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Pan-Gondwanaland detrital zircons from Australia analysed for Hf-isotopes and trace elements reflect an ice-covered Antarctic provenance of 700–500 Ma age, T_{DM} of 2.0–1.0 Ga, and alkaline affinity ☆

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Abstract

Eastern Australian sediments of Cambrian, Ordovician, Silurian–Devonian, Triassic, and Neogene ages are known to be dominated by zircons dated 700–500 Ma ("Southwest Pacific–Gondwana igneous component") by the U–Pb SHRIMP method, and thought to be derived from Antarctica, as suggested also by paleogeographical evidence. To extend the characteristics of the provenance we subjected SHRIMPed zircons from the Middle Triassic Hawkesbury Sandstone and four Neogene beach sands to LAM–ICPMS analysis for rock type and Hf-isotope T_{DM} model ages. These data confirm the demonstration (from ages alone) that the beach sands were recycled from the Hawkesbury Sandstone. All five samples have a substantial fraction of 700–500 Ma zircons derived from alkaline rocks with T_{DM} of 2.0–1.0 Ga. We analysed zircons from the nearest exposed alkaline rock of appropriate age in Antarctica: the 550–500 Ma Koettlitz Glacier Alkaline Province of the Ross orogen of the Transantarctic Mountains, emplaced during contemporary transtension. The rock types and T_{DM} of the Koettlitz Glacier Alkaline Province zircons match those of the eastern Australian samples but only over the restricted range of 550–500 Ma. Rocks of 700–550 Ma age and alkaline type are unknown in Antarctic exposures.

Rocks of this age and type, however, abound in the Pan-Gondwanaland orogens. The nearest of these is the Leeuwin Complex of the Pinjarra orogen of southwestern Australia, which connects through the Prydz–Leeuwin Belt with the Mozambique Orogenic Belt. In turn, the Leeuwin Complex is dominated by 700–500 Ma alkaline rocks generated by contemporary transtension. We find that zircons from a beach sand at Eneabba, 450 km north of the Leeuwin Complex, are dominated by alkaline types, so confirming demonstration by age alone that the sand came from the Leeuwin Complex. An important inference is that Pan-Gondwanaland terranes are potential provenances of sediment with zircons of ages 700–500 Ma, model ages 2.0–1.0 Ga, and alkaline affinity.

We compiled the age spectra of our samples with others of the Southwest Pacific–Gondwana igneous component in southern Australia and reviewed their paleogeographical data. The Early Cambrian turbidites of the Kanmantoo Group were deposited from an axial northward paleocurrent that flowed across adjacent Antarctica in Wilkes Land. The Ordovician turbidite was deposited in fore-arc and abyssal fans likewise from a northward paleocurrent that flowed parallel to the uplifted Ross–Delamerian orogen. The Ordovician–Silurian–Devonian Mathinna Supergroup was deposited in a submarine fan system that prograded to the east-northeast

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from high ground in Antarctica. The Hawkesbury Sandstone was deposited in a braided-river system on a surface that sloped to the north-northeast from high ground in Antarctica. Together with the zircon data, the paleogeographical evidence in the Cambrian, Ordovician, Ordovician–Silurian–Devonian, and Triassic all point to a provenance in Wilkes Land, Antarctica of Pan-Gondwanaland (700–500 Ma) terranes with alkaline rocks.

Keywords: Australia; Antarctica; detrital zircons; 700–500 Ma; Pan-Gondwanaland; Hf-isotopes; trace elements; $\boldsymbol{T}_{\mathrm{DM}}$; paleogeography; alkaline provenance

1. Introduction

As a sequel to Sircombe's (1999) U–Pb SHRIMP dating of zircons from eastern Australian sands and sandstone, we analyse the same grains by LAM–ICPMS to ascertain the rock type and Hf model age of the igneous host.

Detrital or inherited zircons of late Neoproterozoic–Early Cambrian (700–500 Ma) age, "the Southwest Pacific–Gondwana igneous component" (Ireland et al., 1994), are the dominant grouping in many Paleozoic granites, greywackes, and gneisses of the Delamerian and Lachlan orogens (Ireland et al., 1998; Williams, 1992), and in Triassic sandstone and Neogene littoral sands in eastern Australia (Sircombe, 1999), summed up in Veevers' (2000a, p. 110–130) chapter called "Antarctic–Beardmore–Ross and Mirny provenances saturate Paleozoic–Mesozoic East Gondwanaland with 0.6–0.5 Ga zircons" (Fig. 1). According to Sircombe (1999), "Although the 480–520 Ma Ross–Delamerian Orogeny may explain some of the Southwest Pacific–Gondwana age grouping, the bulk of these provenance ages occur between 550–650 Ma and require further explanation …. Neoproterozoic convergence of the Beardmore Microcontinent in the Central Transantarctic Mountains may have been more widespread than is currently exposed in Antarctica. In particular, the basement of the Wilkes Subglacial Basin is unknown, but lies in a location that palaeodirection studies and tectonic history suggest could have been the source of the Lachlan Orogen and the Hawkesbury Sandstone of the Sydney Basin …. beaches [on the eastern Australian margin] are dominated by Neoproterozoic zircons probably derived from a source that now lies over 7000 km [away], due to a favourable pathway through an intermediate sediment repository in the Sydney Basin."

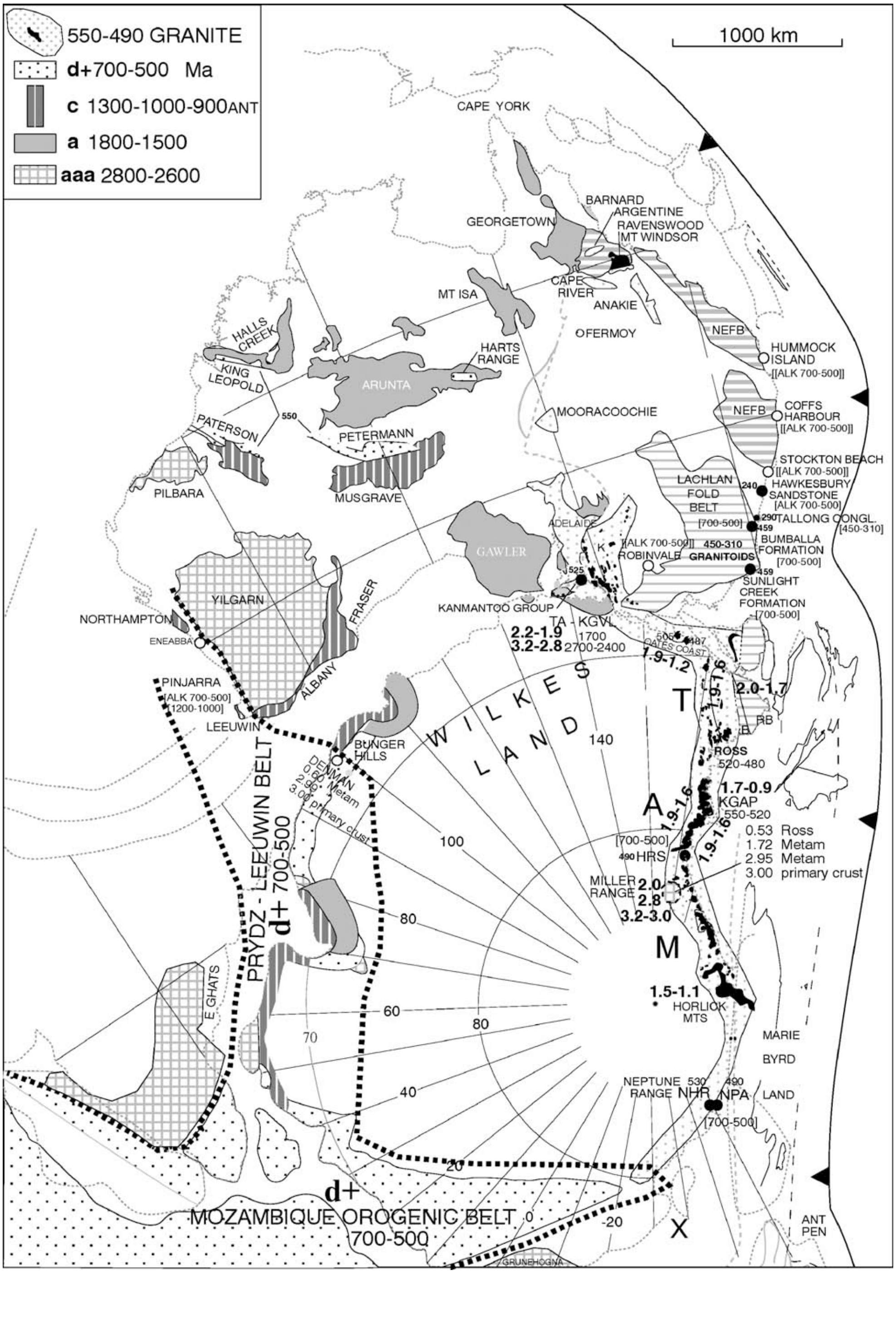
In Western Australia, the Eneabba sand (Sircombe and Freeman, 1999) was derived from the Perth Basin or Leeuwin Complex or both, and the Perth Basin Ordovician (490–450 Ma) and Permian (300–250 Ma) sandstones were derived from the Leeuwin Complex (Cawood and Nemchin, 2000; Veevers et al., 2005).

In the Adelaide region, the Early Cambrian Kanmantoo turbidite with 700–500 Ma zircons (Ireland et al., 1998) was deposited from paleocurrents that came from Antarctica (Veevers, 2000a, p. 200, 206) before the intrusion of the Delamerian granites. The presumed provenance of the Kanmantoo is an ice-covered part of East Antarctica. Following Sircombe (1999), Veevers (2000a, p. 114, 121) regarded an unexposed Beardmore–Ross orogen resulting from the collision of a Beardmore microcontinent with Antarctica (Borg and DePaulo, 1991) as a potential source of the 600–550 Ma zircons in the Kanmantoo and other sediments in eastern Australia. Subsequent work in Antarctica (e.g., Goodge et al., 2002, 2004) and our recognition of the older (700–600 Ma) part of the Southwest Pacific–Gondwana igneous component (Ireland et al., 1994; Sircombe, 1999) seem to invalidate the concept of the Beardmore orogen. The 650–500 Ma interval saw Gondwanaland assembled by oblique convergence that drove internal rotation and counter-rotation of cratons (cogs) embedded

Fig. 1. East Gondwanaland (Veevers, 2000a, fig. 127) including the Mozambique Orogenic Belt and the Prydz–Leeuwin Belt (Veevers, 2003), showing bedrock of ages (Ma) and $\boldsymbol{T}_{\mathrm{DM}}$ model ages (Ga) represented in detrital zircons. Archean of India (3.4–2.9, 2.5 Ga) from Mojzsis et al. (2003) and of Dronning Maud Land (~3.0 Ga Grunehogna province) from Groenewald et al. (1995). The beach sands are shown by open circles, sedimentary rocks by filled circles. East Antarctic data from Fitzsimons (2003), Transantarctic Mountains from Goodge et al. (2004), Read et al. (2002), $\boldsymbol{T}_{\mathrm{DM}}$ (Ga, in bold) from Borg et al. (1990), Borg and DePaulo (1991, 1994), and Storey et al. (1988, 1994). The 550–520 Ma Koettlitz Glacier Alkaline Province (KGAP) has a $\boldsymbol{T}_{\mathrm{DM}}$ of 1.42 and 1.25 Ga (Mellish et al., 2002) within the range 1.7–0.9 Ga, as described below. × marks the 175 Ma granite in the Whitmore Mountains (Storey et al., 1988) and the 1000 Ma gneiss in the Haag Nunataks (Storey et al., 1994). The mildly deformed Adelaide Fold Belt is paralleled by the 520–500 Ma Delamerian granites and intensely deformed Kanmantoo Fold Belt (K)(Veevers, 2000a) continuous through the 505 and 487 Ma granites (dated below) of the Oates Coast with the Ross orogen. Younger fold belts are the 450–310 Ma Lachlan Fold Belt and 300–200 Ma New England Fold Belt (NEFB). B = Bowers Terrane; HRS = Holyoake Range; KGAP = Koettlitz Glacier Alkaline Province; NHR = Hannah Ridge Formation; NPA = Patuxent Formation, Neptune Range; RB = Robertson Bay Terrane; TA–KGVL = Terre Adélie–King George V Land.

in fold belts (Veevers, 2003). A 650–570 Ma stress-field changed to a different set of azimuths at 570 Ma, and deformation/plutonism terminated at 500 Ma with the Ross and Delamerian subduction events along the paleo-Pacific margin. Characteristic of the 650–500 Ma interval in the interior are anorogenic magmas that include A-type (alkaline) magma drawn into pull-aparts by extensional jogs along the strike-slip system.

It is a terrane of this kind in ice-covered East Antarctica that we suspect to have provided the 700–550 Ma zircons in eastern Australia as well as the 550–500 Ma zircons, which could have come also from the Ross orogen.



The Hawkesbury Sandstone contains only rare zircons from the 450–300 Ma granites of the Lachlan Fold Belt (Veevers, 2000a, p. 122) so we rule out any substantial contribution from the Lachlan Fold Belt, including the Ordovician turbidite with detrital 700–500 Ma zircons. The Lachlan Fold Belt was presumably buried beneath an aggrading fluvial plain in the Triassic. The NNE-ward cross-dip azimuth of the Hawkesbury indicates the paleoslope (Veevers, 2000a, p. 122), and the reciprocal bearing indicates the potential provenance of a Pan-Gondwanaland terrane in East Antarctica.

Of the eastern Australian sediments treated here, the Hawkesbury is the last to have been deposited directly from the provenance. The modern beach sands of north-eastern Australia were recycled from the Hawkesbury, and the Pliocene beach sand in the Murray Basin at Robinvale was recycled from the Ordovician turbidite, the Hawkesbury Sandstone, or both.

These hypotheses from paleogeography and zircon ages are now constrained further by trace-element analysis that indicates the rock type and by Hf-isotope analysis that indicates the model age of the provenance. The new kind of evidence allows us to confirm or reject the provenances indicated by paleogeography and age, and to detail the provenance further by rock type and model age.

2. Analysis of SHRIMPed zircons by LAM–ICPMS

2.1. Methods of analysis

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).

According to Belousova et al. (2002), trace-element abundances in igneous zircons, as determined by electron microprobe and laser-ablation microprobe ICPMS analysis, are shown to be sensitive to source-rock type and crystallization environment. The concentrations of 26 trace elements in zircons from a wide range of different rock types reveal distinctive elemental abundances and chondrite-normalised trace-element patterns for specific rock types. Trace-element abundance in zircons increases from ultramafic through mafic to granitic rocks. Average content of REE is typically less than 50 ppm in kimberlitic zircons, up to 600–700 ppm in carbonatitic and lamproitic zircons, and 2000 ppm in zircons from mafic rocks, and can reach per cent levels in zircons from granitoids and pegmatities. Relatively flat chondrite-normalised REE patterns with chondrite-normalised Yb/Sm ratios from 3 to 30 characterise zircons from kimberlites and carbonatites, but Yb/Sm is commonly over 100 in zircons from pegmatites. Th/U ratios typically range from 0.1 to 1, but can be 100–1000 in zircons from some carbonatites and nepheline syenite pegmatites. The geochemical signatures characteristic of zircon from some rock types can be recognised in bivariate discriminant diagrams, but multivariate statistical analysis is essential for the discrimination of zircons from most rock types.

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 ($\boldsymbol{T}_{\mathrm{DM}}$). 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. $\boldsymbol{T}_{\mathrm{DM}}$ model ages are expressed in Ga (e.g., 2.0–1.8 Ga), and the implicit 0.1 Ga signifies 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).

We applied this kind of analysis to the mounted 0.70–0.50 Ga zircons from the eastern Australian Triassic Hawkesbury Sandstone and four beach sands that had been dated by the U–Pb SHRIMP method (Sircombe, 1999), and from another sample of a Western Australian beach sand, dated by the U–Pb SHRIMP method (Sircombe and Freeman, 1999). Hf-isotopes were analysed on a laser ablation microprobe multi-collector inductively coupled plasma mass spectrometer (LAM–MC–ICPMS) and trace elements on an electron microprobe (EMP) and LAM–ICPMS.

The electron microprobe was 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 to be converted to concentrations. These elements, together with U data collected during the SHRIMP 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, debated by Hoskin and Ireland (2000), has been demonstrated by statistical analysis of larger databases (Belousova et al., 2002).

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.

In the plot of $\varepsilon_{\mathrm{Hf}}$ vs. age, (e.g., Fig. 4), with the Chondritic Unfractionated Reservoir (CHUR) reference line at zero, zircons that plot below the line had host magmas derived in part from older recycled crustal material, and those above the line from juvenile mantle sources. The same relations apply in the plot of ^{176}Hf/^{177}Hf vs. age, with the higher reference line of the Depleted Mantle (DM).

For the calculation of $\varepsilon_{\mathrm{Hf}}$ 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 ($\boldsymbol{T}_{\mathrm{DM}}$) based on a depleted-mantle source, we have adopted a model with $(^{176}\mathrm{Hf}/^{177}\mathrm{Hf})_i = 0.279718$ and $^{176}\mathrm{Lu}/^{177}\mathrm{Hf} = 0.0384$ 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. $\varepsilon_{\mathrm{Hf}}$ values and model ages used in the figures were calculated using the value 1.93×10^{-11} yr^{-1} proposed by Blichert-Toft et al. (1997); values for $\varepsilon_{\mathrm{Hf}}$ and model ages calculated using this value lie between other proposed values of the decay constant (1.865×10^{-11} yr^{-1}, Scherer et al., 2001; 1.983×10^{-11} yr^{-1}, Bizzarro et al., 2003).

$\boldsymbol{T}_{\mathrm{DM}}$ model ages, which are calculated using the measured ^{176}Lu/^{177}Hf of the zircon, give a minimum age for the source material of the magma from which the zircon crystallised. These model ages are comparable to Nd/Sm model ages. We have calculated also a "crustal" model age ($\boldsymbol{T}_{\mathrm{DM}}^{C}$) which assumes that its parental magma was produced from an average continental crust ($^{176}\mathrm{Lu}/^{177}\mathrm{Hf} = 0.015$) that originally was derived from the depleted mantle. $\boldsymbol{T}_{\mathrm{DM}}^{C}$ gives optimum ages.

The analytical data for our samples are given in the Background Online Dataset.

3. Eastern Australian Triassic sandstone and Neogene beach sands

3.1. Ages

Common peaks (Fig. 2) fall within the regional age clusters defined in Veevers (2000a, p. 110) and refined in Veevers et al. (2005) (Table 1). As interpreted by Sircombe (1999), the near-congruence of the dominant **d**+ (0.7–0.5 Ga) peak suggests that the sands at Hummock Hill Island, Coffs Harbour, Stockton Beach, and Robinvale were derived from the Hawkesbury Sandstone or other eastern Australian body of rock with the same ages (**d**+) of zircons. Minor peaks (**e** — Lachlan Fold Belt, **f** — New England Fold Belt, Veevers, 2000a, p. 112; **ddd**, **c**, **aa**, **aaa**) confirm the congruence.

The Triassic Hawkesbury Sandstone and the Ordovician turbidites are first-cycle deposits from the provenance. Sircombe (1999) suggested, and we confirm, that the beach sands are derived from the Hawkesbury Sandstone. The turbidite zircons have spectra similar to those of the Hawkesbury, but with peaks at 520 Ma and 538 Ma some 60 million years (m.y.) younger than the Hawkesbury peaks at 571 and 600 Ma. The peaks at 860 (**ddd**) and 1060 Ma (**c**) correspond with those in the turbidites. Likewise, the peak of ~550 Ma in the Mathinna and Stony Head zircons corresponds to those in the Ordovician and Triassic rocks, and zircons in the range 1300–1000 Ma correspond to **c**. It seems that the same provenance yielded sediment with the same spectral peaks **d**+ and **c** during the Late Ordovician and Silurian–Devonian, and, 200 million years later, during the Middle Triassic. The Ross–Delamerian orogen was being unroofed in the Ordovician and would have provided a flood of 550–500 Ma zircons to the depocentres, which correspond to the 520 and 538 Ma peaks; the situation in the Permian and Triassic had changed such that peak was shifted 60 m.y. older to reflect a greater contribution from slightly older terrane, consistent with the idea that part at least of the Ross orogen was covered by Permo–Triassic sediment. In turn, this suggests a super-terrane in adjacent Antarctica with **d**+ and **c**, and capable of supplying sand to the Ordovician and Silurian–Devonian fans and Triassic rivers.

Other examples of **d**+ in southeastern Australia, the Transantarctic Mountains, and the Neptune Range are shown in Fig. 3. The median age lies about 600 Ma, so that the bulk of the zircons must have been derived from outside the Ross orogen, which is no older than 550 Ma. As we shall see later, and according to Goodge et al. (2004), sediments in the Transantarctic Mountains were derived from within and west of the Ross orogen; it follows that the preponderance of ages between 700 and 550 Ma signifies a provenance that extends in space to the west and in time to 700 Ma.

3.2. Rock types and model ages ($\boldsymbol{T}_{\mathrm{DM}}$)

An extensive study of the trace-element patterns of zircons (Belousova, 2000) has shown correlations

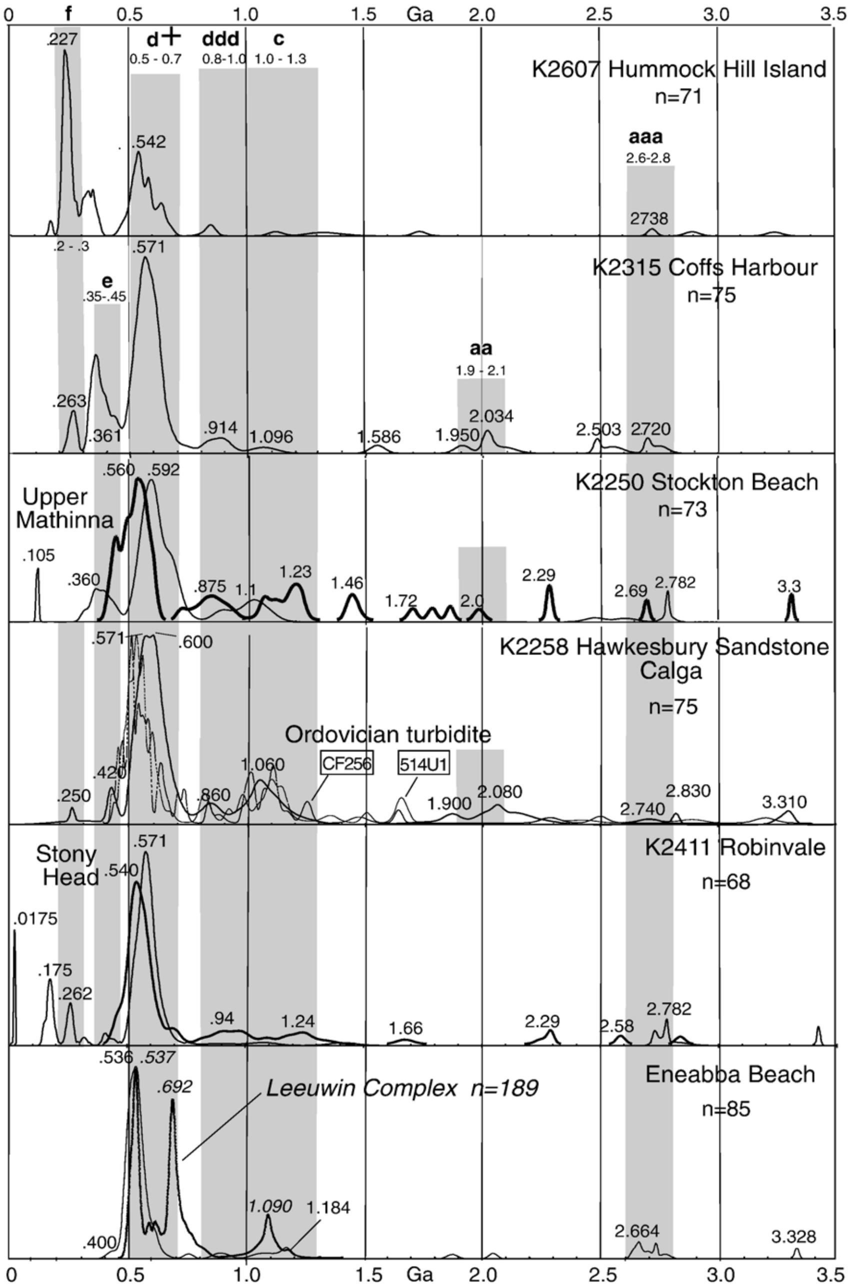


Fig. 2. Probability distribution diagram (Ludwig, 2001) of U–Pb SHRIMP zircon ages of eastern Australian samples in order of increasing latitude over the range 0–3.5 Ga, from the dataset in Sircombe (1999). Correlation of peaks by grey lines identified by regional age clusters (Table 1; Veevers et al., 2005), with **d**+ expanded to cover the main cluster ("Southwest Pacific–Gondwana igneous component") between 0.7 and 0.5 Ga. Clusters **f** (0.3–0.2 Ga) and **e** (0.45–0.35 Ga) in eastern Australia are from Veevers (2000a, p. 114). The plot of the first-cycle K2258 Hawkesbury Sandstone is augmented by plots (in fine lines) of two samples of Ordovician turbidite: 514U1 — the 459 Ma (Gisbornian) Bumballa Formation from the Shoalhaven River, and CF256 — the 459 Ma (Gisbornian) Sunlight Creek Formation from the Genoa River (Fergusson and Fanning, 2002). The plot of K2250 Stockton Beach (fine line) is augmented by the plot of the Ordovician–Devonian Upper Mathinna Supergroup (thick line), and that of K2411 Robinvale (fine line) by that of the Ordovician–Devonian Stony Head Sandstone (thick line), both from Black et al. (2004). The lowermost plot shows the Eneabba sand (fine line) (from the dataset in Sircombe and Freeman, 1999) and the Leeuwin Complex (Collins, 2003) from southwestern Australia.

Table 1
Clusters of zircon ages of bedrock in southwestern Australia and East Antarctica (Veevers et al., 2005). See also Fig. 36

Code	Ga
d	0.6–0.5
d+	0.70–0.50
dd	0.725–0.65
ddd	1.00–0.80
c	1.30–1.00 [−900 ANT]
bb	1.40–1.30
b	1.50–1.30
a	1.80–1.50
aa	2.10–1.90
aa′	2.60–2.50
aaa	2.80–2.60
aaaa	3.05–2.90

between these patterns and the chemical composition of the magmatic host rocks. The fields for different rock types tend to overlap in two-dimensional space so that CART (Classification And Regression Trees) analysis was applied to classify each individual zircon grain in terms of its rock type (Belousova et al., 2002, Figs. 7 and 8). CART is a diagnostic statistical program that was developed for classifying a set of objects (chemical analyses), based on multivariate measurements of characteristics of each of the objects (zircon grains).

Zircons from some rock types can be discriminated with a reasonable degree of probability. Zircons from alkaline rocks (syenites, larvikites, nepheline syenites, carbonatites) and mafic rocks (diabases, basalts) are recognised with a probability exceeding 80% (Belousova, 2000). The frequency of finding detrital zircons from the uncommon alkaline rocks (carbonatite, syenite) is low. For example, in analyses of more than 3000 detrital zircons, Griffin et al. (2004) found 6% classified as carbonatitic and less than 1% as of syenitic origin.

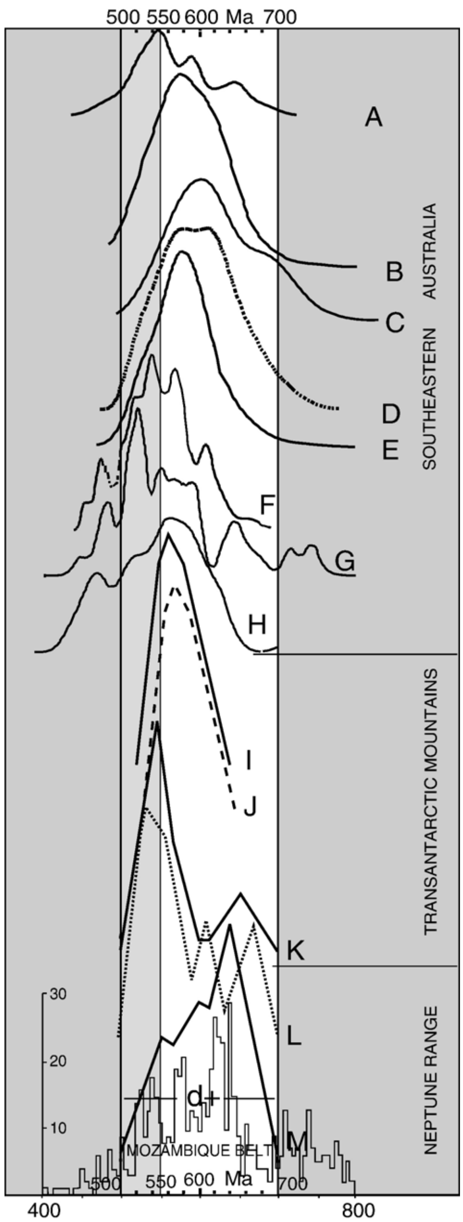


Fig. 3. Nested age profiles of the **d**+ (700–500 Ma) cluster in samples A–H from southeastern Australia (from Fig. 2), I–K from the Transantarctic Mountains, L and M from the Neptune Range, Antarctica, and a histogram of ages from the Mozambique Belt. **d**+ comprises the 550–500 Ma range of the Ross orogeny (light grey) and the 700–550 Ma range (clear) of the rest of East Gondwanaland, in particular the Mozambique Belt. Three samples peak within the Ross range, two peak at 550 Ma, and the eight remaining peak within the 700–550 Ma range. (A) K2607 Hummock Island Hill modern sand. (B) K2315 Coffs Harbour modern sand. (C) K2250 Stockton Beach modern sand. (D) K2258 Triassic Hawkesbury Sandstone. (E) K2411 Pliocene Robinvale sand. (F) 514U1 — the 459 Ma (Gisbornian) Bumballa Formation from the Shoalhaven River. (G) CF256 — the 459 Ma (Gisbornian) Sunlight Creek Formation from the Genoa River, both from Fergusson and Fanning (2002). (H) Ordovician–Devonian Upper Mathinna Supergroup, Tasmania (Black et al., 2004). (I) 98268G Cambrian Goldie Formation, Dolphin Spur, central Transantarctic Mountains, longitude 172°E (Goodge et al., 2002). (J) 98206A Cambrian Goldie Formation, Softbed Ridges, central Transantarctic Mountains, longitude 164°E (Goodge et al., 2002). (K) HRS Middle Cambrian to Early Ordovician Starshot/Douglas Formation, central Transantarctic Mountains, latitude 82.0°S, longitude 160.5°E (Goodge et al., 2004). (L) NPA Middle Cambrian (515 Ma) Patuxent Formation, Neptune Range, latitude 83.7°S, longitude 59.2°W (Goodge et al., 2004). (M) NHR Early Cambrian (556–510 Ma) Hannah Ridge Formation, Neptune Range, latitude 83.8°S, longitude 57.3°E (Goodge et al., 2004). The histogram of ages from the Mozambique Belt (Kröner and Stern, 2005, after Meert, 2003) is enclosed within L except for extremes <500 and >700 Ma.

About 70% were classified as granitoids and about 20% as mafic rocks.

A few grains were classified initially as kimberlite solely on the basis of Lu. These grains contain U > 69 ppm, Y > 194 ppm, and Yb > 36 ppm. According to Belousova et al. (2002), the U content of kimberlite lies between 3 and 69 ppm, Y between 4 and 194 ppm, and Yb between 0.16 and 36 ppm. Zircons with contents greater than these values lie outside the kimberlite field and remain unclassified. In the supplementary dataset, they are designated “unclassified ex-kimberlite”.

Some analyses fall outside the fields, suggesting that the original database was not fully representative. In the original database for example, zircons from carbonatites were represented by samples from only two carbonatites: the 732 Ma Mud Tank carbonatite from central Australia and the 380 Ma Kovdor carbonatite from the Kola Peninsula, Russia. Also important to note is that the classification is based on zircons from igneous rocks only.

3.2.1. Hummock Island sand

In the range of interest (700–500 Ma), peaks at 542 and 586 Ma are mirrored by peak ages of alkaline zircons at 540 and 586 Ma (Fig. 4). Five zircons are classified as alkaline (carbonatite), 2 as unclassified, 4 as mafic rocks, 11 as granitoids with <65% SiO_2, and 1 as granitoids with 70–75% SiO_2 (Table 2).

ε_{Hf} ranges from 8 to −13 parts/10^4, $^{176}Hf/^{177}Hf$ from 0.2821 to 0.2826, with outliers at 0.2816 and 0.2813. Hf model ages (Table 4, Fig. 15a) of all but a few grains are concentrated between 1.0 and 2.0 Ga.

3.2.2. Coffs Harbour sand

Zircons in the Coffs Harbour sand (Fig. 5) and the Hawkesbury Sandstone have common peaks and troughs within the age clusters (Table 3).

The peak age of all zircons (571 Ma) is slightly younger than that of the alkaline zircons (586 Ma) (Fig. 5). Eleven zircons are classified as alkaline (7 as carbonatite and 4 as syenite), 1 as unclassified, 8 as mafic rocks, 24 as granitoids <65%, and 20 as granitoids 70–75% (Table 2). ε_{Hf} ranges from 8 to −13 parts/10^4, $^{176}Hf/^{177}Hf$ from 0.2821 to 0.2826, with outliers at 0.2816 and 0.2813.

As in the Hummock zircons, Hf model ages (Table 2, Fig. 15b) of all but a few grains are concentrated between 1.0 and 2.0 Ga.

3.2.3. Stockton Beach sand

The peak age of all zircons (592 Ma) is the same as that of the alkaline zircons (593 Ma) (Fig. 6).

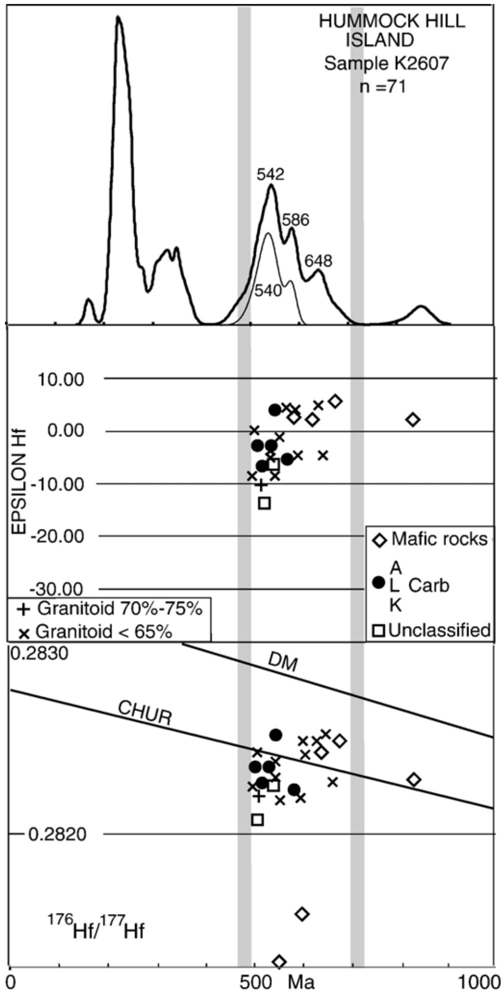


Fig. 4. Zircons (sample K2607) from Hummock Hill Island, Queensland (151.47°E, 24.02°S). *Above*, probability distribution diagram (Ludwig, 2001) of SHRIMP zircon ages 1000–0 Ma (Sircombe, 1999), out of a total sample of 71 grains, with peaks at 542, 586, and 648 Ma. 700–500 Ma range is delimited by grey bands, and the ages (fine line) of zircons from alkaline rocks (carbonatite) peak at 540 Ma. *Middle*, ε_{Hf} (difference between the sample and a chondritic reservoir in parts/10^4) vs. ages of zircons with trace-element classification of source igneous rock (Belousova et al., 2002). *Below*, $^{176}Hf/^{177}Hf$ of zircons with discriminant lines marked CHUR (chondritic unfractionated reservoir) and DM (depleted mantle) vs. age of zircons with trace-element classification. ALK = alkaline; Carb = carbonatite.

Twenty-one zircons are classified as alkaline (carbonatite), 3 as unclassified, 4 as mafic rock, 18 as granitoid <65%, and 2 as granitoid 70–75% (Table 2). ε_{Hf} ranges from 8 to −31 parts/10^4, $^{176}Hf/^{177}Hf$ from 0.2821 to 0.2815, with an outlier at 0.2811.

Most Hf model ages (Table 4, Fig. 15c) are concentrated between 1.0 and 2.0 Ga, with a second group between 2.0 and 3.0 Ga.

Table 2
Rock types of the 238 grains (62% of all 381 grains) aged 700–475 Ma, plotted in Fig. 9

Rock type	K2607 Hummock	K2315 CH	**K2258 HS**	K2250 Stockton	K2411 Robinvale	Total	%
Carbonatite	5	7	**9**	21	24	66	28
Alkaline		11	**11 (21%)**				
Syenite		4	**2**			6	2
Unclassified	2	1		3	3	9	4
Mafic rock	4	8	**9 (17%)**	4	3	28	12
Granitoid 70–75%	1	20	**21 (38%)**	2	3	47	20
Granitoid < 65%	11	24	**13 (24%)**	18	16	82	34
Total	23	64	**54**	48	49	238	100

3.2.4. Hawkesbury Sandstone

The peak ages of all zircons (571, 600 Ma) overlap that of the alkaline zircons (572 Ma) (Fig. 7).

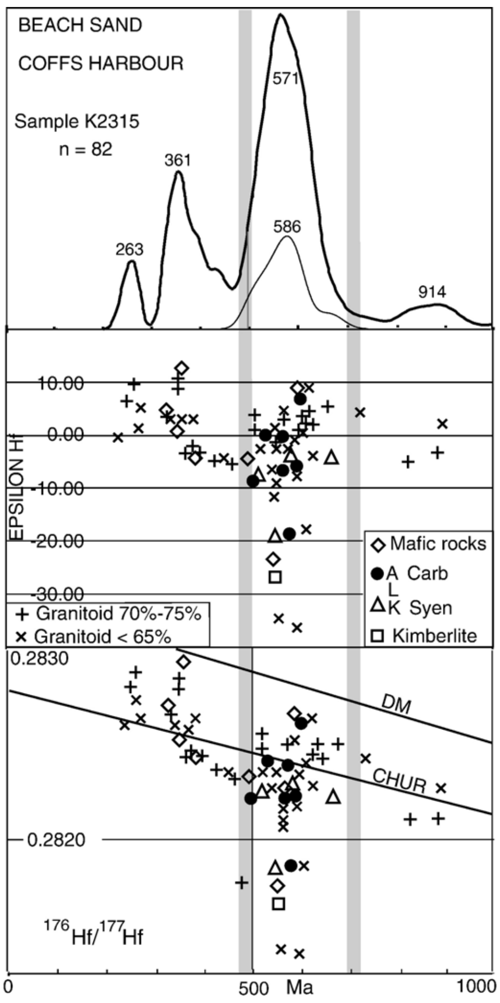


Fig. 5. Zircons (sample K2315) from beach sand at Coffs Harbour, NSW (153.14°, 30.29°S), with the same plots as Fig. 4. ALK = alkaline; Carb = carbonatite; Syen = syenite.

Nine zircons are classified as carbonatite and 2 as syenite, 9 as mafic rock, 13 as granitoid <65%, and 21 as granitoid 70–75% (Table 2). ε_{Hf} ranges from 8 to −38 parts/10^4, with an outlier at −53.5. ^{176}Hf/^{177}Hf ranges from 0.2826 to 0.2813, with an outlier at 0.28075. These values correspond to a T_{DM} of 3.2 Ga, suggesting an origin in a protolith of old recycled crust. Outliers in other samples have ε_{Hf} between −27 and −49 and, and T_{DM} between 2.2 and 2.9 Ga.

As in the Stockton Beach sand, most Hf model ages (Table 4, Fig. 15d) are concentrated between 1.0 and 2.0 Ga, with a second group between 2.0 and 3.0 Ga.

3.2.5. Robinvale sand

The peak age of all zircons (577 Ma) is slightly younger than that of the alkaline zircons (585 Ma) (Fig. 8). Twenty-four zircons are classified as carbonatite, 3 as unclassified, 3 as mafic rock, 16 as granitoid <65%, and 3 as granitoid 70–75% (Table 2). ε_{Hf} ranges from 8 to −30 parts/10^4. ^{176}Hf/^{177}Hf ranges from 0.2826 to 0.2815.As in the Stockton Beach sand, most Hf model ages (Table 4, Fig. 15e) are concentrated between 1.0

Table 3
Hawkesbury Sandstone (K2258) and Coffs Harbour sand (K2315) with common peaks and troughs within age clusters

K2258	K2315	Cluster		Potential provenance
250	263	**f**	300–200	New England Fold Belt
420	361	**e**	450–350	Lachlan Fold Belt
571, 600	592	**d**+	700–500	(Part only) Beardmore–Ross, Mirny
860	914	**ddd**	1000–800	Rayner province of East Antarctica
1060	1096	**c**	1300–1000	Adelie Land, Musgrave, Albany–Fraser
1900	1950	**aa**	2100–1900	Capricorn Orogen, T_{DM} of parts of
2080	2034			Transantarctic Mountains
2740	2720	**aaa**	2800–2600	Yilgarn Craton, Capricorn Orogen

All values in Ma.

and 2.0 Ga, with a second group between 2.0 and 3.0 Ga.

3.3. Differentiation of the second-cycle sands from the first-cycle sandstone

Differentiation from the Hawkesbury Sandstone (filled symbols in Fig. 9; bold in Fig. 10 and below) entails these changes:

Unclassified: from **0%** to 1.5–9% in all other samples.
Syenite: from **4%** to 6% in K2315, 0% in the others.
Enriched: carbonatite: from **17%** to similar (11% K2315, 22% K2607) or greater (44% K2250, 49% K2411); and mafic granitoid: from **24%** to greater (33–48%).
Impoverished: dolerite, basalt, mafic rock: from **17%** to the same in one sand and less in the other three; and felsic granitoid: from **39%** to less (31% in K2315) to much less (4% to 6% in the others).

According to Sircombe and Stern (2002), "Grain survivability has been correlated in some cases with U content (Heaman and Parrish, 1991), but survivability depends on metamictization [radiation damage], which in turn depends on uranium content and, possibly most importantly, age. A high U grain will survive transportation through to deposition and subsequent analysis if transportation occurs before α-decay damage becomes too great. The combination of high-energy environments and relatively recent dominant sources (typically 650–150 Ma) can be seen in data from zircon in modern beach sand in eastern Australia…(Sircombe, 1999)", the subject of our present study. Sircombe and Stern (2002) concluded that compared with ~3000 Ma zircons the "relatively recent" zircons in the eastern Australian beach sands, even those with high U content (median 209 ppm, 95 percentile 629 ppm), were little damaged.

We test this notion from our analyses (Fig. 9). In K2258, the zircons classified as felsic granitoids have a mean U content of 231 ppm and a median of 153 ppm (range 24–849 ppm), which compares with the slightly greater values in K2315: 347 ppm and 297 ppm (109–850 ppm) (values from Sircombe (1999)). In the alkaline zircons, K2258 has a mean of 210 and a median of 212 ppm, and a range of 65–300 ppm; K2315 has a mean of 258 ppm, a median of 178 ppm, and a range of 65–600 ppm (Fig. 9). The mean is slightly higher than that in K2258, but with the <100 ppm values excluded, the K2258 mean would be 326 ppm and the range 101–849 ppm, which match those of K2315. As noted above, zircons of felsic–granitoid affinity (with low U) have been preferentially eliminated from the sand (Fig. 10), counter to the idea that high U signifies weak grains. The grains with alkaline affinity have a similar U content in both sandstone and sand, and in turn are similar in U content to that of the felsic granitoid zircons. Nevertheless, the sands have been enriched in alkaline grains during transport. In these samples, the U content appears to have little or no bearing on the survivability of the zircons during transport.

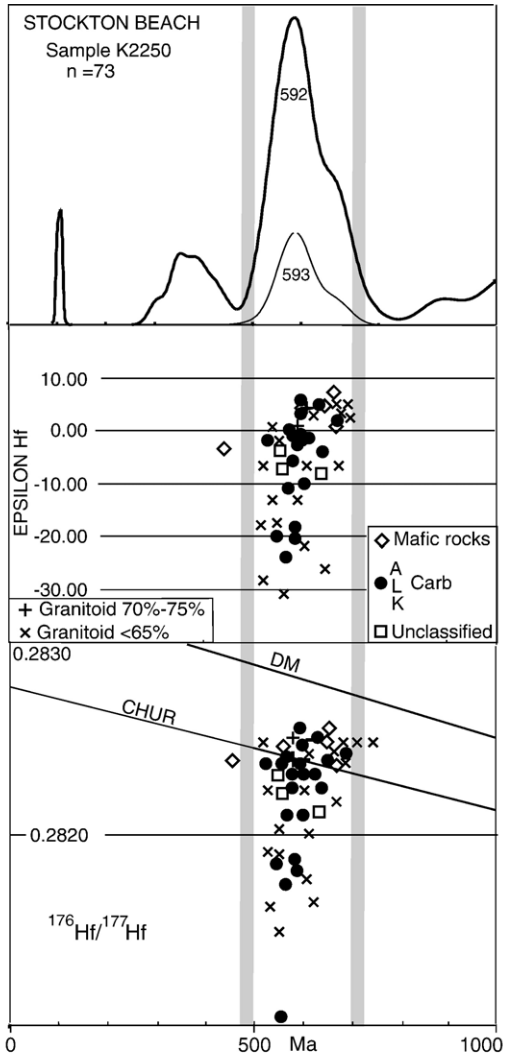


Fig. 6. Zircons (sample K2250) from Stockton Beach, NSW (151.89°E, 32.83°S). Ages from alkalines shown by fine line. ALK = alkaline; Carb = carbonatite.

3.4. Summary and discussion

The near-congruence of ε_{Hf} and $^{176}Hf/^{177}Hf$ of the 700–500 Ma zircons is striking (Fig. 11). The dominant rock type (Table 2) is alkaline in K2250 and K2411, mafic granitoid in K2607 and K2315, and felsic

Table 4
T_{DM} (plain) and T^{C}_{DM} (italics) according to rock type (Figs. 15–18)

Type	Unclassified	Carbonatite	Syenite	Mafic	Granitoid	
					<65% SiO_2	70–75% SiO_2
Sample						
K2607	1.32–1.58	0.97–1.37		1.01–1.17	0.97–1.43	1.47
	1.82–2.26	*1.24–1.88*		2.17, 2.62		
				1.21–1.51	*1.16–1.98*	*2.04*
				3.15, 3.91		
K2315	2.11	0.88–1.41	1.29–1.36	0.86–1.32	0.86–1.56	0.94–1.28
	3.10	1.83	1.85		1.84, 2.48	
		1.04–1.97	*1.74–1.83*	*1.03–1.72*	*1.12–2.18*	*1.19–1.73*
		2.65	*2.63*		*2.63, 3.64*	
K2250	1.25–1.51	0.93–1.23	0.93–1.20	1.02–1.23	1.04–1.17	
		1.23–2.02			1.38–2.30	
	1.70–2.07	*1.15–1.64*		*1.11–1.61*	*1.24–1.67*	*1.28–1.52*
		1.64–2.95			*1.89–3.38*	
K2258		**0.94–1.31**	**0.88–1.05**	**0.99–1.35**	**0.92–1.56**	
		1.61–2.56		**1.77**	**1.88**	**1.82–2.50**
		1.15–1.75		***1.05–1.39***	***1.25–1.84***	***1.15–2.14***
		2.25–3.83		***2.47***	***2.70***	***2.56–3.71***
K2411	1.08–1.33	0.90–2.28	0.98	1.40, 1.93	0.97–1.29	1.13–1.93
	1.42–1.81	*1.11–3.36*		*1.27, 1.91, 2.79*	1.59, 2.20	*1.46–2.64*
					1.40–1.73	
					2.24, 3.17	

granitoid in K2258. Overall, the most common rock type is mafic granitoid (34%), followed closely by carbonatite and syenite (30%), then felsic granitoid (20%), mafic rock (12%), and unclassified (4%).

With abundant 700–500 Ma zircons (Veevers, 2000a, p. 112; Fergusson and Fanning, 2002), Ordovician turbiditic sandstones of the Lachlan Fold Belt of southeastern Australia are a potential source of the Triassic Hawkesbury Sandstone, but the dearth of 450–320 Ma zircons from the voluminous zircon-bearing granites of the Lachlan Fold Belt (B.C. Chappell, pers. comm., 2004) in the Hawkesbury Sandstone rules out the Lachlan Fold Belt as a provenance. The Hawkesbury Sandstone is the provenance of most of the 700–500 Ma zircons in the second-cycle beach sands in the north (Sircombe, 1999), and probably the zircons in the Robinvale sand of the Murray Basin (Veevers, 2000a, p. 119), which could have come also from recycled Ordovician turbidite of the Lachlan Fold Belt.

In seeking the primary provenance, we depend on the first-cycle zircons in the Triassic Hawkesbury Sandstone, augmented by the second-cycle zircons from the northern sands such as those from Coffs Harbour, whose ages (Table 3) and properties (Fig. 11) overlap those of the Hawkesbury. Parts of the Panthalassan margin, including those in Antarctica (Ross High, Veevers, 2000a, p. 303) and southeastern Australia (265–230 Ma, Kohn et al., 2002), were uplifted in the Early Triassic (250–242 Ma). The Ross provenance could have supplied 550–490 Ma zircons but not the 700–550 Ma fraction.

Zircons from the Coffs Harbour sand (open symbols in Figs. 12–14) plot in the same place as those from the Hawkesbury Sandstone (solid symbols). In Fig. 12, Y vs. Nb/Ta, the Hawkesbury carbonatites are overlapped by the Coffs Harbour ones, and the Hawkesbury syenites lie in the middle of the Coffs Harbour ones. All except one of the grains (a granitoid) lie within or between the carbonatite and syenite fields. The same overlapping relation applies in Fig. 13, yttrium vs. uranium. Seven fall within the carbonatite and syenite fields, 4 fall in the field of mafic rocks, 3 in granitoids, and 6 outside. In Fig. 14, Y vs. Yb/Sm, the overlapping relation applies, but 9 fall in the carbonatite field, 3 in granitoids, 2 in mafic rock, and 6 outside.

The rock types of the Triassic Hawkesbury Sandstone zircons (K2258) (Table 2, bold) (Fig. 10) reflect the primary provenance, in decreasing order of abundance, of felsic granitoids, mafic granitoids, alkaline rocks, and mafic rocks. The spectrum of rock types and the range of ε_{Hf} and $^{176}Hf/^{177}Hf$ in K2250 Stockton (Fig. 6), indubitably from K2258, match those of K2411 Robinvale in the Murray Basin (Fig. 8), suggesting a common provenance in the Hawkesbury Sandstone or a common set of recycled zircons in the Hawkesbury Sandstone and the Ordovician turbidite of the Lachlan Fold Belt.

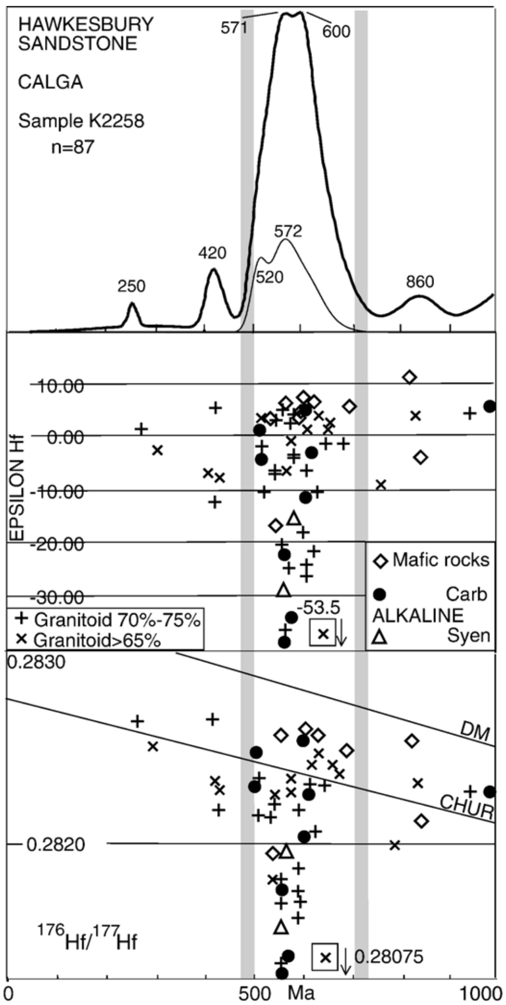


Fig. 7. Zircons (sample K2258) from the Hawkesbury Sandstone at Calga, NSW (151.22°E, 33.43°S). The 700–500 Ma concentration of carbonatite zircons is delimited by grey bands. ALK = alkaline; Carb = carbonatite; Syen = syenite.

3.5. Summary: alkaline zircons

All but two of the alkaline zircons are confined to the 700–500 Ma interval, and their properties overlap, except the lower values of ε_{Hf} and $^{176}Hf/^{177}Hf$ of a single grain in K2258 (Fig. 11), which reflect old recycled crust.

Excluding Hummock Island, which has the major peak ~215 Ma, and minor peaks at 542, 586, and 648 Ma, the alkaline zircons have peaks between 572 and 593 Ma, mean 584 Ma (Fig. 11, above), effectively the same as all zircons (571 and 592 Ma, mean 580 Ma).

Values of ε_{Hf} range from 8 to −38 parts/10^4 and of $^{176}Hf/^{177}Hf$ from 0.2826 to 0.2810, with all but 10 of them below the Chondritic Unfractionated Reservoir (CHUR) reference line, indicating that their host magmas were derived in part from older crustal material.

3.6. Hf model ages

To calculate model ages ($\boldsymbol{T}_{DM}$) 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. ε_{Hf} values and model ages used in the figures were calculated using the value 1.93×10^{-11} yr^{-1} proposed by Blichert-Toft et al. (1997) (Figs. 15–18, Table 4).

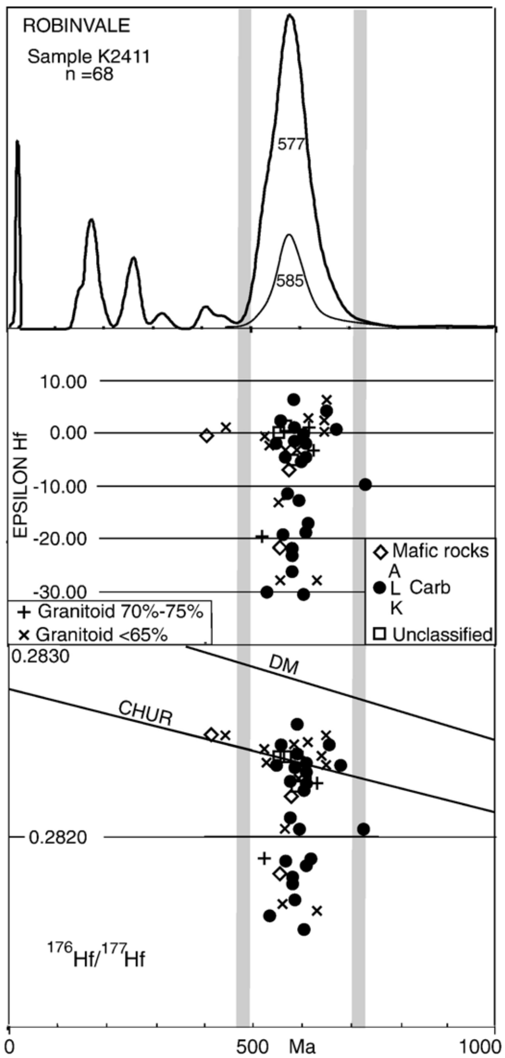


Fig. 8. Zircons (sample K2411) from Pliocene sand (Loxton–Parilla Sand, Murray Basin) at Robinvale, NSW (142.65°E, 34.79°S). Ages of the alkalines shown by fine line. ALK = alkaline; Carb = carbonatite.

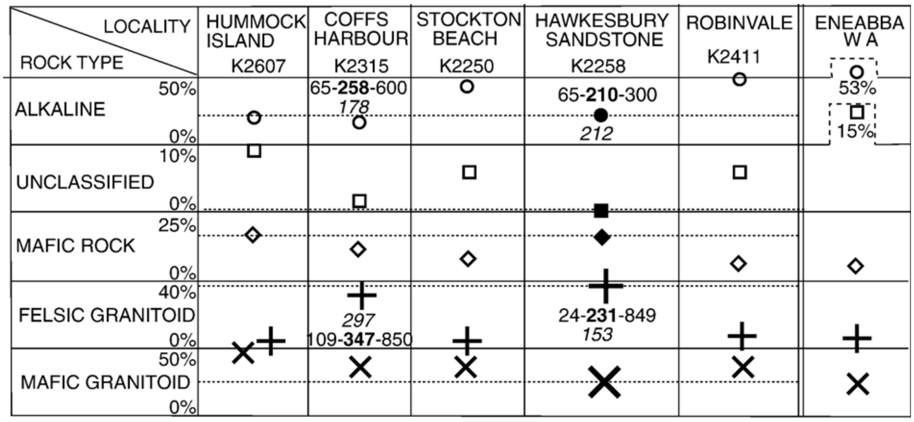


Fig. 9. Percentage of zircons by rock type from eastern Australia (Table 2) and Eneabba, Western Australia. The (variable) percentage scale is shown on the left-hand column. The values of the Hawkesbury Sandstone zircons are carried through by the dotted line. The content of U (ppm) in zircons from the Hawkesbury Sandstone and the derived Coffs Harbour sand is given for the alkaline and felsic granitoid fields, in terms of the range of values, with the mean (bold) and median (italics).

The first observation is that the model ages of most grains lie between 2.00 and 1.00 Ga (Figs. 15 and 16). The few older model ages extend to 3.91 Ga. Grouped by rock type (Figs. 17 and 18), the model ages follow the same distribution, with these differences:

Mafic rock model ages are almost wholly confined between 1.00 and 2.00 Ga; most lie between 1.00 and 1.50 Ga. Syenite, all 4 from K2315, are concentrated in T^{C}_{DM} about 1.80 Ga with a single value of 2.63 Ga. Carbonatite model ages from every sample (total of 66) are almost wholly confined between 1.00 and 2.00 Ga, with a trail extending between 2.00 and 3.83 Ga. Similarites in the range of ages within clusters are:

	Carbonatite	Mafic rock
Coffs Harbour K2315	0.88–1.97 Ga	0.86–1.72
Hawkesbury Sandstone K2258	0.94–1.75 Ga	0.88–1.39

4. Koettlitz Glacier Alkaline Province as a potential provenance of 550–500 Ma zircons

The nearest known region of alkaline composition is the Koettlitz Glacier Alkaline Province (KGAP) (Cooper et al., 1997; Read et al., 2002), at 163.00°, 78.25°S in southern Victoria Land within the Transantarctic Mountains, 100 km southwest of McMurdo Station, and some 2000 km distant in the Triassic from the Hawkesbury Sandstone (Fig. 1). The next nearest, 12000 km distant, are 530–490 Ma A2-type granitoids and 512 Ma syenites of Dronning Maud Land (Jacobs and Thomas, 2004), and, farther still, the 520–500 Ma alkali feldspar granite, quartz syenite, and syenite of the Cape Granite Suite of South Africa (Da Silva et al., 2000).

As summarized by Read et al. (2002), the Koettlitz Glacier Alkaline Province encompasses the area of southern Victoria Land that is dominated by alkaline rather than calc–alkaline igneous rocks, which crop out 150 km to the south and 60 km to the north. The main rock types are A2-type granite (Eby, 1992), alkaline diorite, nepheline syenite, and carbonatite. The carbonatite contains zircon, and the magmas were derived from the mantle, and not from carbonate metasediment in the country rock. Ages are by TIMS ^{238}U/^{206}Pb on zircon and titanite, a single SHRIMP on zircon, and our LAM–ICPMS ages (Figs. 19 and 20), all errors 2σ. In order of increasing age, the ages are:

507±12 Ma OU63304 nepheline syenite, LAM–ICPMS ^{238}U/^{206}Pb on 1 piece of zircon (Fig. 20).

517±4 Ma — OU70692 Penny Hill Granite (A2-type), conventional ^{238}U/^{206}Pb on 75 titanites (Read et al., 2002, p.149, Fig. 7).

530±3 Ma — OU63300 carbonatite, conventional ^{238}U/^{206}Pb on 6 concordant pieces of a single zircon (Hall et al., 1995).

531±24 Ma — OU63304 Radian Ridge (nepheline) Syenite, SHRIMP on zircons (n = 11) (Cooper et al., 1997).

533±13 Ma OU63300 carbonatite, LAM–ICPMS ^{238}U/^{206}Pb on 4 pieces of zircon (Fig. 19).

534±3 Ma — OU70587 Glee Intrusives (quartz monzonite) conventional ^{238}U/^{206}Pb on >100 titanites (Read et al., 2002, p.149, fig. 7).

535±9 Ma — OU70393 Panorama Pluton (monzonite) conventional ^{238}U/^{206}Pb on >100 titanites (Mellish et al., 2002, p. 139, fig. 7).

ROCK TYPE / SAMPLE	UNCLASSIFIED	ALKALINE CARBONATITE	ALKALINE SYENITE	DOLERITE BASALT, MAFIC	GRANITOID SiO2 <65%	GRANITOID SiO2 70-75%
K2607 n=23 Hummock Is beach sand	9	22		17	48	4
K2315 n=64 Coffs Harbour beach sand	2	11	6	12.5	37.5	31
K2250 n=48 Stockton beach sand	6	44		8	38	4
K2258 n=54 Hawkesbury Sandstone		**17**	**4**	**17**	**24**	**38**
K2411 n=49 Robinvale beach sand	6	49		6	33	6
OU63300 n=5 Radian Ridge carbonatite				100		
OU63304 n=5 Radian Ridge neph syenite		60		40		
OU70572 n=7 Kempe Glacier monzogabbro				14	29	57
OU70573 n=11 Kempe Glacier monzonite				36	36	28
OU70587 n=6 Kempe Glacier qtz monzonite				33	17	50
OU70692 n=23 Kempe Glacier granite				29	21	50
GVX44 n=10 Drake Head granodiorite			10		10	80
GVX110 n=48 Archangel granite		4		2	58	36
ENEABBA n=41 SAND	15	35	18	5	22	5

Fig. 10. Types of host rock (%) (Belousova et al., 2002) inferred from detrital zircons with ages 700–470 Ma from eastern Australia (K2258 Hawkesbury Sandstone in bold) in order of increasing southern latitude (from the top) and from Western Australia (at the bottom). In between are 550–500 Ma zircons from the bedrock of the Koettlitz Glacier Alkaline Province and the Oates Coast of Antarctica.

536±10 Ma — OU70455 Dromedary Mafic Complex (diorite) conventional $^{238}U/^{206}Pb$ titanite and zircon (Mellish et al., 2002, p.139, fig. 7).

539±4 Ma — OU70572 Glee Intrusives (monzogabbro), conventional $^{238}U/^{206}Pb$ on 50 titanites, OU70573 monzonite, 60 titanites (Read et al., 2002, p.149, fig. 7).

545±12 Ma OU63304 nepheline syenite, LAM–ICPMS $^{238}U/^{206}Pb$ on 4 pieces of zircon (Fig. 20).

551±4 Ma — quartz syenite, granite, Skelton Glacier (Rowell et al., 1993).

567±12 Ma OU63300 carbonatite, LAM–ICPMS $^{238}U/^{206}Pb$ on one piece of a large crystal (L-02).

The conventional and LAM–ICPMS $^{238}U/^{206}Pb$ ages of OU63300 – 530±3 and 533±13 Ma – and of OU63304 – 531±24 and 545±12 Ma – overlap each other, in the range of 531 to 551 Ma, with outliers by LAM–ICPMS analysis of single grains at 567±12 and 507±12 Ma.

The Koettlitz Glacier Alkaline Province is interpreted as having formed 551–530 Ma in a transtensional shear that pre-dated the 520 Ma onset of Ross Orogeny subduction in this area.

Mellish et al. (2002) determined the Nd–Sm $\boldsymbol{T}_{DM}$ of a gabbro at 1.25 Ga and of a monzonite at 1.42 Ga, and

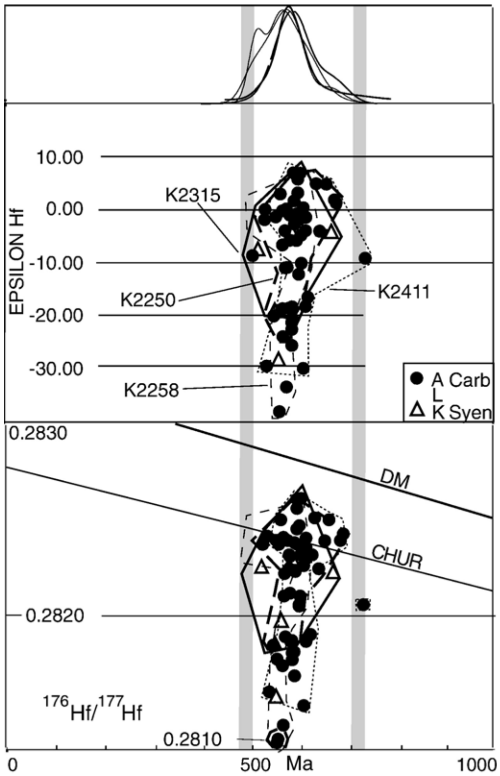


Fig. 11. Summary properties of alkaline zircons from the Hawkesbury Sandstone (K2258) and derived sands — Coffs Harbour (K2315), Stockton Beach (K2250), and Robinvale (K2411). The age distribution is above, the ε_{Hf} in the middle, and $^{176}Hf/^{177}Hf$ below. ALK = alkaline; Carb = carbonatite; CHUR = chondritic unfractionated reservoir; DM = depleted mantle; Syen = syenite.

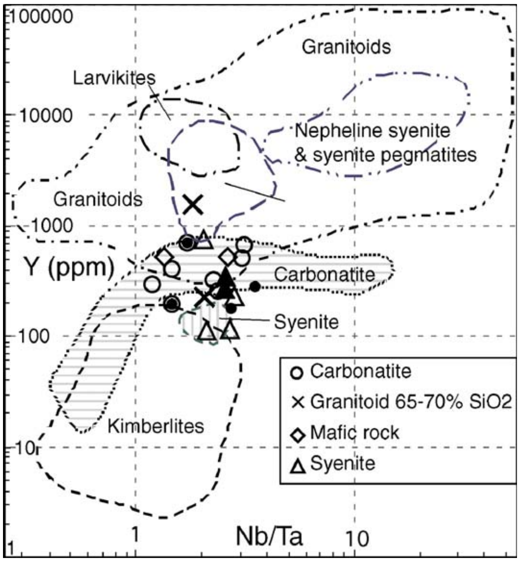


Fig. 12. Zircons 700–500 Ma classified as carbonatite in the "short" CART tree (Belousova, 2000; Belousova et al., 2002) — 6 from the Hawkesbury Sandstone (filled symbols), 14 from Coffs Harbour sand (open symbols). After further trace-element analysis, the zircons were classified in the "full" CART tree — Hawkesbury as 4 carbonatite, 2 syenite; Coffs Harbour 7 carbonatite, 4 syenite, 2 mafic rock, 1 granite 65–70%, and plotted on the fields of zircon compositions used as discriminants for various rock types. This figure shows yttrium vs. niobium/tantalum.

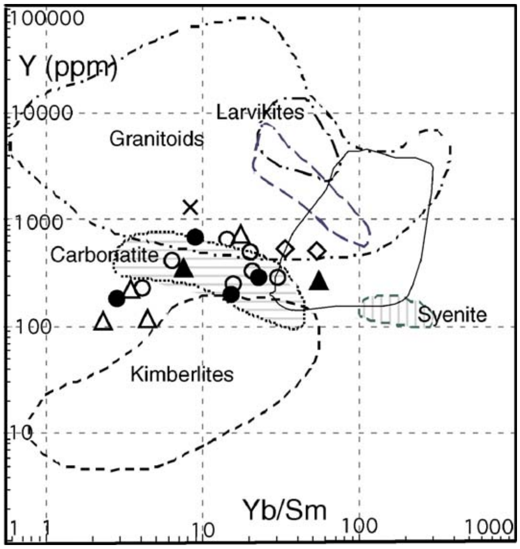


Fig. 14. As in Fig. 12, yttrium vs. ytterbium/samarium.

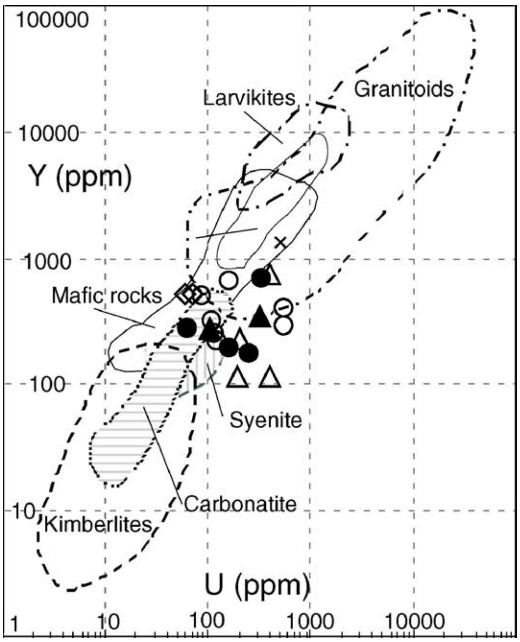


Fig. 13. As in Fig. 12, yttrium vs. uranium.

Cooper et al. (1997) found 1.32 Ga for the Dismal Syenite.

From samples OU63300, OU63304, OU70572, OU70573, OU70587, and OU70692, we analysed zircons for trace elements and Hf-isotopes (Figs. 19–24).

4.1. Trace-element and Hf-isotope analysis

4.1.1. OU63300 carbonatite dyke

A carbonatite dyke (Fig. 19) at Radian Ridge was dated by conventional U–Pb methods as 530 ± 3 Ma (2σ) (Hall et al., 1995), here using $^{206}Pb/^{238}U$ to conform with our ages (n = 6, U 100–600 ppm; other grains up to 2636 ppm). Other zircons from the dyke are dated by LAM–ICPMS as 533 ± 13 Ma (2σ) (n = 4) with concordance; pieces with high U – up to 8000 ppm – are discordant. A piece of a large (5 mm) zircon (piece no. L-02) is dated (concordantly) as 567 ± 12 Ma. The 5 pieces are classified as derived from mafic rock (Belousova et al., 2002).

Of the 3 concordant pieces further analysed for trace elements by LAM–ICPMS and classified for rock type (Figs. 25–27), 2 are mafic rock and one granitoid with 70–75% SiO_2. Two explanations for the misclassification are possible: (1) the original database is not fully representative and does not cover the full range of zircon composition from carbonatites, or (2) the zircons in the carbonatite dyke are xenocrysts.

The 'misclassification' of the 530 Ma zircons using trace element signatures is unlikely to be due to a xenocrystic origin, since the crystals are euhedral (no resorption), and the carbonatites at Radian Ridge occur

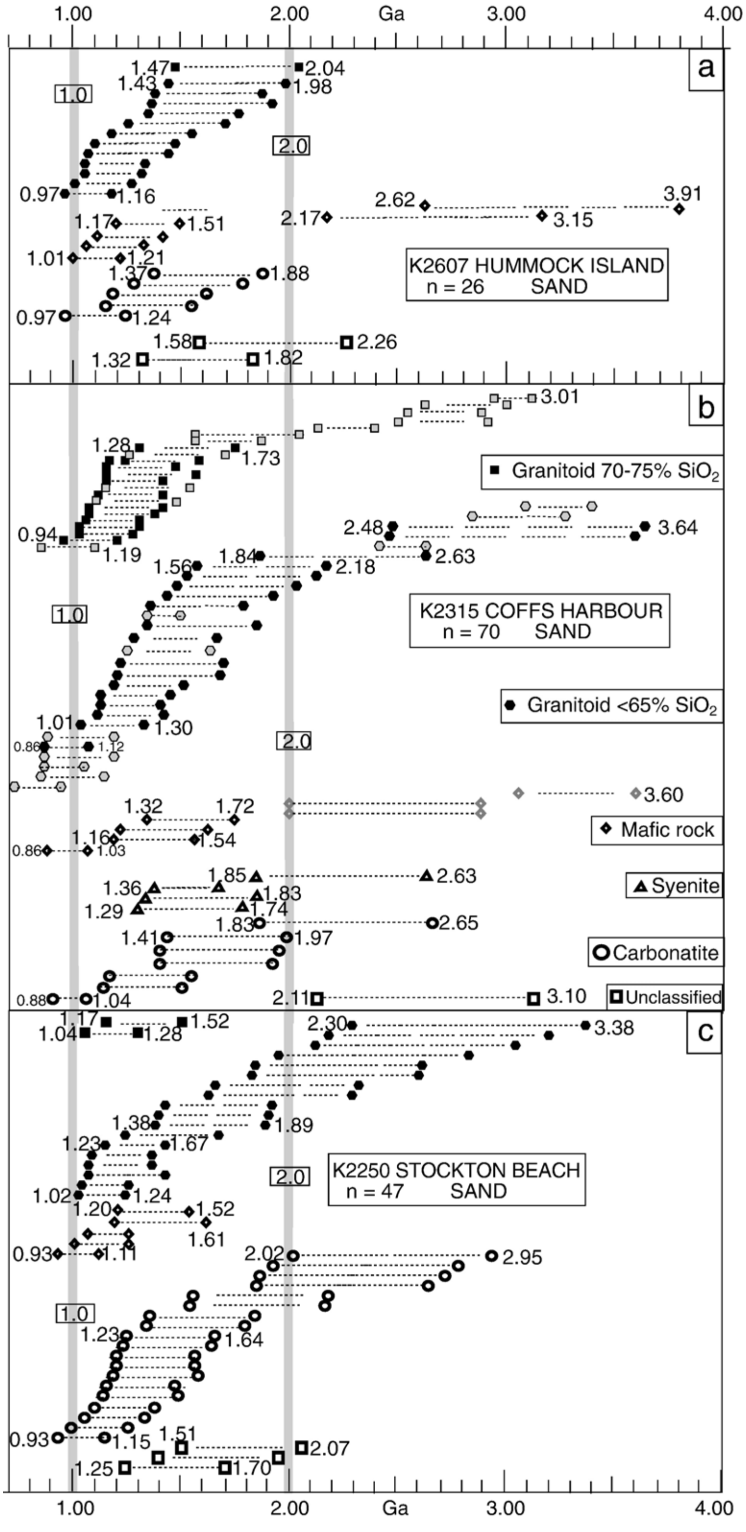


Fig. 15. Model ages of zircons from eastern Australia. T_{DM} (minimum) and T^{C}_{DM} (optimum) are given for each grain, as described in Section 2. Zircons with U–Pb age between 734 and 440 Ma (Southwest Pacific–Gondwana group) are in black, and are discussed here, zircons with age outside this range are in grey.

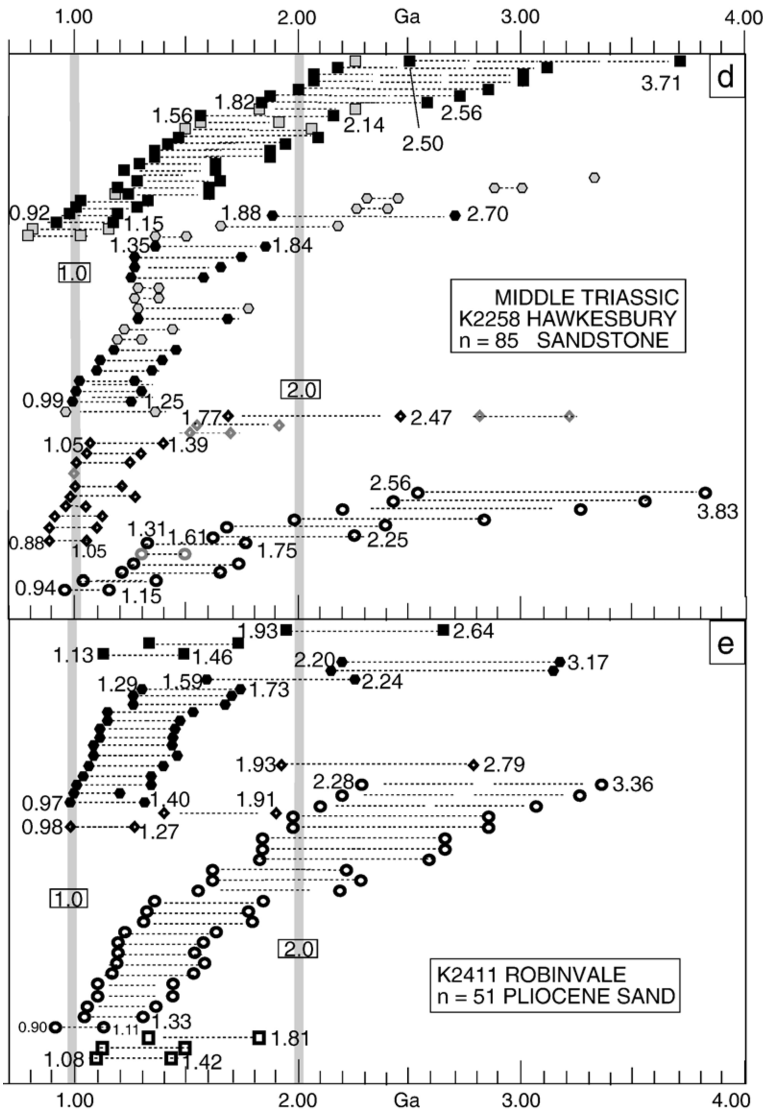


Fig. 16. Model ages of zircons from eastern Australia. $\boldsymbol{T}_{\mathrm{DM}}$ (minimum) and $\boldsymbol{T}^{C}_{\mathrm{DM}}$ (optimum) are given for each grain, as described in Section 2. Zircons with U–Pb age between 734 and 440 Ma (Southwest Pacific–Gondwana group) are in black, and are discussed here, zircons with age outside this range are in grey.

within nepheline syenite rather than gabbro. Nothing in the exposed Ross orogen bedrock in that part of the Transantarctic Mountains is old enough to have provided the 567 Ma crystal. Also, it is unlikely that carbonatitic activity lasted for 30 m.y. (567–530 Ma). However, by rejecting a xenocrystic origin for all but one of the grains we are simply shifting rather than solving the conundrum. These are unusual carbonatites: fenitization – alkali metasomatism – is either absent or is dissimilar to the normal highly alkaline type, and the Sr isotope ratio is elevated above what one would expect of a mantle-derived magma. The 567 Ma megaphenocryst (especially with the agreement at 530–533 Ma of all the other concordant pieces) would seem to be xenocrystic, but from an unknown source.

Calcite from the dyke has a Nd-isotope $\boldsymbol{T}_{\mathrm{DM}}$ model age (X in Fig. 28b) of 1.5 Ga (Hall et al., 1995).

4.1.2. OU63304 nepheline syenite

Zircons from sample OU63304 of a nepheline syenite at Radian Ridge (Fig. 20) are dated by ^{206}Pb/^{238}U SHRIMP as 531±24 Ma (Cooper et al., 1997) (n=11, U 107–1162 ppm; a discordant grain has 2079 ppm) (Fig. 20). Four zircons from the syenite are dated by LAM–ICPMS as 545±12 Ma and one as 507±12.

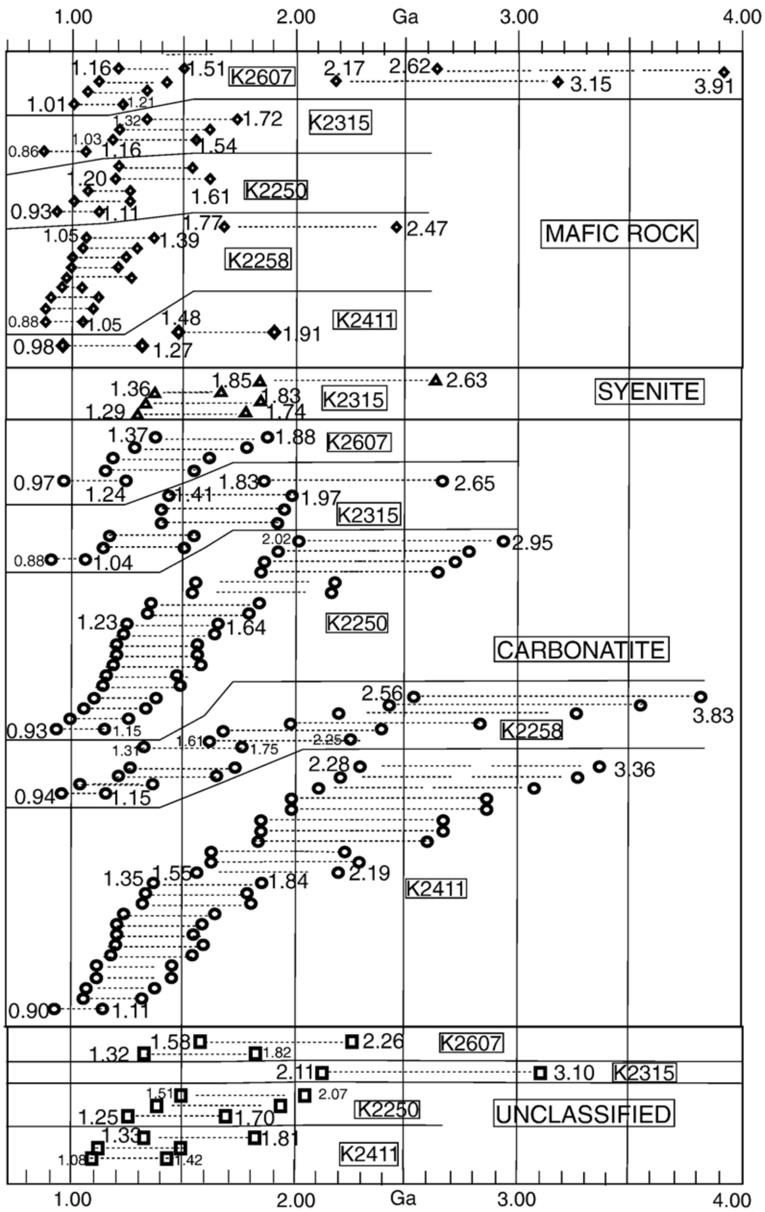


Fig. 17. Model ages of zircons from eastern Australia grouped by rock type.

The classification is 3 carbonatite and 2 mafic rock. Of the 5 zircons further analysed for rock type, one is carbonatite, 2 syenite, and one each of mafic rock and granitoid with 65–70% SiO_2 (Figs. 25–27). The classification of 3 zircons as alkalines agrees with that of the host rock.

A whole-rock sample has a Nd-isotope T_{DM} model age (×, Fig. 28c) of 1.4 Ga (Hall et al., 1995).

4.1.3. OU70572 Glee Intrusives: monzogabbro

Samples OU70572 and OU70573 of the Glee Intrusives (Fig. 21) at the Royal Society Range are dated by conventional U–Pb on titanite (n=50) as 539±4 (Read et al., 2002). Seven zircons are classified by trace-element content as 4 felsic granitoid, 2 mafic granitoid, and 1 mafic rock.

4.1.4. OU70573 Glee Intrusives: monzonite

Zircons of the Glee monzonite comprise 3 felsic granitoid, 4 mafic granitoid, and 4 mafic rock (Fig. 22).

4.1.5. OU70587 Glee Intrusives: quartz monzonite

Titanite (n>100) is dated by conventional U–Pb as 534±3 Ma (Read et al., 2002). 3 zircons are felsic

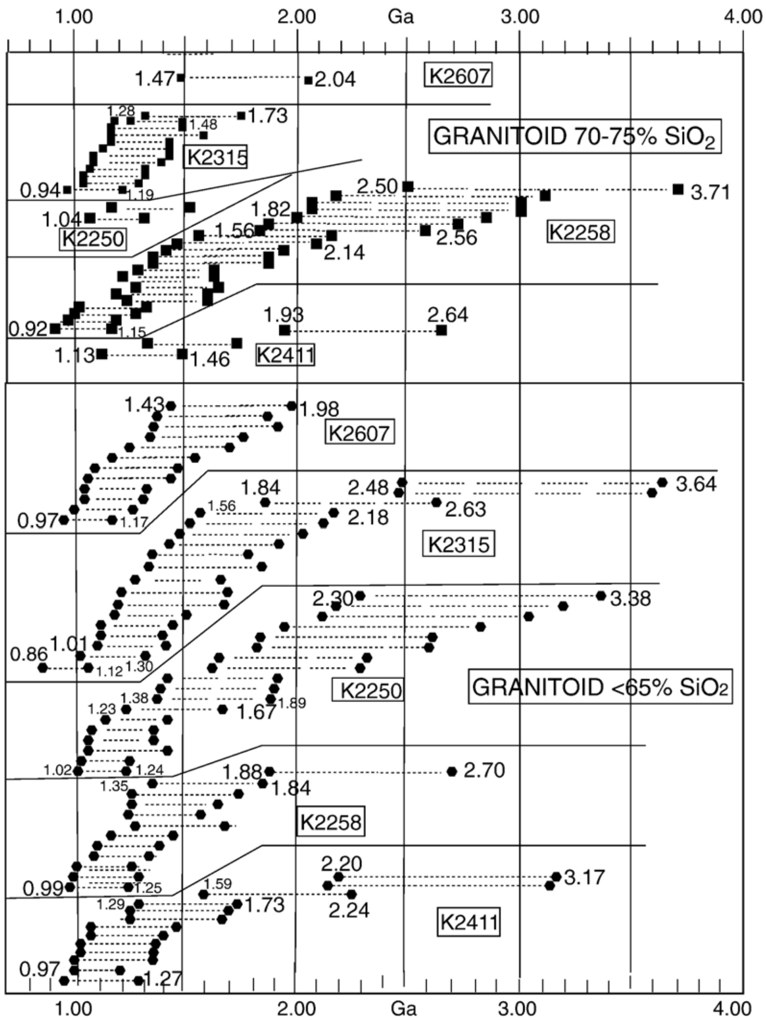


Fig. 18. Model ages of zircons from eastern Australia grouped by rock type.

granitoid, 1 is mafic granitoid, and 2 are mafic rock (Fig. 23).

4.1.6. OU70692 Penny Hill granite

Titanite is dated by conventional U–Pb as 517 ± 4 Ma (Read et al., 2002). Zircons are 11 felsic granitoid, 5 mafic granitoid, and 7 mafic rock (Fig. 24).

4.1.7. Trace-element analysis of OU63300 and 63304 (Figs. 25–27)

Three zircons from the OU63300 carbonatite and 5 from the OU63304 nepheline syenite were classified by CART on plots (Belousova, 2000) of yttrium vs. uranium (Fig. 25), yttrium vs. ytterbium/samarium (Fig. 26), and hafnium vs. yttrium (Fig. 27). All the zircons have Hf contents less than 1.1 wt.% (Fig. 27), characteristic of zircons from alkaline rock types (Belousova et al., 2002). The only grain classified as from carbonatite falls within the carbonatite field on Figs. 26 and 27. The 2 syenites lie near the syenite field but have Y < 100 ppm (Fig. 25), which is characteristic of zircons that crystallize from mafic unfractionated rock. Of the 3 grains classified as from mafic rocks, 2 plot inside or near the mafic (basic) field on Fig. 26. The 2 zircons classified as from granitoids show high U (>300 ppm) and Y (>1000 ppm) contents, typical of zircons in high-Si granitoids.

4.1.8. Summary of rock types

Zircons from the carbonatite and nepheline syenite have Hf contents less than 1.1 wt.%, characteristic of zircons from alkaline rock types. Of the 8 analysed zircons of the nepheline syenite, 5 are carbonatite and the others mafic rock. Of the 13 analysed zircons of the

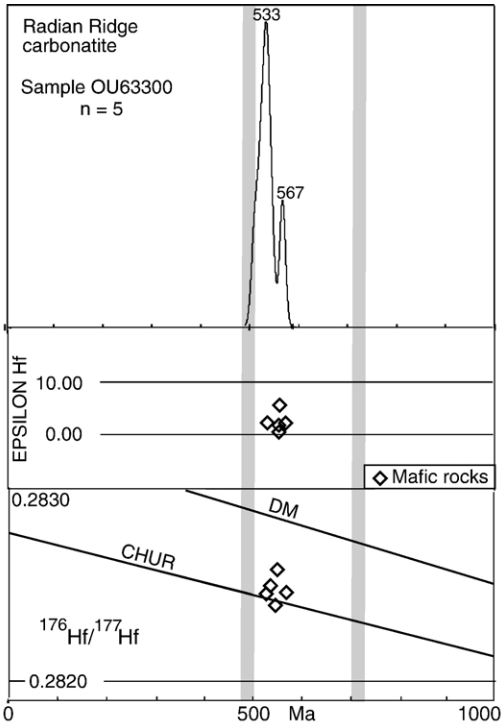


Fig. 19. Zircons from sample OU63300 from a carbonatite dyke at Radian Ridge (Hall et al., 1995). Above, probability distribution diagram (Ludwig, 2001) of U–Pb LAM–ICPMS zircon ages, with peaks at 533 and 567 Ma. 700–500 Ma range is delimited by grey bands. Middle, ε_{Hf} (difference between the sample and a chondritic reservoir in parts/10^4) vs. ages of zircons with trace-element classification of source igneous rock (Belousova et al., 2002). Below, $^{176}Hf/^{177}Hf$ of zircons with discriminant lines marked CHUR (chondritic unfractionated reservoir) and DM (depleted mantle) vs. age of zircons with trace-element classification.

carbonatite, only 1 is carbonatite, and the rest are mafic rock. Zircons in the remaining samples are mainly granitoid 70–75% SiO_2, with minor amounts of granitoid <65% SiO_2 and mafic rock.

4.2. Model ages (Fig. 28)

The model ages of the Koettlitz Glacier Alkaline Province samples are plotted on Fig. 28 between those of the Oates Coast granitoids (above) and those of other Transantarctic Mountains rocks and the detrital zircons of eastern Australia (below). The Penny Hill Granite ranges from 1.7 to 1.0 Ga, and the others have a narrower range of 1.5–0.9 Ga, including the 1.5–1.2 Ga range in the Dismal Syenite, Panorama monzonite and gabbro (Fig. 28a).

From the distribution of Sm–Nd model ages ($\boldsymbol{T}_{DM}$), Borg et al. (1990) and Borg and DePaulo (1991,1994) distinguished four provinces in the Transantarctic Mountains (Figs. 1 and 28h):

(a) 1.9–1.6 Ga in the Transantarctic Mountains between northern Victoria Land and 100 km south of the Beardmore Glacier.
(b) 1.5–1.1 Ga south of the Beardmore Glacier extending to the Horlick Mountains.
(c) 2.0–1.7 Ga in the Bowers and Robertson Bay terranes of northern Victoria Land.
(d) In the Miller Range, $\boldsymbol{T}_{DM}$ from 510 Ma granites is ~2.0 Ga and $\boldsymbol{T}_{DM}$ from metamorphic rocks is 2.72, 2.83, 3.10, and 3.48 Ga. The Archean $\boldsymbol{T}_{DM}$ are consistent with the ~3.0 Ga primary magmas dated by Goodge and Fanning (1999). The $\boldsymbol{T}_{DM}$ of ~2.0 Ga (Borg et al., 1990) is interpreted as indicating Proterozoic crust beneath the over-thrusted Nimrod Group. In Terre Adélie and King

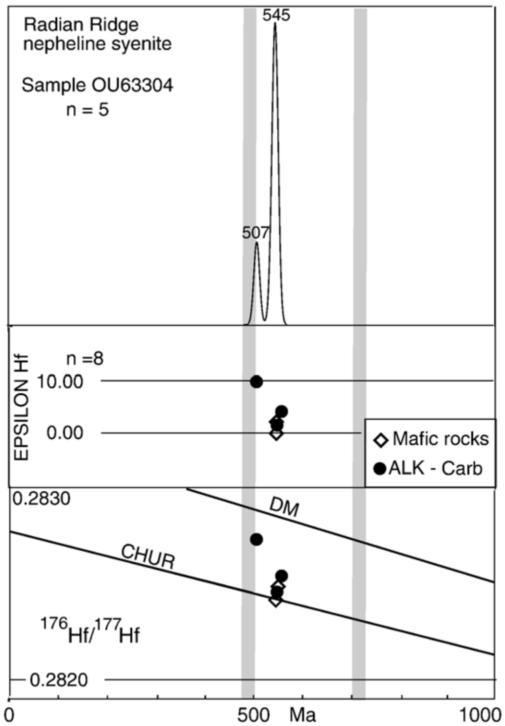


Fig. 20. Zircons (sample OU63304) from a nepheline syenite at Radian Ridge (Hall et al., 1995; Cooper et al., 1997). Above, probability distribution diagram (Ludwig, 2001) of U–Pb LAM–ICPMS zircon ages, with peaks at 507 and 545 Ma. 700–500 Ma range is delimited by grey bands. Middle, ε_{Hf} (difference between the sample and a chondritic reservoir in parts/10^4) vs. ages of zircons with trace-element classification of source igneous rock (Belousova et al., 2002). Below, $^{176}Hf/^{177}Hf$ of zircons with discriminant lines marked CHUR (chondritic unfractionated reservoir) and DM (depleted mantle) vs. age of zircons with trace-element classification.

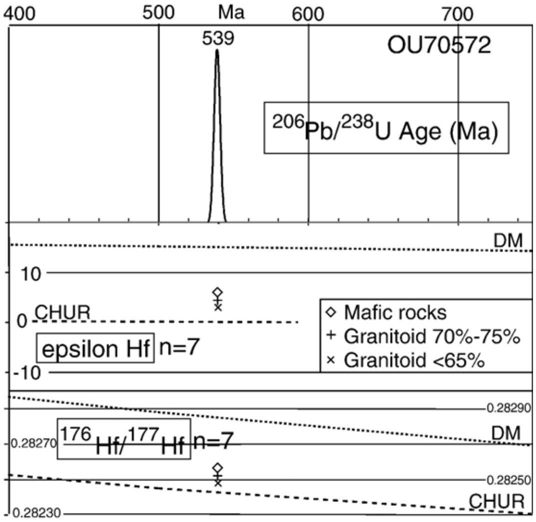


Fig. 21. Titanite from sample OU70572 of the Glee intrusives at the Royal Society Range are dated by conventional U–Pb as 539 ± 4 (Read et al., 2002). Seven zircons were analysed for ε_{Hf} (middle) and $^{176}Hf/^{177}Hf$ (below). Discriminant lines are CHUR (chondritic unfractionated reservoir) and DM (depleted mantle).

George V Land (TA-KGVL of Fig. 1), the $\boldsymbol{T}_{DM}$ of 3.2–2.8 Ga from 2700–2400 Ma rocks and $\boldsymbol{T}_{DM}$ of 2.2–1.9 Ga from 1700 Ma rocks match those in the conjugate Australia (Fitzsimons, 2003).

A range of 1.9–1.2 Ga is found in the Oates Coast granitoids (Fig. 28a).

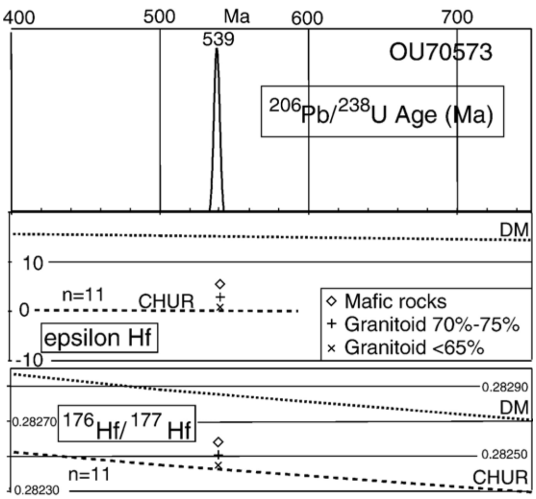


Fig. 22. Titanite from sample OU70573 of the Glee intrusives at the Royal Society Range are dated by conventional U–Pb as 539 ± 4 (Read et al., 2002). Eleven zircons were analysed for ε_{Hf} (middle) and $^{176}Hf/^{177}Hf$ (below). Discriminant lines are CHUR (chondritic unfractionated reservoir) and DM (depleted mantle).

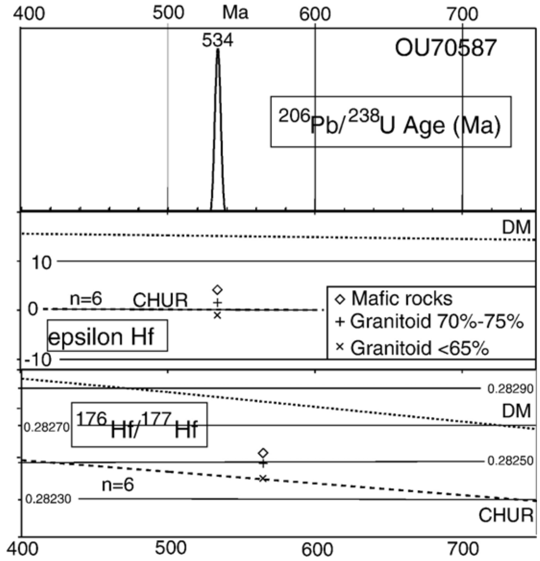


Fig. 23. Titanite from sample OU70587 of the Glee quartz monzonite at the Royal Society Range are dated by conventional U–Pb as 534 ± 3 (Read et al., 2002). Six zircons were analysed for ε_{Hf} (middle) and $^{176}Hf/^{177}Hf$ (below). Discriminant lines are CHUR (chondritic unfractionated reservoir) and DM (depleted mantle).

In the Whitmore Mountains, 175 Ma granite has $\boldsymbol{T}_{DM}$ of 1.7 to 1.3 Ga (Storey et al., 1988), and in the Haag Nunataks, gneiss has $\boldsymbol{T}_{DM}$ of 1.3 to 1.1 Ga (Fig. 28h).

$\boldsymbol{T}_{DM}$ of 2.0–1.0 Ga in the derived eastern Australian sandstone (Fig. 28h) embraces the range of model ages

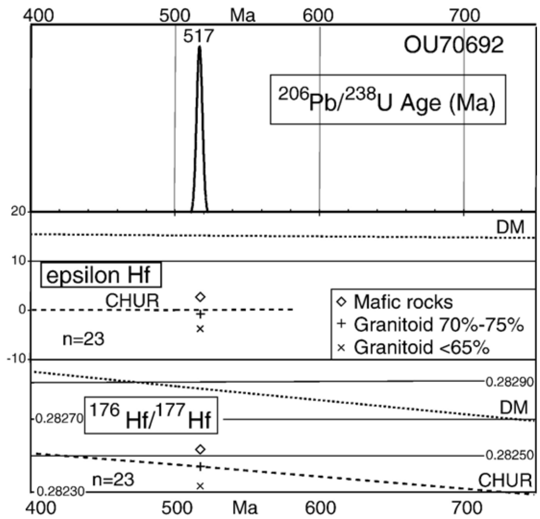


Fig. 24. Titanite from sample OU70692 of the Penny Hill granite at the Royal Society Range are dated by conventional U–Pb as 517 ± 4 (Read et al., 2002). Twenty-three zircons were analysed for ε_{Hf} (middle) and $^{176}Hf/^{177}Hf$ (below). Discriminant lines are CHUR (chondritic unfractionated reservoir) and DM (depleted mantle).

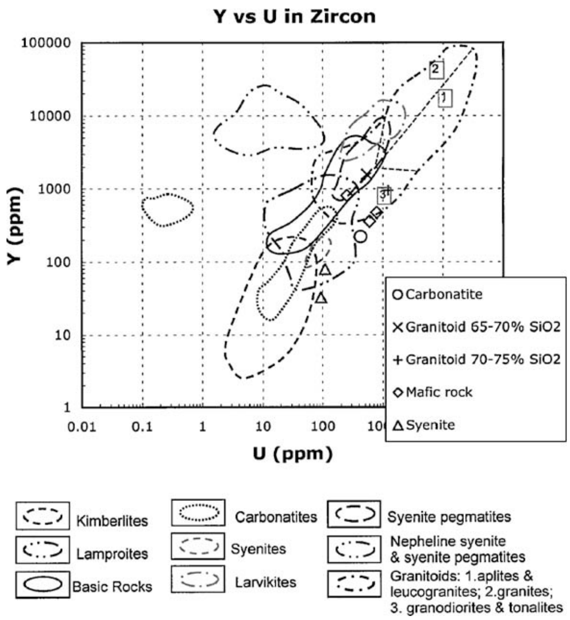


Fig. 25. Analysis of 3 zircons from OU63300 carbonatite and 5 from OU63304 nepheline syenite, both from Radian Ridge, classified by CART. Yttrium vs. uranium.

of the Oates Coast and the Transantarctic Mountains (Koettlitz Glacier Alkaline Province, Horlick Mountains), Whitmore Mountains, and Haag Nunataks, and is also represented in the Leeuwin Complex. All this suggests that the potential provenance of primary 700–500 Ma age contains model ages 2.0–1.0 Ga, and that this terrane may extend to the west of, and underlie, the Ross orogen.

4.3. Interpretation of Antarctic provenances of Eastern Australian sediment (Fig. 29)

The Early Cambrian (525 Ma) turbidites of the Kanmantoo Group (Ireland et al., 1998; Fig. 30f) were deposited from a northward paleocurrent in a trough that from 520 Ma was transformed into the Delamerian orogen. The 700–530 Ma predominant age of the detrital zircons suggests derivation from a provenance of this age. Few zircons have the ages of the exposed rocks in the Terre Adélie and King George V Land – 2700–2400 and 1700 Ma – suggesting that this terrane was narrow, and did not supply significant amounts of detritus to the Kanmantoo Group. Accordingly, we show this terrane as marking the southeastern limit of the Mawson Continent (Fig. 37).

The Ordovician turbidite, with predominant 700–500 Ma zircons, was deposited from axial northerly paleocurrents, and the Ordovician–Devonian Mathinna turbidite, with predominant 700–400 Ma zircons (Black et al., 2004), was deposited from northeasterly paleocurrents (Veevers, 2000a, p. 209, 210, 350) that flowed from an area of postulated **d**+ 700–500 Ma provenance, which augments (in 700–550 Ma age) the potential supply of 550–500 Ma zircons from the Ross orogen.

The 500–400 Ma zircons in the Mathinna turbidite cannot have come from Antarctica, because the youngest rock in this range is 475 Ma (Veevers, 2000a, p. 259). The Lachlan Fold Belt of southeastern Australia has appropriate ages of 480–445 Ma in the Molong Volcanic Arc (Veevers, 2000a, p. 162) and 450 Ma and younger in granitoids (Veevers, 2000a, p. 175) but is ruled out because of its position downslope from Antarctica.

The Antarctic provenance (Fig. 29) contributes to the Hawkesbury Sandstone down the 034° paleoslope across the Lachlan Fold Belt. The Lachlan Fold Belt comprises Ordovician (with 700–500 Ma zircons), Silurian, and Devonian sediments and volcanics, and voluminous granitoids aged 450 to 320 Ma (also with inherited 700–500 Ma zircons; Williams, 1992, 1998; Williams and Chappell, 1998). On the western edge of the Sydney Basin and immediately north of the Bumballa Formation, the Early Permian Tallong Conglomerate, with zircon age peaks at 420 and 330 Ma, and few older than 450 Ma, reflects the provenance of Lachlan Fold Belt igneous rocks. The scarcity of zircons of this age (2 out of 75) in the Hawkesbury Sandstone effectively rules out the Lachlan

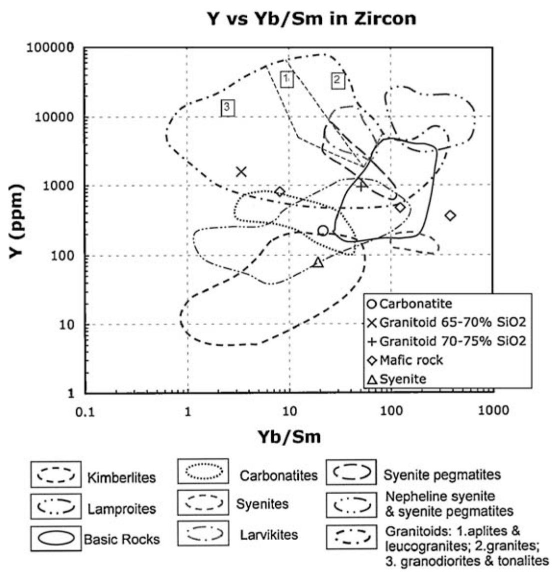


Fig. 26. Analysis of 3 zircons from OU63300 carbonatite and 5 from U63304 nepheline syenite, both from Radian Ridge, classified by CART. Yttrium vs. ytterbium/samarium.

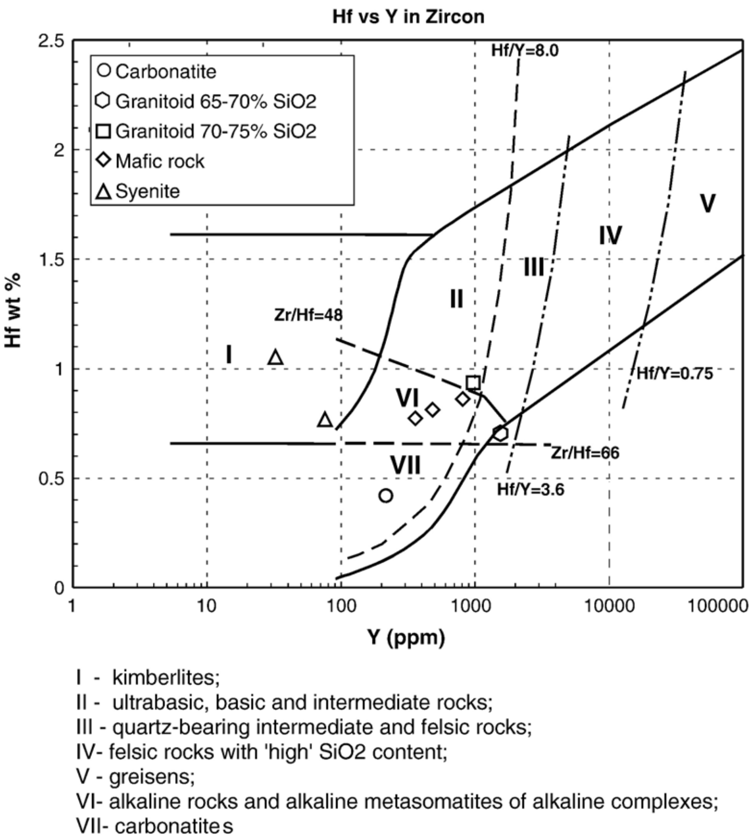


Fig. 27. Analysis of 3 zircons from OU63300 carbonatite and 5 from U63304 nepheline syenite, both from Radian Ridge, classified by CART. Yttrium vs. niobium/tantalum.

Fold Belt, including the Ordovician turbidite with detrital zircons of 700–500 Ma age, as provenance.

The mean cross-dip azimuth (034°) of the fluvial Hawkesbury Sandstone indicates the paleoslope, and the reciprocal bearing leads to the Ross orogen of the Transantarctic Mountains and, in grey with white bands, the wider area in Wilkes Land south of the Oates Coast, marked with ?**d**+.

A grey arrow links the Hawkesbury Sandstone and the beach sands to the north, all with distinctive alkaline 700–500 Ma zircons [[ALK 700–500]]. Another grey arrow links the Hawkesbury Sandstone with the Pliocene Robinvale beach sand with the same alkaline 700–500 Ma zircons; arrows of broken lines indicate the possible provenance of Ordovician turbidite in the Lachlan Fold Belt.

5. Oates Coast

Rb/Sr ages of the Drake Head granodiorite (649± 30 Ma) and the Archangel granite (573±10 Ma) from the Oates Coast (Adams, 1996; Adams and Roland, 2002) suggested Antarctic occurrences of rock in the 700–550 Ma range. The Rb/Sr ages are now superseded by our LAM–ICPMS dating of zircons (from samples supplied by C.J. Adams) in the Drake Head granodiorite as 487±15 Ma (2σ) ($n=8$) and in the Archangel granite as 505±6 Ma (2σ) ($n=8$). At the same time, we analysed the zircons for rock type and model ages (Fig. 28a). The 48 zircons from the Drake Head granodiorite comprise 17 felsic granitoid, 28 mafic granitoid, 2 carbonatite, and 1 mafic rock. The 10 grains analysed from the Archangel granite comprise 8 felsic granitoid, 1 mafic granitoid, and 1 nepheline syenite pegmatite.

6. Eneabba beach sand and the Pan-Gondwanaland Leeuwin Complex of southwestern Australia

The zircons from the Eneabba mineral sand in Western Australia come from the same sample as those with U–Pb SHRIMP ages between 485 – 536 (peak) – 645 Ma (Figs. 2 and 30) (Sircombe and Freeman, 1999). Either the zircons are recycled from the underlying Permian sandstones of the Perth Basin (Cawood and

Nemchin, 2000), which contain zircons with ages of **d** (600–500 Ma) and **dd** (725–650 Ma) (Veevers et al., 2005), or they come direct from the underlying Pinjarra orogen, in particular, from the exposed Leeuwin Complex, 450 km to the south, with age cluster **d** (600–537–500 Ma) and **dd** (725–692–650 Ma)(Collins, 2003; Veevers et al., 2005), or from both.

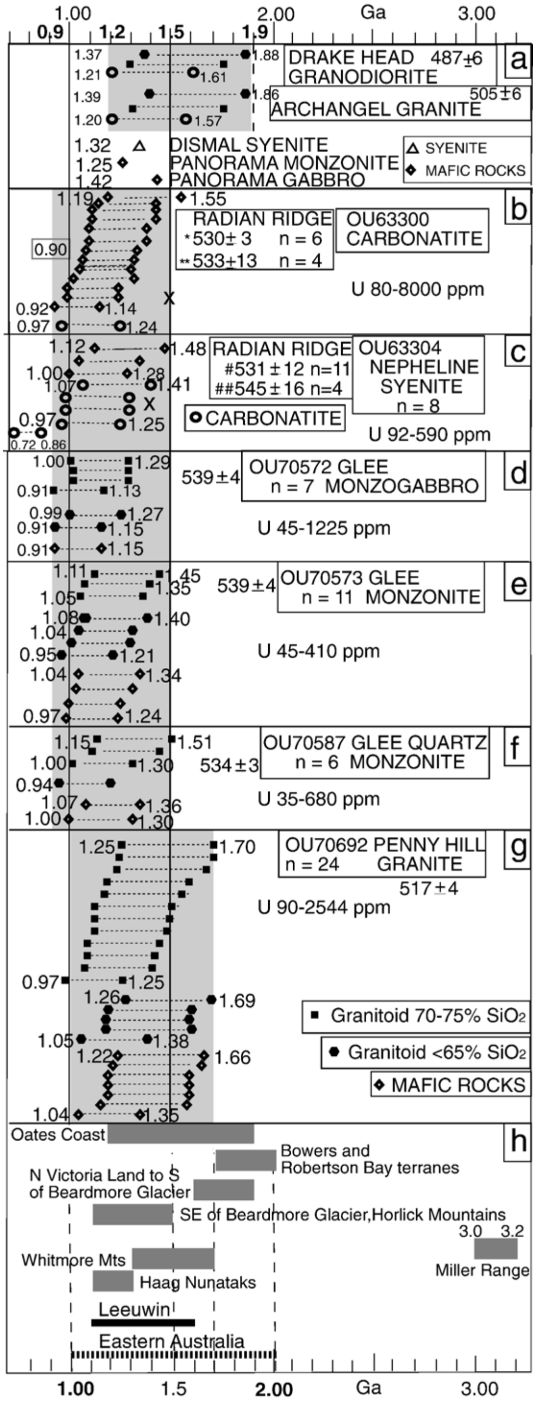


Fig. 28. Model ages (Ga) of zircons aged between 470 and 700 Ma (a) to (g), and model ages of whole rocks (a, lower part) and (h). Model ages of each zircon are plotted according to their classification in 6 groups [symbols in (a), (c), (g)] and from the youngest T_{DM} to the oldest T^C_{DM}. T_{DM} is a minimum age for the depleted mantle source of the magma from which the zircon crystallised. T^C_{DM} is a "crustal" model age, which assumes that its parental magma was produced from an average continental crust ($^{176}Lu/^{177}Hf=0.015$) that was derived originally from the depleted mantle. (a) (Above) Zircons from sample GXV44 (IGNS R no. 13707) of the Drake Head granodiorite, Oates Coast, northern Victoria Land (Adams and Roland, 2002) dated by LAM–ICPMS as 487±15 Ma (2σ) ($n=8$). The 48 grains analysed for rock type comprise 17 felsic granitoids, 28 mafic granitoid, 2 carbonatite, and 1 mafic rock. (Middle) Zircons from sample GXV110 (IGNS R no. 13779) of the Archangel granite, Outrider Nunatak, northern Victoria Land (Adams, 1996) dated by LAM–ICPMS as 505±6 Ma (2σ) ($n=8$). The 10 grains analysed for rock type comprise 8 felsic granitoids, 1 mafic granitoid, and 1 nepheline syenite pegmatite. (Below) Samples from the Koettlitz Glacier Alkaline Province (KGAP), showing the whole-rock Nd-isotope model age of the Dismal Syenite (Cooper et al., 1997) and the Panorama Monzonite and Panorama Gabbro (Mellish et al., 2002). (b–g). Samples from the Koettlitz Glacier Alkaline Province (KGAP), southern Victoria Land. (b) Zircons from sample OU63300 of a carbonatite dyke at Radian Ridge. (c) Zircons from sample OU63304 of a nepheline syenite at Radian Ridge are dated by U–Pb SHRIMP# ($^{206}Pb/^{238}U$) ($n=11$, U 107–1162 ppm; a discordant grain has 2079 ppm) as 531±12 Ma (Cooper et al., 1997). Four zircons from the syenite are dated by LAM–ICPMS## as 545±16 Ma (2σ) and one as 507±6 (Fig. 20). Of the 8 zircons analysed for rock type, 5 are carbonatite and 3 mafic rock. A whole-rock sample has a Nd-isotope T_{DM} model age (×) of 1.4 Ga (Hall et al., 1995). (d) Titanite from samples OU70572 and OU70573 of the Glee monzogabbro at the Royal Society Range are dated by conventional U–Pb as 539±4 (Read et al., 2002). 4 zircons are felsic granitoid, 2 mafic granitoid, and 1 mafic rock. (e) Zircons from sample OU70573 of the Glee monzonite comprise 3 felsic granitoid, 4 mafic granitoid, and 4 mafic rock. (f) Titanite from sample OU70587 of the Glee quartz monzonite are dated by conventional U–Pb as 534±3 (Read et al., 2002). In OU70587, 3 zircons are felsic granitoid, 1 mafic granitoid, and 2 mafic rock. (g) Titanite from sample OU70692 of the Penny Hill granite are dated by conventional U–Pb as 517±4 (Read et al., 2002). Zircons are 12 felsic granitoid, 5 mafic granitoid, and 7 mafic rock. (h) Nd T_{DM} model ages in (1) the Transantarctic Mountains from Borg and DePaulo (1994) except Miller Range from Fitzsimons (2003), (2) the Whitmore Mountains and Haag Nunataks (Storey et al., 1988, 1994), (3) the Leeuwin Complex (Collins, 2003), and (4) Hf T_{DM} model ages of detrital zircons from eastern Australia (Figs. 15–18).

The Leeuwin Complex "is but a small onshore outcrop of an extensive region of Neoproterozoic orogenesis that stretches over 500 km out to sea" (Collins, 2003). "The 650–580 Ma collision of East and West Gondwanaland by closure of the Mozambique Ocean and continued Pan-African contraction to 500 Ma generated the Mozambique Orogenic Belt and an orthogonal belt through Prydz Bay to Cape Leeuwin" (Veevers, 2000a, p. 278). As an offshoot of the Mozambique orogenic belt (the East African–Antarctic

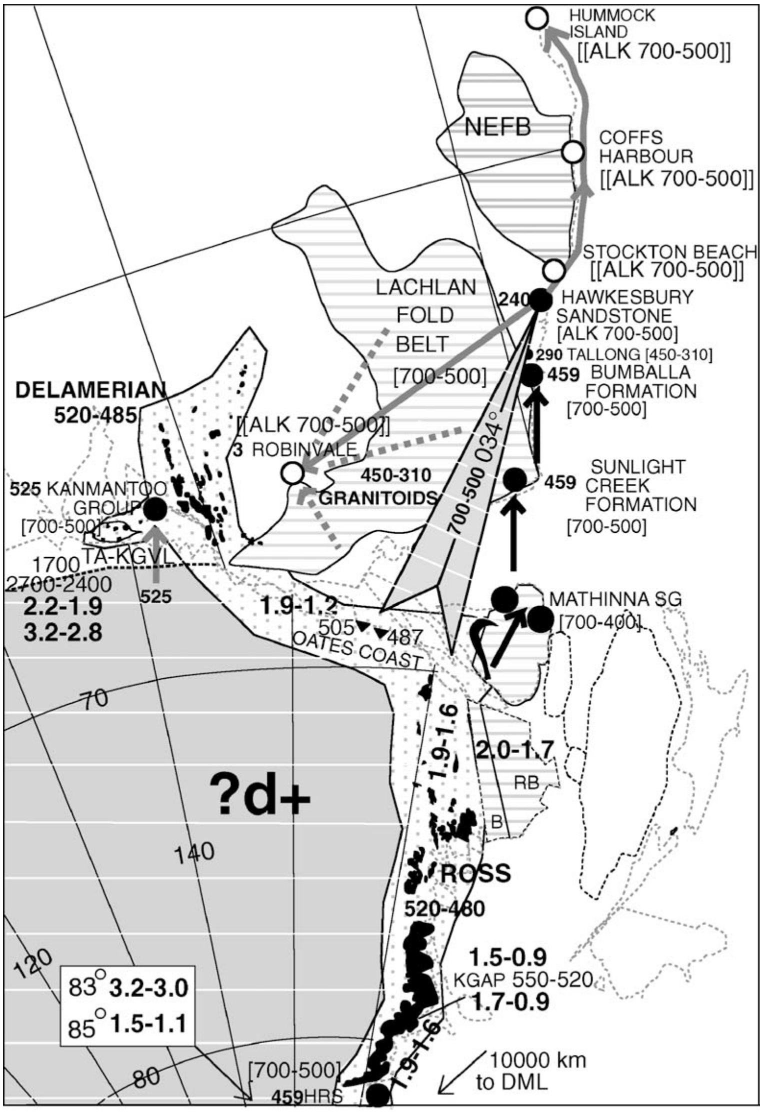


Fig. 29. Easternmost Gondwanaland in the Middle Triassic (base from Fig. 1). Ages in Ma (e.g., 520), model ages in Ga (1.5–1.1). First-cycle 700–500 Ma alkaline zircons are denoted by a filled circle and [ALK 700–500], and second-cycle ones by an open circle and [[ALK 700–500]]. DML = Dronning Maud Land; B = Bowers terrane; RB = Robertson Bay terrane; SG = Supergroup; TA–KGVL = Terre Adélie–King George V Land.

orogen of Jacobs and Thomas, 2004), the Pinjarra orogen registers typical Pan-Gondwanaland (650–500 Ma) events (Veevers, 2003, 2004), including abundant alkaline rocks. According to Fitzsimons (2003), "The Leeuwin Complex is dominated by felsic orthogneiss, ranging from granodiorite to alkali granite … 860–650 and 540–520 Ma protoliths are typical A-type granites … Wilde and Murphy (1990) note that the emplacement of relatively alkaline granites … was consistent with a continental rift environment at 550–500 Ma … Another possibility was suggested by Harris (1994), who noted that this time period was characterized by sinistral transcurrent displacement both within the Leeuwin Complex and Pinjarra Orogen as a whole, and argued that local extension in the Leeuwin Complex was generated within an extensional jog of the strike-slip system".

Veevers et al. (2005) found that in 2 of the 3 samples of Permian sandstone from the Perth Basin analysed for Hf and trace elements 6 out of 15 zircons or 40% within the range 700–500 Ma (minor peak) were alkaline (carbonatite), confirming their provenance in the Leeuwin Complex.

Forty-one Eneabba zircons were analysed for trace elements and classified by CART as follows: 53% alkaline (35% carbonatite, 18% syenite), 22%

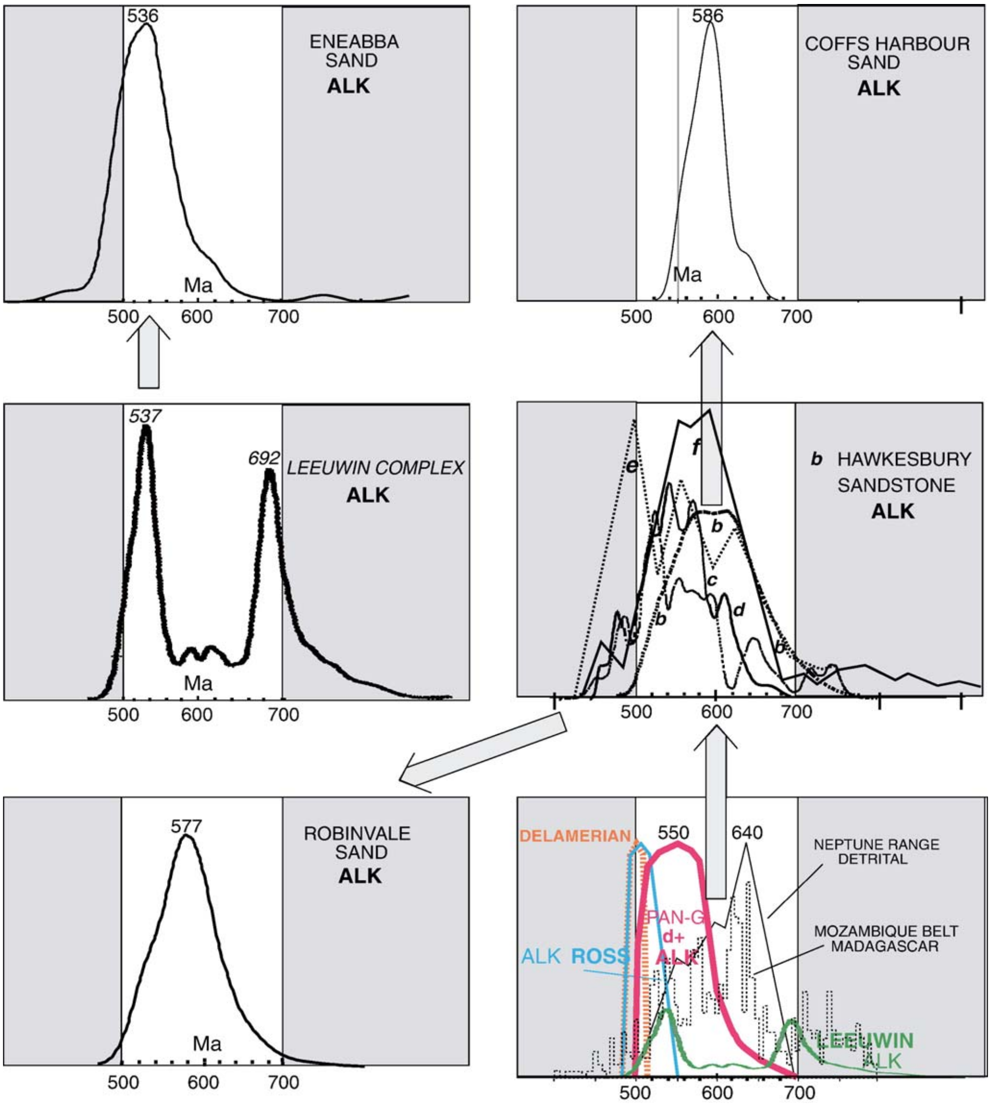


Fig. 30. Probability age distribution of 700–500 Ma zircons in Australia and Antarctica, all (except those from the Delamerian orogen and Neptune Range) with a component of alkaline affinity (ALK). Eneabba sand (Sircombe and Freeman, 1999) was derived (arrow) from the Leeuwin Complex (Collins, 2003). The other distributions are examples of the Southwest Pacific–Gondwana igneous component. Coffs Harbour and Robinvale sands from Figs. 5 and 8, respectively. The middle right-hand frame groups ***b*** the Hawkesbury Sandstone distribution with ***c*** the Ordovician Bumballa Formation and ***d*** Sunlight Creek Formations (from Fig. 2), ***e*** an Ordovician turbidite from Mt Kosciusko (Ireland et al., 1998), and ***f*** the Early Cambrian Balquhidder Formation of the Kanmantoo Group (Ireland et al., 1998). The lower right-hand diagram shows the age range of the 515–490 Delamerian orogen, 550–490 Ma Ross orogen, including the Koettlitz Glacier Alkaline Province, 700–500 Neptune Range detritus, and 800–490 Ma Leeuwin Complex. The histogram comprises 695 U–Pb zircon ages of the Mozambique Belt of East Africa and Madagascar from Kröner and Stern (2005) updated from Meert (2003).

granitoid <65% SiO_2, 15% unclassified, and 5% each of mafic rock and granitoid 70–75% SiO_2 (Figs. 9 and 10). The dominant alkaline group reflects the alkaline provenance in the Leeuwin Complex of the Pinjarra orogen. With more than half the grains classified as alkaline, and with a 700–500 Ma range of age, the Eneabba zircons resemble in age and alkaline rock type the beach sands of eastern Australia and their immediate provenance of the Hawkesbury Sandstone. The Hawkesbury zircons cannot have come from the Leeuwin Complex or its derivatives, because the Hawkesbury was in a different drainage system in the Triassic, that of eastern Australia–Antarctica (Fig. 31). What the similarity implies is

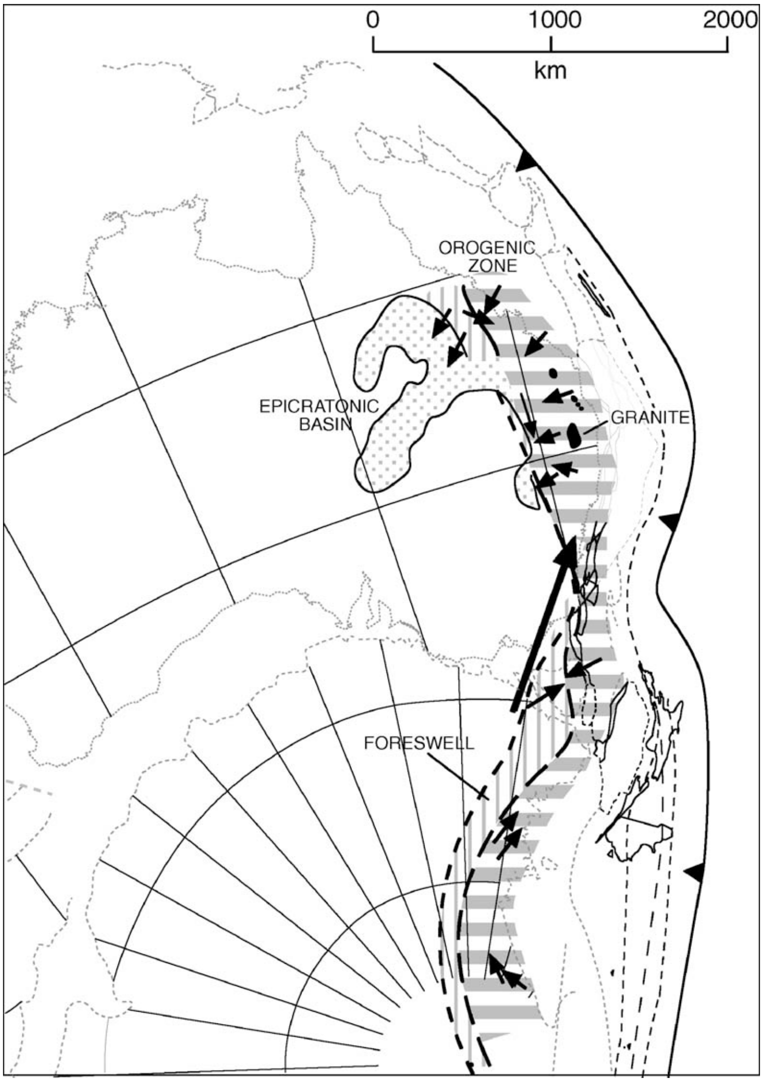
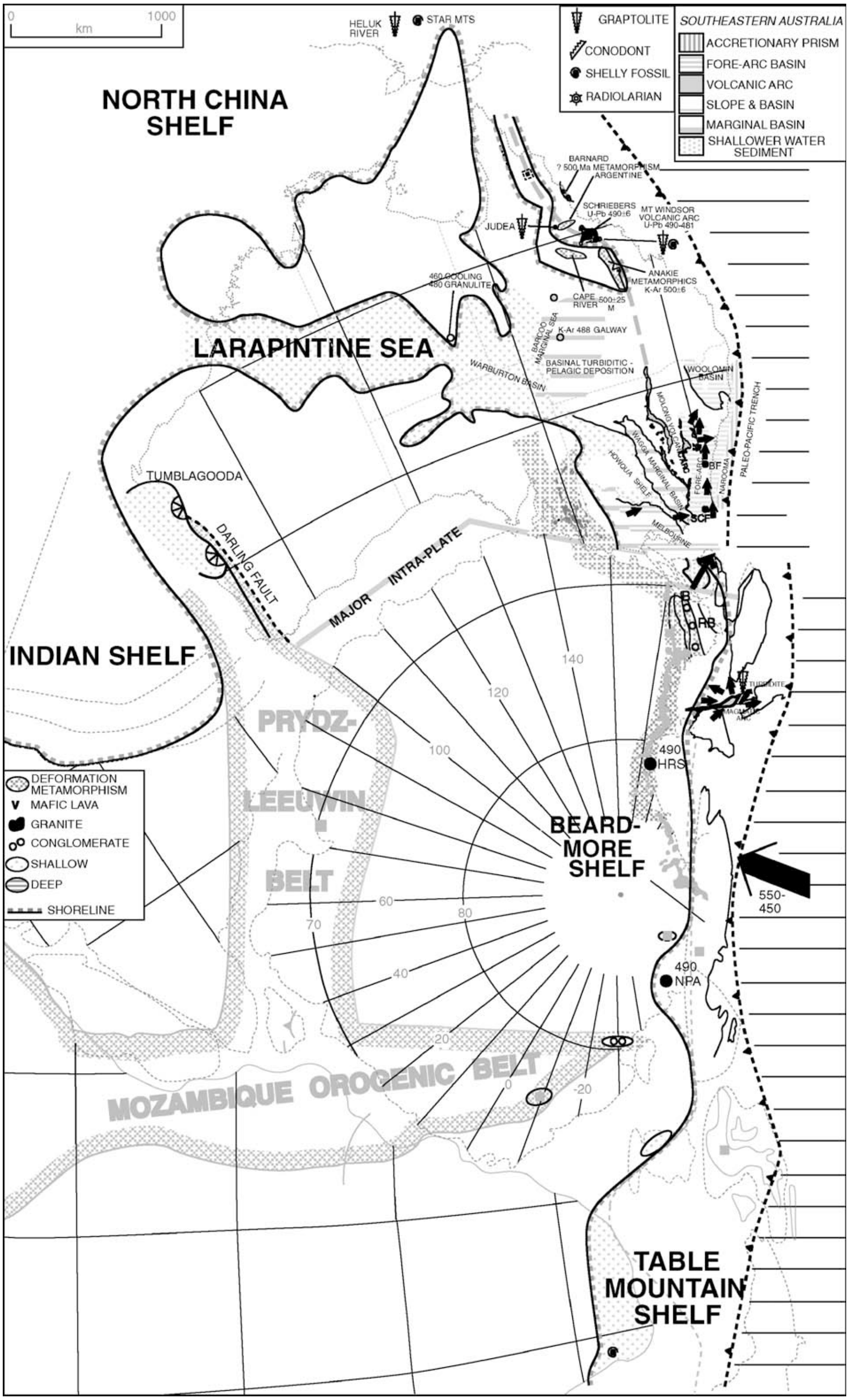


Fig. 31. Paleogeographic setting of the Hawkesbury Sandstone in the Middle Triassic. From Veevers (2000a, fig. 331, p. 303). Arrows indicate paleoslope, including the long arrow for the Hawkesbury Sandstone.

that both sand and sandstone came from common provenances involved in the Pan-Gondwanaland events (650–500 Ma) that accompanied assembly (Veevers, 2003).

7. Pan-Gondwanaland (700–500 Ma, d+) alkaline zircons and rocks

Pan-Gondwanaland (700–500 Ma, **d**+) alkaline zircons (Fig. 30) are common in Australia within a global epoch of carbonatitic magmatism at about 600 Ma (Bell, 2005). We summarize the derivation of the sands and sandstones, as follows: (1) the Eneabba alkaline sand was derived (arrow) from the 537 Ma component of the alkaline Leeuwin Complex. (2) The Coffs Harbour alkaline sand was derived from ***b*** the Hawkesbury alkaline Sandstone. (3) The Southwest Pacific–Gondwana igneous component of ***b*** the Triassic Hawkesbury alkaline Sandstone, ***c*** the Ordovician Bumballa Formation and ***d*** Sunlight Creek Formations (from Fig. 2), ***e*** an Ordovician turbidite from Mt Kosciusko (Ireland et al., 1998), and ***f*** the Early Cambrian Balquhidder Formation of the Kanmantoo Group (Ireland et al., 1998) were derived from the postulated region with 700–500 Ma **d**+ Pan-Gondwanaland zircons (red, lower right-hand diagram) co-extensive with Wilkes Land, Antarctica. The zircon-producing events **d**+, as seen in Australian zircons, are weighted towards the younger half, with a mode at 550 Ma. Also shown within this diagram are the 515–490 Ma Delamerian orogen, 550–490 Ma Ross orogen, including the Koettlitz Glacier Alkaline Province, the 800–490 Ma Leeuwin Complex, and the Mozambique Belt, including Madagascar, which



has its mode about 640 Ma, found also in the sample from the Neptune Range, which adjoins the Antarctic extension of the Mozambique Belt in Dronning Maud Land. All except the Delamerian orogen and Neptune Range are known to have a component of alkaline affinity. Near the Neptune Range, Dronning Maud Land contains rocks dated 700–600 Ma (J. Jacobs, pers. comm., 2005), so widening the extent of regions aged 700–500 Ma. The ages of Australian detrital zircons peak at 550 Ma, and those of the Mozambique Belt peak at 640 Ma. The Mozambique peak reflects syntectonic magmatism during closure of the Mozambique Ocean in what Meert (2003) and Kröner and Stern (2005) call the ~660–610 Ma East African orogeny, attributed by Veevers (2003) to oblique subduction off West Africa between 650 and 570 Ma. The younger ~570–530 Ma Kuunga orogeny reflects post-tectonic granites and pegmatites (Kröner and Stern, 2005) that are common in much of East Gondwanaland. These ages extend to ~490 Ma during oblique subduction along the Pacific margin (Veevers, 2003).

A-type granites from 550–500 Ma left-lateral extension in the Leeuwin Complex and the Koettlitz Glacier Alkaline Province Koettlitz Glacier Alkaline Province were generated during the operation of global stress 2, which saw the final welding of Gondwanaland (Veevers, 2003). At the other end of Gondwanaland, "in Morocco … the margin became a sinistral transform boundary, with peak granite intrusions in extensional jogs at 550–540 Ma" [cf. peak 537±4 Ma in the Leeuwin Complex (Collins, 2003)]. Farther afield, 550–500 Ma alkaline complexes are widely distributed in Africa, and are attributed to the " 'harpoon effect' … when there is reversal in the general sense of movement in a tear fault system" (Black et al., 1985). Other examples are the periphery of the West African Craton, which in Pharusian–Adrar des Iforas contains 580–540 Ma alkalic–peralkalic ring-shaped A-type quartz syenites and granites; in eastern Nigeria 580 Ma alkalic plutons; and in the Rokelides belt 533–500 Ma syenites and alkalic granites (Doblas et al., 2002). Other examples elsewhere in Gondwanaland are rift-related peralkaline rhyolites (509 Ma) in Argentina (Rapela et al., 2003), 650–550 Ma peralkaline granites and rhyolites in the Arabian Shield (Harris, 1985), 590–550 Ma alkaline felsic magmatism in southern India (Miller et al., 1996) and also in the rest of East Gondwanaland (Rajesh et al., 1996). The association of 760–550 Ma alkali granites and syenites in southern India and Sri Lanka and elsewhere in East Gondwanaland along fault lineaments (extensional environments) suggests "a geodynamic signature of East Gondwana during the Pan-African period" (Rajesh et al., 1996).

In "the southern [Dronning Maud Land] part of the [East African–Antarctic] orogen [are] … very large volumes of late-tectonic A2-type granitoids, intruded ca. 530–490 Ma" (Jacobs and Thomas, 2004). This southern part of the Mozambique Orogenic Belt in Central Dronning Maud Land (Jacobs et al., 1998, Veevers, 2000a, p. 269) contains this assemblage of zircon-bearing rocks:

512 Ma post-tectonic syenite batholiths
515 Ma leucogranite dykes
530–490 Ma A2-type granitoids
530–515 Ma granulite-facies metamorphics
530 Ma granodiorite
570–550 Ma metamorphic overgrowth of zircon
610–600 Ma charnockite and anorthosite
700–600 Ma various events (J.Jacobs, pers. comm., 2005).

In their age weighting towards the 600 Ma end of the range, signifying the collision of East and West Gondwanaland (Veevers, 2003), and with voluminous syenite, the Dronning Maud Land assemblage reflects the compositional range, except carbonatite, of the 625–475 Ma zircons of the Coffs Harbour sand and the Hawkesbury Sandstone. Its location, some 10 000 km from the Koettlitz Glacier Alkaline Province, and in the Triassic 12 000 km from the Hawkesbury Sandstone, would rule it out as a provenance, but its voluminous syenite serves as an example of a more extensive alkaline province.

Fig. 32. Ordovician paleogeography of East Gondwanaland, with detail in black, cooling orogens (Ross, Delamerian) and Pan-Gondwanaland belts (Mozambique, Prydz–Leeuwin) in grey. From Veevers (2000a, fig. 307). The large arrow at the trench indicates the direction of movement of the paleo-Pacific plate (Goodge, 1997). The paleoslope arrows in southeastern Australia are from Veevers (2000a, fig. 239), and in New Zealand from Veevers (2000a, fig. 307, p. 279), in an interpretation that the Western Terrane is rotated to an easterly azimuth. The long narrow arrow with tip in NE Tasmania is the paleoslope indicated by the Ordovician–Silurian–Devonian Mathinna Supergroup (Veevers, 2000a, p. 209, 210, 350), which contains detrital zircons with ages of 700–400 Ma (Black et al., 2004). BF = Bumballa Formation; HRS = Starshot/Douglas Formation from the Holyoake Range; NPA = Pataxent Formation, Neptune Range; SCF = Sunlight Creek Formation.

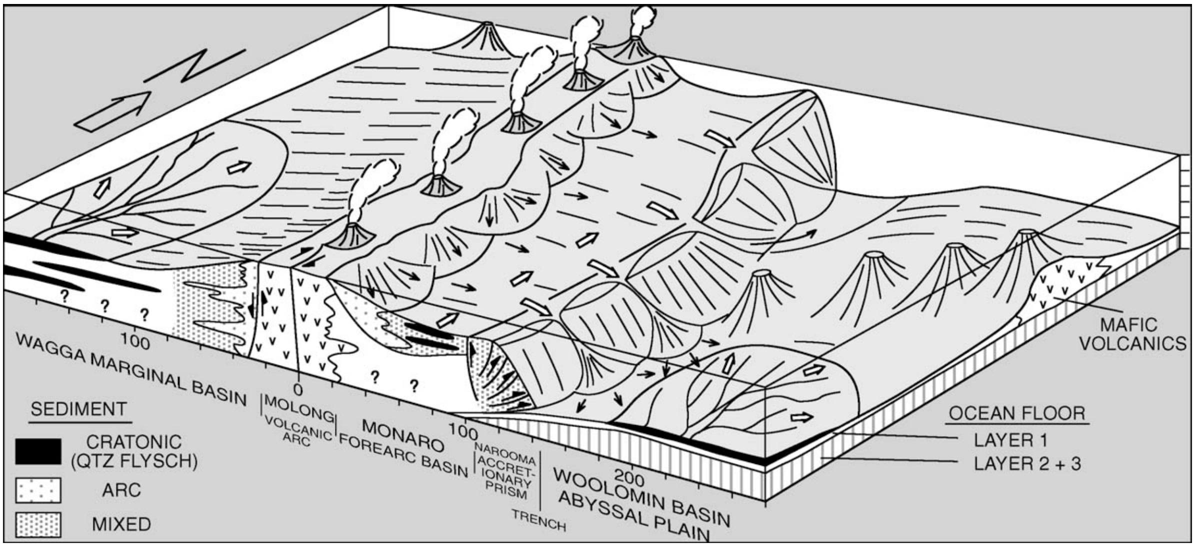


Fig. 33. Late Ordovician eastern Australia showing the longitudinal flow of sediment from Antarctica and the lateral flow from the magmatic arc and through the slope canyons. The longitudinal currents along the fore-arc basin are inferred from the arrows in Fig. 32. From Veevers (2000a, fig. 240, after Powell, 1984, fig. 192).

7.1. Detrital alkaline zircons in Africa, India, and Antarctica

In an (as yet) unpublished analysis of detrital zircons in other parts of Gondwanaland, we have found alkaline (carbonatite) zircons within the range 700–500 Ma in these samples:

(1) 21% in sample AF5 and and 30% in AF6 of Early Permian sandstone from the northeastern Karoo Basin, South Africa.
(2) 13% in the Early Permian sample G7 and 31% in the Early Triassic G8 of the Godavari (Gondwana) Basin of India.
(3) Rare grains in Antarctic samples from the Early Permian of Dronning Maud Land and from the Late Permian of Beaver Lake, Lambert Graben.

The alkaline zircons reflect the 700–500 Ma transtensional tectonics of Gondwanaland.

8. Paleogeography

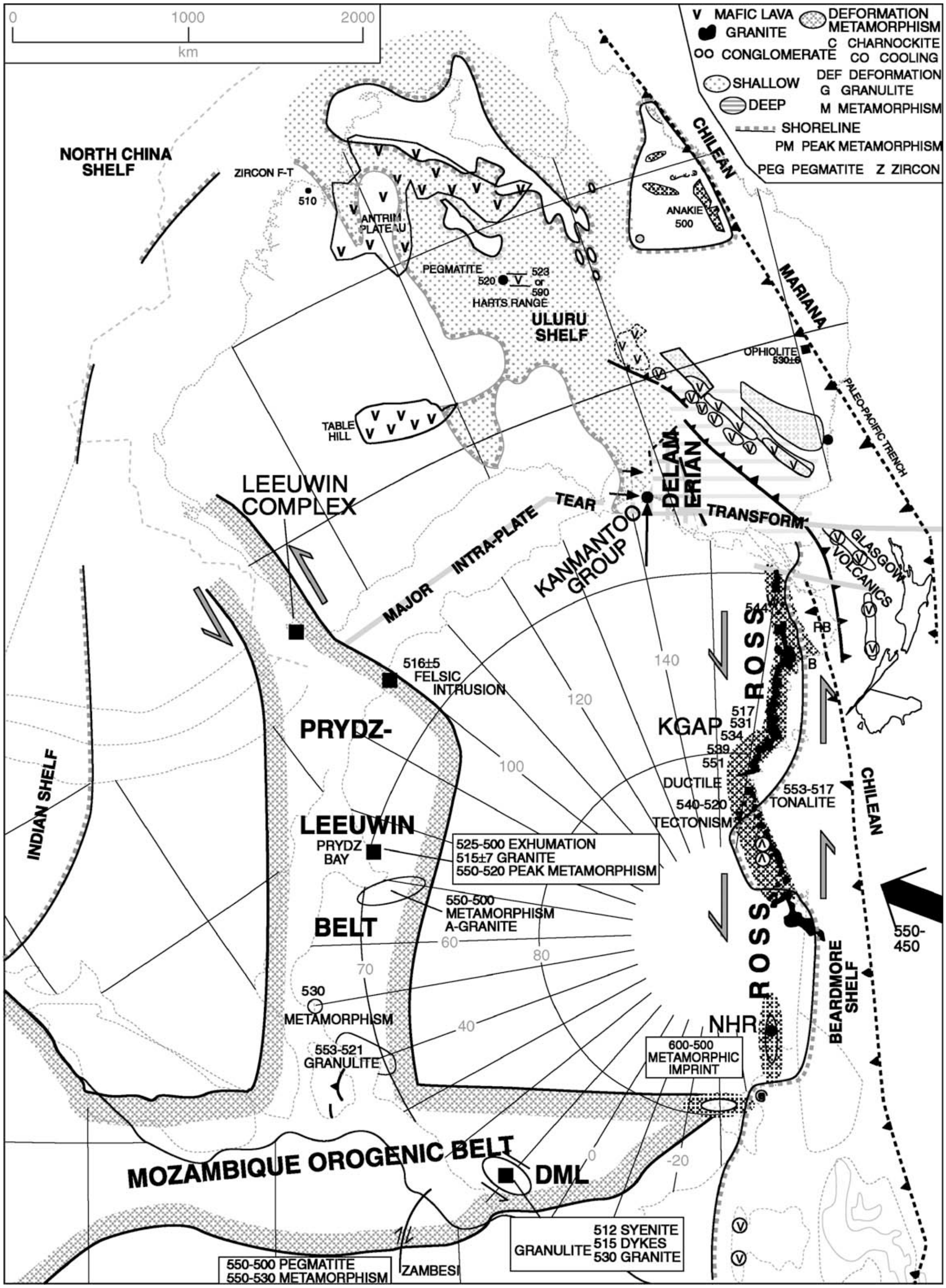
In tracing the changing paleogeography, we step back through the Phanerozoic into the soft-focussed Neoproterozoic.

8.1. Middle Triassic Hawkesbury Sandstone

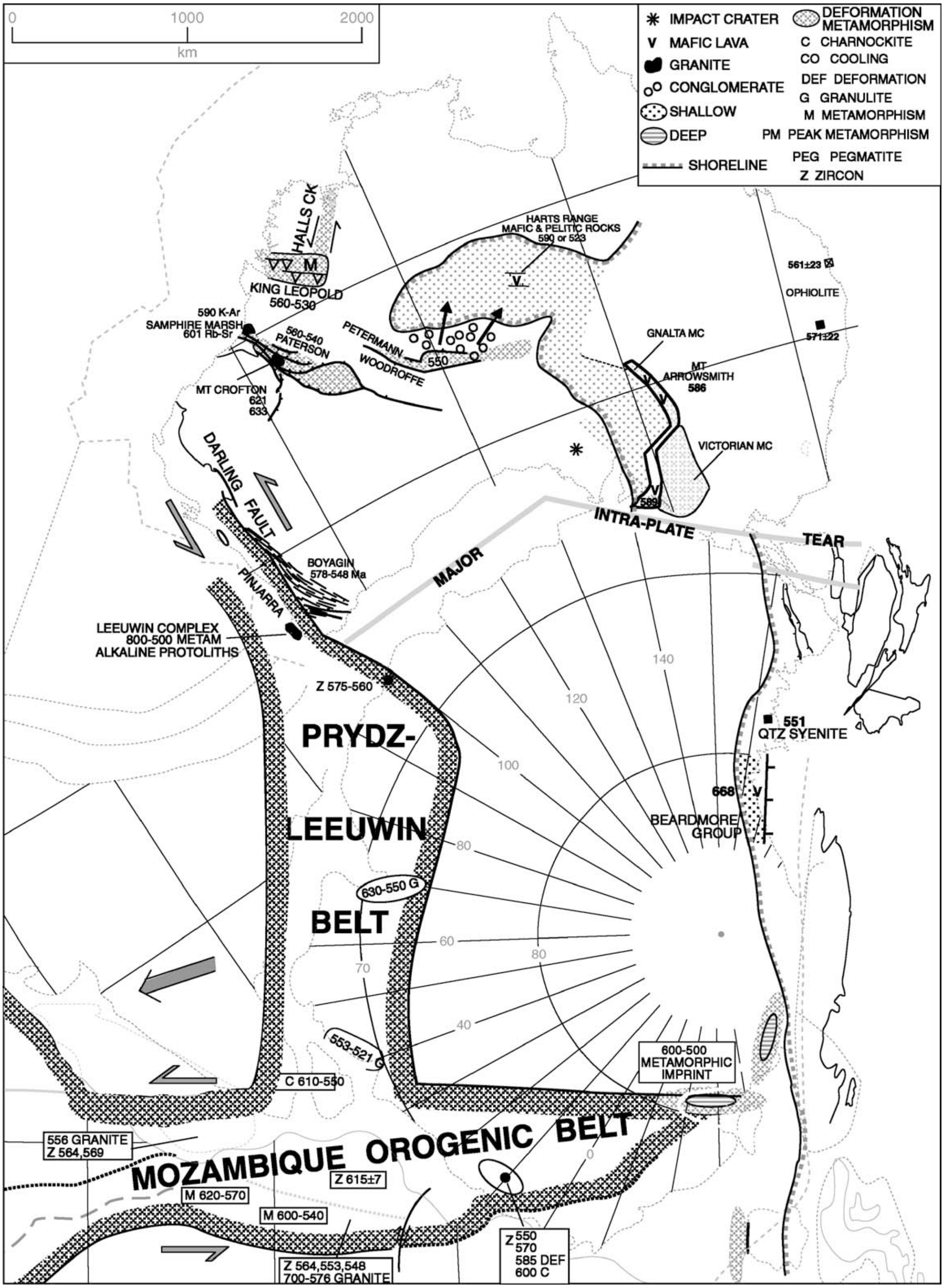
The Hawkesbury Sandstone (Fig. 31) was deposited on the cratonic side of the foreland (Sydney) basin immediately before the 230 Ma terminal Gondwanides II uplift of the overthrusting magmatic orogen (horizontal-bar pattern), which shed volcanolithic sediment cratonwards (Conaghan et al., 1982; Veevers et al., 1994). A foreswell (vertical-line

Fig. 34. 550–500 Ma end-Neoproterozoic and Cambrian. From Veevers (2000a, fig. 305). The 550–500 Ma Ross orogen and Pan-Gondwanaland Mozambique and Prydz–Leeuwin Belts were active (black). The 515–490 Ma Delamerian orogen (shown by the lettering) followed deposition of the Kanmantoo Group from northward axial currents and eastward lateral currents. The Hannah Ridge Formation in the Neptune Range (NHR), with minimum age of 556±13 Ma (Goodge et al., 2004), is a turbiditic sandstone and shale that was intensely deformed before being unconformably overlain by the Middle Cambrian (Boomerangian, 509 Ma — Veevers, 2000a, p. 258) Nelson Limestone. Sample NHR is a felspathic greywacke of the "inboard sandstone unit" (Goodge et al., 2004). "Associated bimodal volcanics formed in an intracontinental rift setting" (Storey et al., 1992) during extensional phases generated by oblique subduction (Goodge, 1997). Oblique subduction contributed to a second Pan-Gondwanaland stress system that operated from 550–450 Ma (Veevers, 2003). Sinistral shears induced local transtension that accommodated the alkaline magmatism of the Koettlitz Glacier Alkaline Province (KGAP) (Read et al., 2002), the alkaline protoliths of the Leeuwin Complex (Fitzsimons, 2003), and the voluminous syenite of Dronning Maud Land (DML) (Jacobs et al., 1998). Off eastern Australia and Antarctica, Chilean-type subduction (Uyeda, 1981) changed to Mariana-type in southeastern Australia.

pattern) in the north shed quartzose sediment into the interior, and in Tasmania into the foreland basin. The Hawkesbury Sandstone braided-river system flowed down a long slope from high ground in Antarctica, which Sircombe (1999) identified as "the basement of the Wilkes Subglacial Basin …[an area of] …



deformation and magmatism resulting from the Neoproterozoic convergence of the Beardmore Microcontinent”. Much later, the beach sands were derived from “an intermediate repository in the Sydney Basin,” now some 7000 km from the primary provenance.



8.2. Ordovician turbidite

In southeastern Australia, Ordovician turbidite (Figs. 32 and 33) was deposited in fore-arc and abyssal fans likewise from a northward paleocurrent that flowed parallel to the uplifted Ross–Delamerian orogen. In Ordovician–Silurian–Devonian Tasmania, turbidite of the Mathinna Supergroup was deposited from north-easterly paleocurrents.

According to Goodge et al. (2004), the Patuxent Formation in the Neptune Range contains detrital zircons as young as ca. 495 Ma, indicating latest Cambrian or younger deposition. We regard it as Early Ordovician (490 Ma). Sample NPA of the Patuxent Formation is a coarse feldspathic arenite, deposited in the same intra-continental rift setting as the Cambrian Hannah Ridge Formation (NHR in Fig. 34). "The Patuxent contains older (680–580 Ma) grains that may represent either early development of the Ross belt in the Pensacola Mountains region or *input from early Pan-African detritus from the southern part of the East African orogen*" (our emphasis) (Goodge et al. (2004, p. 1269).

Sample HRS of the Starshot/Douglas Formation comes from the Holyoake Range, near the Nimrod Glacier. The sandstone and siltstone interfinger with conglomerate, which was shed from the 550–490 Ma Ross orogen. Detrital zircons with ages between 700 and 550 Ma would seem to indicate that a terrane with 700–500 Ma zircons extended westward beneath the ice in Wilkes Land.

8.3. Cambrian paleogeography

A string of batholiths extends through the Transantarctic Mountains (Ross orogen) and Tasmania, and in South Australia (Delamerian). Left-lateral transtension in the Koettlitz Glacier Alkaline Province, Dronning Maud Land, and Leeuwin Complex promoted the intrusion of alkaline rocks.

The Early Cambrian turbidite of the Kanmantoo Group was deposited from an axial northward paleocurrent that flowed across adjacent Wilkes Land, Antarctica (Jago et al., 2003). The Cambrian Hannah Ridge Formation (NHR) and a volcanic–marine sedimentary succession were deposited in the southern Transantarctic Mountains (Fig. 34).

8.4. Late Neoproterozoic 600–550 Ma epoch

The closure of the Mozambique Ocean between West and East Gondwanaland by oblique stresses involved sinistral shearing in the Mozambique orogenic belt and Pinjarra orogen, here following earlier dextral strike-slip. These motions, part of the first Pan-Gondwanaland stress system that operated 650–570 Ma (Veevers, 2003), induced local transtension that accommodated alkaline magmatism, as in the Leeuwin Complex and in the 551 Ma quartz syenite of the Koettlitz Glacier Alkaline Province (Fig. 35). The sedimentary response to these motions in Antarctica is lacking or has not been identified. Earlier, the Beardmore Group of shallow-water sands was deposited with basalt dated 668 Ma on the side of a rifted continental margin (Goodge et al., 2002). Central and northern Australia underwent intense dextral transpression in the Halls Creek, Paterson, and Petermann areas, reflecting oblique subduction along the Antarctic margin (Veevers, 2003).

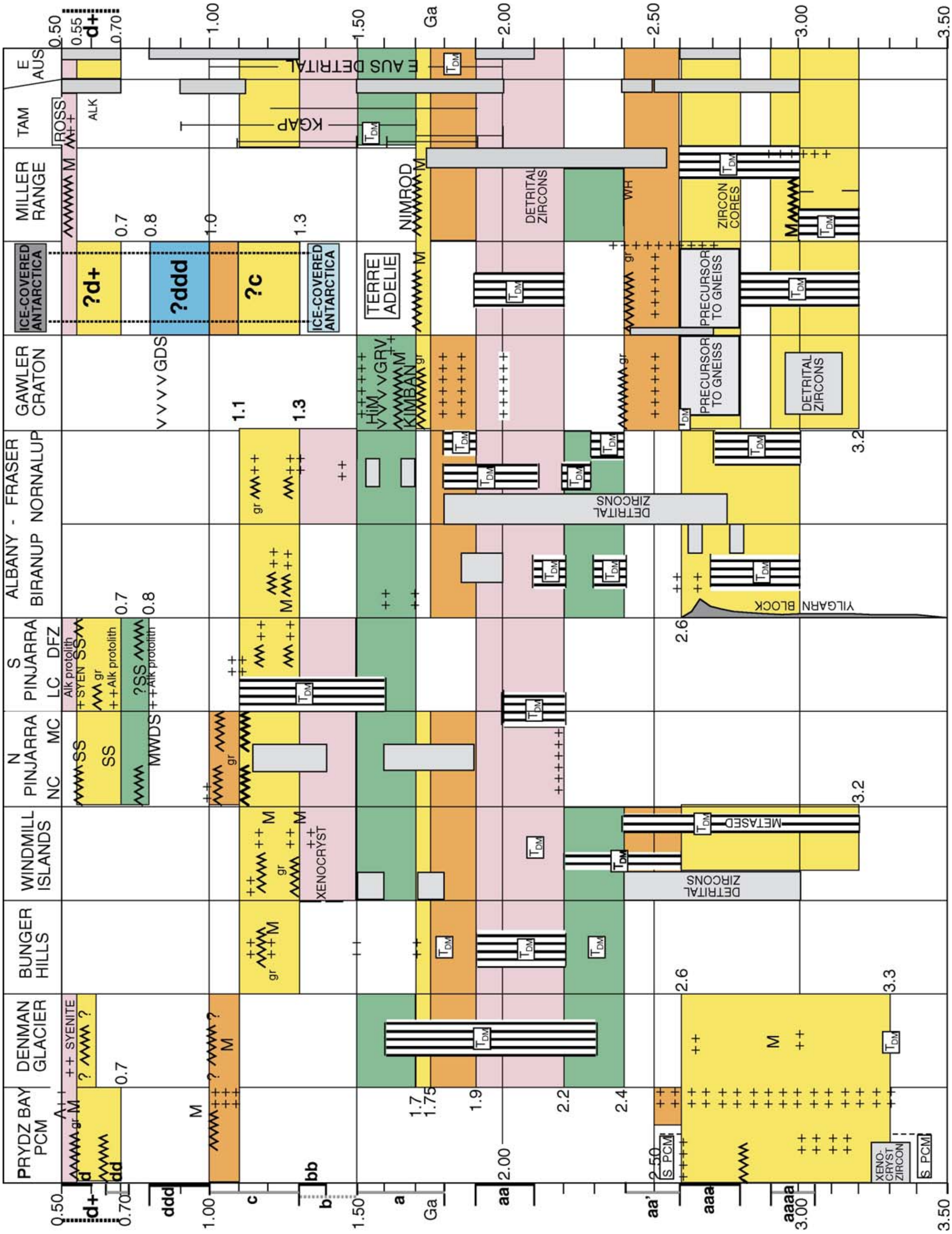
9. Timetable of events in Australia and Antarctica

A comprehensive timetable (3.5 to 0.5 Ga) of regional events based on an heroic effort of U–Pb SHRIMP dating (Fitzsimons, 2003) allows us to define the following epochs that preceded the 700–500 Ma Pan-Gondwanaland epoch (Fig 36).

d+ the 700–500 Ma Pan-Gondwanaland epoch, includes, at the end, the Ross and Delamerian orogenies.
c 1300–1000 Ma, the "Grenville" age of authors.
a 1800–1500 Ma, includes the Kimban and Nimrod orogenies.
aa′ 2600–2400 Ma.
aaaa ~3000, and back to 3300 Ma.

The epochs, defined by age clusters of detrital zircons, guide the interpretation of provenance. Here, in the column above Terre Adélie, we show our

Fig. 35. 600–550 Ma late Neoproterozoic. From Veevers (2000a, fig. 303). The closure of the Mozambique Ocean between West and East Gondwanaland by oblique stresses involved sinistral shearing (SS in Fig. 36) in the Mozambique orogenic belt and Pinjarra orogen (following earlier dextral strike-slip). These motions, part of the first Pan-Gondwanaland stress system that operated 650–570 Ma (Veevers, 2003), induced local transtension that accommodated alkaline magmatism, as in the Leeuwin Complex and in the 551 Ma quartz syenite of the Koettlitz Glacier Alkaline Province. Sedimentary evidence from Antarctica is lacking. Earlier, the Beardmore Group of shallow-water sands was deposited with basalt dated 668 Ma on the side of a rifted continental margin (Goodge et al., 2002). Central and northern Australia underwent intense dextral transpression in the Halls Creek, Paterson, and Petermann areas.


PRYDZ BAY PCM
DENMAN GLACIER
BUNGER HILLS
WINDMILL ISLANDS
N PINJARRA NC MC
S PINJARRA LC DFZ
ALBANY - FRASER BIRANUP NORNALUP
GAWLER CRATON
ICE-COVERED ANTARCTICA
MILLER RANGE
TAM
E AUS

interpretation of the main ages of the Wilkes Land provenance beneath ice-covered Antarctica.

10. Conclusion: Pan-Gondwanaland super-terrane beneath the Antarctic ice (Fig. 37)

In the sector near eastern Australia, we combine the Terre Adélie (TA) and Gawler blocks (both of age **a**) in a minimal model of the Mawson Craton, in place of the maximal model that stretches a farther 1600 km to the Miller Range. The maximal model would provide zircons of 1.7 Ga age, with a minor amounts of 2.4 and 3.0 Ga, and would lack the **d**+ 700–500 Ma detrital zircons of eastern Australia. We prefer a model of a super-terrane between the Bunger Hills and the Transantarctic Mountains comprising cratons of age **c** (1300–1000 Ma) embedded in a matrix of Pan-Gondwanaland fold belts of **d**+ (700–500 Ma) age. This provenance would shed zircons of dominantly **d**+ age, with a minor contribution of **c** age, as found in eastern Australia. The shape of the hypothetical super-terrane was inspired by the composite cogs of the West African, Congo, Amazonia, India–East Antarctica–West Australia that are postulated to have rotated within a matrix of Pan-Gondwanaland fold belts (Veevers, 2003). The size of the individual cratons resembles that of the Gawler Block, and in age that of the nearby 1300–1000 Ma Musgrave Block of central Australia.

The 550–490 Ma subduction-related Ross orogen borders the super-terrane, and, as suggested by the model ages (Fig. 28) that overlap the 1300–1000 Ma range of **c**, may well be underlain by the hypothetical super-terrane.

The Pinjarra orogen contains **d**+ ages as well as **c** (Fig. 36), so that the various hypothetical models by Fitzsimons (2003) and ourselves would have much of Antarctica underlain by a super-terrane of cratons embedded in **d**+ Pan-Gondwanaland fold belts, in the classic style of Africa.

Many Pan-Gondwanaland super-terranes elsewhere are today uplands of isostatically thickened crust (Fig. 37). Our hypothesis of a proximal Antarctic provenance in Wilkes Land is supported by the paleogeographical evidence of uplands sloping northward in at least Cambrian, Ordovician, Permian, and Triassic times. Wilkes Land only became a lowland from the 99 Ma change in azimuth of the Pacific plate (Veevers, 2000b) and the generation of the Australian–Antarctic depression (Veevers, 1982).

Our view was foreshadowed by Goodge et al. (2004, p. 1277) in their "sediment provenance I … Precambrian rocks of the East Antarctic Shield and their Grenville-age mobile belts". Goodge et al. (2004) also point to provenance IV "Grenville and Pan-African sources in Queen [Dronning] Maud Land and the East African orogen", with ages in the 700–600 Ma range newly found in Dronning Maud Land (J. Jacobs, pers. comm., 2005).

> "The Hannah Ridge [NHR] provenance signature indicated that the sediment was deposited in a marginal basin with a major source of late Neoproterozoic detritus. Its provenance appears to be chiefly in Grenville-age roots to the Ross and Pan-African orogens flanking the Kalahari craton, because the detrital-grain ages are remarkably similar to 1090–1030 Ma [Grenville-age] basement in present-day western Dronning Maud Land, Coats Land, and the Namaqua–Natal belt (Fitzsimons, 2000), implying that the principal source of detritus was an intermontane or upland region of the East African orogen. Because the Hannah Ridge sample is dominated by Grenville-age and Pan-African-age components and is nearly devoid of any grains older than ca. 1200 Ma, the nearby major shields (Kalahari, Indian, and East Antarctic) were likely either covered during Early Cambrian time or had drainages that flowed away from the present-day Pensacola Mountains. The younger population (650–500 Ma) is also consistent with an East African orogen provenance" (Goodge et al., 2004, p. 1268).

We note that older ages, back to 1171±25 Ma are known from Dronning Maud Land (Jacobs et al., 2003). The East African orogen was cited by Williams and

Fig. 36. Time–space diagram for Precambrian terranes on either side of the Antarctic–Australian join. From Fitzsimons (2003, figs. 2, 6, 9). Ages (Ga) by the U–Pb zircon zircon method. The colour bands indicate zircon-producing epochs. + = granite; wiggly line = deformation; A = A-type granite; Alk = alkaline; DFZ = Darling Fault Zone; E AUS = eastern Australia; GDS = Gairdner dyke swarm; gr = granulite-facies metamorphism; GRV = Gawler Range Volcanics; HiM = high-grade metamorphism; LC = Leeuwin Complex; M = metamorphism; MC = Mullingarra Complex; MWDS = Mundine Well dyke swarm; N = north; NC = Northampton Complex; S = south; S PCM = southern Prince Charles Mountains; SS = sinistral shear; SYEN = syenite; T_{DM} = model age; TAM = Transantarctic Mountains; WR = whole-rock. Miller Range also from Goodge and Fanning (1999), Transantarctic Mountains detrital zircons from Goodge et al. (2004, fig. 12), Nd model ages from Borg and DePaulo (1994). Hf-isotope model ages of eastern Australian sands and sandstone from this work. Yilgarn ages from Cawood and Nemchin (2000). Age clusters (**d** – **aaaa**) in southwestern Australia and East Antarctica from Veevers et al. (2005). **d**+ is the 700–500 Ma Pan-Gondwanaland epoch. **c** (1300–1000 Ma) is the "Grenville" age of authors (e.g., Jacobs et al., 1998; Goodge et al., 2004). The column above Terre Adélie shows our (informed) guess about the main ages of the provenance beneath ice-covered Antarctica.

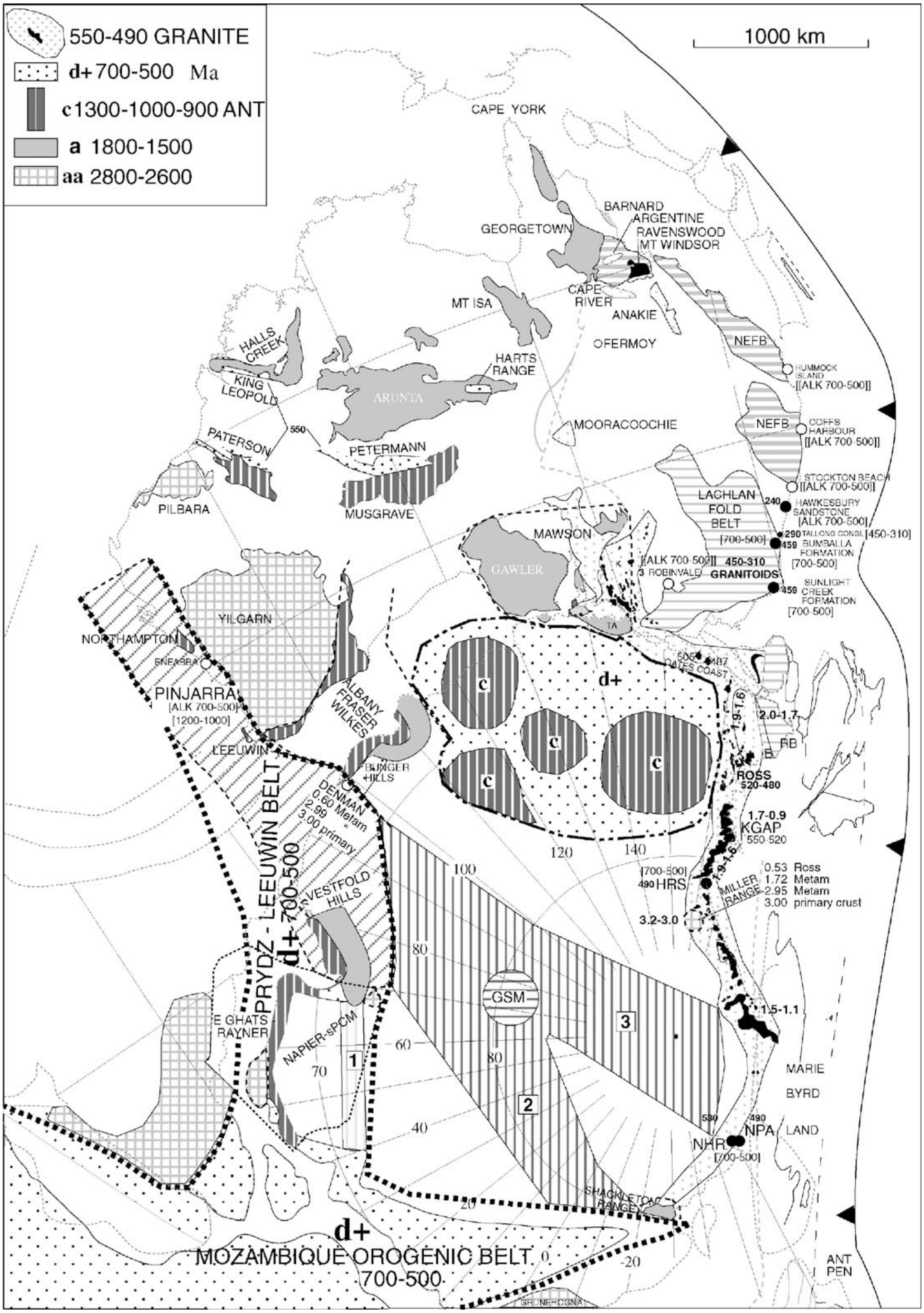


Fig. 37. Hypothetical ages and kind of sub-glacial bedrock in Antarctica on a base from Fig. 1, which should be seen for abbreviations. The grey vertical-line pattern signifies "the three potential pathways for the Pinjarra Orogen [oblique-line pattern] across East Antarctica" (Fitzsimons, 2003), including that [1] of Boger et al. (2001). [2] and [3] split off past the Gamburtsev Sub-glacial Mountains, which Veevers (1994) modelled as originating by mid-Carboniferous shortening of an intracratonic basin but without generating zircons (cf. the Alice Springs orogen of central Australia). The 700–500 Ma Southwest Pacific–Gondwana igneous component has a hypothetical provenance in the stippled areas marked **d**+ in proximal Wilkes Land, Antarctica, between the Transantarctic Mountains and the Bunger Hills.

Chappell (1998) as a potential source of 650–500 Ma zircons in Australia, but the proximal Wilkes Land is the simpler choice.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.earscirev.2005.11.001.

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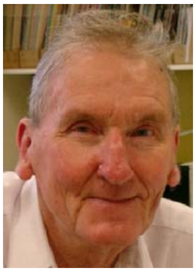

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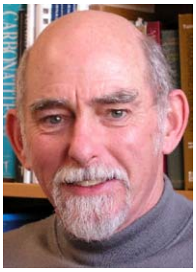

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