



Eoarchean crustal evolution of the Jack Hills zircon source and loss of Hadean crust

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Abstract

Given the global dearth of Hadean (>4 Ga) rocks, 4.4–4.0 Ga detrital zircons from Jack Hills, Narryer Gneiss Complex (Yilgarn Craton, Western Australia) constitute our best archive of early terrestrial materials. Previous Lu–Hf investigations of these zircons suggested that felsic (low Lu/Hf) crust formation began by ~4.4 to 4.5 Ga and continued for several hundred million years with evidence of the least radiogenic Hf component persisting until at least ~4 Ga. However, evidence for the involvement of Hadean materials in later crustal evolution is sparse, and even in the detrital Jack Hills zircon population, the most unradiogenic, ancient isotopic signals have not been definitively identified in the younger (<3.9 Ga) rock and zircon record. Here we show Lu–Hf data from <4 Ga Jack Hills detrital zircons that document a significant and previously unknown transition in Yilgarn Craton crustal evolution between 3.9 and 3.7 Ga. The zircon source region evolved largely by internal reworking through the period 4.0–3.8 Ga, and the most ancient and unradiogenic components of the crust are mostly missing from the record after ~4 Ga. New juvenile additions to the crust at ca. 3.9–3.8 Ga are accompanied by the disappearance of unradiogenic crust ca. 3.9–3.7 Ga. Additionally, this period is also characterized by a restricted range of $\delta^{18}\text{O}$ after 3.8 Ga and a shift in several zircon trace element characteristics ca. 3.9–3.6 Ga. The simultaneous loss of ancient crust accompanied by juvenile crust addition can be explained by a mechanism similar to subduction, which effects both processes on modern Earth. The oxygen isotope and trace element information, although less sensitive to tectonic setting, also supports a transition in zircon formation environment in this period.

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1. INTRODUCTION: EMPIRICAL CONSTRAINTS ON HADEAN–ARCHEAN TRANSITIONS

The nature of crust and the tectonic processes operating on early Earth are difficult to constrain due to the fragmentary Eoarchean and essentially absent Hadean rock record (cf. O'Neil et al., 2008). In the absence of a paradigm for early geodynamics, numerous authors have attempted to extend plausible models to early Earth conditions with differing conclusions (e.g., Davies, 1992, 2006; van Hunen and van den Berg, 2008; Sizova et al., 2010; Gerya, 2013).

Alternatively, various lines of isotopic and mineral evidence from cratons have been interpreted to indicate substantial changes in crustal evolution ca. 3 Ga, possibly connected with the onset of plate tectonics (Shirey and Richardson, 2011; Dhuime et al., 2012; Naeraa et al., 2012; Debaille et al., 2013). However, the search for evidence of older tectonic regimes is limited by the dearth of samples and potentially compounded by the efficacy of crustal recycling by plate tectonics (e.g., Scholl and von Huene, 2010) or some other mechanism.

Despite the paucity of Hadean rocks, detrital zircons from a pebble metaconglomerate at the “discovery site” in the Jack Hills, Western Australia do include Hadean materials, and range 4.4–3.0 Ga in age (e.g., Compston and Pidgeon, 1986; hereafter this population is referred to

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as the “Jack Hills zircons”). Various aspects of the >4 Ga Jack Hills zircons’ geochemistry have been used to infer their formation in low-temperature, hydrous, granite-like melting conditions (e.g., Mojzsis et al., 2001; Peck et al., 2001; Watson and Harrison, 2005; Harrison et al., 2008). In particular, previous work on the Lu–Hf isotopic systematics of Jack Hills zircons demonstrated a dominantly unradiogenic Hadean population (Amelin et al., 1999; Harrison et al., 2005, 2008; Blichert-Toft and Albarède, 2008; Kemp et al., 2010) with isolation of low-Lu/Hf (enriched) reservoirs as early as 4.5 Ga and persistence of that material in the crust for at least several hundred million years (Harrison et al., 2008; Kemp et al., 2010). Highly unradiogenic materials within error of the solar system initial Hf isotopic composition were noted by Harrison et al. (2005, 2008) and persist until at least 4 Ga. The large range in initial ϵ_{Hf} (initial $^{176}\text{Hf}/^{177}\text{Hf}$ normalized to an assumed chondritic uniform reservoir, or CHUR) may suggest continuous extraction, perhaps to ~ 4.0 to 3.9 Ga (Harrison et al., 2005; Blichert-Toft and Albarède, 2008).

The dominant Jack Hills age group at ~ 3.6 to 3.3 Ga is geochemically distinct from the broader Hadean population in several important respects, suggesting that an important transition(s) occurred between 4.0 and 3.6 Ga in the Yilgarn Craton crust. Zircons younger than 3.6 Ga have considerably more radiogenic Hf as a whole, suggesting a diminished influence of ancient Hadean crust in the zircon source area before 3.6 Ga (Amelin et al., 1999; Bell et al., 2011). In addition, some post-Hadean juvenile input to the crust is required to explain the most radiogenic <3.6 Ga zircons (Bell et al., 2011). The Jack Hills oxygen isotope record also changes during the Eoarchean: although concordant Hadean zircons commonly populate the range $\delta^{18}\text{O}_{\text{SMOW}} \sim 3\text{‰}$ to 8‰ , with a few reported higher values (Mojzsis et al., 2001; Peck et al., 2001; Cavosie et al., 2005; Trail et al., 2007b), the <3.8 Ga population appears more mantle-like (cf. Peck et al., 2001; Bell and Harrison, 2013; Bell et al., 2011). This probably reflects the sourcing of these younger zircons from magmas which included fewer aqueously altered materials (Bell and Harrison, 2013; Bell et al., 2011). Scattered highly positive and negative $\delta^{18}\text{O}$ values in the Eoarchean may also point to post-crystallization disturbance.

Trace element-based indicators are also useful for monitoring the changing petrogenesis of the Jack Hills zircons; application of the Ti-in-zircon thermometer to the Hadean population revealed average crystallization temperatures (T^{zln}) ~ 680 °C – similar to temperatures seen in hydrous granitic magmas, and notably lower than the majority of zircons from mantle-derived igneous complexes or terrestrial impact magmas (Watson and Harrison, 2005; cf. Fu et al., 2008; Harrison, 2009; Harrison et al., 2007; Hellebrand et al., 2007; Wielicki et al., 2012; Carley et al., 2014). Zircons from 4.0 to 3.3 Ga have T^{zln} similar to the Hadean distribution (Bell et al., 2011), with the curious exception of the period ~ 3.91 to 3.84 Ga, in which a large group of concordant zircons yield a remarkably low average apparent T^{zln} of ~ 600 °C, with values extending to subsolidus temperatures as low as 525 °C (Bell and Harrison, 2013). Other geochemical peculiarities of zircons

in this time period led Bell and Harrison (2013) to interpret this distinct group as resulting from solid-state recrystallization (Hoskin and Black, 2000), likely due to a thermal event in the zircon source terrane(s). The application of more comprehensive trace element analyses to other 4.0–3.6 Ga zircons, along with electron imaging and prior Ti-thermometry and oxygen isotope measurements (Bell and Harrison, 2013) in this time period, provides a clearer picture of the fundamental nature of these samples (i.e., metamorphic vs. magmatic) and their role in crustal evolution.

The Jack Hills zircon population is poorly represented outside of the two prominent age groups at 3.6–3.3 Ga and 4.2–3.8 Ga, so the true nature of its crustal evolution has remained uncertain. We present 160 new Lu–Hf–Pb isotopic measurements (by the coupled Hf–Pb protocol of Woodhead et al., 2004) on 148 Jack Hills detrital zircons ranging in age from 4.2 to 3.3 Ga, with the majority dated to between 4.0 and 3.6 Ga. We also include measurements on 26 zircons from several nearby ca. 2.6 Ga granitoids not previously studied for Lu–Hf, including a previously unsampled microgranite 150 m from the discovery site, which further constrain the NGC crust’s Lu–Hf systematics after detrital zircon deposition. Increased sampling in the Eoarchean clarifies the nature of the Hf distribution in this period and demonstrates an important transition in crustal evolution whose timing was not evident from previous sampling. This new dataset, combined with data from previous Lu–Hf studies of detrital and granitoid zircons at Jack Hills, allows for the tracing of NGC crustal evolution from the early Hadean to 2.6 Ga. We also present 49 new trace element measurements on <4 Ga Jack Hills zircons and compare the record of change in the Lu–Hf system to the oxygen isotope, trace element, and Ti thermometry records to further constrain the nature of these events in the Eoarchean Yilgarn Craton crust.

2. METHODS

Zircons were selected for analysis from the sample set of Bell and Harrison (2013). They were previously dated by ion microprobe either by Bell and Harrison (2013) or Holden et al. (2009). All detrital zircons were collected from pebble metaconglomerate at the discovery site. Bell and Harrison (2013) analyzed most samples for Ti and $\delta^{18}\text{O}$ and thirty-one Eoarchean samples for rare earth elements (REE) and other trace elements. Granitoid zircons were taken from the interior and margin of a granite intruding the metasediments ca. 3 km southwest of the discovery site (the “Blob” granite of Spaggiari et al., 2007). In addition, some zircons were also analyzed from a microgranite intruding banded iron formation ca. 150 km southwest of the discovery site. More detailed information on sample site locations is given in Electronic Annex EA-1.

2.2. Lu–Hf–Pb measurements

We used backscattered electron and cathodoluminescence images of our zircons to target the placement of nominally 69 μm diameter laser ablation pits made using a Photon Machines 193 nm ArF ATL laser with a 4 Hz rep-

etition rate coupled to a Thermo-Finnigan Neptune MC-ICPMS. Analyses were made over several days in April and May of 2013. We used the coupled Hf–Pb analysis technique (distinct from the laser-ablation split-stream technique described by Fisher et al., 2014a) of Woodhead et al. (2004) to switch between measuring a Yb–Lu–Hf mass set (^{171}Yb , ^{173}Yb , $^{174}\text{Yb}/^{174}\text{Hf}$, ^{175}Lu , $^{176}\text{Yb}/^{176}\text{Lu}/^{176}\text{Hf}$, ^{177}Hf , ^{178}Hf , ^{179}Hf) for Lu–Hf systematics to a Pb mass set (206, 207, 208) for estimating age, using the analysis sequence described by Bell et al. (2011). Briefly, this involves measuring for 11 s on the Yb–Lu–Hf mass set and for 5 s on the Pb mass set in each analytical cycle; the first 2 s of each set were disregarded to allow for magnet settling. We repeated this sequence for 15 cycles or until the zircon was ablated through, with most analyses continuing for 10 or 11 cycles. We corrected data for our samples using the standard zircons AS3 (Paces and Miller, 1993) and Mud Tank (Black and Gulson, 1978). We used NIST-610 glass as a secondary Pb isotope standard, given its Pb isotopic homogeneity and lack of known matrix effect that would complicate its use as a standard for zircon analyses. Data from all standard analyses are graphed in Fig. 1 and tabulated in Electronic Annex EA-2. Data from all unknown analyses are tabulated in EA-3, and representative CL images shown in EA-4.

Detrital zircon ages presented for this study are those measured during ICP-MS analysis, in order to more faithfully match Hf isotopic compositions to zircon age.

Although the vast majority of zircons display $^{207}\text{Pb}/^{206}\text{Pb}$ ages from LA-ICPMS and ion microprobe that agree within a few percent (see Fig. 2A, C, D), 13 analyses with Eoarchean ion microprobe ages display $>5\%$ disagreement (Fig. 3). These analyses display LA-ICPMS ages both >4 Ga and <3.6 Ga. An additional 18 zircons displayed >4 Ga LA-ICPMS ages despite having 4.0–3.8 Ga ion microprobe ages. Given the inferred disturbance to some zircons' U–Pb systems during the Eoarchean (Bell and Harrison, 2013), this suggests that some ion microprobe ages in this period may represent only small surficial domains or may be artifacts from zircon disturbance. However, the majority of zircons in this period do display good agreement between ages. The reverse situation, of Eoarchean LA-ICPMS ages among zircons with ion microprobe ages outside this period, is not common in this dataset.

Only domains within the zircon that record a homogeneous Pb isotopic age for at least three concurrent Hf–Pb cycles were considered. Another concern in the correct assignment of age to Hf isotopic composition is the possibility of ancient Pb loss, which can cause a lowering of the $^{207}\text{Pb}/^{206}\text{Pb}$ age with relatively little loss of concordance. Use of the younger apparent age would cause an artificial lowering of the zircon's calculated ε_{Hf} . Accordingly, most zircons used in this study were $>95\%$ concordant according to ion microprobe U–Pb analyses, and many were less than 2% discordant (along with 17 $<90\%$ concordant – listed in Electronic Annex EA2 and shown

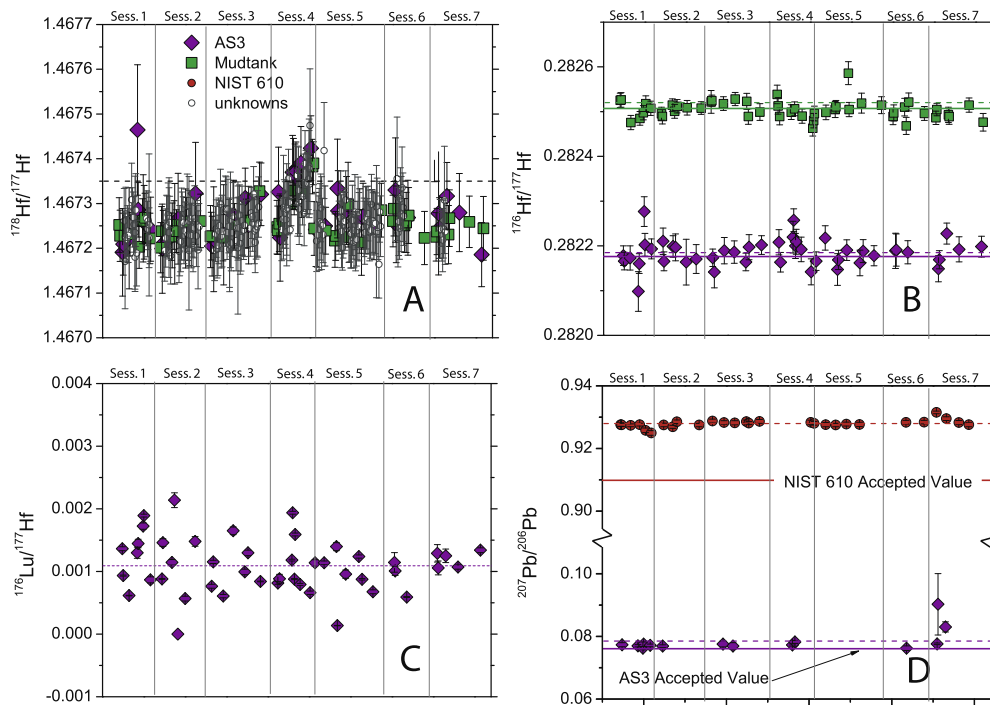


Fig. 1. Standard analyses over all sessions. Solid lines indicate accepted values, dashed lines indicate the average over the indicated standards. (A) $^{178}\text{Hf}/^{177}\text{Hf}$ for all zircon standard and unknown analyses after mass-fractionation correction, with accepted value of Thirlwall and Anczkiewicz (2004). (B) $^{176}\text{Hf}/^{177}\text{Hf}$ after mass-fractionation correction and peak-stripping for ^{176}Yb and ^{176}Lu . (C) $^{176}\text{Lu}/^{177}\text{Hf}$ for the AS3 standard after mass-fractionation correction and peak-stripping. (D) $^{207}\text{Pb}/^{206}\text{Pb}$ for the AS3 and NIST 610 standards. Mass fractionation correction was not applied to the Pb isotopes, but in-session correction factors were assigned to all standard and unknown analyses based on standard analyses.

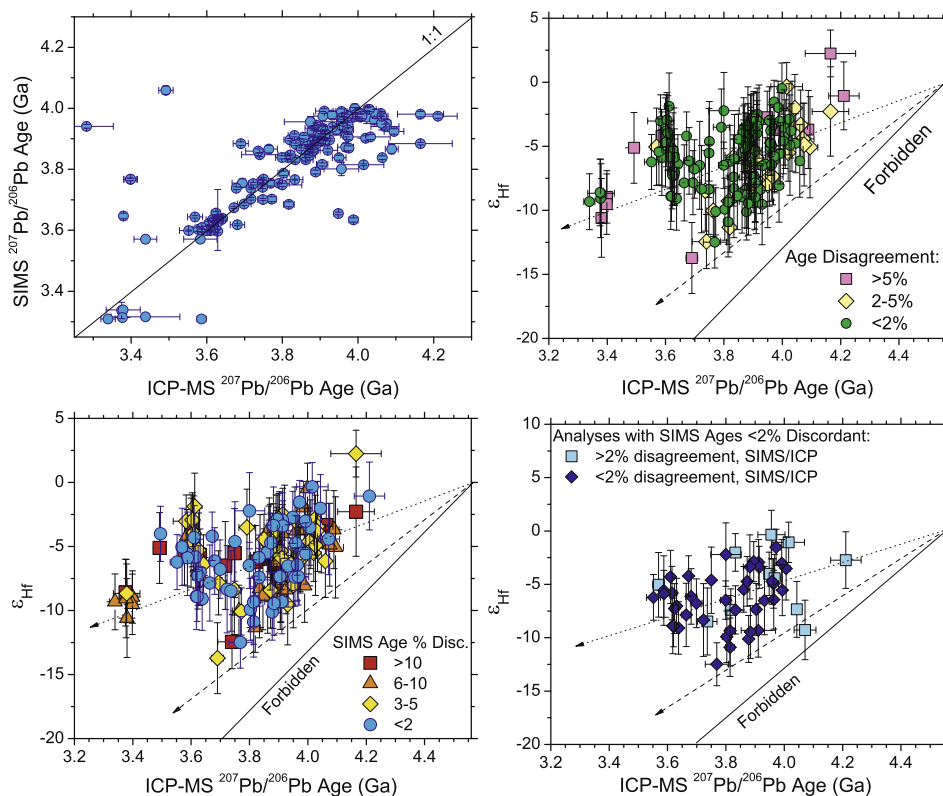


Fig. 2. Hf–Pb samples in several potential indicators of age/Hf composition mismatch. 2σ external error bars are shown. (A) Ion microprobe (“SIMS”) vs. LA-ICPMS age estimates with the 1:1 agreement line shown. Most samples agree within 2%. (B) our samples in ϵ_{Hf} vs. age space, grouped by ion microprobe-ICPMS age disagreement. (C) Our samples in ϵ_{Hf} vs. age space, grouped by the percent discordance of the ion microprobe age. (D) Analyses with ion microprobe ages less than 2% discordant grouped by percent disagreement between ion microprobe and ICPMS ages. The dashed line reflects, for reference, the evolution of a primordial felsic reservoir ($^{176}\text{Lu}/^{177}\text{Hf} = 0.0125$ following the modern upper continental crust value of Chauvel et al., 2014) and the dotted line that of a primordial mafic reservoir ($^{176}\text{Lu}/^{177}\text{Hf} = 0.02$).

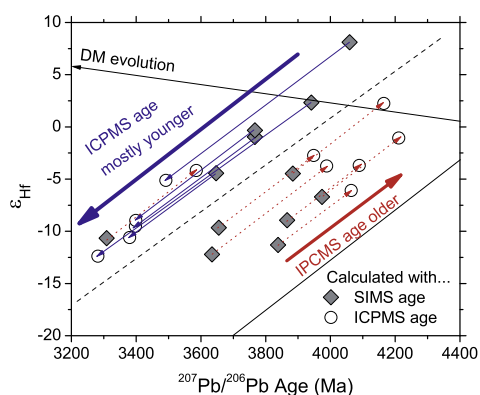


Fig. 3. Detrital zircons with $>10\%$ age disagreement between the ion microprobe and LA-ICPMS results. The age, ϵ_{Hf} distributions for these grains using both the ion microprobe and LA-ICPMS $^{207}\text{Pb}/^{206}\text{Pb}$ ages are shown. Error bars have been omitted to facilitate comparison. Arrows are drawn from the ion microprobe age/ ϵ_{Hf} to the ICPMS age/ ϵ_{Hf} .

in Fig. 2C). There is little qualitative difference in the ϵ_{Hf} vs. age distribution of the $<2\%$ discordant zircons (Fig. 2D) vs. the full sample set (Fig. 2B, C). Because we do not have a measure for concordance during the LA-ICPMS analysis,

these ion microprobe concordance measurements cannot be linked to the zircon Hf composition definitively, but we consider the good agreement of ages between the techniques to show little room for systematic error based on this uncertainty for this particular dataset.

Common Pb contamination is another concern in the correct matching of age with Hf composition, since it can lead to artificially higher $^{207}\text{Pb}/^{206}\text{Pb}$ ages. Although our setup was unable to monitor ^{204}Pb to assess common Pb contamination we did measure ^{208}Pb . Common Pb manifests in such measurements as a mixing in of radiogenic Pb with a high- $^{208}\text{Pb}/^{206}\text{Pb}$, high- $^{207}\text{Pb}/^{206}\text{Pb}$ end member (e.g., Blichert-Toft and Albarède, 2008). Fig. 4 shows our data in $^{208}\text{Pb}/^{206}\text{Pb}$ vs. $^{207}\text{Pb}/^{206}\text{Pb}$. The low $^{208}\text{Pb}/^{206}\text{Pb}$ and lack of obvious mixing with a common Pb end member among the detrital zircons stands in contrast to two of the sampled igneous units (samples from the interior and the margin of the “Blob” granite of Spaggiari et al., 2007). The former granitoid results are similar to apparent common Pb contamination seen in an earlier solution ICPMS study of the Jack Hills detrital zircons (Blichert-Toft and Albarède, 2008). We conclude that common Pb contamination is not significant among our studied detrital zircons. Zircons from the local ca. 2.6 Ga granitoids (Pidgeon and Wilde, 1998) are forced to an age of 2.67 Ga for the consid-

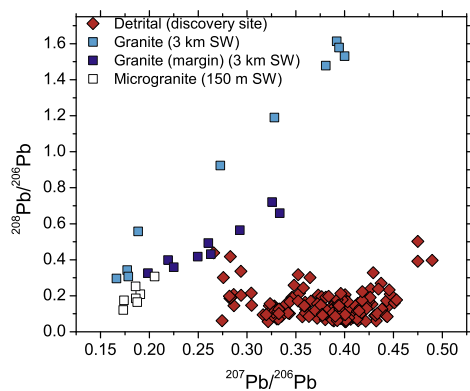


Fig. 4. LA-ICPMS Pb isotope data in $^{208}\text{Pb}/^{206}\text{Pb}$ vs. $^{207}\text{Pb}/^{206}\text{Pb}$. Several metaigneous units of known age ca. 2.7 Ga show zircon compositions skewing towards higher $^{208}\text{Pb}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ – expected for common Pb contamination (see, e.g., Blichert-Toft and Albarède, 2008, for a similar example). Detrital Jack Hills zircons do not appear to be affected. Because of the apparent contamination and the artificially old ages it causes, we will use an age of 2.67 Ga when considering the Hf isotopic compositions of our meta-igneous zircons.

eration of their Hf isotopic compositions to avoid the artificially older ages that result from the apparently widespread common Pb contamination.

We have omitted from our figures all data points from this study with 2σ error bars $>4\epsilon$, but these 12 analyses do not qualitatively change the ϵ_{Hf} -age distribution and are tabulated along with the graphed data in EA-3. We have time-corrected our Hf isotope ratios using the ^{176}Lu decay constant of Soderlund et al. (2004) and the CHUR parameters of Bouvier et al. (2008). All data from previous work are evaluated using the same parameters, sometimes requiring a recalculation of ϵ_{Hf} from the original study.

2.3. Trace elements

We carried out analyses for Ti, P, REE, Hf, U, and Th on 4.0–3.3 Ga zircons using the CAMECA *ims1270* ion microprobe at UCLA in three sessions during December 2008, January 2011, and May 2012 (i.e., before Lu–Hf–Pb analysis). Primary O⁻ beam intensities of ~ 15 nA and a spot diameter of ~ 30 μm were used. Secondary ions were detected at low MRP ($m/\Delta m \sim 2000$) and high energy offset (-100 eV). NIST610 standard glass was used for calibration. All data are presented in Electronic Annex EA-5.

3. RESULTS

Zircons in the period 4.0–3.6 Ga differ from the prevailing Hadean and <3.6 Ga Jack Hills zircon populations in several geochemical variables relevant to petrogenesis and crustal history. Although $\sim 70\%$ of zircons within the main 4.2–3.8 and 3.6–3.3 Ga populations have U–Pb systems $<10\%$ discordant, within the 3.8–3.6 Ga age minimum only $\sim 50\%$ of zircons are $<10\%$ discordant (data from Bell and Harrison, 2013). Zircons in the period 3.9–3.6 Ga are also more likely to be richer in Hf and U than the prevailing Jack Hills zircon population.

3.1. Lu–Hf–Pb

Fig. 5 shows our data in ϵ_{Hf} vs. age space, along with previous Jack Hills detrital zircon Hf measurements (Amelin et al., 1999; Harrison et al., 2005, 2008; Blichert-Toft and Albarède, 2008; Kemp et al., 2010; Bell et al., 2011). Fig. 5A includes all Hf isotopic data from previous studies of the zircons. The superchondritic results found by Harrison et al. (2005) and Blichert-Toft and Albarède (2008) by solution ICP-MS and laser ablation ICP-MS analyses for Lu–Hf tied to ion microprobe U–Pb ages have not been replicated by later studies (including this study), which have found almost exclusively negative ϵ_{Hf} values. Fig. 5B filters the database of previous results to those measured using a concurrent Lu–Hf and Pb measurement technique, which minimizes the danger of incorrect age correction of the Hf isotopic data. This filtered dataset is used for the remainder of the figures and discussion and includes the data of Bell et al. (2011), Kemp et al. (2010), and most of the data of Harrison et al. (2008).

Our 4.0–3.8 Ga samples define a distribution similar to that of the majority of Hadean zircons in both range and trajectory in ϵ_{Hf} vs. age space, with all but one sample displaying negative ϵ_{Hf} . Neither the most radiogenic (within error of a projected depleted mantle evolution line) nor the most unradiogenic (within error of the solar system initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratio, marked as “Forbidden” on figures) portions of the Hadean population are sampled by Jack Hills zircons after ~ 4 Ga. With similar Hf–Pb sampling of the Hadean and Eoarchean (181 4.0–3.6 Ga zircons, vs. 144 >4.0 Ga zircons in the database), it seems that isotopic remnants of this unradiogenic portion of the Hadean crust are at least much less prominent in the later record. After 3.7 Ga, the zircon population at Jack Hills becomes strikingly more radiogenic, losing the most unradiogenic portion of the >3.8 Ga record as well as requiring post-Hadean juvenile input.

3.2. Trace elements

Rare earth element (REE) patterns for <4 Ga zircons (Fig. 6) resemble many terrestrial magmatic zircons (e.g., Hoskin and Schaltegger, 2003), and display a steep HREE/LREE slope, low overall LREE, and prominent Ce and Eu anomalies. High U contents above 500 ppm are generally more common in the period 3.9–3.6 Ga, and the trace element ratios Th/U and Yb/Gd also show temporal variations (see Fig. 7). In particular low Th/U ratios between 4.0 and 3.8 Ga may reflect zircon disturbance (Bell and Harrison, 2013). On Figs. 6 and 7, U contents and Th/U ratios are age-corrected for decay, denoted by the subscript t .

4. DISCUSSION

The shift towards more radiogenic compositions among the younger zircons is further illustrated in Fig. 8, which shows results from this and previous studies along with all >3.8 Ga Jack Hills zircon ϵ_{Hf} results by the Hf–Pb method projected to 3.5 Ga along an upper crust-type reservoir ($^{176}\text{Lu}/^{177}\text{Hf} = 0.0125$; Chauvel et al., 2014). The

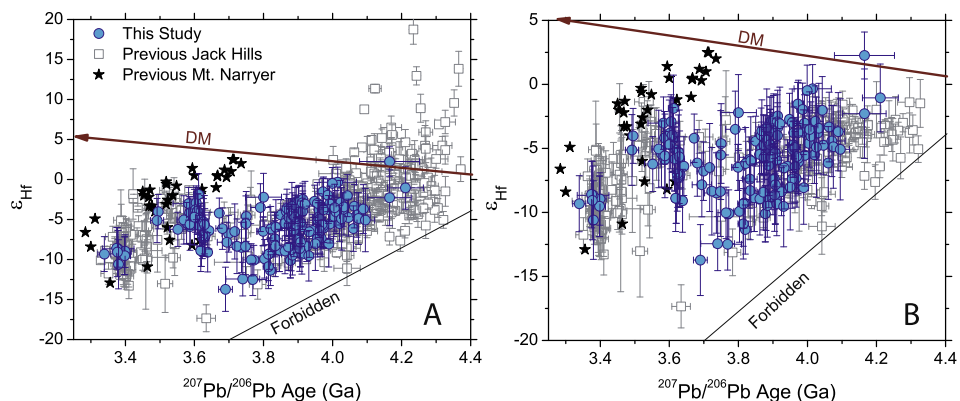


Fig. 5. (A) Our data plotted in ϵ_{Hf} vs. crystallization age space along with a database of detrital zircons measured in previous studies of Archean metasediments in the Jack Hills (JH) and nearby Mt. Narryer (MN) localities. 2σ external error bars are shown. (B) The same plot, with the database of previous Jack Hills results restricted to those analyzed by the coupled Hf–Pb method. DM evolution curve for both plots calculated by linearly projecting the current DM ϵ_{Hf} of +18 to zero at 4.56 Ga. Data for previous Jack Hills detrital zircons from Amelin et al. (1999), Bell et al. (2011), Blichert-Toft and Albarède (2008), Harrison et al. (2005, 2008), and Kemp et al. (2010); data for Mt. Narryer detrital zircons from Nebel-Jacobsen et al. (2010). Previous Jack Hills coupled Hf–Pb data from Bell et al. (2011), Harrison et al. (2008), and Kemp et al. (2010).

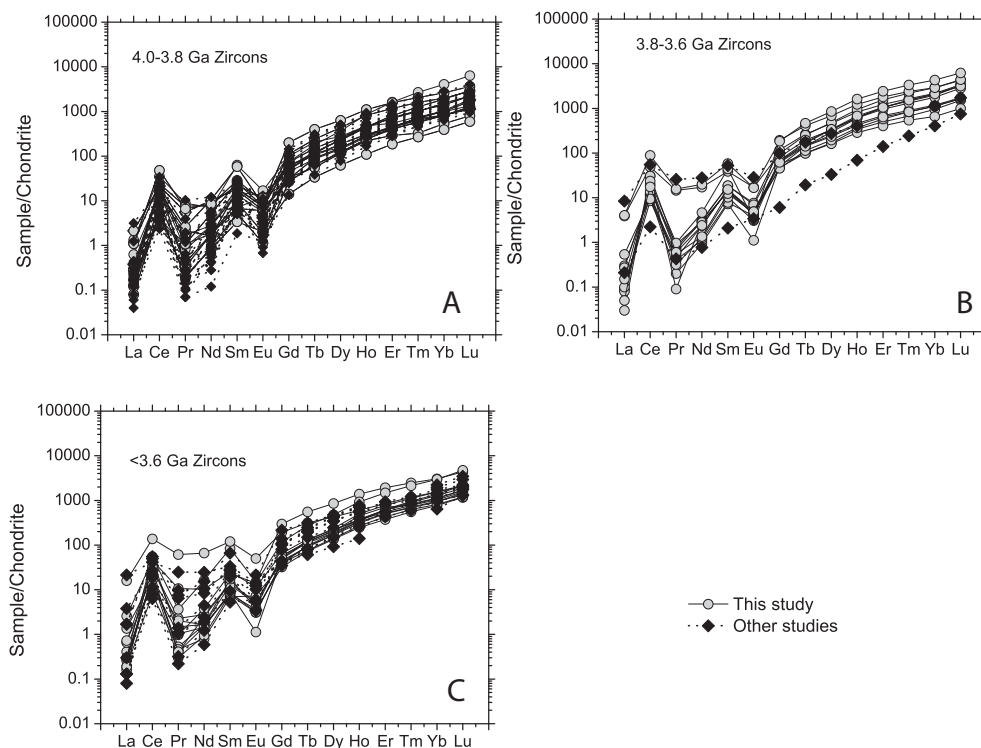


Fig. 6. Post-Hadean REE results from this and several earlier studies of Jack Hills zircons. Most display classical terrestrial magmatic zircon patterns (low LREE/HREE, pronounced Ce and Eu anomalies), although elevated LREE among some analyses may point to a degree of alteration. Analyses from this study that overlapped cracks or inclusions are excluded. (A) 4.0–3.8 Ga zircons; (B) 3.8–3.6 Ga zircons; (C) <3.6 Ga zircons. Data from other studies are taken from Bell and Harrison (2013), Cavosie et al. (2006), Crowley et al. (2005), and Peck et al. (2001).

younger zircon population is strikingly more radiogenic than would result from remelting of the Hadean crust alone. Origins in relatively evolved felsic magmas (as used for this projection) for most zircons are likely, based on other geochemical characteristics. These include the low Ti-in-zircon crystallization temperatures in the vast major-

ity of studied Jack Hills zircons (e.g., Watson and Harrison, 2005) and the granitoid-like inclusion assemblages (e.g., Mojzsis et al., 2001; Hopkins et al., 2008, 2010). The good fit of low-Lu/Hf, felsic-type reservoirs to many of the >3.7 Ga Jack Hills zircons is therefore unsurprising. Although the origin of some zircons could be explained

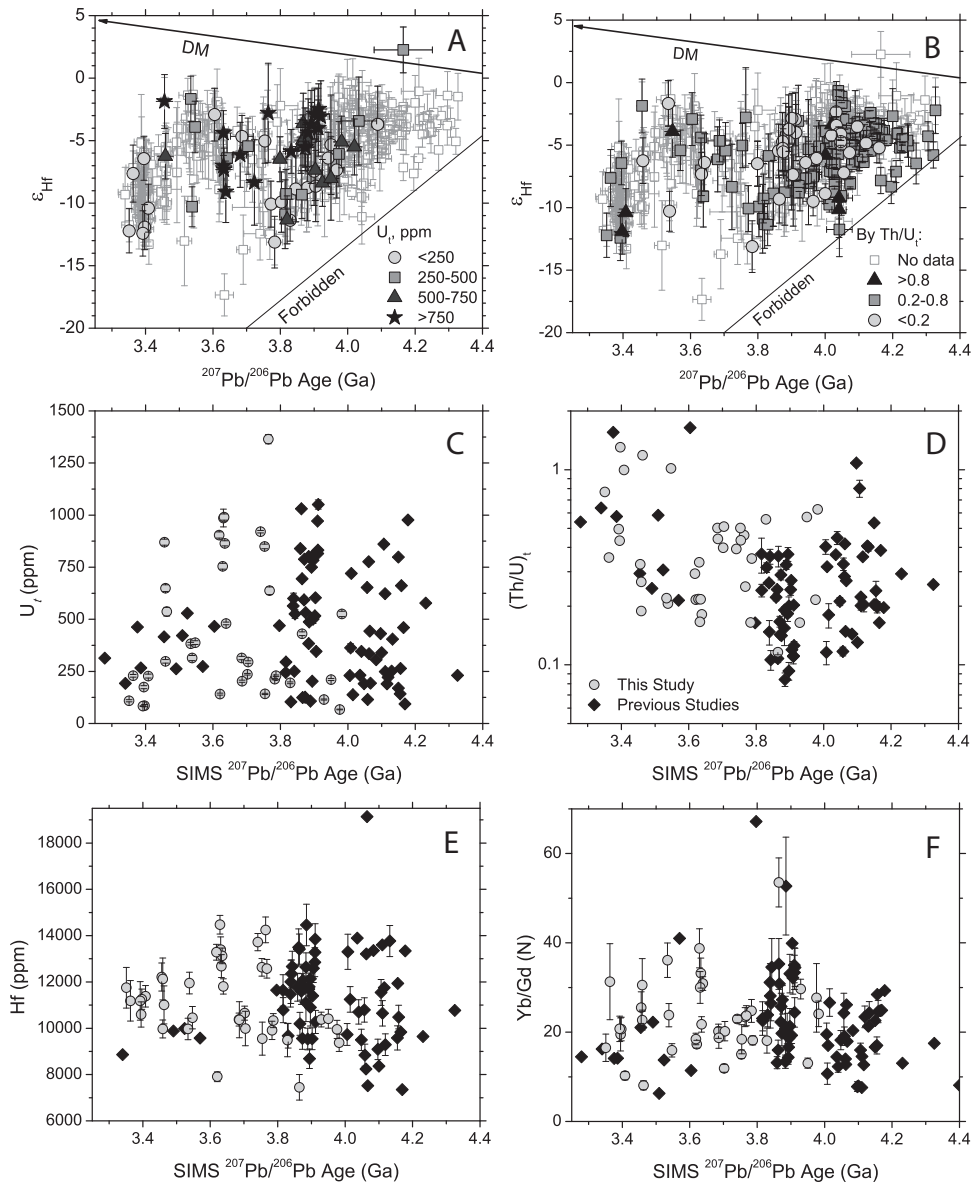


Fig. 7. Temporal variability of trace element contents and ratios among Jack Hills zircons along with their relationships to the Hf isotopic distribution. (A) ϵ_{Hf} vs. age in the Jack Hills zircons, grouped by U content. (B) ϵ_{Hf} vs. age in the Jack Hills zircons, grouped by Th/U. (C) U vs. age from this and previous studies. (D) Th/U vs. age from this and previous studies. (E) Hf vs. age from this and previous studies. (F) Yb/Gd vs. age from this and previous studies. U and Th/U are age-corrected for radioactive decay since zircon crystallization. Yb/Gd is normalized to the chondritic ratio. The legend for panels C–F is shown in panel D. References for data from other studies are in Fig. 6 caption. Ages plotted in panels C–F were measured by ion microprobe (denoted “SIMS”).

by the remelting of an ancient mafic reservoir (e.g., Kemp et al., 2010) mixed with younger material, the totality of the evidence suggests otherwise. Because melting of the mantle yields basalt (modeled in figures with $^{176}\text{Lu}/^{177}\text{Hf} \sim 0.022$), modeling the evolution of the early Jack Hills crust with only felsic reservoirs is unlikely to capture the entirety of its history. Any felsic reservoirs we invoke will have resulted from a more complicated earlier history involving mantle melting at some stage(s), but we demonstrate that some Hf isotopic compositions do require derivation from a low-Lu/Hf (i.e., felsic) reservoir.

The coincidence between the discontinuities in the Jack Hills Hf isotopic record, the truncation of oxygen isotope compositions at 3.8 Ga found by Bell and Harrison (2013), and subtle changes in the trace element composition of the zircons points to the Eoarchean and especially the interval 3.9–3.7 Ga as an important period of transition in the evolution of early Yilgarn Craton crust. However, in determining the significance of the Hf isotopic distribution in this time interval, it is important to assess the potential effects of ancient Pb loss on the Hf isotopic record.

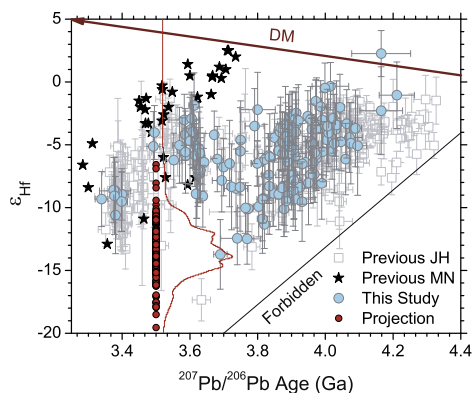


Fig. 8. Data from this and previous studies as labeled in Fig. 5. Red, closed circles are ≥ 3.7 Ga zircon Hf compositions projected forward to 3.5 Ga along an upper crust-type reservoir to simulate the expected ϵ_{Hf} range for the younger crust if it were only composed of felsic Hadean crust. The highly unradiogenic portion of the >3.7 Ga crust is not well-represented in the younger crust. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.1. Potential effects of Pb loss

Although recent Pb loss leads to U–Pb discordance with little change in the $^{207}\text{Pb}/^{206}\text{Pb}$ age, a zircon that has undergone ancient Pb loss may have a partially to fully reset $^{207}\text{Pb}/^{206}\text{Pb}$ age with little resulting U–Pb discordance in the present day, depending on the timing of loss. Incorrect age assignment to Hf isotope measurements, particularly in the case of sampling mixed age domains, can lead to large deviations in the calculated ϵ_{Hf} (e.g., as modeled by Harrison et al., 2005). Along the same lines, artificial lowering of the $^{207}\text{Pb}/^{206}\text{Pb}$ age through Pb loss leads to artificially lowered ϵ_{Hf} determinations (e.g., Vervoort, 2011; Kemp et al., 2012; Guitreau and Blichert-Toft, 2014; Fisher et al., 2014a). It is therefore important to assess the possibility that ancient Pb loss in some Jack Hills zircons has led to artificially unradiogenic ϵ_{Hf} , and we present several models of Pb loss in Hadean zircons in Fig. 9. Jack Hills zircons measured for Lu–Hf systematics in both this and previous studies (Amelin et al., 1999; Harrison et al., 2005, 2008; Kemp et al., 2010; Bell et al., 2011) have average $^{176}\text{Lu}/^{177}\text{Hf} \sim 0.0008$ with a standard deviation of 0.0006. We thus model Pb loss with an envelope of 2 ϵ_{Hf} -age trajectories corresponding to $^{176}\text{Lu}/^{177}\text{Hf}$ of 0.002 and zero. We also plot the evolution of a TTG-like (i.e., tonalite–trondjemite–granodiorite) reservoir ($^{176}\text{Lu}/^{177}\text{Hf} = 0.005$; Guitreau et al., 2012) for comparison.

Pb loss has been proposed as a mechanism to generate some of the unradiogenic ϵ_{Hf} signatures among Jack Hills zircons (Kemp et al., 2010; Guitreau and Blichert-Toft, 2014), with Kemp et al. (2010) proposing that unradiogenic signatures suggested as evidence for felsic Hadean crust (Harrison et al., 2005, 2008) were artifacts of Pb loss. Fig. 9A and B show modeled Pb loss from a 4.2 Ga zircon resulting from remelting of such a long-lived mafic reservoir and subjected to Pb loss at either 3.3 Ga (A; a known metamorphic event affecting the NGC; Myers, 1988) or 3.7 Ga

(B; age of oldest NGC units; Fletcher et al., 1988; Kinny et al., 1988). Fig. 9C shows that production of 4.3–4.0 Ga zircons within error of the initial solar system $^{176}\text{Hf}/^{177}\text{Hf}$ (Harrison et al., 2008) could only occur in an ultralow Lu/Hf reservoir or by Pb loss from the early products of such a reservoir (modeled here from the oldest possible hypothetical zircon at ca. 4.56 Ga).

Such Pb loss events could lower zircon age and ϵ_{Hf} without incurring significant U–Pb discordance and could theoretically produce many of the moderately unradiogenic zircons in the Hadean and Eoarchean Jack Hills record. However, the lowering of Hadean zircons' apparent $^{207}\text{Pb}/^{206}\text{Pb}$ age by several hundred million years, as required of the Pb loss model, would necessitate significant degrees of Pb loss (e.g., 60% or more for the most unradiogenic Eoarchean zircons). Although Pb loss events have been proposed for Jack Hills zircons during the Eoarchean (Trail et al., 2007a; Abbott et al., 2012; Bell and Harrison, 2013), such high degrees of Pb loss is likely to alter the internal texture of the zircons, especially the fine oscillatory zonation that characterizes most recognized igneous textures among Jack Hills zircons (e.g., Cavosie et al., 2005; Trail et al., 2007b). Zircons in our sample set that Bell and Harrison (2013) suggested have undergone significant Pb loss tend to be more radiogenic; they are shown by the high-U, low-Th/U group seen at ca. 3.9–3.8 Ga on Fig. 7A and B. Although some magmatically zoned Eoarchean zircons displaying several hundred million years' worth of ancient Pb loss were noted by Iizuka et al. (2009), these appear to be an unusual case and also were reported to display sector zonation instead of the oscillatory zonation seen among these zircons (which is more susceptible to blurring during alteration). Significant Pb loss may, however, be consistent with the patchy, altered textures seen in most studied 3.9–3.6 Ga zircons (Fig. 10). The latest clustering of highly unradiogenic, oscillatory zoned zircons at ca. 3.9 Ga points to this time as the last unambiguous magmatic event in this crustal source's history, with much of the 3.9–3.7 Ga record potentially although not certainly altered by Pb loss and artificially lowered ϵ_{Hf} .

4.2. Crustal reservoirs

Overall, the Jack Hills ϵ_{Hf} distribution is best explained by the mixing of several crustal reservoirs. We identify potential crustal components in Fig. 11 and Table 1, some of which appear to be absent from the zircon record after 4.0 and 3.7 Ga. The 3.7 Ga step is particularly dramatic and is observed just before the zircon population becomes markedly more radiogenic. Before this point, a heterogeneous distribution of mostly negative ϵ_{Hf} points to diverse crustal origins in the Hadean. Fig. 11 shows the projected evolution of both mafic and felsic materials formed ca. 4.56 Ga (i.e., the oldest possible age). The occurrence of zircons more unradiogenic than these evolution lines necessitates their origins in either lower-Lu/Hf materials or by the artificial lowering of apparent age due to Pb loss.

The most unradiogenic compositions identified by previous studies are within error of the solar system initial

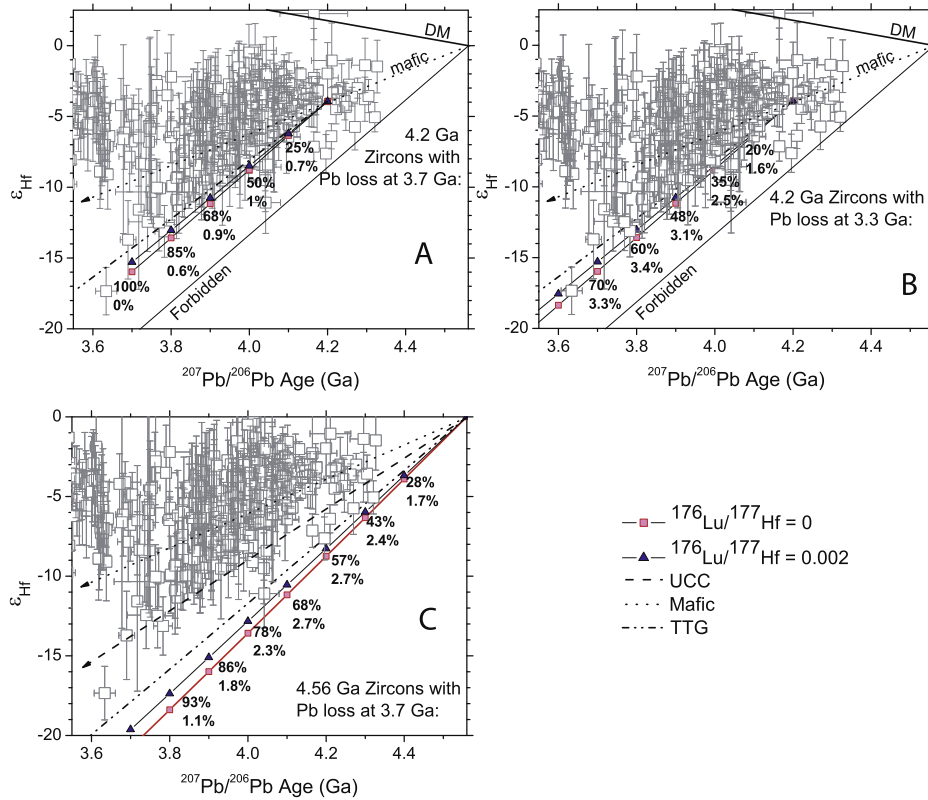


Fig. 9. Modeled potential explanations of the unradiogenic Hf isotopic compositions of Reservoir A and B zircons by Pb loss (or long-lived evolution of TTG-like reservoirs). In each plot, labels on the modeled points are written with the percent Pb loss on the top and the percent U–Pb discordance ($^{206}\text{Pb}/^{238}\text{U}$ vs. $^{207}\text{Pb}/^{206}\text{Pb}$ ages) for the grain today resulting from such a Pb loss event and assuming no subsequent Pb loss (a best-case scenario, given the modern-day Pb loss seen among most Jack Hills zircons). (A and B) Models for formation of Reservoir B grains by Pb loss from Reservoir C zircons originally crystallized at 4.2 Ga. (C) Models for formation of Reservoir A showing both TTG reservoir evolution and Pb loss trajectories.

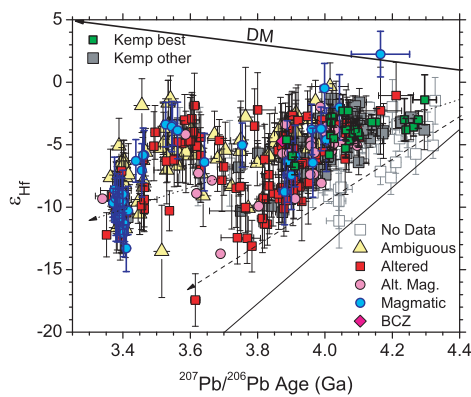


Fig. 10. Jack Hills detrital zircons in ϵ_{Hf} vs. age space, grouped by type of internal zonation (as shown by CL imaging), incorporating imaging data from several studies. Grains from this study, Bell et al. (2011), and Bell and Harrison (2013) are classified as either “altered,” “magmatic,” “altered magmatic” (original magmatic zoning still apparent despite alteration), ambiguous. “BCZ” grain displays broad concentric zones that might be primary broad oscillatory zonation or blurred, originally thinner oscillatory zonation. Grains from Kemp et al. (2010) are classified into their set of 16 “best” grains (characterized by unaltered oscillatory zonation, high degree of concordance, and magmatic Th/U) and all others.

$^{176}\text{Hf}/^{177}\text{Hf}$, with concordant U–Pb ages between 4.35 and 4.0 Ga (Harrison et al., 2005, 2008). They require the isolation of materials with Lu/Hf well below that for average modern upper continental crust by ~ 4.4 to 4.5 Ga (Harrison et al., 2005, 2008). We refer to this material as Reservoir A. A very early isolated TTG-like reservoir with $^{176}\text{Lu}/^{177}\text{Hf} \sim 0.005$ (based on TTG measurements by Guitreau et al., 2012) can account for most of these grains. An important alternative is the artificial lowering of some “Reservoir A” zircons’ apparent ages by ancient Pb loss, in which case the latest apparent extent of Reservoir A at ca. 4 Ga would not necessarily have geological significance.

The large group of zircons which are less radiogenic than the oldest possible (i.e., 4.56 Ga) mafic reservoir also demonstrate that part of the Hadean record requires an extended felsic history even apart from Reservoir A (Fig. 11). Zircons in this group which are too radiogenic to have been produced from Reservoir A alone we refer to as products of Reservoir B. Involvement of ancient or younger upper crust-type reservoirs, remelting of ancient basaltic crust to form more felsic reservoirs (at or before ca. 4.2 Ga for the youngest and most unradiogenic Reservoir B zircons), or significant mixing with Reservoir A could all explain the origin of this material. Reservoir B appears to evolve by internal reworking (and/or mixing

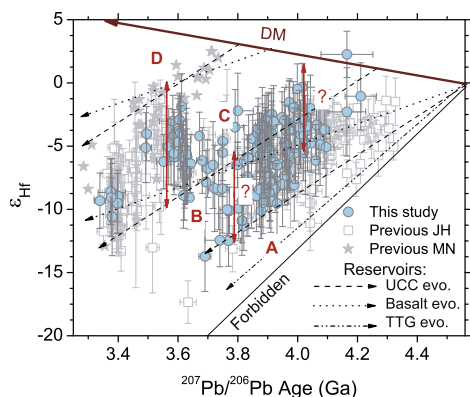


Fig. 11. The zircon record modeled by a mixture of hypothetical basaltic and felsic reservoirs (see Table 1). Reservoir A materials are within error of the forbidden region (alternatively consistent with an ancient very low-Lu/Hf reservoir, e.g., TTG). Reservoir B materials require significant ancient felsic history. The Hf systematics of Reservoirs C and D are explainable by a variety of compositions. Reservoirs A and B were lost to the zircon record during the Hadean or Eoarchean, whereas Reservoir C may be expressed among the youngest Jack Hills zircons and Reservoir D is post-Hadean (if extracted from our modeled DM, then ca. 3.9–3.8 Ga). “UCC”: upper continental crust-type reservoir with $^{176}\text{Lu}/^{177}\text{Hf} = 0.0125$ (Chauvel et al., 2014); basaltic reservoir $^{176}\text{Lu}/^{177}\text{Hf} = 0.02$; “TTG” = tonalite-trondjemite-granodiorite type reservoir with $^{176}\text{Lu}/^{177}\text{Hf} = 0.005$ (Guitreau et al., 2012).

between Reservoir A and more radiogenic materials) between their formation and 3.7 Ga, its last manifestation in the Jack Hills record. Ancient Pb loss during NGC magmatic and metamorphic events in the period 3.3–3.7 Ga (Fletcher et al., 1988) could produce many of the Reservoir B zircon signatures from originally more radiogenic zircons, but as discussed in Section 4.1 the youngest and most unradiogenic grains would require very high degrees of Pb loss for mid- to early-Archean events (see Fig. 9A, B) and based on zircon internal textures (Fig. 10) this process may not dominate the zircon record until after 3.9 Ga.

The origins of the more radiogenic >3.8 Ga zircons and the more unradiogenic <3.8 Ga zircons are significantly less constrained than Reservoirs A and B, and are consistent with both remelting of ancient mafic or more recent felsic crust (or mixtures between such materials). We label this Reservoir C. There is no discrete separation in Hf isotopic

composition between Reservoirs B and C, with the distinction between them being the theoretical consideration of their relationship with an ancient mafic reservoir. Finally, the more radiogenic <3.7 Ga crust represents mixing between Reservoir C and another reservoir extracted prior to 3.7 Ga (Reservoir D). Detrital zircons from Mt. Narryer, another location in the NGC, reveal the presence of juvenile crust at ~ 3.9 to 3.8 Ga (Nebel-Jacobsen et al., 2010). Given the coincidence between the juvenile nature of these zircons and the first appearance of more juvenile materials among younger Jack Hills zircons, it is likely that they sample crust derived from the same event.

Most of these reservoirs are consistent with sources identified in previous studies of Jack Hills zircons, with the exception of the highly unradiogenic Reservoir A, which is evident in Harrison et al. (2005, 2008) but not seen in Kemp et al. (2010). This is almost certainly due to the small number of >4 Ga zircons ($n = 44$ out of 68 total) analyzed by Kemp et al. (2010) relative to that of Harrison et al. (2005, 2008; $n = 220$; although $n = 60$ Hadean zircons for coupled Hf–Pb measurements in Harrison et al., 2008) combined with the very small fraction of the Hadean zircon population represented by Reservoir A (ca. 3%; 7% of Hadean Harrison et al., 2008 coupled Hf–Pb measurements). A sample of 44 Hadean zircons would be expected to produce only 1 member of Reservoir A, a minor discrepancy (although the 3 expected if considering only the Harrison et al., 2008 results may be of greater concern).

Models of Eoarchean crustal evolution for the Jack Hills source crust must account for the Hf isotopic discontinuity accompanying the loss of Reservoir B and appearance of Reservoir D at ca. 3.8–3.7 Ga. The last appearance at ca. 4.0 Ga of zircons from sources within error of the solar system initial $^{176}\text{Hf}/^{177}\text{Hf}$ (Harrison et al., 2008) may also be significant, although the concomitant shift toward more positive ϵ_{Hf} is not in evidence and the low number of Reservoir A samples make the timing of its disappearance uncertain. The fate of Reservoirs C and D is also an interesting question, requiring samples younger than the Jack Hills detrital zircons themselves.

A broad survey of detrital zircon Hf isotope compositions in modern Yilgarn Craton drainages (Griffin et al., 2004) identified several zircon populations consistent with the internal reworking of 3.8 Ga felsic crust until ~ 2.6 Ga (see Fig. 12), although they derive from other regions of

Table 1

A description of our posited crustal reservoirs in the Jack Hills detrital zircon record, including approximate formation and residence times. Mafic reservoirs are modeled with $^{176}\text{Lu}/^{177}\text{Hf} = 0.02$, and felsic reservoirs as the upper continental crust value of $^{176}\text{Lu}/^{177}\text{Hf} = 0.0125$ (Chauvel et al., 2014). The TTG value of 0.005 (Guitreau et al., 2012) is used for Reservoir A.

Reservoir	Formation time	$^{176}\text{Lu}/^{177}\text{Hf}$	Behavior	Persists to	Residence time
A	>4.4 Ga	≤ 0.005	Mixed with B or C?	~ 4 Ga	~ 0.5 Ga
B	Perhaps >4.4 Ga; perhaps younger additions	<0.02 ; may mix with A and C?	Mixed with A or C?	3.7 Ga	0.5–0.8 Ga
C	Perhaps >4.4 Ga; perhaps younger additions	Mafic? Felsic? A mixture?	<3.7 Ga: mixed with B? >3.7 Ga: mixed with D	≤ 3.3 Ga	≥ 0.9 Ga
D	3.9–3.8 Ga	Mafic? Felsic? A mixture?	Mixed with C	?	?

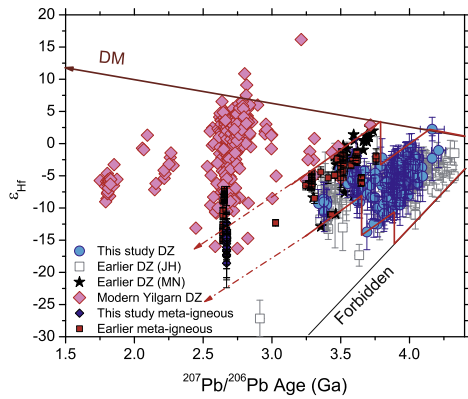


Fig. 12. Narryer Gneiss Complex (NGC) meta-igneous (Kemp et al., 2010; this study) and detrital zircons along with 1.5–3.8 Ga detrital zircons within 10% of U–Pb concordia from modern drainages in the Yilgarn Craton (Griffin et al., 2004). Unlabeled symbols are as on Fig. 5. Red arrows represent the ϵ_{Hf} , age evolution trajectories for 3.8 and 4.2 Ga UCC-like reservoirs (i.e., $^{176}\text{Lu}/^{177}\text{Hf} = 0.0125$), which bound the <3.7 Ga Jack Hills distribution. There is little evidence for felsic Hadean crustal involvement in the sources of <3 Ga zircons. “DZ” = “detrital zircons.” (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the Yilgarn Craton and their relationship with crust sampled by the detrital zircons is uncertain. The composition of the detrital zircon source is uncertain after 3.3 Ga due to the relatively few grains sampled for Lu–Hf, but zircons from 3.7 to 2.6 Ga NGC granitoids largely overlap the $^{176}\text{Hf}/^{177}\text{Hf}$ of the 3.7–3.3 Ga detrital population (Kemp et al., 2010). Zircons from the ca. 2.6 Ga granitoids in the NGC range between -5 and -20ϵ (Kemp et al., 2010; this study), overlapping with the wider Yilgarn Craton distribution, but demonstrating the persistence of some more ancient or more felsic crust within the NGC (Fig. 12) and

potentially representing the evolution of the detrital zircon source itself. The episodic loss of ancient crust in this terrane appears to show an increase in crustal residence times with decreasing age: Reservoir A forms by at least ca. 4.4 Ga (Harrison et al., 2005, 2008) and resides in the crust for up to 0.5 Ga; Hadean Reservoir B is lost at 3.9–3.7 Ga (with interpretations possibly complicated by Pb loss); potentially younger Hadean Reservoir C crust is expressed until at least 3.3 and perhaps 2.6 Ga. This trend may reflect increasing crustal stability in a cooling Earth.

4.3. Magma types and alteration history of the Jack Hills source

In Fig. 13A we present previous ion microprobe multi-collector oxygen isotope results for Jack Hills zircons (Cavosie et al., 2005; Trail et al., 2007a; Harrison et al., 2008; Bell et al., 2011; Bell and Harrison, 2013) vs. age, demonstrating the lack of concordant zircons both significantly above and below the mantle range after ca. 3.8 Ga (Bell and Harrison, 2013) with the exception of several grains at 3.6 Ga. Peck et al. (2001) present single collector ion microprobe oxygen isotope data, including 16 <3.6 Ga zircons with average $\delta^{18}\text{O}$ higher than the mantle value. However, uncertainties arising from the less reliable technique, smaller dataset, and lack of reproducibility of several high- $\delta^{18}\text{O}$ analyses on several of their Hadean grains in a later study (Cavosie et al., 2005) lead us to not include this dataset in our analysis. Fig. 13B shows $\delta^{18}\text{O}$ vs. ϵ_{Hf} for all samples that have been analyzed for both systems (this study; Harrison et al., 2008; Bell et al., 2011). High- $\delta^{18}\text{O}$ zircons are not well-represented in this dataset. The very low $\delta^{18}\text{O}$ seen among some 4.1–3.6 Ga grains are mostly represented among materials at or more radiogenic than -8ϵ , corresponding to Reservoir C among the >3.7 Ga sample set and Reservoirs C or D after 3.7 Ga.

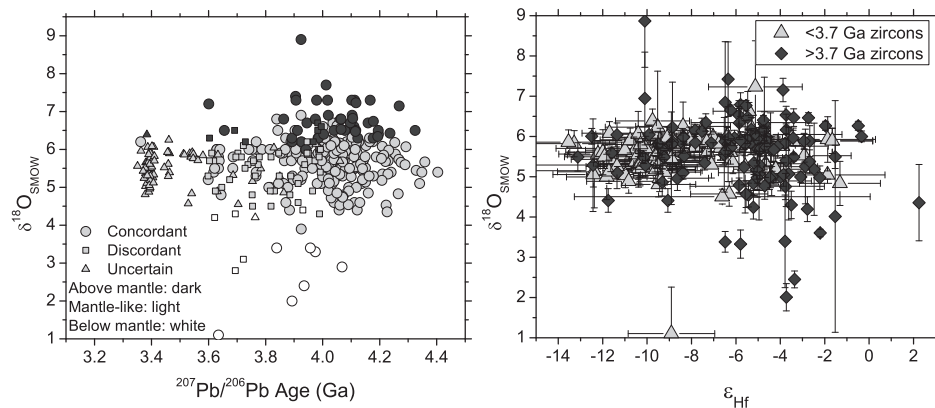


Fig. 13. Multicollector ion microprobe oxygen isotope analyses vs. age for the Jack Hills zircons from several studies (Cavosie et al., 2005; Harrison et al., 2008; Bell et al., 2011; Bell and Harrison, 2013; Trail et al., 2007a,b). Analyses are subdivided into three groups: those within error of the mantle range (defined here as 4.7–5.9‰ relative to SMOW), those significantly above this range, and those significantly below it. As pointed out by Bell and Harrison (2013), deviations from the mantle range become much rarer after 3.8 Ga. This figure omits the data of Peck et al. (2001) because this study was carried out using single collector ion microprobe. Their results include 32 analyses on 16 <3.6 Ga grains which were on average higher than the mantle range, in contradiction to the more numerous multicollector results shown here. This figure also omits several data from Trail et al. (2007b) at ca. 3.9 Ga and +10, along with 4 data reported by Bell and Harrison (2013) at (3.65 Ga, -6), (3.75 Ga, -2), and two at ca. (3.6 Ga, -1).

While none of these data were found by later imaging to have been collected on cracks (Bell and Harrison, 2013), lowered $\delta^{18}\text{O}$ has been noted in disturbed zircon regions in the Jack Hills (Trail et al., 2007a) and this may be further evidence of alteration of zircons in this interval. Indeed, between 3.8 and 3.6 Ga, low $\delta^{18}\text{O}$ is mostly associated with discordant zircon domains. The mantle-like $\delta^{18}\text{O}$ among most of the more unradiogenic zircons and also among the <3.7 Ga population suggests less disturbance (heterogeneous or low- $\delta^{18}\text{O}$) or less sedimentary input (high- $\delta^{18}\text{O}$).

The ca. 3.8 Ga period is also interesting in light of previous trace element studies. Bell and Harrison (2013) identified a group with distinctly low Ti, P, and LREE, high Hf, and coupled high U and low discordance at 3.91–3.84 Ga (“Group II”) which they attributed to recrystallization of older zircon in a metamorphic event, and its coincidence in time with other changes in the zircon record is intriguing. These samples are generally more radiogenic than other zircons during this time period (which are generally below $-8\ \epsilon$) and cluster at ca. 3.9–3.8 Ga and -2 to $-5\ \epsilon$ (high-U, low-Th/U cluster on Fig. 7A, B). Overall, trace elements show a great deal of similarity among zircons throughout the Jack Hills detrital record, but the period 3.9–3.6 Ga does display more common occurrences of high-U (>500 ppm) and -Hf (>12,500 ppm) chemistries. Higher U contents may contribute to the higher rate of discordance among 3.8–3.6 Ga zircons if the zircons did not undergo recrystallization. In addition to recrystallization, these chemical effects may also be imparted by magmatic evolution – for instance, zircon U and Hf concentrations and the Yb/Gd ratio generally rise and the Th/U falls as granitoid magmas evolve through fractional crystallization (e.g., Claiborne et al., 2010). Compared to other time periods, 3.8–3.7 Ga zircons have a restricted range in Th/U and Yb/Gd, lacking the higher Yb/Gd (>30) and lower Th/U (<0.4) common in the rest of the record. Although the similar, low average T^{zlm} of $\sim 700\ \text{°C}$ throughout much of the record (Bell and Harrison, 2013) does suggest mainly granitoid sources, changes to zircon chemistry after 3.8 Ga probably points to a shift in magmatic sources or style. Several trace element ratios (Th/U and Yb/Gd) may suggest these represent zircon growth in more juvenile melts, although high-U and -Hf grains may suggest otherwise.

This potential change in provenance at ca. 3.8 Ga based on trace element chemistry is corroborated by the similar timing of the last abundant high $\delta^{18}\text{O}$ occurrence and by the first appearance of more radiogenic crust in the Jack Hills Hf record (along with the juvenile signatures in contemporaneous Mt. Narryer detrital zircons; Nebel-Jacobsen et al., 2010). It is likely that these three signals are causally linked. The more evolved magmatic signal at ~ 3.63 Ga accompanied by a few zircons with high $\delta^{18}\text{O}$ probably points to more felsic sources involved in magma production, including supracrustal materials. Very low $\delta^{18}\text{O}$ and unusual trace element contents consistent with alteration in the period 3.9–3.6 Ga may point to an increased incidence of zircon alteration in this time period, but most of these effects seem to be expressed among the more radiogenic Reservoir C.

4.4. Tectonic implications

Although isotopic evidence for Hadean crust has been identified in several other locations around the planet (e.g., O’Neil et al., 2008, 2013; Iizuka et al., 2009), the abundance of >3.8 Ga materials preserved in the Jack Hills conglomerate and the extensive geochemical investigations of the zircons in this population have made it thus far a unique window into early Earth. Our potential Eoarchean crustal loss event is identifiable because of the extensive Hf isotopic analyses on Jack Hills zircons, given that Reservoirs A and B are a minority of the population. The loss of these unradiogenic materials from the zircon record may be key to understanding the (lack of) preservation of Hadean crust on the planet today – for instance, if the transitions seen in the Jack Hills detrital population during this time period represent a global event which destroyed or partially destroyed the pre-existing crust.

The discontinuity in the zircon Hf record at ~ 3.9 to 3.7 Ga is characterized by both the loss of Hadean felsic crust and the addition of juvenile crust. Based on the Mt. Narryer detrital zircons, this probably involved melting of the depleted mantle (Nebel-Jacobsen et al., 2010). The Manfred Complex in the extant NGC, which comprises the remnants of a ca. 3.7 Ga layered mafic intrusion (Fletcher et al., 1988), is another indication of juvenile input to the NGC crust at this time. Materials less radiogenic than a hypothetical primordial mafic reservoir are present until 3.9–3.7 Ga and absent thereafter, requiring either the loss or the significant dilution of this unradiogenic material in the region of active reworking. Given the introduction of more juvenile material into the NGC at ca. 3.9–3.8 Ga, the causes of this Hf isotopic discontinuity and the probable alteration of zircons during this time period (Bell and Harrison, 2013) may be linked. The shifts in zircon geochemistry after 3.8 Ga probably reflect a changing magmatic scenario, with the lack of high- $\delta^{18}\text{O}$ zircons reflecting less metasedimentary input into magmas. The lack of lower Th/U and higher Yb/Gd signatures in the period 3.8–3.7 Ga probably largely reflects zircon generation during reworking of this more juvenile material (although this interpretation is complicated by the higher incidence of high-U and -Hf zircons in this period).

The Eoarchean Hf isotopic record at Jack Hills suggests crustal evolution characterized by the simultaneous destruction of older felsic crust and formation of juvenile crust, and requires a mechanism(s) that can accomplish both. Although the nature of Eoarchean lithosphere is speculative, two potential scenarios for the Jack Hills zircon source are a subduction-like environment and meteoritic bombardment (Hopkins et al., 2010; Bell and Harrison, 2013). On the modern Earth, coupled crustal loss and gain are the major feature of Hf isotopic evolution in accretionary orogens (Collins et al., 2011). Subduction simultaneously recycles crust (e.g. Scholl and von Huene, 2010) while introducing juvenile melts into the crust. In the Phanerozoic, subduction-related orogens are often expressed in the zircon Lu/Hf record as an excursion toward more positive ϵ_{Hf} and the loss of highly unradiogenic materials (Collins et al., 2011), similar to the Eoarchean Jack Hills

record. At ~ 4.0 Ga, the last appearance of Reservoir A may signal a similar loss of crustal material, although the small number of samples representing Reservoir A renders interpretations about the timing of loss more uncertain. Subduction initiation is a poorly understood process, but either induced or spontaneous nucleation of subduction zones is likely to involve heating of the upper plate (Stern, 2004), consistent with other indicators of possible metamorphism and zircon disturbance.

Other mechanisms for producing this pattern of crustal evolution as reflected in the Hf isotopic distribution are difficult to find on present-day Earth. A large enough meteorite impact (or multiple impacts, given that this is the time period of the hypothesized Late Heavy Bombardment; Tera et al., 1974), obliterating part of the crust is an alternative explanation. Meteorite impacts may also homogenize the nearby crust (Darling and Moser, 2012), which for a small enough volume of Reservoir B might account for its disappearance if homogenized with a large proportion of more radiogenic material. Such an event would also have significant thermal effects on surrounding crust (Abramov and Mojzsis, 2009). Bell and Harrison (2013) interpreted the geochemistry of some ca. 3.9–3.8 Ga zircons as indicative of recrystallization, which were tentatively linked to the Late Heavy Bombardment. Both Abbott et al. (2012) and Trail et al. (2007a) found ca. 4.0–3.8 Ga rims on Hadean zircons, also consistent with heating at this time. The possibly disturbed $\delta^{18}\text{O}$ and clearly disturbed internal textures of many Eoarchean zircons are also consistent with metamorphic alteration of zircons in this interval. However, the lack of a clear higher- T^{Xln} signal among zircons in this time period, a characteristic of impact melt-grown zircons (Wielicki et al., 2012), led Bell and Harrison (2013) to conclude that possible Late Heavy Bombardment effects on the zircons were probably limited to far-field crustal heating rather than a nearby impact that might be expected to obliterate or homogenize much of the Jack Hills source crust. Sufficiently energetic distant impacts might be sufficient to heat or potentially melt crust in the Jack Hills zircon source, but it is unclear how they would accomplish crustal recycling or homogenization and juvenile melt addition at distance. While exogenic sources of heating and zircon disturbance are consistent with some features of Eoarchean Jack Hills zircons, it is not clear that they would account for the loss of Reservoir B. It is also unclear whether other, endogenic mechanisms of crust homogenization would lead to the apparent abrupt loss of Reservoir B rather than a gradual decline in its prominence in the zircon record.

Of these two scenarios, we consider the most likely mechanism to create this Eoarchean Hf isotopic discontinuity to be a destructive plate boundary process operating at ca. 3.9–3.7 Ga, destroying ancient crust while generating juvenile crust. The existence of subduction-like processes during the Eoarchean – and even their viability in the Neoproterozoic – is contentious (see Stern, 2007). The higher heat content of the early Earth, due to higher radioactivity and accretional energy, would undoubtedly have influenced mantle convection and its expression on the lithosphere. Models variously support (e.g., Davies, 2006; van Hunen and van den Berg, 2008; Korenaga, 2013) or contra-

vene (e.g., Davies, 1992; Gerya, 2013) the role of early subduction on a warmer Earth. Some models suggest instead the existence of quasi-subduction regimes involving shallow underthrusting of oceanic crust (Sizova et al., 2010) or only short episodes of intermittent subduction (e.g., O'Neill et al., 2007; van Hunen and van den Berg, 2008) during the Archean. Empirical evidence has been limited due to the sparse Archean and absent Hadean rock records, although thermobarometry of mineral inclusion assemblages in Jack Hills zircon have been interpreted as evidence for an underthrusting, subduction-like regime at 4.2–4.0 Ga (Hopkins et al., 2008, 2010). Hf isotopic evidence cannot distinguish among these subduction-like scenarios, beyond demonstrating crustal loss and gain. Evidence for disturbance of some Eoarchean Jack Hills zircons suggests metamorphic heating (mostly evident in the more radiogenic Reservoir C), but whether this was connected to the events surrounding crustal loss and addition at 3.9–3.7 Ga is uncertain. The loss of Hadean crust in two apparent steps at 4.0 and 3.7 Ga and the relatively short-lived period of juvenile input at ca. 3.8–3.7 Ga are suggestive of episodic rather than continuous crustal loss and juvenile addition in the NGC during the Eoarchean. However, since the Jack Hills zircons represent an unknown portion of the Archean crust, our data cannot distinguish between episodic, short-lived local crustal overturn – if subduction-like, then similar to many convergent boundaries today – and the continuous operation of such a mechanism during the Archean but in different regions around the planet.

5. CONCLUSIONS

The Lu–Hf systematics of Jack Hills zircons indicate an important transition in crustal evolution during the Eoarchean. Crust formed before 4 Ga evolved by internal recycling and mixing among various reservoirs (potentially obscured by ancient Pb loss among some zircons) until 3.9–3.8 Ga, when the appearance of more radiogenic materials (mirrored at the Mt. Narryer site, Nebel-Jacobsen et al., 2010) indicates new juvenile addition to the crust. Much of the Hadean crust was lost from the zircon record between 3.9 and 3.7 Ga, and <3.7 Ga zircon ϵ_{Hf} compositions are consistent with mixing between the remaining more radiogenic Hadean crust and new juvenile addition. The coincident loss of ancient crust and input of juvenile crust is plausibly but tentatively explained by a destructive plate-boundary process, suggesting the operation of some form of plate tectonics at least by the Eoarchean. The loss of ancient crust at ca. 4 Ga may point to a similar episode, but the small number of samples with which this ancient reservoir is represented limits confidence in the timing of its disappearance. Comparison of ancient Narryer Gneiss Complex zircons from detrital and igneous units with detrital zircons in the modern Yilgarn Craton reveals that Hadean crust was lost from the Yilgarn Craton in stepwise fashion, much of it within 0.5–0.8 Ga of Earth's formation. If these crustal loss events were more widespread than the Yilgarn Craton then they would have important implications for the preservation of Hadean crust during Archean and later tectonic events.

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APPENDIX A. SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.gca.2014.09.028>.

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