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# Early Archean crustal evolution of the Jack Hills Zircon source terrane inferred from Lu–Hf, $^{207}Pb/^{206}Pb$, and $\delta^{18}O$ systematics of Jack Hills zircons

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**Abstract**

Several lines of isotopic evidence – the most direct of which is from Hadean Jack Hills zircons – suggest a very early history of crust formation on Earth that began by about 4.5 Ga. To constrain both the fate of the reservoir for this crust and the nature of crustal evolution in the sediment source region of the Jack Hills, Western Australia, during the early Archean, we report here initial $^{176}Hf/^{177}Hf$ ratios and $\delta^{18}O$ systematics for <4 Ga Jack Hills zircons. In contrast to the significant number of Hadean zircons which contain highly unradiogenic $^{176}Hf/^{177}Hf$ requiring a near-zero Lu/Hf reservoir to have separated from the Earth's mantle by 4.5 Ga, Jack Hills zircons younger than ca. 3.6 Ga are more radiogenic than –13ε (CHUR) at 3.4 Ga in contrast to projected values at 3.4 Ga of –20ε for the unradiogenic Hadean reservoir indicating that some later juvenile addition to the crust is required to explain the more radiogenic younger zircons. The shift in the Lu–Hf systematics together with a narrow range of mostly mantle-like $\delta^{18}O$ values among the <3.6 Ga zircons (in contrast to the spread towards sedimentary $\delta^{18}O$ among Hadean samples) suggests a period of transition between 3.6 and 4 Ga in which the magmatic setting of zircon formation changed and the highly unradiogenic low Lu/Hf Hadean crust ceased to be available for intracrustal reworking. Constraining the nature of this transition provides important insights into the processes of crustal reworking and recycling of the Earth's Hadean crust as well as early Archean crustal evolution.


## 1. INTRODUCTION

The suggestion that the silicate Earth differentiated to form a continental-like crust during its first few hundred million years was, until recently, highly controversial. In contrast to the traditional paradigm of continental growth occurring largely since 4 Ga or later (e.g., Taylor and McLennan, 1985), isotopic evidence has recently emerged suggesting that enriched, possibly continental reservoirs developed substantially before that time during the so-called Hadean eon. For example, evidence for very early (>4.35–4.53 Ga) differentiation of the silicate earth has been inferred from $^{142}Nd/^{144}Nd$ variations in terrestrial samples (Caro et al., 2003) and the contrast between $^{142}Nd/^{144}Nd$ in chondrites and the silicate Earth (Boyet and Carlson, 2005), although this is also explicable in terms of a non-chondritic bulk silicate Earth (Dauphas and Chaussidon, 2011). Nd isotopic evidence for a region of enriched Hadean crust is inferred from $^{142}Nd/^{144}Nd$ data for amphibolites from the Nuvvuagittuq Greenstone Belt (O'Neill et al., 2008), but inconsistent with other data (e.g., Cates and Mojzsis, 2009).

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Independent evidence for early felsic crust comes from the $^{176}Hf/^{177}Hf$ compositions of detrital Jack Hills zircons, Narryer Gneiss Complex, Western Australia (Harrison et al., 2005, 2008; Blichert-Toft and Albarède, 2008). Zircons tend toward low Lu/Hf ratios, such that the ingrowth of $^{176}Hf$ from beta decay of $^{176}Lu$ is typically minimal. Thus zircons reflect, with minimal correction for radiogenic ingrowth, the initial $^{176}Hf/^{177}Hf$ ratio of their host rock. A significant number of Hadean Jack Hills zircons contain highly unradiogenic hafnium, suggestive of derivation from a near-zero Lu/Hf reservoir formed almost immediately following accretion of the planet (Harrison et al., 2005, 2008). In addition, the zircons record oxygen isotope and trace element signatures interpreted to imply the existence of surface water (e.g., Mojzsis et al., 2001) and water-saturated granitic melting conditions (Watson and Harrison, 2005) by 4.3 Ga, which are also suggestive of continental crust.

One interesting aspect of the Nd and Hf isotopic evidence for early crust formation is that the inferred early enriched reservoir(s) has apparently not been significantly reworked and sampled by younger rocks. Also, only very small quantities of Hadean materials bearing this signature survive. It is likely that this early enriched crust has been destroyed well before the present day, but examination of the <4 Ga portion of the Jack Hills detrital zircon population should shed light on the extent and longevity of this reservoir in the Jack Hills source terrane(s) during the early Archean.

Although the vast majority of Lu–Hf isotopic analyses (Harrison et al., 2005, 2008; Blichert-Toft and Albarède, 2008) have concentrated on the >4 Ga Jack Hills zircons, the detrital population ranges in age from ~3 to nearly 4.4 Ga (Holden et al., 2009). In this paper, we present the largest dataset to date (130 analyses) of Lu–Hf measurements of <4 Ga Jack Hills zircons and use this record to investigate how late into Earth's history the early low Lu/Hf reservoir is evident in the Jack Hills detrital population. We also evaluate the relative importance of crustal growth vs. reworking over the ca. 1 billion year detrital zircon Lu–Hf isotope record in an effort to constrain the chemical and tectonic evolution of the Yilgarn Craton.

## 2. GEOLOGIC SETTING

The Jack Hills are located in the northwestern corner of the Yilgarn Craton, Western Australia, within the Narryer Gneiss Complex (Fig. 1). The Narryer complex consists of Early to Late Archean orthogneisses and several metasedimentary associations, some of which host >4 Ga zircons. The relationship between the metasediments and orthogneisses in the Jack Hills and throughout the Narryer terrane is uncertain. The present contacts between the crystalline and metasedimentary units are thought to be tectonic rather than depositional (Nutman et al., 1991; Spaggiari et al., 2007). Despite broad agreements between the ages of younger detrital zircons in Jack Hills metasediments and the ages of Narryer gneisses (Nutman et al., 1991; Maas and McCulloch, 1992), whole-rock REE geochemistry (Maas and McCulloch, 1992) of the metasediments and more detailed comparison of the age distributions

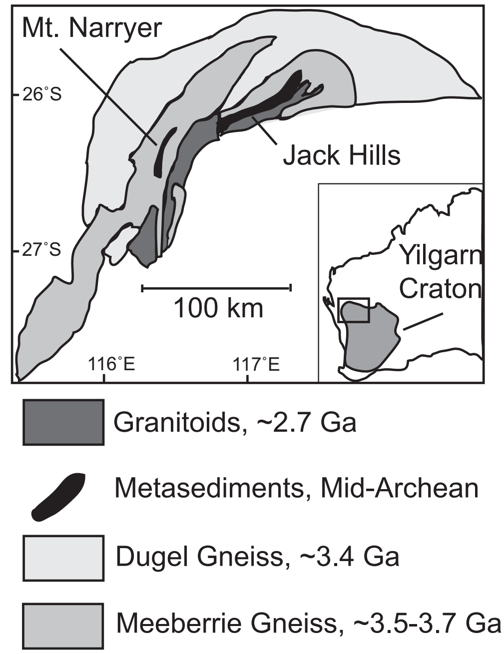


Fig. 1. Geologic sketch map of the Narryer Gneiss Complex, after Myers (1988a). Location of Jack Hills and Mt. Narryer indicated.

(Maas and McCulloch, 1992; Amelin, 1998) suggest that the presently exposed Narryer gneisses are distinct from the source of Archean zircons in the Jack Hills population. It is therefore best to consider the detrital zircon and Narryer gneiss record separately for the purpose of constraining crustal evolution in the region.

The largest concentrations of Hadean grains are found within apparently fluvial (Williams and Myers, 1987) pebble metaconglomerates likely deposited at ~3 Ga (Spaggiari et al., 2007). U–Pb age surveys of the population tend to reveal maxima in the age distribution at 3.4 and 4.1 Ga, the younger being much more prominent, and a gap (or minimum) in the distribution between about 3.6 and 3.8 Ga (Kober et al., 1989; Amelin, 1998; Crowley et al., 2005; Holden et al., 2009). Automated SHRIMP age analysis of >100,000 zircons has revealed that concordant Hadean (>4 Ga) grains make up approximately 5% of the metaconglomerate population (Holden et al., 2009).

Observable magmatic rocks in the Narryer Gneiss Complex span ages from 2.6 to 3.73 Ga (Nutman et al., 1991; Spaggiari et al., 2007) (Fig. 1). A widespread unit, the Meeberrie gneiss, contains protoliths ranging from 3.73 Ga tonalites to 3.6 Ga granitoids (Nutman et al., 1991) with a prominent monzogranitic unit at 3.68 Ga (Myers, 1988a) (Fig. 1). The Manfred gabbro-anorthosite complex at 3.73 Ga is included in several of the younger gneisses (Myers, 1988a,b). The 3.44–3.49 Ga tonalitic Eurada gneisses and the ~3.38 Ga syeno- to monzogranitic Dugel gneisses occupy the time period most heavily sampled by detrital zircons (Myers, 1988a; Nutman et al., 1991). Several granites and pegmatites dating from ~3.0 to 3.3 Ga are also found within the Narryer Complex (Bennett et al., 1990). Finally, 2.6–2.7 Ga granites intrude the region concomitantly with widespread metamorphism, faulting, and folding (Myers, 1988a; Nutman et al., 1991).

Previous work on crustal evolution of the Narryer Terrane focused on the Sm–Nd and U–Pb compositions of exposed orthogneisses. Maas and McCulloch (1992) recalculated $T_{DM}$ from earlier work (DeLaeter et al., 1985) on the Meeberrie, Eurada and Dugel gneisses and 3.0–3.3 Ga granitoids. The tonalitic portions of the Meeberrie appear to be sourced from relatively juvenile materials, whereas the monzogranitic younger Meeberrie, Dugel, and 3.3 Ga granitoids appear to be sourced largely from older (but <4 Ga) reworked crust with little juvenile input (Maas and McCulloch, 1992). The Eurada gneiss and the 3.0 Ga granitoids appear to be formed from the reworking of distinct sources extracted from the depleted mantle more recently than the Meeberrie (Maas and McCulloch, 1992). The high apparent source μ of the 3.73 Ga Manfred Complex may suggest a substantial component of >4 Ga crust (Fletcher et al., 1988).

Despite the unclear relationship between the sources for Jack Hills detrital zircons and the known geology of the Narryer Gneiss Complex, it is clear that the isotopic characteristics of some Archean Narryer gneisses record evidence for crustal evolution since Hadean times. A large dataset of Lu–Hf data for the younger detrital zircons may provide a parallel, but more detailed, account of crustal evolution in the region for the early and middle Archean.

## 3. METHODS

We sampled the Jack Hills zircon distribution with the goal of obtaining a more complete picture of the age, internal textures, and isotope geochemistry among the younger detrital population. We selected an epoxy mount (RSES51) from the study of Holden et al. (2009) containing approximately 255 randomly picked zircons from the Jack Hills detrital population at the discovery site (Compston and Pidgeon, 1986) from the large collection of Jack Hills grains analyzed at the Australian National University. The dating protocol of Holden et al. (2009) employs automated sampling of each grain for several seconds to establish an estimate of $^{207}Pb/^{206}Pb$. Full U–Pb analysis was done only for grains with apparent $^{207}Pb/^{206}Pb$ ages >3.95 Ga. Therefore most grains employed in this study were not precisely dated. One hundred and twenty nine grains on mount RSES51 were analyzed for both Lu–Hf isotopes and $^{207}Pb/^{206}Pb$ age, with the only further selection being for grains with a large enough uncracked surface area to be used for laser ablation Lu–Hf analyses. This approach, we believe, provides an essentially random sample of that portion of the zircon population large enough for laser ablation sampling.

### 3.1. Imaging for textures

Imaging was mainly accomplished using a scanning electron microscope. A combination of BSE imaging and EDAX were used to identify mineral inclusions (several of which were further studied by electron microprobe for stoichiometry) within the zircons. Cathodoluminescence (CL) imaging was used to elucidate internal structures and zoning. Zircons were sorted into zoning-style categories following the suggestions of Corfu et al. (2003). Categories included (1) oscillatory zoning, (2) core/rim geometry, (3) patchy or irregular zoning, (4) sector zoning, and (5) no (or too faint to be distinguishable) zoning. Inhomogeneous zircons with uncertain patterns were sorted into the "patchy/irregular" category, which became a catchall for ambiguous grains. Due to the possibility for zoning patterns to be rendered uncertain by grain fragmentation during sedimentary cycling, the patchy/irregular category is most likely over-represented.

### 3.2. Coupled Hf–Pb measurements

We measured Lu–Hf systematics and $^{207}Pb/^{206}Pb$ ages for the zircons by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS), employing ThermoFinnigan NEPTUNE MC-ICPMS and associated lasers at the Australian National University and UCLA. A combination of magnet switching and zoom optics switching were used to switch between Lu–Hf and Pb isotopic measurements, adapted for the NEPTUNE from the procedure of Woodhead et al. (2004). This method gives us the potential to deconvolve the results of the semi continuous analyses into definable Hf–Pb domains, increasing the accuracy of the interpretations. Though we do not sample the Lu–Hf and Pb mass sets simultaneously as in the work of, e.g., Xie et al. (2008) (who employ a laser ablation line leading to two separate mass spectrometers), we are able to determine coherent age-Hf domains by bracketing our Hf analyses with Pb analyses showing the same $^{207}Pb/^{206}Pb$ age. One disadvantage of the approach is the lack of information regarding U–Pb discordance. Despite its limitations, however, this combined Hf–Pb approach is more useful for correlating Lu–Hf systematics with an applicable age than the more traditional in situ analysis of U–Pb and Lu–Hf information on separate volumes of material. Despite our fairly large laser spot size (80–100 μm) which runs the risk of overlapping multiple age domains in the horizontal direction, our in situ sampling and ability to detect age domains in the vertical direction gives us a significant advantage also over solution U–Pb and Lu–Hf methods.

We identified separate Hf–Pb age domains on the basis of the $^{207}Pb/^{206}Pb$ ratio, requiring the presence of a plateau in $^{207}Pb/^{206}Pb$ ages for at least three Pb counting cycles. For age domains in the interior of crystals, only Lu–Yb–Hf data (two back-to-back cycles) bracketed by consistent Pb data (three cycles) were considered. Using this method we identified 130 separate Hf–Pb domains among the grains analyzed. Analyses were accomplished during two sessions: Session One took place at ANU in September 2007 and Session Two at UCLA in April 2009. Background subtraction was accomplished online, and all further data reduction was done offline.

#### 3.2.1. *Session One*

Fifty-nine grains (totaling 61 Hf–Pb domains) were analyzed using a 193 nm laser with a circular spot 80 μm in diameter. Ten seconds of counting on the Yb, Lu, Hf mass set (i.e., 171, 173–179, 181) alternated with 3 s of counting on the Pb mass set, with 4 s of magnet settling time between each mass set. A total of 130 s counting time was given to each analysis. See Harrison et al. (2005, 2008) for details of the analytical methods.

### 3.2.2. Session Two

Session Two took place over three days in April of 2009 at UCLA. Statistics related to the accuracy of the peak stripping and mass fractionation corrections were calculated on a day-to-day basis. Sixty-six grains (totaling 69 Hf–Pb domains) were analyzed by laser ablation using an Excistar ArF excimer laser with a circular spot 100 μm in diameter. Eleven seconds of counting on the Yb, Lu, and Hf mass set alternated with 5 s of counting on the Pb mass set (204, 206, 207, 208), and the first 2 s of counting on each mass set were disregarded during data reduction in order to ensure a two-second settling time for the magnet. This leaves 9 s counting on the Yb, Lu, and Hf masses alternating with 3 s counting on Pb considered for the final analysis. A maximum of 160 s (120 used for data) was given to each analysis. Blanks were run before each analysis in this session.

### 3.2.3. Interference and mass fractionation correction

Despite its advantages (e.g., lesser destructivity to the sample), sampling of Lu and Hf in zircon by laser ablation rather than in solution precludes chemical removal of isobaric interferences. Yb, which occurs in zircon at the trace level (Finch and Hanchar, 2003), presents interferences with Hf at masses 174 and 176. Isotopes of Lu and Hf at mass 176, the relevant isotopes involved in the Lu–Hf decay system, also mutually interfere. Analysis by laser ablation thus necessitates peak-stripping to deconvolve the signals at mass 174 and 176. Details of the Hf isotopic analysis and peak stripping procedures for isobaric interference of Yb and Lu on Hf isotopes are given in Harrison et al. (2005, 2008) and Taylor et al. (2008). We tested the accuracy of the peak stripping and fractionation corrections (normalized to ($^{179}$Hf/$^{177}$Hf = 0.7325) by comparing the corrected $^{174}$Hf/$^{177}$Hf and $^{178}$Hf/$^{177}$Hf values for each analysis against the accepted values (0.008657 ± 5 and 1.46735 ± 16 respectively, ±2σ) of Thirlwall and Anczkiewicz (2004) (Fig. 2). Our corrected values for $^{174}$Hf/$^{177}$Hf, which is highly sensitive to the veracity of the 174Yb stripping, agree well on average with the reference value (Fig. 2c and d).

In Session 1, four analyses out of 102 (~4%) fell more than 3σ from the reference value. In Session 2, four

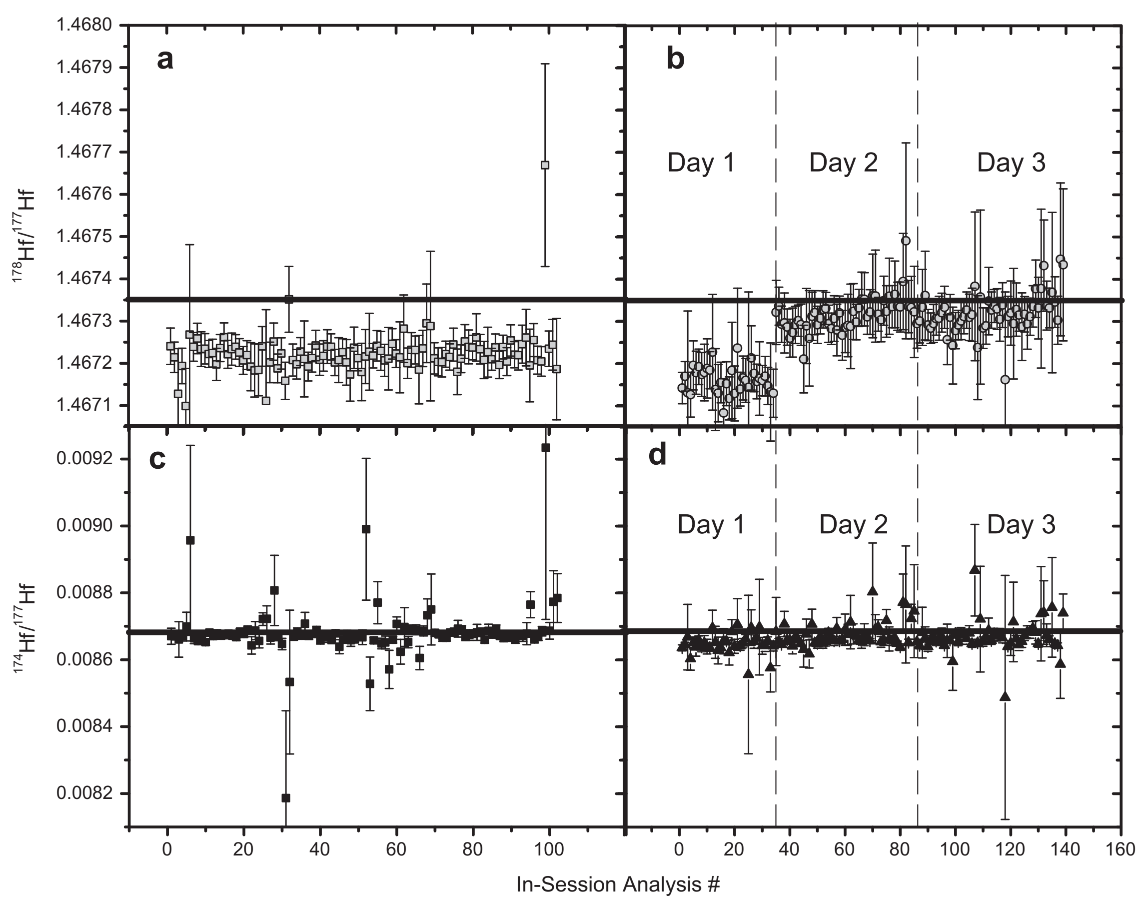


Fig. 2. Hafnium isotopic results for two uniform ratios in nature. (A and B) $^{174}$Hf/$^{177}$Hf results after mass fractionation correction for both analysis sessions. (C and D) $^{178}$Hf/$^{177}$Hf results after mass fractionation correction for both analysis sessions. Results for Session One and Day One of Session Two are uniformly low compared to the accepted value (Thirlwall and Anczkiewicz, 2004). Deviation from the accepted value for $^{178}$Hf/$^{177}$Hf does not appear to correlate with either deviation from the reference value for $^{174}$Hf/$^{177}$Hf or from the standards' accepted values for $^{176}$Hf/$^{177}$Hf.

analyses out of 139 (~3%) fell more than 3σ from the reference value: one analysis on Day 1 ($N = 34$), one analysis on Day 2 ($N = 50$), and two analyses on Day 3 ($N = 55$). Our corrected values for $^{178}Hf/^{177}Hf$ are uniformly low by 0.85ε for Session 1 and by 1.29ε for Day 1 of Session 2, which occurred one week before days 2 and 3 of Session 2. During the ANU session, nine out of 102 analyses (including both unknowns and standards) fell more than 3σ from the reference value (Fig. 2a and b). Statistics for the peak-stripping accuracy for the UCLA session were calculated on a day-by-day basis.

This higher than expected incidence of analyses inconsistent with standard values for the isotope ratios is balanced by fractionation- and interference-corrected $^{176}Hf/^{177}Hf$ values for the AS3 and Mud Tank standard zircons that agree well with the reference values of Woodhead and Hergt (2005) (see Fig. 3). In both sessions, mass-discrimination corrections were interpolated from the standard values' offsets and applied to the unknowns bracketed by each set of standards. The standards AS3, Temora-2, and Mudtank were used for calculating $^{176}Hf/^{177}Hf$ offsets; only AS3 and Temora-2 were used for calculating $^{176}Lu/^{177}Hf$ owing to Mudtank's very low Lu/Hf ratio compared to our unknowns (nearly two orders of magnitude below Temora-2 and AS3; Woodhead and Hergt, 2005). The results compare well between the two sessions (see Fig. 4), lending confidence to our conclusion that the data reduction and correction procedures have yielded accurate results. In addition to the standard zircons, the NIST610 standard glass was used as a secondary $^{207}Pb/^{206}Pb$ standard. $^{207}Pb/^{206}Pb$ of standards was sensitive to the $^{207}Pb$ average signal, becoming unreliable at a threshold of 10 millivolts (Fig. 5). The standards with $^{207}Pb$ signals above the threshold fell within two percent of their known values, whereas standards with lower signals were considerably more inaccurate (Fig. 5). Only standards falling above the threshold were considered; all unknowns fell above the threshold as well. Only NIST610 and AS3 standards fell above the threshold and were subsequently used for comparing to unknowns. This result is unsurprising: the Mudtank and Temora-2 zircon standards are much younger than AS3 (732 and 417 Ma compared to 1099 Ma, respectively) and they consequently have lower Pb contents. The Mudtank and Temora-2 Pb data reflect the physical limitations of the technique at low Pb signal – notably lower signal than any of our unknowns or than the relatively Pb-rich AS3 and NIST610 standards. Because of the good agreement of the high-signal standards with their accepted $^{207}Pb/^{206}Pb$ ages, we did not apply a mass fractionation correction to any of our Pb data. We analyzed at mass 204 and 208, and found no appreciable $^{204}Pb$ in our samples. $^{208}Pb/^{206}Pb$ values did not display any trend indicative of common Pb contamination (see e.g., Blichert-Toft and Albarède, 2008). Given the lack of noticeable common Pb contamination among our zircons, we did not apply a common Pb correction to the data.

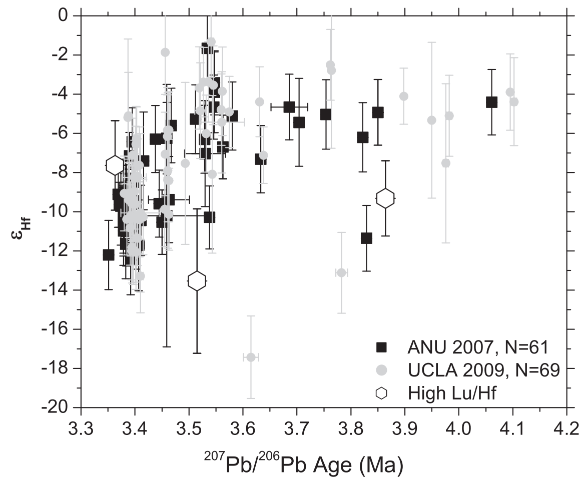


Fig. 4. Comparison of results from ANU and UCLA Hf–Pb sessions in $\varepsilon_{Hf}$ vs. age space. One high Lu/Hf measurement at 2.88 Ga, −28ε was omitted for space purposes.

Fractionation – and interference-corrected $^{176}Lu/^{177}Hf$ for the standard zircons AS3 and Temora-2 compare well with the reference values of Woodhead and Hergt (2005). In-day averages for $^{176}Lu/^{177}Hf$, $^{176}Hf/^{177}Hf$, and $^{207}Pb/$

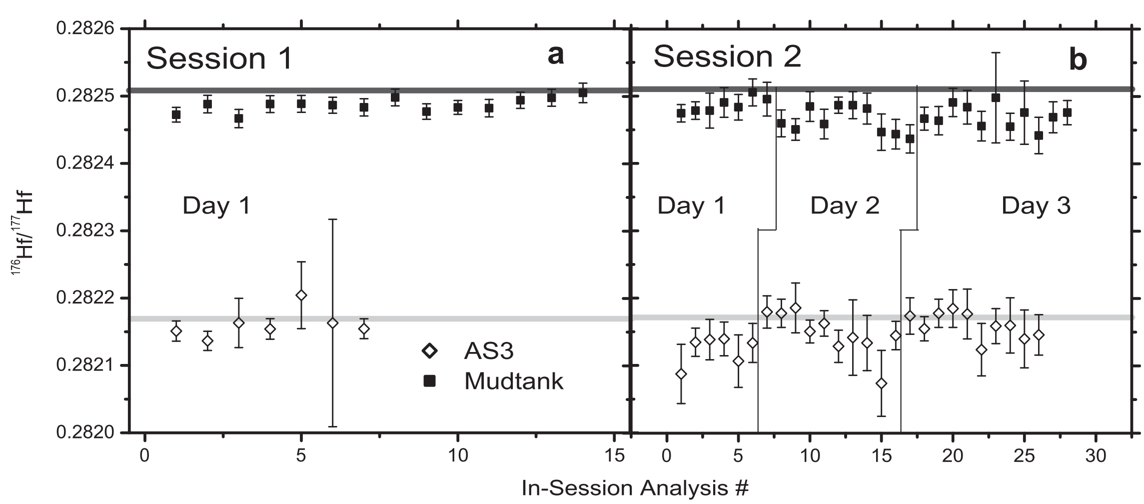


Fig. 3. $^{176}Hf/^{177}Hf$ results for the standard zircons AS3 and Mudtank, for which analytical conditions are closest to the unknowns. (a) Session One data were collected in September 2007 at ANU; (b) Session Two data were collected in April 2009 at UCLA.

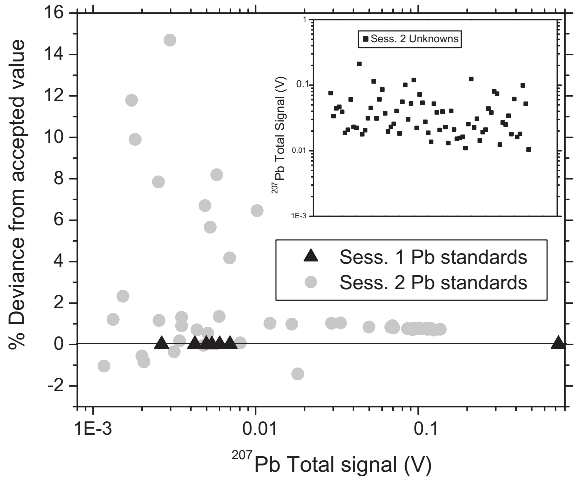


Fig. 5. All Pb standard analyses in % deviance (from expected value) vs. total $^{207}$Pb signal (V) space. No standards were omitted for Session 1, but Session 2 standards below 0.01 V were omitted. Inset: Session 2 unknowns; all are >0.01 V.

$^{206}$Pb of standard zircons are tabulated together with the accepted values in Table 1. Uncertainties are based both on internal uncertainty and the reproducibility of the relevant standards for each quantity.

All $\varepsilon_{Hf}$ values are calculated using the CHUR values of Bouvier et al. (2008), and a decay constant for $^{176}$Lu of $1.867 \times 10^{-11}$ yr$^{-1}$ (Scherer et al., 2004; Soderlund et al., 2004; Amelin, 2005). CHUR was likely not a physical reservoir for long in the early Archean, and so we adopt it only as a well-defined reference value. $\varepsilon_{Hf}$ uncertainties include uncertainties in $^{176}$Hf/$^{177}$Hf, $^{176}$Lu/$^{177}$Hf, contemporaneous CHUR values of these ratios, and uncertainty in the $^{176}$Lu decay constant using the error propagation formulae of Harrison et al. (2008). Lu–Yb–Hf/Pb data for all standards and unknowns are shown in Electronic annex EA-1.

### 3.3. Oxygen isotopes

Analyses of oxygen isotopes in 85 selected grains were made using the CAMECA *ims*1270 ion microprobe at UCLA in March of 2009. A spot size of ~20 µm and primary beam current of ca. 1.5 nA were used (see Trail et al., 2007 for further analytical details). The AS3 zircon standard ($\delta^{18}O_{SMOW} = 5.34$‰; Trail et al., 2007) was used for correction of raw $^{18}$O/$^{16}$O ratios. Oxygen isotope measurements made on grains for which multiple Hf–Pb domains were found are attributed to the Hf-Pb domain closest to the surface of the grain, where the oxygen measurements were made. Data for all oxygen standards and unknowns are shown in EA-1.

### 3.4. Ti thermometry

Ti concentrations for Ti-in-zircon thermometry (Watson and Harrison, 2005) on selected grains were made using the CAMECA *ims*1270 ion microprobe at UCLA in March and August of 2009. Details of the temperature-calculating procedure are given in Watson and Harrison (2005) and analytical conditions for Ti measurement in Harrison and Schmitt (2007). We estimated uncertainties in our temperature calculations by quadratic addition of the roughly 10 °C uncertainty from the model of Watson and Harrison (2005) to uncertainty in our Ti concentrations. In calculating apparent $T^{xlln}$ we assume that the $TiO_2$ and $SiO_2$ activity of the melt were 1 during zircon growth. The ubiquity of quartz among mineral inclusions (see Section 4.1) provides support for the latter assumption. Crystallization temperatures calculated for grains for which multiple Hf-age domains were found are attributed to the Hf-Pb domain closest to the surface of the grain, where the Ti measurements were made.

## 4. RESULTS

### 4.1. Grain textures and zoning

The zircons display several zoning styles under cathodoluminescence imaging. Whereas 57 grains show no zoning, 32 show oscillatory zoning and 2 of the zircons show sector zoning. Chaotic or patchy zoning is evident in 50 grains. Zircons with no zoning tend to be dark-to-medium in CL brightness. Several 3.4–3.7 Ga grains have a well-defined rim-and-core geometry evident under CL. Obvious igneous (oscillatory or sector) zoning and pronounced rim/core

Table 1
In-day averages for $^{176}$Lu/$^{177}$Hf and $^{176}$Hf/$^{177}$Hf of the standard zircons AS3, Temora-2 and Mud Tank. The reference values of Woodhead and Hergt (2005) shown for comparison. AS3 is called "FC-1" by Woodhead and Hergt. Italics indicate the zircon was not used as a standard for the relevant quantity.

| Quantity | Accepted | Session 1 | 2σ | Session 2 d. 1 | 2σ | Session 2 d. 2 | 2σ | Session 2 d. 3 | 2σ |
|---|---|---|---|---|---|---|---|---|---|
| *Temora-2* | | | | | | | | | |
| $^{176}$Hf/$^{177}$Hf | 0.282686 | 0.282696 | 5.4e−5 | 0.282631 | 5e−6 | 0.282625 | 7.1e−5 | 0.282574 | 1.5e−4 |
| $^{176}$Lu/$^{177}$Hf | 0.00109 | 0.001059 | 8.1e−4 | 0.001055 | 6.8e−4 | 0.000932 | 4.5e−4 | 0.001039 | 6.4e−4 |
| *Mud Tank* | | | | | | | | | |
| $^{176}$Hf/$^{177}$Hf | 0.282507 | 0.282486 | 2.1e−5 | 0.282487 | 2.2e−5 | 0.282464 | 3.9e−5 | 0.282471 | 3.3e−5 |
| $^{176}$Lu/$^{177}$Hf[a] | 0.000042 | 0.000049 | 2.4e−6 | 6.08e−6 | 1.0e−6 | 6.54e−6 | 1.3e−6 | 1.26e−5 | 1.5e−5 |
| *AS3* | | | | | | | | | |
| $^{176}$Hf/$^{177}$Hf | 0.282184 | 0.282161 | 4.2e−5 | 0.282124 | 4.3e−5 | 0.282148 | 6.6e−5 | 0.282160 | 3.9e−5 |
| $^{176}$Lu/$^{177}$Hf | 0.001262 | 0.001178 | 5.8e−4 | 0.000931 | 1.9e−4 | 0.001292 | 8.5e−4 | 0.001136 | 4.2e−4 |

[a] Not used for corrections.

geometry are rare in grains older than 3.6 Ga. Around 10% of zircons contain identifiable mineral inclusions at the surface, among which quartz and K-feldspar dominate. Quartz, K-feldspar, muscovite and biotite are present in 3.4 Ga zircons while quartz is found in the 3.5–3.75 Ga zircons. One ilmenite inclusion was found in a 3.75 Ga zircon. All CL and inclusion information are given in Electronic annex EA-2.

### 4.2. Coupled Hf–Pb analyses

Results from the two analysis sessions agree well in both Lu–Hf systematics and ages despite their collection in different laboratories (Fig. 4), highlighting the accuracy of the peak-stripping protocol. Nearly all of the 130 Hf–Pb domain data points fall at realistic values of $^{176}Lu/^{177}Hf$ for zircon (<~0.001). Four analyses fall above 0.002 in $^{176}Lu/^{177}Hf$, which may indicate inaccuracies in the peak-stripping procedure for these few analyses (4/130; ~3%). These analyses are marked in all figures. One of these suspect analyses has a $^{207}Pb/^{206}Pb$ age of ~2.9 Ma and lies at ~−28ε. It is noticeably younger than the vast majority of zircons found in previous studies of the Jack Hills; this apparent age probably reflects ancient Pb loss. Its patchy zonation may also suggest alteration. Though its great distance from DMM in $\varepsilon_{Hf}$ space may suggest a highly unradiogenic source, its high Lu/Hf renders further interpretation of the data point suspect. We do not include it in most of our figures. Ages resemble the distribution shown in previous studies (e.g., Crowley et al., 2005) with a large age peak ca. 3.4 Ga and minor peaks ca. 3.45 and 3.55 Ga (Fig. 6). Fig. 7 displays the same data with the Hf–Pb domains grouped by the zonation style of their zircons.

We refer to the solar system initial $^{176}Hf/^{177}Hf$ ratio, below which no solar system samples should plot, as the Primordial Hafnium Bound (PHB) for the rest of this work and compare our analyses to this bound. The proportion of domains displaying highly unradiogenic Hf (i.e., plotting near PHB) decreases with decreasing age, such after 3.8 Ga few plot near PHB (see Fig. 7). Less than 4 Ga zircons within a few ε units of PHB display textures under CL suggestive of a metamorphic origin, so the significance of their unradiogenic hafnium in terms of igneous activity in the source terrane(s) is uncertain. The distribution in $^{207}Pb/^{206}Pb$ ages compares well to that observed in the rest of the Jack Hills distribution, with a major peak near 3.4 Ga and a minimum between 3.6 and 3.8 Ga (Holden et al., 2009; Crowley et al., 2005; see Fig. 6). Hf-Pb data for all samples can be seen in Electronic annex EA-2.

### 4.3. Oxygen isotopes

$\delta^{18}O_{SMOW}$ values for the zircons average 5.49 ± 0.43‰ (1σ), in good agreement with the average mantle value of ~5.3 ± 0.3‰ (1σ, Valley, 2003). Ten zircons fall outside the range of common mantle values: seven zircons have $\delta^{18}O$ above 5.9‰ and three zircons are below 4.7‰. There is no clear correlation of $\delta^{18}O$ with age, $\varepsilon_{Hf}$ or crystallization temperature (see Fig. 8). $\delta^{18}O$ values for all samples are shown in EA-2.

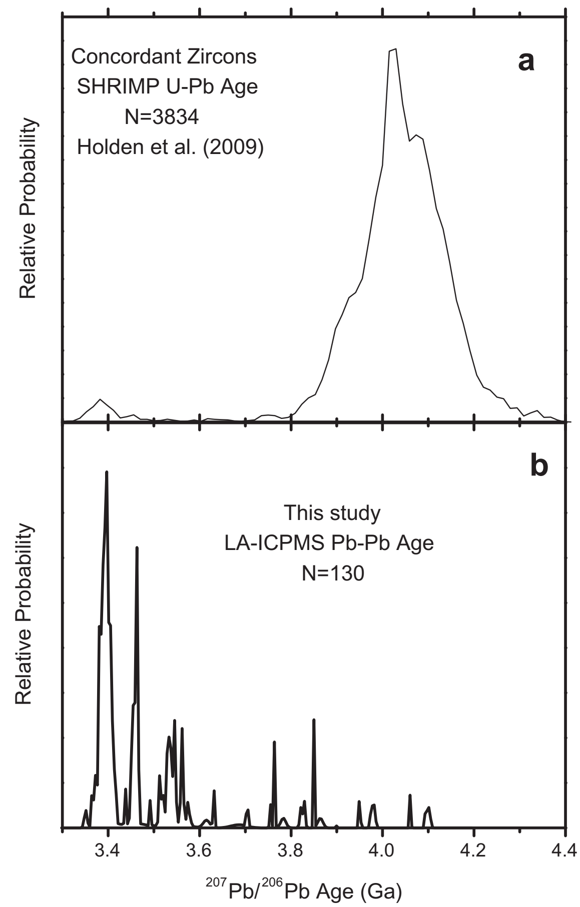


Fig. 6. Distributions in $^{207}Pb/^{206}Pb$ ages in the Jack Hills zircons from (a) Holden et al.'s (2009) survey of Hadean Jack Hills zircons using SIMS U–Pb dating and (b) ages from this study. The small <4 Ga peaks (e.g., at 3.4 Ga) in the Holden et al. (2009) data represent zircons with initially Hadean-appearing $^{207}Pb/^{206}Pb$ ages that upon closer analysis had younger cores.

### 4.4. Ti thermometry

Ti abundances in the zircons range from 0.89 to 36 ppm, indicating crystallization temperatures ($T^{xlln}$) ranging from 567 to 935 °C. Crystallization temperatures average 679 ± 124 °C (2σ). There is no apparent correlation between $T^{xlln}$ and age, $\varepsilon_{Hf}$ or $\delta^{18}O$ (see Fig. 8). Values of [Ti] and $T^{xlln}$ for all samples are shown in EA-2.

## 5. DISCUSSION

There are several notable differences in $\varepsilon_{Hf}$, $\delta^{18}O$, and $T^{xlln}$ between the Hadean zircon record in the Jack Hills and the younger zircons sampled here. The age distribution in our zircons displays several discrete peaks rather than the more homogeneous age distribution seen in the Hadean (see Fig. 6). Zircons in the 3.4 Ga age peak exhibit a narrow range in age with a wide range in $\varepsilon_{Hf}$ (–6 to –14). Minor age peaks at 3.45 and 3.5–3.6 Ga demonstrate similar behavior. These groups behave similarly in $\delta^{18}O$, exhibiting a range in $\delta^{18}O$ from 4.5 to 6.5‰ SMOW. There is no

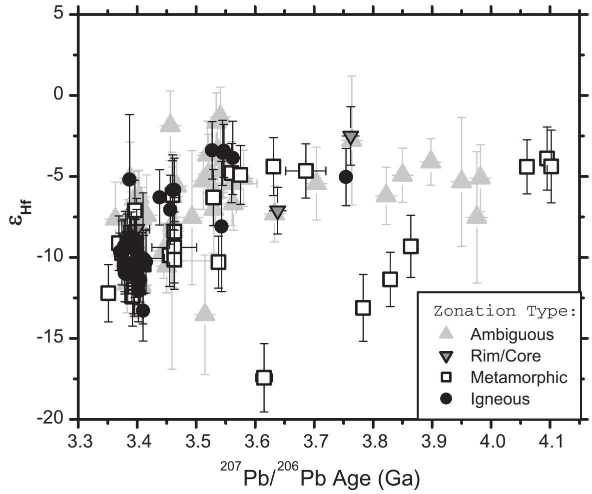


Fig. 7. Jack Hills zircons from this study in $\varepsilon_{Hf}$ vs. age space, with zircons grouped by textures as imaged by cathodoluminescence. The "metamorphic" group consists of zircons with patchy or disrupted zoning; the "igneous" group consists of zircons with oscillatory or sector zoning (or both). Oscillatory zonation is rare >3.6 Ga. Interestingly the most unradiogenic zircons <4 Ga display metamorphic textures, indicating that their hafnium compositions probably do not reflect source terrane magmatic evolution.

correlation between $\varepsilon_{Hf}$ and $\delta^{18}O$ within each of the age groups. All groups exhibit large ranges in $T^{xlln}$, indistinguishable from the Hadean record.

Interestingly, our finding of almost exclusively mantle-like $\delta^{18}O$ among the <3.8 Ga zircons differs from the results for similarly aged Jack Hills zircons reported by Peck et al. (2001). Peck et al.'s 3.3–3.6 Ga zircons average ~6.3‰ SMOW ($n = 32$ spot analyses on 16 grains). The discrepancy between these two datasets may owe partly to undersampling in the earlier study – whereas Peck et al. analyzed only 16 crystals with ages between 3.3 and 3.6 Ga for a total of 32 analyses, we have analyzed 76 individual crystals between the ages of 3.2 and 3.8 Ga, likely yielding a more representative sample. It is also the case that we do not pre-screen our samples for U–Pb concordance, and given Trail et al.'s (2007) and Booth et al.'s (2005) finding that discordant Jack Hills zircons tend toward lower $\delta^{18}O$ there is some danger that these grains may not reflect primary magmatic $\delta^{18}O$. However, the similarity of our average $\delta^{18}O$ to that of 214 concordant Hadean Jack Hills zircons previously analyzed by ion microprobe (Peck et al., 2001; Cavosie et al., 2004; Trail et al., 2007; Harrison et al., 2008) suggests that any systematic error in the younger, non-screened zircons is likely not significant. Interestingly, several of our zircons fall below 5‰ SMOW (though within

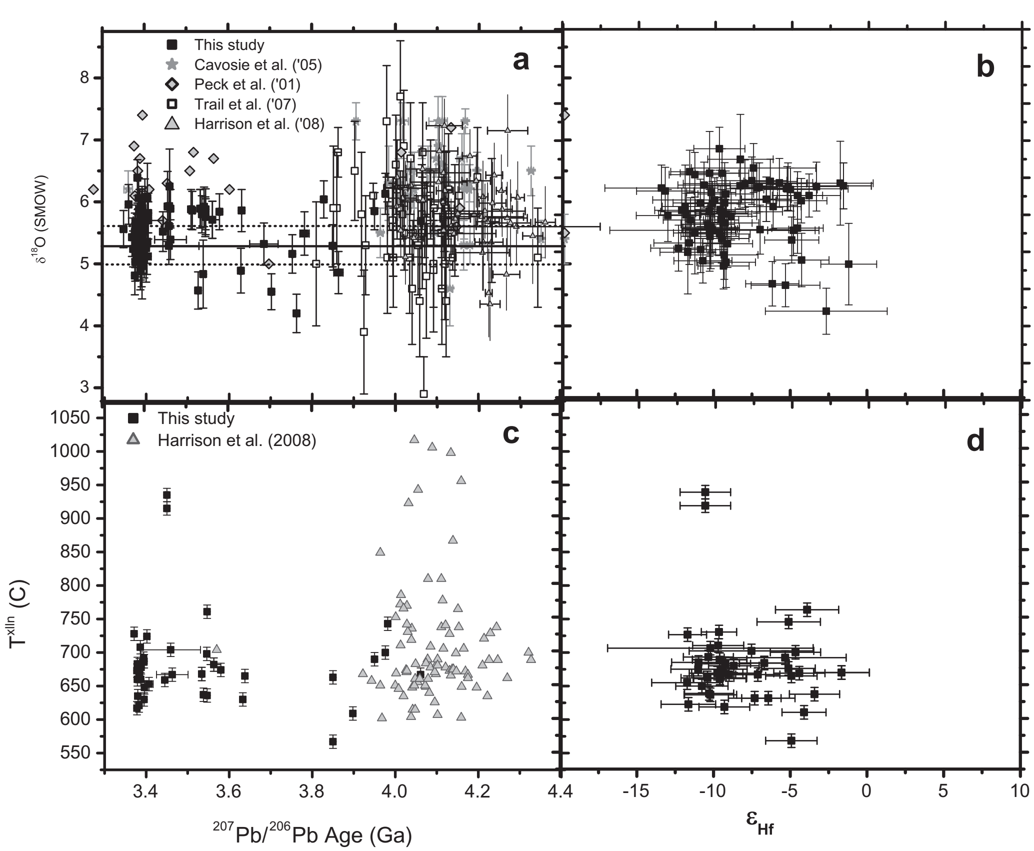


Fig. 8. Indicators for environment of formation among the studied Jack Hills zircons. (a) age vs. $\delta^{18}O$, (b) $\varepsilon_{Hf}$ vs. $\delta^{18}O$, (c) age vs. $T^{xlln}$, (d) $\varepsilon_{Hf}$ vs. $T^{xlln}$. No correlations are apparent.

the range of values found by previous studies), and may indicate the remelting of higher temperature, hydrothermally altered materials. However, it is not clear from the small sample size whether this is a significant part of the younger zircon population, which mostly clusters about mantle values.

The variables of age, $\varepsilon_{Hf}$ and $\delta^{18}O$ can be used for provenance interpretations for the <4 Ga zircons. It is likely that the large spreads in $\varepsilon_{Hf}$ at each age peak are due to the mixing of material from multiple sources at different initial $^{176}Hf/^{177}Hf$ ratios to form the magma in question. This is consistent with the spread in $\delta^{18}O$, which could reflect minor source variations in $\delta^{18}O$ about a mantle value. The distinct clusters may suggest a low number of discrete source units. The ages of the younger clusters are consistent with the ages of some orthogneiss units in the Narryer Gneiss Complex (Kinny et al., 1988; Myers, 1988a,b; Nutman et al., 1991). Zircons from the Dugel Gneiss reveal a crystallization age of 3375 ± 26 Ma, the Eurada Gneiss yields zircon ages of ~3.45–3.49 Ga, and zircons from the various portions of the Meeberrie Gneiss range from younger than 3.40 to ~3.73 Ga (Nutman et al., 1991). In comparison to the <3.6 Ga zircons, the Hadean record would be more suggestive of derivation from a multitude of sources. This smoother distribution in the Hadean detrital zircons could be effected also if the Hadean zircons have undergone multiple sedimentary cycles – the population thus likely deriving from a larger total area and number of protoliths.

Despite these consistent ages, others (e.g., Maas and McCulloch, 1992) have pointed to geochemical discrepancies between the detrital zircon-bearing metasediments and the Narryer orthogneisses that may indicate the gneisses are not the source of the younger detrital zircons. The Narryer orthogneisses display HREE depletion and widely variant positive and negative Eu anomalies, in contrast to the unfractionated HREE and consistently negative Eu anomaly in the metasediments. However, these differences could be balanced by a high proportion of mafic sediment (also suggested by detrital chromite and high Cr, Ni in the metasediments). A more relevant dataset for comparison was compiled by Kemp et al. (2010), who report age and Lu–Hf information for 70 metaigneous zircons separated from gneisses in the Narryer Gneiss Complex. Fig. 9 shows our data in the context of both (a) earlier studies of detrital Jack Hills zircons and (b) the metaigneous zircons of Kemp et al. (2010). Narryer orthogneiss zircons range in age from 2.6 to 3.75 Ga and overlap with the more radiogenic of the <3.8 Ga Jack Hills zircons, though there are slight discrepancies in the peak ages. It appears that a large proportion of the more radiogenic <4 Ga Jack Hills zircons are at least consistent with derivation from local gneisses. The lack of more unradiogenic zircons among the Narryer gneisses would prove more puzzling in this context, perhaps requiring a less radiogenic reservoir of material, no longer outcropping in the area, which recorded many of the same events 3.3–3.75 Ga as the Narryer gneisses. It may be that the metasediments' derivation from this wider set of source lithologies accounts for the chemical discrepancies observed by Maas and McCulloch (1992), though the large mafic component needed to balance the REE discrepancies between Narryer gneisses and the metasediments may not be an excellent source for the large component of radiogenic zircons. However, due to the still unconstrained nature of the relationship between the Jack Hills source terrane(s) and the extant Narryer gneisses, for this study we consider the identity of the younger zircons' protoliths to remain an open question. For the remainder of this paper we will draw conclusions about the geochemistry and crustal evolution of the source region for the Jack Hills metaconglomerate, whatever this source(s) might be in terms of extant rock units.

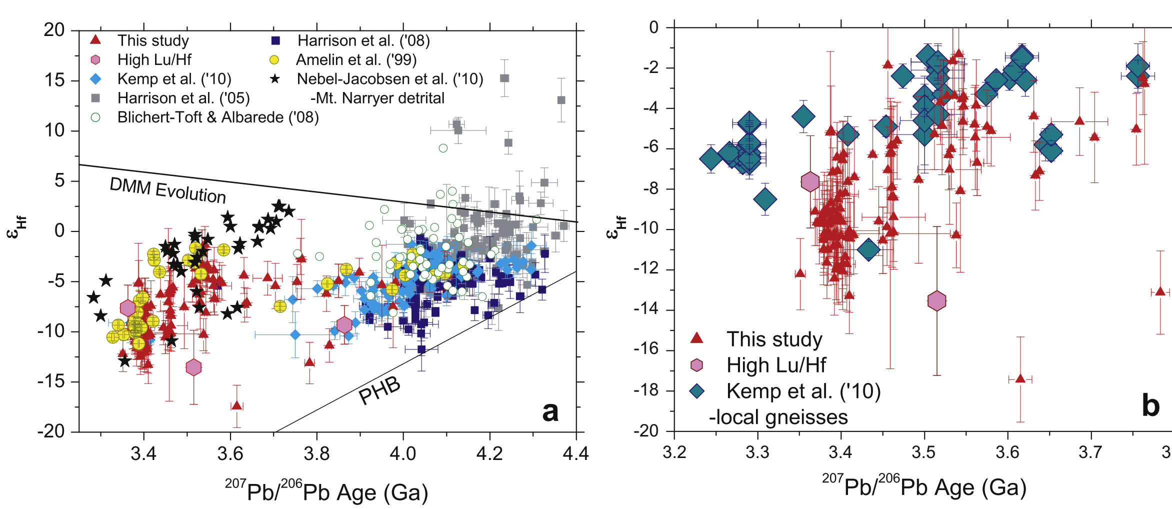


Fig. 9. Jack Hills zircons in age vs. $\varepsilon_{Hf}$ space from this and several previous studies. (a) Our data compared to other Jack Hills detrital zircon studies. The "PHB" line represents the evolution of a reservoir with the stated $^{176}Lu/^{177}Hf$ separated from CHUR at 4560 Ga. As in Fig. 4, a high Lu/Hf analysis at 2.88 Ga, −28ε is omitted. (b) Our 3.2 – data shown with metaigneous zircon analyses from the Narryer Gneiss Complex. Data from several of these studies were normalized to slightly different CHUR values; we have renormalized to the CHUR values of Bouvier et al. (2008) for a more apt comparison to our data.

### 5.1. Implications of initial hafnium isotopes and model extraction ages

Model mantle extraction ages for the crust represented in any zircon population are dependent upon the choice of $^{176}$Lu/$^{177}$Hf ratio for the crust. In the case of detrital zircon populations, the original host rocks are not available for analysis and reasonable assumptions must be made regarding $^{176}$Lu/$^{177}$Hf for the grains in question. The simplest method involves assuming a uniform $^{176}$Lu/$^{177}$Hf for the population in the absence of contrary evidence. We consider several models with differing values (Fig. 10a–c). The first model (Fig. 10a) uses $^{176}$Lu/$^{177}$Hf = 0.01, which is close to the average for volcanic rocks from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/Start.asp; see Sarbas, 2008) and consistent with the bulk crust value of 0.008 preferred by Rudnick and Gao (2003). A second model (Fig. 10b) explores the possibility of a mafic origin for the zircons with $^{176}$Lu/$^{177}$Hf = 0.022. A third model (Fig. 10c) uses a value derived by fitting a reservoir evolution line to the least radiogenic of the <3.8 Ga zircons with igneous zonation, which yields a value of ~0.006. Depleted mantle parameters were calculated by extrapolating from an assumed present $\varepsilon_{Hf}$ value of +18 to a value of zero at 4.56 Ga, assuming no appreciable external changes to the $^{176}$Lu/$^{177}$Hf of the reservoir apart from the decay of $^{176}$Lu over geologic time. As an additional note of caution, in the case of source mixing during magma formation, as is likely for igneous zircons at 3.4 Ga, the model age for any particular zircon may not have much significance and model ages for zircons from the extreme ends of the $\varepsilon_{Hf}$ distribution will be most significant in terms of source material extraction age.

#### 5.1.1. *Uniform models*

The two more felsic models with $^{176}$Lu/$^{177}$Hf = 0.01 (average felsic volcanics) and $^{176}$Lu/$^{177}$Hf = 0.006 (best fit to younger distribution) generally yield depleted mantle

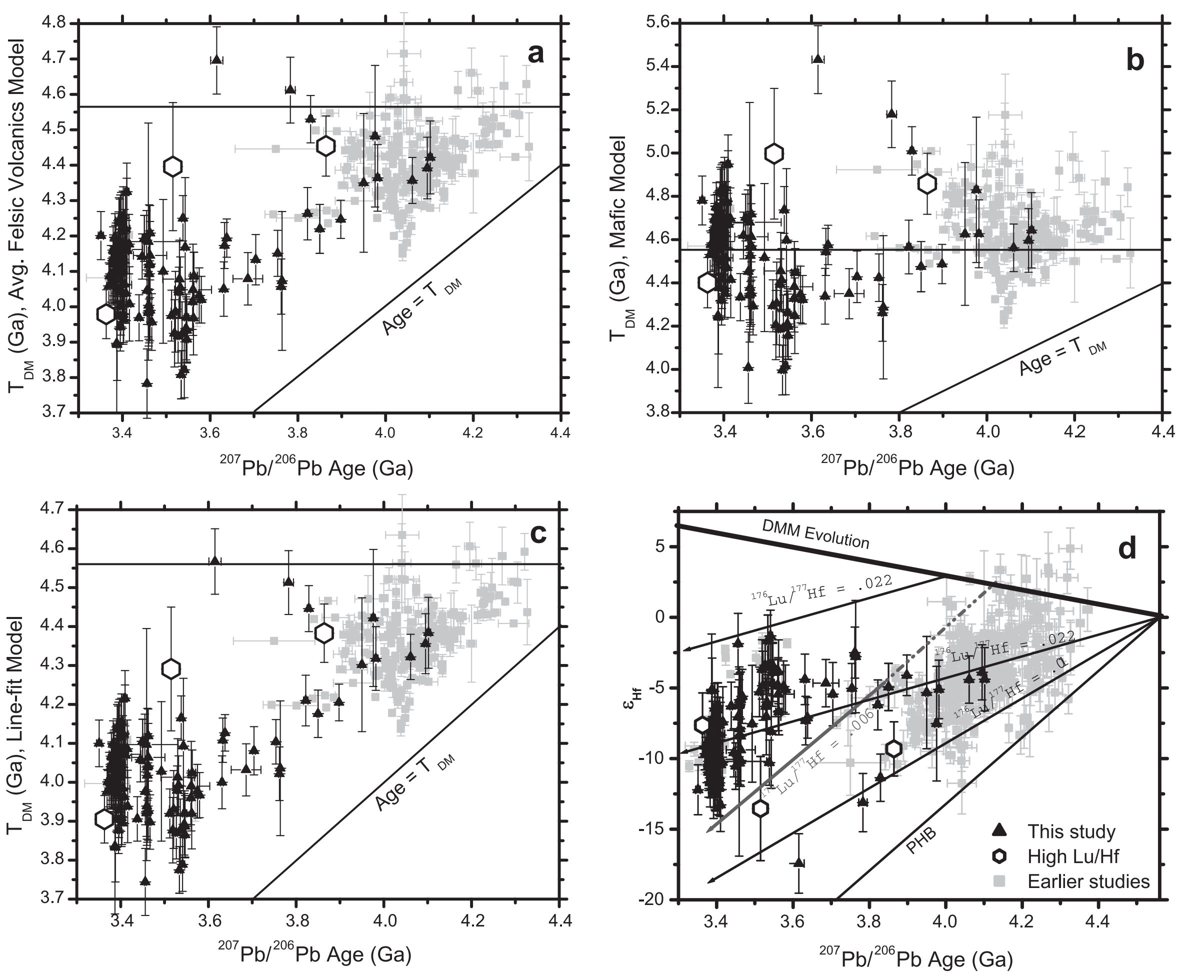


Fig. 10. Several models for zircon Lu–Hf extraction ages. (a) Uniform model with $^{176}$Lu/$^{177}$Hf = 0.01. (b) Uniform $^{176}$Lu/$^{177}$Hf = 0.022. (c) Uniform $^{176}$Lu/$^{177}$Hf = 0.006. (d) A basis for more complex models incorporating multiple past reservoirs. See the text in Section 5.1.2. Felsic and mafic reservoirs are shown originating at 4.56 Ga, along with a necessary juvenile reservoir sometime <4.2 Ga and a hypothetical $^{176}$Lu/$^{177}$Hf = 0.006 reservoir fit to the <3.6 Ga distribution. Analyses with unusually high $^{176}$Lu/$^{177}$Hf are marked with gray hexagons and should be regarded with caution; one at 2.88 Ga and −28ε is omitted. The data marked "earlier studies" are the detrital zircon data shown in Fig. 9a from Amelin et al. (1999), Harrison et al. (2005, 2008), Blichert-Toft and Albarède (2008), and Kemp et al. (2010).

extraction ages ($T_{DM}$'s) for the <3.6 Ga materials between 3.8 and 4.3 Ga. At ~3.8 Ga there is a fairly abrupt transition in both models in the average $T_{DM}$. Formation of all 3.4–3.45 Ga zircons directly from a long-lived mafic reservoir of $^{176}Lu/^{177}Hf = 0.022$ (a value derived by Amelin et al., 1999 from the slope of their age, $\varepsilon_{Hf}$ array) is unlikely given the unrealistically high model ages of >4.56 Ga for the most unradiogenic zircons. The most unradiogenic 3.4 Ga zircons are also (as shown in Fig. 7) magmatically zoned, demonstrating that they represent igneous materials rather than older material metamorphosed at 3.4 Ga, which is a likely origin for the patchily zoned <4 Ga zircons plotting near PHB. A direct mafic source is also inconsistent with the observed granitic mineral inclusions (quartz + K-feldspar + micas) and with minimum melting conditions inferred from low $T^{xlln}$ among the zircons.

*5.1.2. More complex extraction age models*

One possibility for the derivation of the younger zircons is a granitic source only recently remelted from an older, long-lived mafic source. In the above calculations and Fig. 10a–c we assume that each modeled reservoir was extracted directly from the mantle. This is a simplified model, as direct mantle melts would have typical basaltic Lu/Hf ratios (higher than felsic, but with variations depending on garnet content). The two lower Lu/Hf reservoirs would most likely have formed from a mafic reservoir that was extracted from the mantle at some unspecified time in the past – and thus the calculated extraction ages for the two lower Lu/Hf reservoirs should be viewed as minimum model ages. This does not, however, erase the necessity for the most unradiogenic Hadean zircons and the far more radiogenic <3.6 Ga zircons to be derived from distinct source reservoirs.

Fig. 10d shows the evolution of hypothetical reservoirs that might form the basis for a more complex model of Jack Hills source terrane(s) development, including reservoirs with the same $^{176}Lu/^{177}Hf$ ratios investigated in the uniform-composition models. Felsic and mafic reservoirs isolated at planet formation permissively bracket the more unradiogenic among the sampled Jack Hills materials, though as shown in Fig. 10d no <3.6 Ga magmatic grains approach the felsic evolution line. Mafic reservoirs extracted at 4.56 and 4.0 Ga bracket most 3.5–4.0 Ga zircons and the more unradiogenic 3.4–3.5 Ga zircons, though some felsic history is required for zircons below ~$-10\varepsilon$ at 3.45 and 3.4 Ga (many of which display igneous zonation). A variety of possible source terrane evolutions are shown. For example, a hypothetical history involving the extraction of a felsic reservoir from a 4.56 Ga mafic reservoir is shown to be consistent with the <3.6 Ga data; so also would be mixtures (of varying degrees) of ancient mafic and felsic reservoirs.

Despite the many working hypotheses consistent with these data, several things are clear from this figure. First, the <3.6 Ga materials must be derived largely from different sources than the unradiogenic Hadean zircons – either younger materials with a long felsic history or felsic materials derived more recently from a very ancient mafic reservoir. Fig. 10d shows the latter scenario for the derivation of unradiogenic 3.4 Ga magmas. The most unradiogenic Hadean material is not unambiguously sampled after 3.6 Ga. At the same time, model ages show that the more unradiogenic zircons (below $-10\varepsilon$ at 3.4 Ga) must have been sourced from a reservoir with Lu/Hf lower than typical mafic rocks, though not inconsistent with ancient remelts of mafic crust. Second, unlike most of the sampled Hadean zircons (Harrison et al., 2005, 2008; Kemp et al., 2010), the more radiogenic materials among the <3.8 Ga distribution require juvenile mantle melts at some point in the late Hadean to post-Hadean history of the source terrane (with the present zircons sourced partially from reworkings of these mantle melts). Using Fig. 9, estimates of the timing for the simplest model – a direct mafic source – fall ~4 Ga.

### 5.2. Formation environment and petrogenesis

The relatively narrow distribution of the zircons about a mantle-like $\delta^{18}O$ value ($5.49 \pm 0.43‰$ $\delta^{18}O_{SMOW}$, $\pm 1\sigma$) suggests little systematic contribution to the host rocks from materials involved in low-temperature aqueous alteration. For the igneous zircons, this likely precludes a large degree of (meta-) sediment assimilation into host magmas. These results are in contrast to the much more variant Hadean oxygen record which despite the similar average $\delta^{18}O_{SMOW}$ value of 5.72‰ has a higher degree of variation at $\pm 0.8‰$ ($\pm 1\sigma$). The Hadean record contains many grains falling above 6.5‰ that likely reflect significant contributions from older sedimentary materials (see Fig. 8a).

The crystallization temperatures recorded in the zircon Ti abundances of $679 \pm 62$ °C ($1\sigma$) suggest that, like the majority of Hadean zircons, the younger population if igneous represent close to minimum melting conditions of intermediate to felsic magmas. An igneous origin is indeed suggested by the oscillatory zoning evident in 32 grains. The 107 grains displaying patchy, irregular, or no zoning are more ambiguous in origin. The 50 patchily-zoned grains may have undergone recrystallization or metamorphic overprinting (Corfu et al., 2003), which might obscure the original igneous Hf and O isotopic compositions, but nevertheless except in the noted cases of highly unradiogenic patchy grains these apparently metamorphic grains do not differ systematically from other zircons in their geochemistry. Though there is no apparent systematic relationship among the distributions of $\delta^{18}O$ or $\varepsilon_{Hf}$ and zoning style, grains with $T^{xlln}$ <600 °C tend to display either no zonation or patchy/irregular zonation, though these zonation categories also include higher-$T^{xlln}$ grains. From 3.4 to 3.6 Ga, patchily and irregularly zoned zircons occur in the same age intervals as the apparently more pristine oscillatorily zoned zircons, and zircons with no zoning occur alongside them.

### 5.3. Global comparison

Pietranik et al. (2008) compiled a Lu–Hf-age dataset of zircons from several Archean cratons and interpret it to reveal several pulses of continental growth between 4.5 and 2.8 Ga. Many zircons in this compilation are contemporaneous with the younger Jack Hills zircons and may provide a comparison for other regions where early Archean crustal evolution left some lithic record. We plot our age vs. $\varepsilon_{Hf}$ data with Pietranik et al.'s (2008) data for Slave Craton detrital zircons and Amelin et al.'s (2000) data for detrital zircons from the Acasta Gneiss, Barberton Mountain Land, Pilbara Craton and Itsaq Gneiss (Fig. 11). We have normalized all hafnium compositions to the CHUR values of Bouvier et al. (2008) for comparison. Zircons with $\varepsilon_{Hf}$ values as low as –10 occur in the Acasta Gneiss from 3.6 to 3.4 Ga. Interestingly, the sampled Acasta Gneiss zircons overlap considerably in $\varepsilon_{Hf}$ with zircons from our 3.55 Ga broad age peak and may indicate parallel crustal reworking histories in the two terranes for this time period.

Pietranik et al. (2008) interpret Mid- to Late-Archean zircons from the Slave Craton to lie along a mafic reservoir evolution line that suggests a mantle extraction age of ~4.2 Ga. Many of our samples are also compatible with origins from a remelted mafic Hadean reservoir and overlap the reported compositions of Slave and Superior province zircons. However, our 3.4 Ga zircons reach much more unradiogenic compositions than those found in other cratons for the same time period. It is likely that the unusually unradiogenic younger Jack Hills zircons are a unique resource in determining the fate of early felsic crust. This is compounded by the apparent lack of highly unradiogenic signatures among detrital zircons of similar age from the nearby Mt. Narryer (Nebel-Jacobsen et al., 2010).

### 5.4. Synthesis: crustal evolution from 3.0 to 4.0 Ga

While a powerful approach for elucidating juvenile crustal addition vs. remelting of older crust, Lu–Hf isotopic data do not constrain the tectonic environment in which the metaconglomerate catchment area evolved. The apparent contrasts between older and younger zircons in both Lu–Hf and oxygen isotope systematics may suggest different magmatic settings and possibly different reservoirs of material for <3.6 and >4 Ga protoliths. Further study of <4 Ga Jack Hills zircons and the Narryer Gneiss Complex may be needed to constrain the specific geologic context in which the Hadean grains have been preserved and the younger grains formed, but some constraints are evident now.

The change in Lu–Hf systematics with age precludes the preservation or remelting of significant amounts of the most enriched sampled Hadean materials (that falling on or near the PHB) into younger magmas and requires at least some contribution from late- to post-Hadean juvenile crust. Why this unradiogenic reservoir ceased to be available for reworking is unclear. Solutions involving the erosion and loss of this crustal material (for instance, by some form of tectonic denudation) are intriguing but await further analysis of the period 3.6–4 Ga to determine whether any magmatic zircons bearing this signature are evident in a more representative sampling. This period is sparsely sampled at present due to its coincidence with a minimum in the zircon age distribution at 3.6–3.8 Ga.

Despite the transition in the Lu–Hf systematics with time, a large separation in model ages for Hadean and younger zircons is only achieved with a felsic precursor for the younger magmas. The isotopic evidence does not rule out an alternate scenario in which most <3.6 Ga zircons derive from a remelted mafic Hadean precursor indistinguishable from the more radiogenic of the sampled Hadean materials. Derivation from remelting of mafic Hadean materials is also consistent with the Lu–Hf systematics of contemporaneous zircons from several spatially distinct cratons (Amelin et al., 2000; Pietranik et al., 2008; Fig. 11), and is likely a common petrogenesis among Early Archean crust. We must also consider the possibility of a mixture of various sources, Hadean and younger, in the production of younger magmas. Further sampling 3.6–4 Ga will constrain the form of the distribution and determine whether the younger Jack Hills zircons are indeed best modeled by magmas derived from felsic or mafic precursor materials (or a mixture).

Whether the melts from which the <3.6 Ga Jack Hills zircons formed are remelts of mafic or felsic materials they appear to be largely felsic themselves. Ti-in-zircon $T^{xlln}$ throughout the age distribution suggest close to minimum melting conditions. There is no obvious distinction between the Hadean and younger populations in $T^{xlln}$. The mineral inclusion suite is only well characterized for the 3.4 Ga age peak, but here appears largely consistent with a granitic melt: quartz and K-feldspar dominate. The largely mantle-like $\delta^{18}O$ among <3.6 Ga zircons suggest little contribution of sedimentary material to the magmas. This is corroborated for grains in the 3.4 Ga age peak by the smaller proportion of muscovite among mineral inclusions compared to the Hadean (e.g., Hopkins et al., 2008, 2010). The apparently granitic $T^{xlln}$ combined with the mantle-like $\delta^{18}O$ of most grains suggests the <3.6 Ga zircons are likely

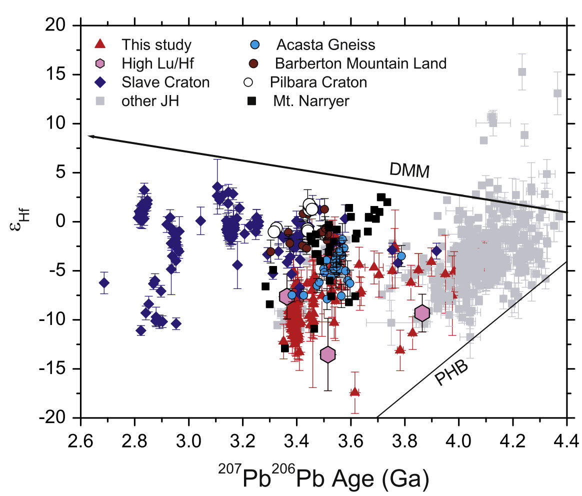


Fig. 11. Jack Hills detrital zircons from this and previous studies compared with zircons of similar age from other Archean cratons. Slave Craton data are from Pietranik et al. (2008); Acasta Gneiss, Barberton Mountain Land, and Pilbara Craton zircons are from Amelin et al. (2000); Mt. Narryer detrital zircon data are from Nebel-Jacobsen et al. (2010); earlier Jack Hills detrital zircon data as for Fig. 10d. We normalized all Lu–Hf data to the CHUR parameters of Bouvier et al. (2008) for comparison to our data.

derived from I-type granitic melts. In contrast, a significant proportion of the Hadean grains appear on the basis of mineral inclusions to be from S-type melts (Hopkins et al., 2008, 2010). This suggests a transition to a different magmatic style with possible tectonic implications. Both the Lu–Hf systematics and other geochemical indicators of petrogenesis independently suggest a transition between the Hadean and <3.6 Ga source areas. Whether this is due to the zircons deriving from separate tectonic terranes or one region undergoing continuous geologic evolution away from S-type granite production is yet unclear.

## 6. CONCLUSIONS

Age, $\varepsilon_{Hf}$, and $\delta^{18}O$ results for <3.8 Ga zircons in the Jack Hills detrital record reveal important differences between the Hadean and younger zircon populations. Whereas the majority of igneous zircons from both time periods appear to result from minimum melting of a low Lu/Hf source, the <3.6 Ga zircons lack the highly unradiogenic materials sampled in the Hadean, require at least some juvenile input not seen among the Hadean zircons, and appear less likely to reflect aqueous alteration (hydrothermal or low-T) among their source materials. This indicates a substantial provenance difference between the Hadean and younger grains. Whether this indicates separate tectonic terranes remains to be seen. For petrogenesis of the <3.6 Ga magmas by remelting of an older felsic source, there is an abrupt transition of the $\varepsilon_{Hf}$ distribution at 3.6–3.8 Ga; models based on the remelting of Hadean mafic materials for some of the younger zircons remove the abrupt transition but still require disappearance of the most unradiogenic Hadean materials. A larger dataset for the period from 3.6 to 4 Ga will clarify the fate of the unradiogenic Hadean component and further constrain possible tectonic scenarios accounting for the $\varepsilon_{Hf}$ distribution in the younger Jack Hills record. Further surveys of geochemistry among the older and younger zircon populations will also help to elucidate the relationship between the two groups. The 3.6–4 Ga portion of the Jack Hills record is potentially one of the best resources on the planet for probing this poorly understood period of early Earth history, especially given that <3.6 Ga zircons preserve some of the most unradiogenic hafnium seen in the early Archean. Further constraining the geologic behavior of the source region 3.6–4 Ga will have important implications for the tectonic evolution of this fragment of the very early continental crust.


## ACKNOWLEDGMENTS

We thank Dianne Taylor, Karen Ziegler, and Axel Schmitt for invaluable instruction in analyzing our samples. This research was conducted with support from a grant from NSF-EAR's Petrology/Geochemistry Program to T.M.H. and an NSF Graduate Research Fellowship (DGE-0707424) to E.A.B.


## APPENDIX A. SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gca.2011.06.007.

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