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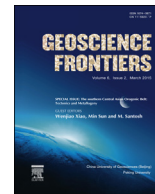


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Research paper

Tracking the Cretaceous transcontinental Ceduna River through Australia: The hafnium isotope record of detrital zircons from offshore southern Australia

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ABSTRACT

The middle–upper Cretaceous Ceduna River system traversed continental Australia from the NE coast to the centre of the southern coast. At its mouth, it formed a vast delta system that is similar in scale to the Niger delta of West Africa. The delta system is composed of two main lobes that represent different phases of delta construction. A recent hypothesis has challenged the traditional idea that both lobes of the delta were derived from a transcontinental river system by suggesting that the upper lobe (Santonian–Maastrichtian) is instead derived from a restricted catchment within southern Australia. Hf isotopic data presented here fingerprint the original source of the upper delta lobe zircons to NE Australia, with data comparing well with similar U–Pb and Lu–Hf isotopic data from the Lachlan Orogen, the New England Orogen, the eastern Musgraves Province and the northern Flinders Ranges. These data do not preclude a model where the lobe is derived from recycled Eromanga Basin sediments during a phase of late Cretaceous inland Australian uplift, but when coupled with reconnaissance low-temperature thermochronometry from the region of the Ceduna River course indicating widespread Triassic–Jurassic exhumation, and comparisons with detrital zircon data from the Winton Formation upstream of any proposed uplift, we suggest that both lobes of the Ceduna Delta are likely to be derived from a transcontinental Ceduna River.

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1. Introduction

The southern margin of Australia formed during the protracted separation of Australia from Antarctica that involved Jurassic–Cretaceous intra-East Gondwana rifting, followed by final separation along the central southern Australia margin by ca. 83.5 Ma in the Campanian (Krassay and Totterdell, 2003; Williams et al., 2011). This break-up of the last vestige of Gondwana led to the formation of the largest preserved delta system in Australia,

covering an area of ca. 126,000 km² and found off the continent's southern coast (Figs. 1 and 2). The delta is thought to be sourced from a now-extinct transcontinental river system that traversed the continent in the middle to late Cretaceous from its distributary channel at the middle south coast, near the town of Ceduna, to its headwaters that are now found in central and northeast Australia (Veevers, 2000; Macdonald et al., 2013) (Figs. 1 and 2). Yet much is controversial and unknown about the evolution of this river system. Particular controversy surrounds the temporal change in source areas over the time of the delta system's existence and the timing and process of exhumation of central Australia—the catchment area of the river system.

The Ceduna Sub-basin (Fig. 2) is the main depocentre in the large Bight Basin off the southern Australian coast. It contains two deltaic sequences that have been identified using seismic

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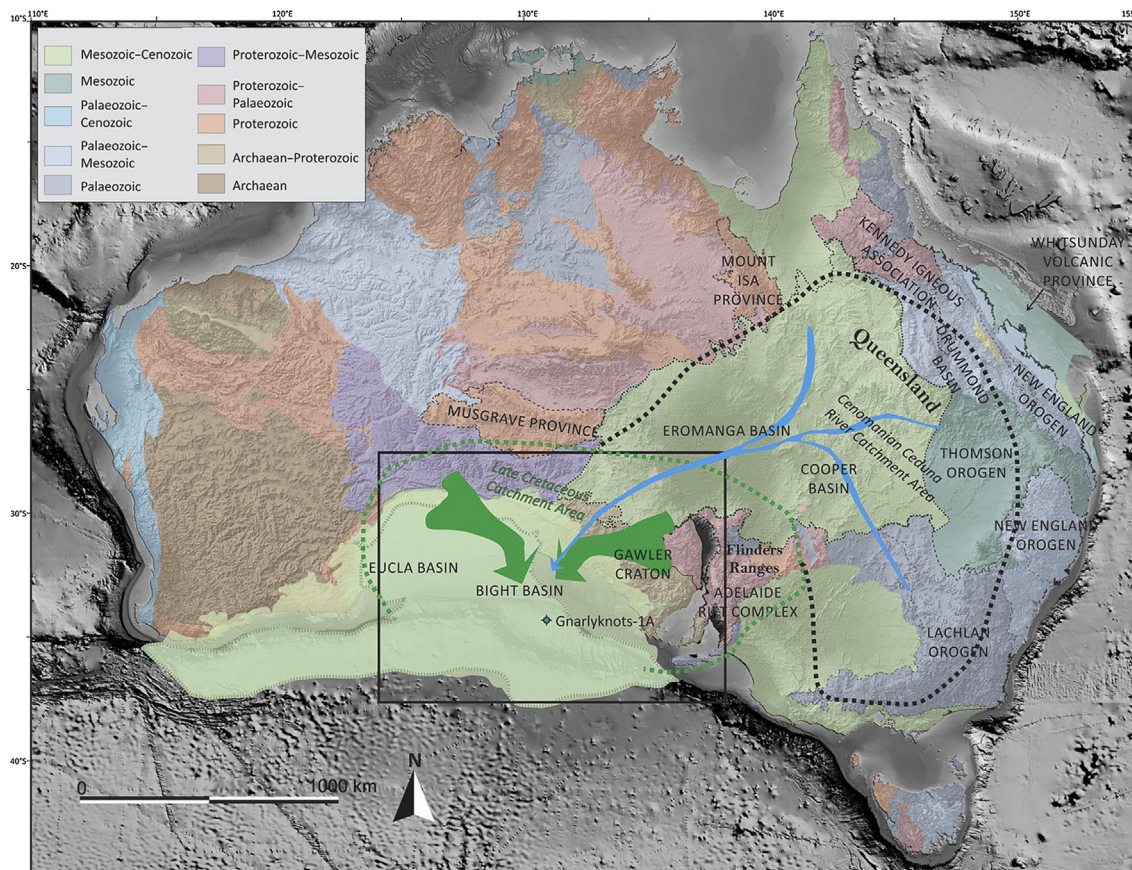


Figure 1. Digital elevation map of Australia and its continental shelf with the broad ages of exposed geology indicated. The dotted lines indicate the proposed different catchment areas of the Cenomanian lower Ceduna Delta (black dotted line) and the Santonian-Maastrichtian upper Ceduna Delta (green dotted line) (modified from [Macdonald et al., 2013](#)). Location of [Fig. 2](#) is indicated by the box.

interpretation ([Macdonald et al., 2012](#)); a lower Cenomanian delta, represented by the White Pointer Supersequence, consisting of the Platypus and lower Wigunda formations, and an overlying Santonian to Maastrichtian delta composed of the Hammerhead Supersequence, which contains the Potoroo and upper Wigunda formations. Gnarlyknots-1A is an offshore well ([Figs. 1 and 2](#)) that preserves the best record of retrieved core available from the basin. This well forms the most complete succession available to study, yet it only penetrated the upper delta (the Hammerhead Supersequence).

Previous studies have suggested that both deltas were derived from a SW-flowing trans-continental river system that was sourced from the NE – either from the immediately older to contemporaneous Eromanga Basin ([King and Mee, 2004](#)) ([Fig. 1](#)), or from the NE coastal region of Australia (Queensland, [Veevers, 2000](#)). [Macdonald et al. \(2013\)](#) argued that the lower delta may well be sourced from Queensland, but they suggested that a phase of uplift associated with renewed rifting of Australia from Antarctica in the late Cretaceous rejuvenated the river system and that the upper delta was sourced from a much reduced catchment area within a NW–SE arc stretching from the Flinders Ranges to the Musgrave Province ([Fig. 1](#)).

Here we present new Hf isotopic data from detrital zircons, whose U-Pb age data have been, for the most part, previously published ([Macdonald et al., 2013](#)). The Hf isotopic data are compared with comparable data from elsewhere in central and eastern Australia to better fingerprint the source region of this highly explorative sedimentary basin.

2. Analytical methods

2.1. Zircon U-Pb geochronology

Existing U-Pb data from [Macdonald et al. \(2013\)](#) were used to recalculate the Hf isotopic data back to the formation of the individual zircon domains analysed in this study. This was possible because the same grains were analysed for Hf in this study that were analysed for U-Pb in [Macdonald et al. \(2013\)](#). In addition, extra U-Pb data were obtained from sample 74322 to increase the dataset. These data were obtained on a Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) using a New Wave UP-213 laser attached to an Agilent 7500cx Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at Adelaide Microscopy, The University of Adelaide. Analysed zircons had been previously imaged under cathodoluminescence in both this study and [Macdonald et al. \(2013\)](#). A laser spot size of 30 μm and repetition rate of 5 Hz was used for U-Pb analyses. Age calculations and corrections were completed using the software GLITTER with use of the primary zircon standard GJ-1, TIMS normalization data $^{207}\text{Pb}/^{206}\text{Pb} = 608.3$ Ma, $^{206}\text{Pb}/^{238}\text{U} = 600.7$ Ma and $^{207}\text{Pb}/^{235}\text{U} = 602.2$ Ma ([Jackson et al., 2004](#)). Instrument drift was corrected for in GLITTER via standard bracketing every 15–20 unknowns and application of a linear correction. Accuracy of the methodology was verified by repeated analyses of Plešovice zircon ($^{206}\text{Pb}/^{238}\text{U} = 337.13 \pm 0.37$ Ma; [Sláma et al., 2008](#)). Isotope ratios are presented uncorrected for common lead, with Concordia plots generated using Isoplot 4.15.

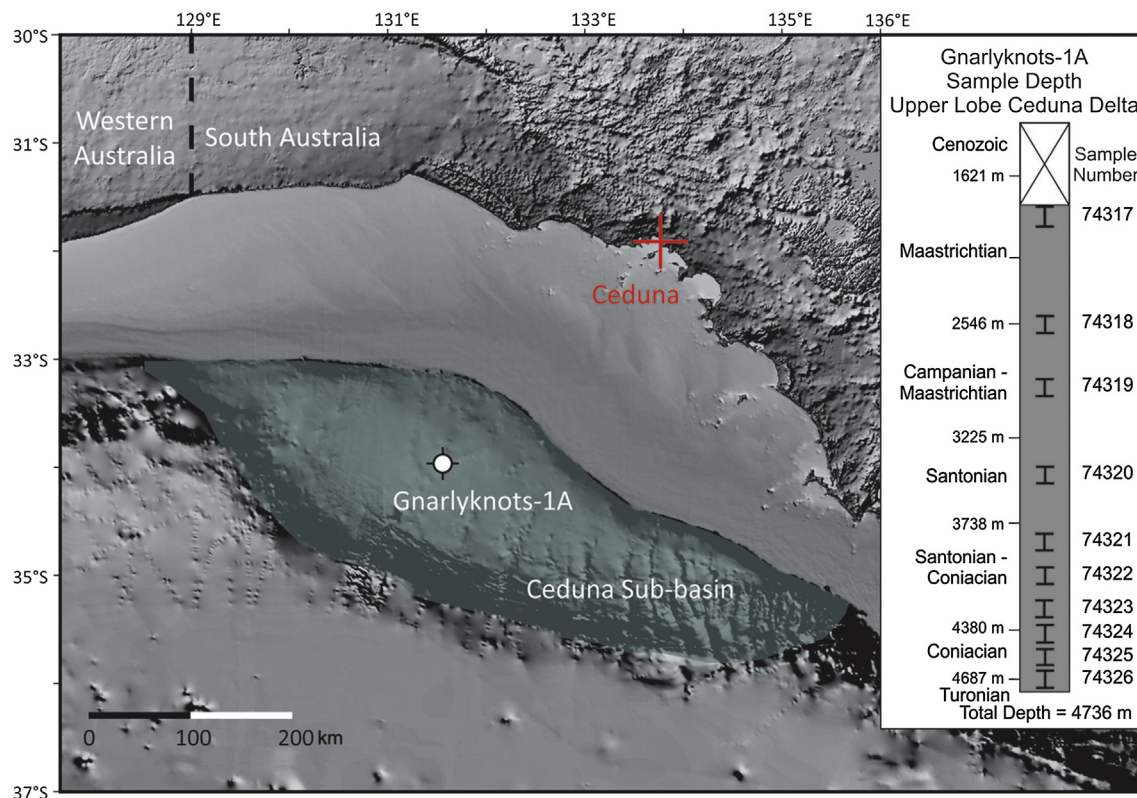


Figure 2. The Ceduna Sub-basin of the Bight basin off the coast of southern Australia. The location of the Gnarlyknots-1A well is indicated as is the town of Ceduna, close to the inferred Cretaceous location of the delta distributary channel. Inset is a schematic log of the Gnarlyknots-1A well with the location of the samples indicated (log modified from Macdonald et al., 2013).

Kernel density estimates, probability density plots and histograms were all plotted using Density Plotter, a Java program developed by and described in Vermeesch (2012). An adaptive bandwidth was used for the kernel density estimates. A fixed age range of 0–3500 Ma and histogram bin width of 100 Ma was used for consistency across all plots. Data used were $\pm 10\%$ concordant.

2.2. Zircon Lu-Hf isotope analyses

In situ LA-MC-ICPMS Lu-Hf isotope analyses were carried out at the University of Adelaide facility using a New Wave Research 193 nm Excimer laser attached to a Neptune multi-collector ICP-MS system as per Payne et al. (2013). Only grains with U-Pb ages having $\leq 10\%$ discordance were analysed for Lu-Hf isotope composition. Analysis locations were in the same spot as concordant U-Pb spots. The bulk of analyses were carried out using a beam diameter of $\sim 50 \mu\text{m}$ for large and a minimum of $\sim 25 \mu\text{m}$ for smaller grains. Typical ablation times were 40–100 s using 5 Hz repetition rate, 4 ns pulse rate, and an intensity of $\sim 10 \text{ J/cm}^2$. Zircons were ablated in a helium atmosphere, which was then mixed with argon upstream of the ablation cell.

Analyses used a dynamic measurement routine with ten 0.524 s integrations on ^{171}Yb , ^{173}Yb , ^{175}Lu , ^{176}Hf (+Lu + Yb), ^{177}Hf , ^{178}Hf , ^{179}Hf and ^{180}Hf , one 0.524 s integration on ^{160}Gd , ^{163}Dy , ^{164}Dy , ^{165}Ho , ^{166}Er , ^{167}Er , ^{168}Er , ^{170}Yb and ^{171}Yb , and one 0.524 s integration of Hf oxides with masses ranging from 187 to 196 amu. An idle time of 1.5 s was included between each mass change to allow for magnet settling and to negate any possible effects of signal decay. The measurement cycle was repeated 15 times providing a total maximum measurement time of 3.75 min including an off-peak baseline measurement. Hf oxide formation rates for all analytical

sessions in this study were in the range 0.1–0.07%. Hf mass bias was corrected using an exponential fractionation law with a stable $^{179}\text{Hf}/^{177}\text{Hf}$ ratio of 0.7325. Yb and Lu isobaric interferences on ^{176}Hf were corrected for following the methods of Woodhead et al. (2004). ^{176}Yb interference on ^{176}Hf was corrected for by direct measurement of Yb fractionation using measured $^{171}\text{Yb}/^{173}\text{Yb}$ with the Yb isotopic values of Segal et al. (2003). The applicability of these values were verified by analysing JMC 475 Hf solutions doped with varying levels of Yb with interferences up to $^{176}\text{Yb}/^{177}\text{Hf} = \sim 0.5$. ^{176}Lu isobaric interference on ^{176}Hf was corrected using a $^{176}\text{Lu}/^{175}\text{Lu}$ ratio of 0.02655 (Vervoort et al., 2004) assuming the same mass bias behaviour as Yb. Confirmation of accuracy of the technique was monitored using the Plešovice, Mudtank and Temora II zircon standards. Mean $^{176}\text{Hf}/^{177}\text{Hf}$ values for each standard along with the published values are given in Supplementary Table 2. $\epsilon_{\text{Hf}}(T)$, and T_{DM} crustal were calculated using the ^{176}Lu decay constant after Scherer et al. (2001). T_{DM} crustal was calculated using the methods of Griffin et al. (2002) with an average crustal composition of $^{176}\text{Lu}/^{177}\text{Hf} = 0.015$.

3. Results

3.1. Additional U-Pb zircon data Gnarlyknots-1A sample 74322

A further 55 zircon U-Pb data were acquired from sample 74322, sampled from the Turonian to Santonian Wigunda Formation to increase the number of data available from this sample. The analysed grains were selected without using any particular criteria, to avoid undue bias in the data collection. Fifty three of the data are within 10% of concordance (Supplementary Table 1, Fig. 3). The new data complement the existing data of Macdonald et al. (2013), with

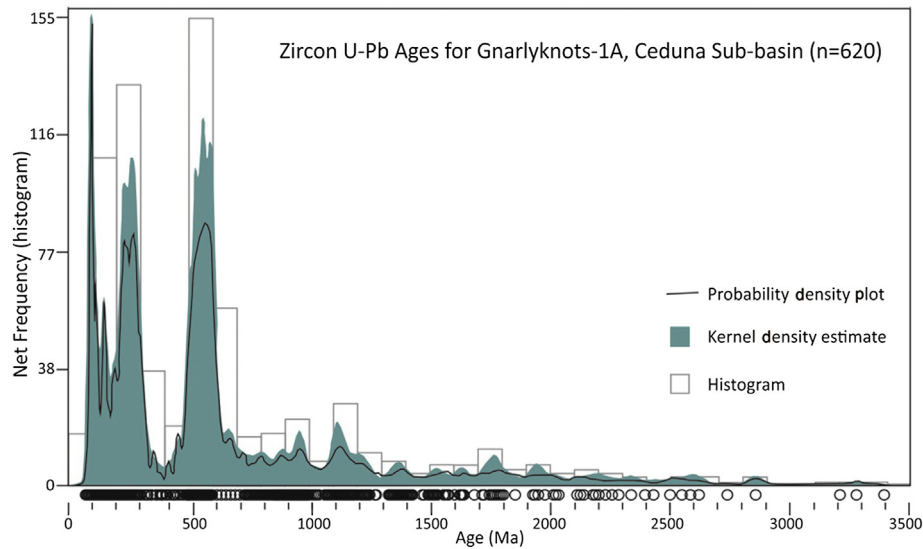


Figure 3. Combined probability density distribution, kernel density estimate plots and histograms of U-Pb age data from the Gnarlyknots-1A well that samples the Turonian–Maastrichtian succession within the central Ceduna Sub-basin. Plotted with the program ‘Density Plotter’ (Vermesch, 2012). The $^{207}\text{Pb}/^{206}\text{Pb}$ age is used for zircons older than 1000 Ma, whilst the $^{206}\text{Pb}/^{238}\text{U}$ age is used for younger analyses due to the different half-lives of the parent uranium isotopes.

a few data yielding Mesoarchaean–Neoproterozoic ages, some 1800–2100 Ma detritus, late Mesoproterozoic ages, a minor concentration in the Tonian–Cryogenian, major detrital peaks in the Ediacaran–Cambrian and Carboniferous–Triassic and a final concentration of Cretaceous-aged detritus. The youngest concordant $^{206}\text{Pb}/^{238}\text{U}$ age is 98.0 ± 2.6 Ma (2σ error), which is slightly older than the maximum depositional age of 91.3 ± 3.2 Ma reported from this sample in Macdonald et al. (2013), consistent with the sample being Turonian–Santonian in age.

3.2. Hf isotope data from Gnarlyknots-1A

Corrected $\epsilon\text{Hf}(t)$ values from Gnarlyknots-1A are given in Fig. 4. Lu–Hf isotope ratios were taken from samples 74318, 74319, 74321, 74322, 74323 and 74326 and as shown, all samples yield large variations in age corrected ϵHf values, ranging from highly evolved (–46.4) to very juvenile (+19.9). There are distinct and diffuse populations in the dataset that correspond to the U–Pb age populations that, in a number of cases, distinguish between similar-aged populations, emphasizing the importance of obtaining Hf isotope data where possible to distinguish between source regions.

With one exception, all 3000–2300 Ma zircons show negative $\epsilon\text{Hf}(t)$ values indicating evolved sources for those zircons. The exception is a zircon (ca. 2859 Ma, second oldest zircon of the sample) with a highly positive $\epsilon\text{Hf}(t)$ value that demonstrates a juvenile source for this grain. There is a broad trend of less negative values with increasing age in this population with $\epsilon\text{Hf}(t)$ values ranging from –19.6 to +9.1, suggesting that younger Archaean zircons may have crystallised from reworked Mesoarchaean crust. A second population at ca. 2000–1400 Ma, with $\epsilon\text{Hf}(t)$ values ranging from +7.4 to –8.4, has an inverse trend from the Archaean examples with increasingly negative values with increasing age, suggesting a greater involvement of the Mantle in the source magmas.

Late Mesoproterozoic zircons (ca. 1260–1080 Ma) appear to show two subpopulations, both of similar age. One population consists of zircons with moderately evolved $\epsilon\text{Hf}(t)$ values (–6.7 to –5.0), whilst the second population is characterised by near zero $\epsilon\text{Hf}(t)$ values (–1.5 to +1.9). This suggests two different zircon

sources. One zircon (ca. 1139 Ma) has an $\epsilon\text{Hf}(t)$ value of +11.7, indicating a highly juvenile source.

Zircons spanning the Mesoproterozoic–Neoproterozoic boundary, between ca. 1030–895 Ma, show generally positive ϵHf values. This suggests more Mantle involvement in the source magma. Epsilon Hf values range from –9.6 to +19.7 although most values lie between –1.8 and +9.3.

Zircon grains dated between the Cryogenian and the Ordovician (ca. 800–450 Ma) make up ca. 40% of the total analysed zircons. The older zircons in this population (ca. 800–650 Ma) plot about the zero ϵHf line, broadly between +5 and –3. After ca. 650 and until ca. 455 Ma, many zircons show a vertical spread between about +2.1 and highly evolved values down to –17.5. There is also a smaller population of ca. 570–513 Ma zircons with highly negative values (–28 to –23.3).

Silurian and Devonian zircons are absent, but Carboniferous to Lower Jurassic zircons (~360–180 Ma) form two distinct $\epsilon\text{Hf}(t)$ populations. An evolved population ($\epsilon\text{Hf}(t) = -13.3$ to –3) of ca. 360–180 Ma zircons and a second population that overlaps in age (ca. 320–200 Ma), but generally younger than the previous population, has moderately juvenile $\epsilon\text{Hf}(t)$ values ranging from –0.6 to +8.5 with most falling between +3 and +8.5.

A final population of lower Jurassic–Cretaceous zircons (ca. 180–95 Ma) contains moderate to highly juvenile $\epsilon\text{Hf}(t)$ values (+4.3 to +12.8). Within this population a tight grouping (approx. 74%) of juvenile zircons occur between ca. 130 Ma and ca. 95 Ma.

4. Discussion

4.1. U–Pb age provenance of Upper Ceduna Delta

The 620 U–Pb data now available from $\leq 10\%$ concordant detrital zircons from the Gnarlyknots-1A core (from Macdonald et al., 2013 and this study) (Fig. 3) show the limited input of Archaean and Palaeoproterozoic detritus in the delta, despite the proximity of rocks with similar crystallisation ages exposed close to the delta distributary channel in the Gawler Craton (Hand et al., 2007; Reid and Hand, 2012). This suggests that much of the adjacent margin wasn’t exposed in the Santonian to Maastrichtian, or at least that the part of the Ceduna River that traversed the Gawler Craton

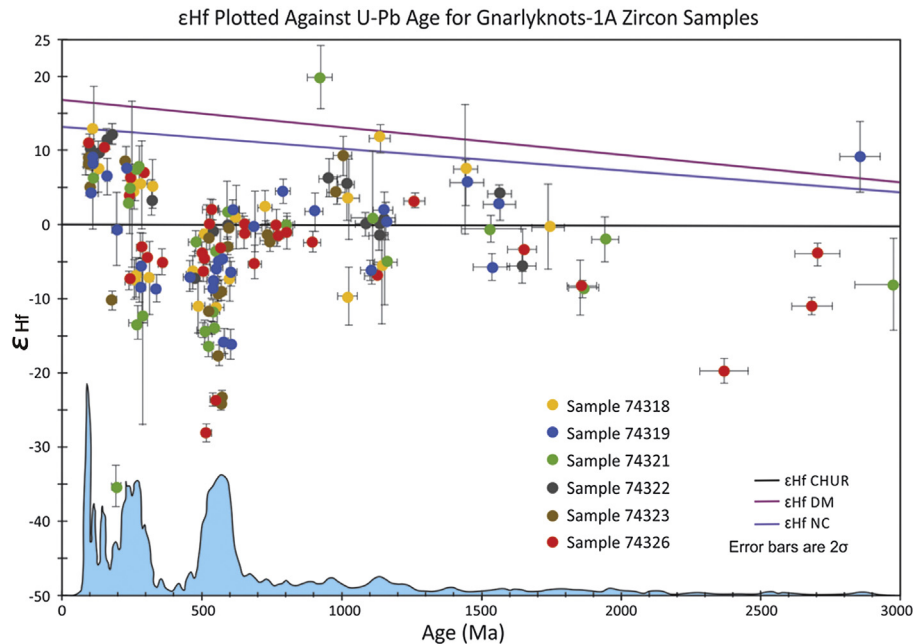


Figure 4. Hf isotopic data, presented as $\epsilon\text{Hf}(t)$ values, versus age. The light blue curve below is the kernel density estimate presented in Fig. 4 to indicate relative abundance of age populations. CHUR = Chondrite Universal Reservoir (Bouvier et al., 2008), DM = Depleted Mantle (Vervoort and Blichert-Toft, 1999), NC = New Crust (Hawkesworth et al., 2010).

wasn't erosional over this part of its path, at that time. The first sizable peak in detrital ages occurs at ca. 1150–1100 Ma. This is older than many of the Musgraves Province granites, but does overlap with the younger end of magmatism in this area (Smithies et al., 2011; Kirkland et al., 2013). Similar-aged inherited zircons (xenocrysts) have been reported within the Phanerozoic granites that intrude the Lachlan Orogen of southeast and east Australia (Kemp et al., 2006). The Palaeozoic sedimentary country rocks to these intrusions are also rich in similar-aged zircon detritus that is thought to be sourced from Antarctica, or elsewhere in Gondwana (Squire et al., 2006). There is an age minimum at approximately 1050 Ma with an increase back to zircons with Tonian and Cryogenian ages (Fig. 3). Granitic igneous rocks of this age are rare in Australia, but again, inherited and detrital zircons of this age are common within later granites and metasedimentary rocks in the Lachlan Orogen (Kemp et al., 2006; Squire et al., 2006) and also from Cryogenian to Palaeozoic sedimentary rocks from the Centralian Superbasin (Maidment et al., 2007). The first really major concentration of detrital zircon ages occurs in the Ediacaran–Cambrian (Fig. 3), which overlaps with magmatism in the Adelaide Rift Complex (Foden et al., 2006) and is reflected by similar-aged detrital zircons, and inherited zircons in the Lachlan Orogen (Kemp et al., 2006; Squire et al., 2006; Fergusson et al., 2013) and in the Centralian Superbasin (Maidment et al., 2007). There is a significant lack of detrital zircon ages through the Silurian, Devonian and Carboniferous, despite the frequency of granites of this age found in the Lachlan Orogen. The next major zircon age peak records Permian and Triassic ages. Granitoid magmatism of this age is only found exposed in Australia in the New England Orogen of east and northeast Australia (Fig. 1) (Phillips et al., 2011; Chisholm et al., 2014; Jeon et al., 2014). Further U–Pb detrital zircon ages occur in the late Jurassic to middle Cretaceous, coeval with voluminous silicic volcanism in eastern Australia (including the ca. 135–95 Ma Whitsunday Silicic LIP; Bryan et al., 2012) (Fig. 1). These findings are similar to those suggested by Macdonald et al. (2013), Tucker et al. (2013) and Tucker (2014).

4.2. Provenance implications of Hf isotope data

The Hf isotopic record, of the same zircons whose U–Pb ages are discussed above, adds an independent data set to help evaluate the provenance of the Gnarlyknots-1A sandstone samples. When the measured Hf isotopes are corrected for the crystallisation ages of the zircon (and therefore the age at which the Hf was trapped in the zircon), and normalised to the Chondrite Uniform Reservoir (CHUR) and plotted against its age, the resulting figure (Fig. 4) reveals some interesting trends. These temporal isotopic trends reflect the evolution of magmas, in which the detrital zircons originally grew, within the source regions. The main age trends have been discussed in the results section above; here we discuss their similarity, or dissimilarity, to comparable data from eastern and south-central Australia that form possible source regions (Figs. 1 and 5).

Limited Archaean data are available from the Gnarlyknots-1A zircons, but the general decrease in $\epsilon\text{Hf}(t)$ values with decreasing age, noted above, is broadly reflected in the inherited zircon data from SE Australian granites (Kemp et al., 2006) (Fig. 5). Late Palaeoproterozoic–early Mesoproterozoic data from Gnarlyknots-1A are similar in Hf isotopic values to those seen in the Mount Painter region (northern Flinders Ranges) of South Australia (Figs. 1 and 5) (Kromkhun et al., 2013), and from the eastern part of the Musgraves Province (Smits et al., 2014), which bound the suggested catchment area of the Ceduna River to both sides (Fig. 1). Stenian zircons may be sourced from the Musgraves Province of central Australia, or recycled from the Lachlan Orogen of SE Australia. The $\epsilon\text{Hf}(t)$ versus Age plot shows that although there is overlap between the Gnarlyknots-1A data and the younger zircons from the Musgraves (Smithies et al., 2011; Kirkland et al., 2013), the more evolved zircons are outside the Musgraves trend, but do overlap with coeval zircons from the Lachlan Orogen (Kemp et al., 2006) (Fig. 5), suggesting that these might be more likely source for these grains. The prominent trend of decreasing age and decreasing $\epsilon\text{Hf}(t)$ values between ca. 1000 and 600 Ma is also broadly mirrored in the Lachlan Orogen granites inherited zircon data, as is the marked

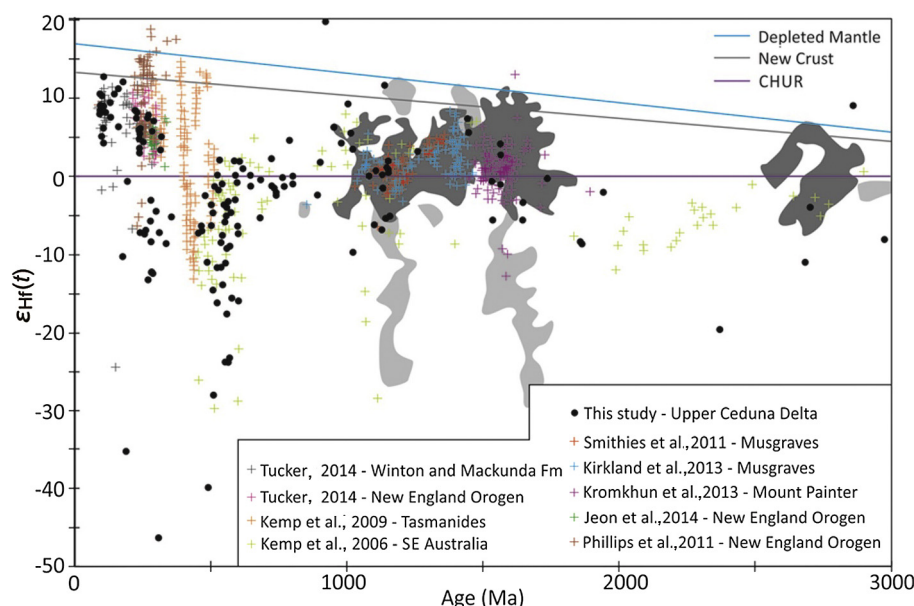


Figure 5. Epsilon Hf(*t*) versus age plot of data presented in this study (black dots) comparing with similar data from eastern and central Australia. Grey fields are data from the Musgraves Province presented in [Smits et al. \(2014\)](#), dark grey equates to the majority of the data, whereas the light grey fields are field of more sparse data.

shift to evolved values in the Ediacaran ([Kemp et al., 2006](#)) ([Fig. 5](#)). [Kemp et al. \(2009\)](#) recorded Hf isotopic data for many Palaeozoic granites in the Lachlan Orogen, equivalent-aged zircons from Gnarlyknots-1A are noticeable by their absence ([Fig. 5](#)). This may be because these data come predominantly from the south of the Lachlan Orogen, away from the probable headwaters of the Ceduna River system. We suggest that older, inherited zircons in the granites better represent the detrital zircons in the surrounding sedimentary rocks, which are the country rocks to the Palaeozoic granites, and were presumably entrained in the granites as xenocrysts. These sedimentary rocks form much of the Lachlan and Thompson Orogens of eastern Australia and appear to have been eroded and recycled into the Ceduna River system, whereas zircons that crystallised in the granites, which are more numerous in the southern parts of the orogeny, did not.

Permian and Triassic detritus in the Upper Ceduna delta fall into two distinct fields, a slightly older evolved group and a more juvenile group. The juvenile group overlaps well with data from the New England Orogen ([Phillips et al., 2011](#); [Jeon et al., 2014](#); [Tucker, 2014](#)), although data from the New England Batholith does stretch to much more juvenile values than recorded in zircons from Gnarlyknots-1A ([Phillips et al., 2011](#)) ([Fig. 5](#)). The more evolved zircon population may be sourced from the Kennedy Igneous Association ([Champion and Bultitude, 2012](#)) of central and northern Queensland. No Hf data are available from these Carboniferous–Permian (ca. 345–260 Ma) extrusive and intrusive rocks, but neodymium isotope data yield evolved values ([Champion and Bultitude, 2012](#)). Finally, late Jurassic–middle Cretaceous detrital zircon overlaps with similar data collected from the Cretaceous Mackunda and Winton Formations in Queensland ([Tucker, 2014](#)), the upper part of the latter formation has recently been dated as being deposited in the Turonian, with the single youngest concordant zircon dated at 92.5 Ma ([Tucker et al., 2013](#)), coeval with the upper delta in the Ceduna Sub-basin.

4.3. Constraints on the Ceduna River system and the evolution of central Australia

The provenance data presented here support the original origin of detrital zircons found today in the Turonian to Maastrichtian part

of the Ceduna Delta system to lie in NE Australia, in Queensland (broadly the area outlined as the ‘Cenomanian Ceduna River Catchment Area’ in [Fig. 1](#)) ([Bryan et al., 1997](#); [Veevers, 2000](#)). These correlate with Turonian to Santonian mudstones and deltaic sandstones overlain by a voluminous Santonian to Maastrichtian delta lobe ([Macdonald et al., 2012](#)). U–Pb and Hf detrital zircon data are consistent with similar data from the inherited zircons in granites from SE Australia ([Kemp et al., 2006](#)), granites from the New England Orogen and the Kennedy Igneous Association ([Phillips et al., 2011](#); [Champion and Bultitude, 2012](#); [Jeon et al., 2014](#); [Tucker, 2014](#)), from the far north Flinders Ranges and the eastern Musgraves Province ([Kromkhun et al., 2013](#); [Smits et al., 2014](#)) and from the coeval Winton Formation of the uppermost Eromanga Basin ([Tucker, 2014](#)), which was undisputably sourced from N and E Queensland, based on palaeocurrent and detrital heavy mineral data ([Bryan et al., 1997](#); [Tucker et al., 2013](#)). An ultimate source from NE Australia does not, however, disprove the hypothesis of [Macdonald et al. \(2013\)](#), who argued that the Upper Ceduna Delta (Santonian to Maastrichtian) was sourced from a relatively restricted catchment, largely in the present state of South Australia (see [Fig. 1](#)). They argued this based largely on zircon fission track data from southern Australia that show considerable exhumation in the Upper Cretaceous. In this model, the ‘Queensland’-provenance of many of the Ceduna delta zircons would remain valid because they were recycled from the lower Cretaceous formations within the Eromanga Basin.

A caveat to this model is that, unlike coastal Australia, there is very little fission track, or other low-temperature thermochronological data available from inland Australia; especially from the proposed catchment of the Ceduna River through northern South Australia and southwestern Queensland. The results of a reconnaissance study from the central Gawler craton has recently been published ([Reddy et al., 2015](#)) that encompasses a region close to any putative course of the Ceduna River. This study yielded apatite fission track and U–Th–Sm/He ages indicating that this region did not experience major cooling and exhumation after the Triassic–Jurassic (ca. 230–190 Ma). Only one sample yielded younger apatite fission track ages of ca. 130–100 Ma ([Reddy et al., 2015](#)). These data are sparse, but tantalizingly suggest that at least the central Gawler Craton was exhumed before the late

Cretaceous, and that any late Cretaceous river that traversed this region was unlikely to have caused widespread erosion. Post-Jurassic thermal events, captured in the thermochronological record of the Gawler Craton are interpreted as the result of partial resetting by a combination of shallow burial beneath the Eromanga Basin and flow of elevated temperature groundwater within the Eromanga aquifer system (Gleadow et al., 2002; Reddy et al., 2015) that is also seen in the underlying Cooper Basin (Middleton et al., 2014). These data contrast with new information from the Drummond Basin of Queensland, which lies closer to the proposed headwaters of the Ceduna River system (Fig. 1). Here, modelled (U-Th)/He apatite and zircon data suggest a phase of rapid exhumation at ca. 80 Ma (Zhang et al., 2014). In addition to this lack of evidence of late Cretaceous cooling (and therefore presumably exhumation) along the course of the Ceduna River system, away from its headwaters, a new maximum depositional age of ca. 92.5 Ma on the Winton Formation in central Queensland (Tucker et al., 2013), suggests that this part of the Winton Formation (at least) post-dates the Cenomanian Lower Ceduna Delta lobe and is coeval with at least the mixed deltaic/fore-delta mudstones that underlie the main Santonian to Maastrichtian Upper Ceduna Delta lobe (Macdonald et al., 2012). Taken together, these observations suggest that both delta lobes may be deposited from river systems that originated in Cretaceous Queensland. However, more low-temperature thermochronological data are needed both from central Australia, and from detrital minerals in the resulting basins, to truly track the exhumation of Australia and follow the source to sink history of the fill of the extensive Australian Mesozoic basins.

5. Conclusions

Hf isotope data from zircons from Turonian to Maastrichtian sandstones within the Upper Ceduna Delta in the Bight Basin, southern Australia, suggest that the ultimate provenance of many of the zircons in this delta are from NE Australia, in the region of the exposed New England Orogen and the Whitsunday Silicic LIP of Queensland. The data presented here do not solve the debate about whether the 'Queensland-origin zircons' in the Santonian-Maastrichtian upper delta lobe were recycled from the Eromanga Basin during a late Cretaceous pulse of uplift and exhumation as proposed by Macdonald et al. (2013), but correlation with the Winton Formation in Queensland and new reconnaissance low-temperature thermochronological data from the central Gawler Craton (Reddy et al., 2015), suggest that this is not necessary and that the transcontinental Ceduna River is likely to have existed throughout the Cretaceous.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.gsf.2015.06.001>.

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