating ice sheet, and the Callytharra Formation of claystone and carbonate deposited on a quiet shelf during the post-glacial (Sakmarian) sea-level rise. Bedrock was smoothed and striated by the ice (Playford, 2001).

That part of the region west of 120°E sloped north-northwestward from high ground in the south (ruled black pattern of the Wilkes Province, solid black of the Leeuwin Block and Albany Province) along a depositional axis that accumulated 330 m of glacigenic sediment at Collie, through 1950 m in the northern Perth Basin, to 2750 m in the Carnarvon Basin. The Darling Fault line was probably a hinge between the subsiding Perth-Carnarvon Basin and the gently sloping craton and not a scarp, which did not develop until the Late Permian. The craton east of 120°E stood more than 500 m above sea-level and was incised by glacial valleys that drained eastward into the Officer Basin.

6.3. Early Permian (Artinskian, 275 Ma) coal measures (Fig. 7e)

The only known deposits of younger Permian age to have been preserved on the Yilgarn Craton are the Collie Coal Measures, a 1120-m-thick succession of 5- to 15-m-thick cycles of sandstone, siltstone, claystone, and coal deposited in an extensive braided-river floodplain with swamps. The original relief during glaciation was eliminated by glacigenic sediment before the onset of coal-measure deposition (Wilson, 1990). From Wilson's (1989) paleocurrent mean trend to the northwest, Veevers (2000, p. 122) inferred that the provenance lay along the reciprocal bearing to the southeast, in a range that extended from the proximal Albany Province to the distal Gamburtsev region of East Antarctica.

"There is no evidence that the Collie Basin acted as a depocentre surrounded by inwardly dipping palaeoslopes" (Wilson, 1989), and "This conclusion implies that the northwestern and southeastern edges of the basin, which lie along known lineaments, are faults rather than valley sides" (Wilson, 1990). It follows that the southwestern part of the Yilgarn Craton was probably covered by a sheet of Permian glacial and coal-measure sediment (diamond pattern) subsequently stripped off except at Collie where the 1450-m-thick succession is preserved in downfaulted outliers.

Critical evidence pertaining to provenance comes from the Early Permian sample SWY6 (Figs. 3 and 5), which though deposited on the Yilgarn Craton lacks Yilgarn-age (**aaa**) zircons. As noted above, the surface of theYilgarn Craton was probably covered by a sheet of earlier Permian glacigenic sediment that prevented any detritus from the southernmost Yilgarn Craton entering the (presumably alluviated) rivers that flowed along strike north-northwestward (341°) from the Albany Province through Collie to the Perth Basin. The spectra of the Collie samples are effectively confined between 1.8 and 1.0 Ga, with a single peak age **c** with a pediment **bb** (Fig. 5k and l). The closest comparison is with the (immediately upslope) Albany Province and (more distant) Fraser and Wilkes Provinces. According to Wilson (1990), the clast and heavy-mineral suite (Glover, 1952) could have been derived from the nearby Archean Balingup Gneiss Complex and the granitoid terrane to the east but the lack of Yilgarn-age (**aaa**) zircons seems to rule out this possibility.

The geochemistry of the 1300–1100 Ma zircons from both Collie samples (Fig. 3) indicates host rocks with these compositions. Of the 70 zircons analysed, 55 (79%) indicate a granitoid with < 65% SiO_2 (mafic), 10 (14%) a granitoid with 70–75% SiO_2 (felsic), 4 (6%) mafic rocks, and 1 (1%) carbonatite. The Albany Province, the northwestern-most part of the Albany-Fraser-Wilkes Orogen, contains the ~1200 Ma Burnside Batholith and associated plutons, comprising granodiorite, adamellite, and granite (Wilde and Walker, 1984). The Burnside Batholith was sampled by the modern sands P154415 and P154402-20. Of the 25 1300–1100 Ma zircons analysed, 16 (64%) indicate a granitoid with < 65% SiO_2, 7 (28%) a granitoid with 70–75% SiO_2, and 2 (8%) mafic rocks, in the same order of abundance as those in the Collie zircons. In contrast, the 93 samples of granitoids from the south coast Albany area between 117.25°E and 118.50°E (Table 3; Stephenson, 1973, 1974) are dominantly felsic (two-thirds contain >70% SiO_2). But the Hf data appear to discriminate between the Collie and modern samples. The modern sand samples, which indubitably reflect the Burnside Batholith, differ in their Hf data: P154415 zircons in the ~1200 Ma cluster have a mean $\varepsilon_{Hf} = -11.27$ and the model age (T^{C}_{DM}) of the source is 3.20 to 2.16 Ga, with a mean of 2.67. In the Collie zircons in the same age cluster, mean $\varepsilon_{Hf} = 0.37$ and the model age (T^{C}_{DM}) of the source is 2.18–1.71 Ga, with means of 2.00 and 1.96 Ga. These values correspond with the youngest range (T_{DM} = 2.1–1.8 Ga) of the Albany Province. Accordingly, we suggest that the provenance of the Collie zircons lay between the Burnside Batholith and the felsic granitoids in the coastal exposures or farther south still, possibly in the Wilkes Province. Incidentally, the structure of the Wilkes Land lithosphere is comparable to that of the Albany-Fraser Orogen (Reading, 2004).

Table 3
Percentage silica in granitoids from the Albany Province

Granitoid		SiO_2 %	Reference
Albany Adamellite	$n=28$	69–76	Stephenson, 1974
Torbay Adamellite			Stephenson, 1974
orthopyroxene	$n=3$	65	
equigranular	$n=4$	65	
porphyritic (main part)	$n=8$	70	
microadamellite dykes	$n=1$	73	
Mt Manypeaks Adamellite			Stephenson, 1973
coarser-grained granitic gneiss	$n=5$	67–69	
finer-grained granitic gneiss	$n=10$	73–77	
dioritic gneiss	$n=8$	53–59, 65–70	
gneissic facies	$n=4$	65–70	
gneissic facies	$n=7$	70–74	
massive facies	$n=10$	70–75	
microadamellite	$n=5$	68–71	

Downslope from Collie, as part of a northward regression of the shoreline in the northern Perth Basin, the Artinskian Irwin River Coal Measures prograded across a coastal plain to debouch in the Carnarvon Basin as the northwestward-thickening delta complex of the Moogooloo/Cordalia Sandstone (Hocking, 1990a). Mory and Iasky (1996) described paleocurrent data from the outcropping Irwin River Coal Measures on the Irwin Terrace, no more than 5 km from the Darling Fault, as supporting deposition in a deltaic environment by showing "a radiating pattern from the east". The six actual directions shown in their Fig. 10 are (in order from south to north) N, NNW, NE, E, NE, SW, all but the last measurement consistent with paleoflow towards (and not from) a subdued Yilgarn Craton, and contradicting "from the east". This explains the lack of **aaa** (2.8–2.6 Ga, Yilgarn) zircons (Cawood and Nemchin, 2000). As in the other sedimentary rocks in the northern Perth Basin, the Irwin River Coal Measures contain zircons **d**, **dd**, and **ddd**, derivable from the south (Leeuwin Block and Prydz Bay—long arrow) and, blended with **c**, **bb**, and **aa**, all derivable from the southeast, but lacking **aaa** (Yilgarn). Purple zircons in the coeval Collie and Irwin River Coal Measures (Glover, 1952) provide another similarity.

The peak age (**c**) and Nd and T_{DM}^{C} model ages of zircons in SWY6 and PB9 reflect those of bedrock zircons in the Albany and Wilkes provinces; the lower range of Nd ages in PB9 (1.98–1.40 Ga) and its other peak of **d** indicate a second provenance in the Leeuwin Block, with Nd ages of 1.6–1.1 Ga. We conclude that fluvio-deltaic flow was probably continuous from Collie through the Irwin River (IR) area to its mouth in the Carnarvon Basin from provenances in the south and south-southeast, the most proximal of which are the Albany and Wilkes Provinces.

6.4. Late Permian (255 Ma) (Fig. 7f)

The Late Permian (260 Ma) sample SWY5 of the Collie Coal Measures, with the same spectrum and geochemistry as in the Early Permian sample SWY6, indicates continuing drainage from the upland of the Albany-Fraser-Wilkes Orogen.

Sample SWY5 comes from the youngest preserved part of the Collie succession. The post-Permian removal of the entire 300–260 Ma 1.5-km-thick sheet of Permian sediment except at downfaulted Collie would have recycled detrital zircons of ages **a** (1.8–1.5 Ga), **bb** (1.4–1.3 Ga), and principally **c** (1.3–1.0 Ga) into peripheral basins, in particular to the Perth Basin, with its thick succession of Mesozoic and Cainozoic sediments. The only samples exclusively within this range of zircon ages are from the Early Triassic Kockatea Shale (**a**, **bb**, **c**) (Fig. 5c and d), but a readier source is the proximal Northampton Block, with a similar zircon spectrum. Detrital zircons of **a** and **c** in the modern Waroona sand (Fig. 5b) could have been recycled in turn from any of the Permian and Triassic sedimentary rocks of the northern Perth Basin.

Following uplift and erosion in the northern Perth Basin, the braided-stream deposit of the Late Permian Wagina Sandstone rested with an abrupt low-angle unconformity on the Irwin River Coal Measures and Carynginia Formation, and signifies the onset of a regime of rift faulting that continued intermittently to continental breakup in the Cretaceous (Cockbain, 1990). The Wagina Sandstone (PB6) is interpreted as an alluvial fan delta centred at the Darling Fault and as a coal-swamp sandstone around the Northampton Block, and the overlying Dongara Sandstone (PB1-3) as a deltaic deposit that prograded into a shallow sea. With the continued Late Permian marine transgression over the northward paleoslope, the Beekeeper Formation (PB5) was deposited at the edge of an open sea. The age spectra of zircons from the Late Permian rocks of the northern Perth Basin contain all the recognised clusters in the range 2.8–0.5 Ga, with **c** (1.3–1.0 Ga) predominant. Potential provenances of the zircons aged **aaaa** and **aaa** are the Yilgarn Craton; **aa′**, an unknown provenances; **aa**, the Capricorn Orogen, Stirling Range Formation, Mount Barren Group; **a**, the Capricorn Orogen, Northampton Block, Albany and Fraser Provinces, Mount Barren Group, and Gawler Craton; **bb** and **c,** the Northampton Block and Albany and Fraser Provinces; **ddd**, Prydz Bay; **dd** and **d**, the Leeuwin Block. We interpret the main provenances to have been the newly uplifted Northampton Block (**a**, **bb**, **c**), with its surface of Tumblagooda Sandstone (**ddd**, **dd**, **d**), and the rift shoulder of the Yilgarn Craton (**aaa**) newly risen along the Darling Fault.

Zircons in the **c** (1300–1000 Ma) peak of the Beekeeper Formation have mean ε_{Hf}, T_{DM}^{C}, and source composition comparable to those of the overlying Kockatea Formation sample PB8 and coeval Muja Coal Measures SWY5, except the latter come mainly from mafic granitoids. This suggests that the provenance of the Beekeeper Formation resembled that of the Kockatea Formation (Northampton Block) more than that of the Muja Coal Measures (Albany Province).

Sediment from the distal south would have been diluted by sediment from the proximal Northampton Block. Moreover, sediment from the southeast provenances would have been blocked by the rising rift shoulder at the crest of a long eastward to southeastward slope (cf. the slope of Arabia away from the rim that overlooks the Red Sea) that ends in the sump of the Great Australian Bight. In effect, this reversed the NW slope that had prevailed since 490 Ma (Fig. 7c).

6.5. Early Triassic (245 Ma) (Fig. 7g)

No sediment of Triassic age is known on the Yilgarn Craton, but reworked material from the craton associated with Devonian, Permian, and Triassic palynomorphs in Early Cretaceous sediment of the Perth Basin points to missing sections of these ages.

In the northern Perth Basin, the Early Triassic Kockatea Shale contains a basal strandline sandstone (Cockbain, 1990). At outcrop (PB8) the sandstone rests unconformably on the Northampton Block, and at the location of PB4, in a drilled section, it rests unconformably on Late Permian sediments. Both sands were analysed by Cawood and Nemchin (2000) for zircon ages. Confined to 1.85–0.97 Ga (**a**, **bb**, **c**), as represented in the nearby upstanding Northampton Block, the ages indicate cessation of input from the >1.8 Ga (**aaa**, **aa**) and <1.0 Ga (**ddd**, **dd**, **d**) provenances additionally represented in the Late Permian deposits. We interpret the Early Triassic spectrum as reflecting the continuing uplift of the Northampton Block (**a**, **bb**, **c**) from which the Tumblagooda Sandstone (**ddd**, **dd**, **d**) had been stripped in the Late Permian, and the impounding of **d** and **dd** sand from the Leeuwin Block and **aaa** from the western, scarped, edge of the Yilgarn Craton along the shoreline that advanced up the paleoslope during the Early Triassic transgression. Coarse fluvial sandstone continued to accumulate in the southern Perth Basin, marking the southward extension of faulting and uplift along the Darling Fault (Cockbain, 1990). The rift shoulder of the Yilgarn Block would have blocked sediment with **a**, **bb**, **c** zircons recycled from the lost section of Permian sediments, now represented in the remnant outlier at Collie, leaving **aaa** (Yilgarn) zircons untapped.

The zircons in the 1300–1000 Ma peak of PB8 were also analysed for Hf isotopes. Mean $\varepsilon_{Hf} = 0.55$,

T^{C}_{DM} ranges from 2.39 to 1.37 Ga, with a mean of 1.95 Ga, and the zircons were derived from twice as many felsic as mafic granitoids. All these indicators are similar to those in the nearby sample PB9 from the Early Permian Irwin River Coal Measures except T^{C}_{DM} is 0.4 billion years older, and reflects input from the Pinjarra Orogen (T_{DM} = 2.2–2.0 Ga) and Northampton Block (T_{DM} = 1.9–1.6 Ga).

6.6. Late Triassic (225 Ma) (Fig. 7h)

Because no ages of detrital zircons from Late Triassic or younger rocks are known, the maps for this and later times are constructed from sedimentary evidence only.

In the Late Triassic, at a time of global rifting (Veevers, 1990) and after the sea had retreated from the Perth Basin, the alluvial-fan to fluvial Lesueur Sandstone was deposited in response to continued major upfaulting of the Yilgarn Craton. In the northern Perth Basin, 3000 m of sandstone at the foot of the Darling Fault wedge out downslope some 150 km to the northwest (arrow). "Palaeocurrents directions from planar crossbeds are largely to the northwest and, together with the high proportion of feldspar [and 2-cm-long crystals], suggest a provenance from a [proximal] granitic source" (Mory and Iasky, 1996). Sediment flow to the northwest probably merged with the northward flow from the Prydz-Leeuwin Belt.

6.7. Early Cretaceous–Berriasian (140 Ma) and Aptian (116 Ma) (Fig. 7i)

In the outcrop area in the northern Perth Basin (Mory and Iasky, 1996), the Jurassic-Cretaceous (147–137 Ma) Parmelia Formation of fluvial feldspathic sandstone with minor lacustrine siltstone and claystone conformably overlies the similar Yarragadee Formation. Paleocurrents to northwest and southwest (arrows) could reflect radial flow in an alluvial fan. Pebbles of red, white, and black jasper near the base match the Proterozoic outlier of the Noondine Chert to the northeast. The basal (Otorowiri) member contains reworked Devonian, Permian, and Triassic palynomorphs, possibly indicating sediment of this age stripped from the adjacent Irwin Terrace or, with the jasper pebbles mentioned above, eroded from the postulated cover of the Yilgarn Craton (box). Reworked Early Permian and Early Triassic palynomorphs are found through the rest of the column, most likely from upthrown blocks within the Perth Basin or less likely from east of the Darling Fault, including the Collie (C) area (box). These suggestions of Devonian, Permian, and Triassic sedimentary sources on the Yilgarn Craton may reflect the missing section.

The Parmelia Formation thickens to 8 km in the Vlaming (V) Basin and signifies the extreme extension that preceded the 132 Ma continental breakup on the west (broken line) between Australia-Antarctica and Greater India (Cockbain, 1990). On the south, Australia and Antarctica had undergone extension (double-headed arrow) from 160 Ma preceding breakup at 99 Ma (Veevers, 2000).

The Nakina Formation, 30 m of sandstone and claystone with an Early Cretaceous (Aptian, 116 Ma) microflora, was deposited unconformably on the Collie Coal Measures (Wilson, 1990). Further occurrences nearby are known at Donnybrook (DO) and in the Boyup Basin (Backhouse and Wilson, 1989), 40 km south of Collie. The deposition and preservation of the Nakina Formation indicate that the Collie area resumed subsidence by relaxation of the rift shoulder following continental breakup at 132 Ma. The setting of the Perth Basin changed from a rift valley to a wide marine gulf and finally to a continental margin. Deposits were laid down in valleys cut into the Darling Scarp and as the sea advanced across the basin it filled them with shoreline sandstone (Cockbain, 1990), and possibly caused the impoundment of the nonmarine sediment at Collie by raising base-level.

In the Eucla Basin, marine pyritic sandstone and shale that lapped onto the Albany-Fraser Orogen (Hocking, 1990b) are continuous to the north, in the Officer Basin, with marine siltstone and sandstone fringed by nonmarine sandstone (Iasky, 1990), all part of an epeiric sea.

Before Cretaceous breakup, the southern margin adjoined East Antarctica, such that the 1.2 Ga Albany and Fraser provinces and the coeval Wilkes province were a single terrane, and the Darling Mobile belt continued along strike into the Prydz Bay-Denman Glacier province (Fitzsimons, 2000) as part of the Prydz-Leeuwin belt (Veevers, 2000).

From the distribution of Aptian-Albian marine sediment across much of interior Australia, Veevers (2000, p. 98) inferred a topography similar to that of today but with general elevation a few hundred metres lower, entailing this amount of subsequent uplift. The Yilgarn and Pilbara Cratons apparently formed a wide projection lapped by the sea on all sides but the south.

With the retreat of the epeiric sea at the beginning of the Late Cretaceous, at the time of breakup and very slow spreading along the southern margin, the Yilgarn Craton became deeply weathered and lightly etched with a dendritic drainage system.

6.8. Eocene (35 Ma) (Fig. 7j)

The drainage system incised into the Albany-Fraser Orogen and the Yilgarn Craton (Hocking, 1990c; Morgan, 1993; Langford et al., 1995) accumulated middle Eocene fluvial (line) and lacustrine (grey) deposits, including brown coal, which were drowned by late Eocene marine siltstone and spongolite deposited behind the transgressive shoreline (broad broken line) (Hocking and Cockbain, 1990), at a time when spreading in the Southeast Indian Ocean accelerated and Australia finally separated along western Tasmania from Antarctica. In the process, Australia began to move northwards into warmer sub-tropical latitudes to expand the arid zone throughout the inland that caused the degradation of the drainage system (Williams, 2000).

From a hypsometric analysis, Veevers (2000, p. 94) deduced that late Eocene shallow marine sediment at a present elevation of 250 m inland and 0 m at the coast indicates subsequent uplift of 190 m (above a +60 m Eocene sea level) by tilting about a coastal hinge, which, according to Hocking and Cockbain (1990), took place in the Oligocene.

In the Perth Basin (Cockbain, 1990), middle and late Eocene siltstone and carbonate extend offshore from the present coast, and in the Carnarvon Basin extend to the Darling Fault line.

Subsequently, an early Miocene transgression that skirted the Albany-Fraser coast and penetrated (as in the Eocene) into the Eucla Basin left middle Miocene limestone on the Nullarbor Plain at a present elevation of 200 m inland and 0 m at the coast, indicating subsequent uplift of 160 m (above the +40 m Miocene sea level) by tilting about a coastal hinge (Veevers, 2000, p. 93).

6.9. Quaternary (2–0 Ma) (Fig. 7k and l)

The Quaternary climate of Australia is characterised by global glacial–interglacial cycles, exemplified by the current cycle of glacial aridity during the 18 ka Last Glacial Maximum (LGM) and 9 ka warm, wetter interglacial maximum. In southwestern Australia, the eolian dunes, last shaped in the LGM, are oriented such that they were driven by winds from west to west–northwest (Hocking and Cockbain, 1990; Williams, 2000).

Sircombe and Freeman (1999) found that only <11% of zircons in the modern placer sands in the Perth Basin, which lie no more than 60 km from the Archean Yilgarn Craton, are of 2.8–2.5 Ga age. They inferred from this that the Yilgarn Craton contributed little sediment in the Mesozoic and Cainozoic to the Perth Basin, against the long-held assumption that the Yilgarn Craton dominated as a provenance. Instead they found that the modern placer sands were probably derived ultimately from Proterozoic orogens marginal to the Yilgarn Craton, among them the Pinjarra Orogen including the Leeuwin Block to the west, and the Albany-Fraser Orogen to the south.

Cawood et al. (2003) traced zircons from the headwaters of the Frankland River in the Yilgarn Craton to its lower reaches in the Albany Province. They found that Yilgarn detritus fell from 100% in the headwaters to 25% in the lower (incised) reaches by dilution from the Albany Province.

The Nd model ages (in Ga) of granites and gneisses of the subdivisions of the Yilgarn Craton, from Fletcher et al. (1994), are effectively T_{DM}, with the same or similar constants as in Fitzsimons (2003), and are augmented by T_{DM} of the Eastern Goldfields (Champion and Sheraton, 1997) and T_{DM} by Hf isotopes from the northern Yilgarn Craton (Griffin et al., 2004). The full range of the Yilgarn Craton, 3.8–2.6 Ga, with peaks at 3.2 and 3.0 Ga, is overlapped by the model ages of P154415 and duplicated by the 3.04 Ga model age of P154402-20. Sand samples shown are Fr21, from the headwaters of the Frankland River, with peak age of 2.65 Ga (Cawood et al., 2003), and the samples described above, P154415 with T_{DM}^{C} model ages and P154402-20 with T_{DM}, both with the peak ages shown by the letter symbols.

Yilgarn (Archean) detrital zircons (grey broken-line pattern in Fig. 7l) are found in samples P154402-20 and not in P154415, explained by zircons being blown in from the Yilgarn Craton to P154402-20 during the intensely windy LGM 18 000 years ago but not blown from the Frankland River to P154415 today.

Zircons from Australian continental dunefields were analysed by Pell et al. (1997). They found (1) that each desert consists of material from several protosource areas, some local, others up to 850 km away; (2) that most of the protosource areas no longer contribute sediment to the dunefields, reflecting changes in climate and sediment transport; (3) that most sand material has been reworked from older fluvial and marine deposits. From a study of the Great Victoria Desert of South Australia-Western Australia, Pell et al. (1999) concluded that the sand was derived mainly from local bedrock with very little subsequent eolian transport. The arguments were countered by Wopfner and Twidale (2001).

7. Denudational history of the Yilgarn Craton since 300 Ma (Fig. 9)

The denudational history of the Yilgarn Craton since 300 Ma is indicated by direct evidence from apatite fission-track analysis and vitrinite-reflectance data.

7.1. Apatite fission-track analysis

Kohn et al.'s (2002) analysis of southwestern Australia from 300 Ma to the present is based on samples from the Archean Yilgarn Craton and adjacent Proterozoic terranes south of 30°S and west of 124° (Fig. 1, *inset*). The chronology is marked by these denudation rates: (1) Rising from 300 Ma (Carboniferous–Permian), a broad maximum (shaded) of >14 m/Ma between 270 (Early Permian) and 165 Ma (Middle Jurassic) with peaks at 245 Ma (Early Triassic) and 200 Ma (Early Jurassic), entails denudation of >14 m/Ma × 105 million years ≥ 1470 m, equivalent to the initial thickness of the Permian strata at Collie (>1350 m). (2) A second maximum (shaded) of >5 m/Ma between 50 Ma (early Eocene) and 22 Ma (early Miocene) with a peak of 10 m/Ma at 35 Ma (late Eocene), entailing denudation of >5 m/Ma × 28 million years ≥ 140 m.

Denudation starting at 300 Ma (Carboniferous–Permian) corresponds with the widespread extension in Gondwanaland (Syn-Rift I of Song and Cawood, 2000), and concomitant accumulation of glacigenic sediment at the base of the Pangean Supersequence (Veevers, 1990). According to Etheridge and O'Brien (1994), initial extension involved 100% to 400% northwest–southeast extension beneath most of the present continental shelf of the western margin. In the southwest, extension led to the accumulation of the Stockton Formation in the Collie Basin and other glacigenic deposits on the Yilgarn Craton and the Nangetty Formation of the Perth Basin (Fig. 7d).

7.2. Vitrinite-reflectance data from Collie

The only younger (post-glacial) Permian rocks preserved on the Yilgarn Craton are the Collie Coal Measures (Fig. 7e). The original relief during glaciation was eliminated by glacigenic sediment before the onset of coal-measure deposition, all subsequently stripped off except in the Collie area where it is preserved in downfaulted outliers.

From vitrinite-reflectance data of Collie coals, Le Blanc Smith (1993) inferred that maximum coal burial temperature was possibly up to 100°C and that ~6.5 km of missing section were removed since the youngest age of deposition of 260 Ma. Using a lower assumed surface temperature from a constant heat-flow model appropriate for a sedimentary blanket overlying the crystalline basement, Kohn et al. (2002) revised this estimate to ~4 km. They found that "the vitrinite reflectance data and the apatite fission track data suggest that a substantial thickness of Upper Palaeozoic [and Mesozoic] sedimentary rocks extended across the crystalline rocks of the study area, and that the Collie and adjacent basins are preserved outliers of this accumulation." This entails a total thickness of sediment at Collie of 1.35 km of preserved Permian rock together with ~4 km of subsequently removed Mesozoic rock for a total ~5.35 km. The maximum extent of the missing section is indicated in Fig. 7d–h by the diamond pattern. If, as depositional trends suggest, the basin structure at Collie is typical of the wider area, then the thickness of the missing section elsewhere on the southwestern Yilgarn Craton would be the same (Freeman, 2001; Le Blanc Smith, 1993). A volumetric study (cited by Kohn et al., 2002) of Paleozoic and Mesozoic sediment deposited in the Ordovician and younger basins that flank the Yilgarn and Pilbara Cratons led to an estimated thickness of ~4 km of rock removed from the cratons at an overall average denudation rate of ~9 m/Ma. As noted above, the denudation rate from apatite fission-track analysis (Fig. 9) exceeded 14 m/Ma during the Permian–Jurassic, well above the overall rate.

A postulated 5-km-thick Permian and Mesozoic sedimentary blanket over the 0.5×10^6 km^2 Yilgarn Craton would resemble the Colorado Plateau of similar area with a 3-km-thick Permian and Mesozoic sedimentary blanket on Mesoproterozoic basement (Cook and Bally, 1975). A notable difference is the fate of the cover: all but a few fragments of the Yilgarn cover were removed soon after it was deposited, possibly because it was elevated during the Mesozoic as shoulders of the rift-valley systems that preceded breakup along the western and southern margins. The postulated thick cover explains the minor contribution of **aaa** (Archean) zircons and the major contribution of possibly recycled **c** (1.3–1.0 Ga) zircons in the Permian and Triassic samples from the Perth Basin.

7.3. Sediment-accumulation rate in the Perth Basin

Accelerated denudation from 270 Ma corresponds with the lacuna between the Irwin River Coal Measures and the Wagina Sandstone, seen in the detrital zircons of the northern Perth Basin formations that overlie the low-angle unconformity (Fig. 7f). Accelerated denudation at 245 Ma (Early Triassic) and 205 Ma (earliest Jurassic) (Fig. 7g and h) shows in the faster accumulation rate (Veevers, 2000; Veevers and Tewari, 1995), the latter during Syn-Rift II-1 (Song and Cawood, 2000). Further accelerated denudation from 165 Ma (Middle Jurassic) corresponds with the 154.3 Ma inception of seafloor spreading in the Argo Abyssal Plain (Veevers, 2000) and reaches a maximum of 800 m/Ma with deposition of the Parmelia Formation associated with the strike-slip deformation that preceded 131.9 Ma inception of seafloor spreading in the Perth Abyssal Plain. Relaxation that followed the inception of seafloor spreading in the Late Cretaceous is reflected in the minimal rates of denudation and accumulation. Following the 60 Ma onset of the deposition of the Kings Park and Porpoise Bay Formations and during the 43 Ma transpressional events and Oligocene uplift of the southern margin (Veevers, 2000), denudation rates rise above 5 m/Ma until their final fall in the Neogene (Table 4).

In conjugate Antarctica, in the region of the Lambert Graben in the northern Prince Charles Mountains, apatite fission-track data "indicate that the basement experienced substantial cooling during the late Paleozoic, followed by slow reheating (due to sedimentary burial?) during almost the entire Mesozoic, followed, finally, by a phase of accelerated

Table 4
Accumulation rate of Permian, Mesozoic, and Cenozoic formations of the northern Perth Basin

Formation	Top	Bottom	Span	Thickness	Accumulation	Rate
	Ma	Ma	Ma	m	m/Ma	log
Tamala	0	1.8	1.8	150	83	1.9
Wadjemup	1.8	11.2	9.4	289	31	1.5
Stark Bay	14.8	23.8	9	230	26	1.4
Porpoise Bay	37	49	12	382	32	1.5
Kings Park	49	61	12	532	44	1.65
Coolyena	65	112	47	276	6	0.8
Leederville/ South Perth	112	137	25	1340	54	1.7
Paramelia	137	147	10	8000	800	2.9
Yarragadee	147	165	18	3000	167	2.2
Cadda	165	180	15	392	26	1.4
Cockleshell						
Gully	180	206	26	2075	80	1.9
Lesueur	206	242	36	2200	61	1.8
Woodada/ Kockatea	242	250	8	1053	132	2.1
Wagina/ Dongara	253	258	5	336	67	1.8
Irwin River/ Highcliff	272	280	8	642	80	1.9
Holmwood	280	288	8	450	56	1.75
Nangetty	288	300	12	1500	125	2.1

Data from Cockbain (1990).

cooling during the Cretaceous" (Lisker et al., 2003). The late Paleozoic cooling took place at the same time as the initiation of the Lambert Graben, possibly as an "impactogen" (Sengor et al., 1978) during shortening in the ancestral Gamburtsev Mountains (Veevers, 1994).

8. Summary of events since 300 Ma on and about the Yilgarn Craton

8.1. Carboniferous–Permian (300 Ma) onset of Syn-Rift I, base of Pangean Supersequence

The original glacial relief ranged from 330 m in the southwest (Collie) across a bevelled surface (semi-circular outline in Fig. 9) to 500 m in the east. The craton was flanked at a hinge on the west by a rapidly subsiding sedimentary basin and on the south by high ground. Tillite and black shale filled in depressions on the craton and thickened northward in the sedimentary basin.

8.2. Early Permian (275 Ma) continued subsidence

Rivers from the south flowed NNW and deposited widespread fluvial coal measures on the craton and basin. Local uplift and erosion accompanied growing tectonic relief.

8.3. Late Permian (255 Ma) rise of the cratonic shoulder

With increasingly intense rift faulting, the western edge of the craton started to become uplifted in a (Darling) shoulder that overlooked the basin and sloped to the east and southeast. In places, the western craton started to become denuded of its recently deposited cover; in other places, as at Collie, deposition continued.

8.4. Early Triassic (245 Ma) incision of the cratonic shoulder

The shoulder extended to the south and any sedimentary cover was deeply incised by drainage. Piedmont fans accumulated at the foot of the shoulder scarp, and sediment was carried eastward and southeastward across the craton. Depressions in the craton accumulated sediment.

8.5. Late Triassic (225 Ma) continued incision of the cratonic shoulder

The shoulder continued to rise. An accelerated rate of uplift before the 206 Ma onset Syn-Rift II-1 resulted in another outpouring of sediment in piedmont fans.

8.6. Late Jurassic (154.3 Ma) climactic uplift

Another cycle of uplift (Syn-Rift II-1) produced an even thicker wedge of piedmont deposit at the same time as the 154.3 Ma breakup and onset of spreading along the northwestern margin. Proterozoic jasper and possibly Devonian, Permian, and Triassic sedimentary cover were stripped from the craton during this climactic uplift.

8.7. Early Cretaceous (132 Ma) relaxation of the cratonic shoulder

Following breakup and the onset of spreading along the western margin, the cratonic shoulder at Collie subsided so that valleys across the scarp became filled with marine sediment. On the east the craton was onlapped by sediment deposited from an epeiric sea. The craton formed a wide peninsula a few hundred metres lower than today between the ocean on the west and the epeiric sea on the east.

8.8. Late Cretaceous (99–65 Ma) epeiric uplift

Following the complex of events at 99 Ma, including the breakup of Australia and Antarctica along the southern margin, the subdued topography of much of the craton rose through a few hundred metres and became deeply weathered and lightly etched by drainage.

8.9. Eocene (50–33 Ma) subsidence of the southern and western parts of the craton

Following the complex of events at 43 Ma, including accelerated spreading in the Southeast Indian

Ocean, the southern and western parts of the craton subsided beneath the sea.

8.10. Oligocene (30 Ma) uplift of southern and western parts of the craton

The craton was uplifted by 190 m by tilting about a coastal hinge.

8.11. Early Miocene (23 Ma) renewed subsidence of the southern and western parts of the craton

In a second episode, the southern and western parts of the craton subsided beneath the sea.

8.12. Late Miocene (11 Ma) uplift of the southern and western parts of the craton

The craton was uplifted by 160 m by tilting about a coastal hinge.

8.13. Quaternary (2–0 Ma) state of the craton

Today, the craton surface is a plateau that rises from elevations of 200 m at a scarp in the west to a broad crest at 500 m and down again to 200 m in the east (Milligan et al., 1997). The western and southern periphery is drained by coastal streams, the interior by an etched surface of dry lakes and valleys, the preservation of which indicates very low rates of denudation outside the areas in the south affected by uplift.

The Frankland River in the south conveys sediment from the craton to the sea, but the streams in the west convey little, if any, sediment to the coast, as was so during at least the Ordovician, Early Permian, and Early Triassic.

9. Conclusion

Of the Ordovician, Permian, Early Triassic, and Quaternary sediment of the Perth Basin sampled for zircons, only the Late Permian ones contain significant populations of Archean (Yilgarn) zircons. In other words, the Yilgarn Craton has not contributed to sediments on the west during these periods except the Late Permian. The chief contributors during these periods were Proterozoic orogens.

Other evidence suggests that the craton was covered by a (now missing) cover of sedimentary rock including one or more of Proterozoic, Devonian, Permian, and Triassic ages. Whether the Archean zircons in the Late Permian rocks came direct from the craton or were recycled from the sedimentary cover is not known. The increased influx of sediment during the Jurassic matched by a second peak of the denudation rate would seem to require a primary supply from the craton, unless parts of the Pinjarra Orogen were uplifted within the basin (Sircombe and Freeman, 1999). This question could be resolved by dating zircon from the rapidly accumulated Jurassic Cockleshell Gully, Yarragadee, and Parmelia Formations.

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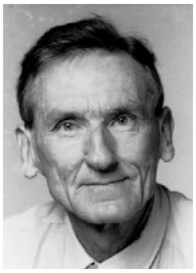

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