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Precambrian Research xxx (2010) xxx–xxx

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Reworking of Earth's first crust: Constraints from Hf isotopes in Archean zircons from Mt. Narryer, Australia

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ARTICLE INFO

Article history:
Received 11 August 2009
Received in revised form 28 June 2010
Accepted 9 July 2010
Available online xxx

Keywords:
Hadean
Hafnium in zircon
Jack Hills
Mt. Narryer
Model ages
Crustal growth

ABSTRACT

Discoveries of >4 Ga old zircon grains in the northwest Yilgarn of Western Australia led to the conclusion that evolved crust formed on the Earth within the first few 100 Myrs after accretion. Little is known, however, about the fate of the first crust that shaped early Earth's surface. Here we report combined solution and laser-ablation Lu–Hf–U–Pb isotope analyses of early Archean and Hadean detrital zircon grains from different rocks of the Narryer Gneiss Complex (NGC), Yilgarn Craton, Western Australia. The zircons show two distinct groups with separate evolutionary trends in their Hf isotopes. The majority of the zircon grains point to separation from a depleted mantle reservoir at ~3.8–3.9 Ga. The second Hf isotope trend implies reworking of older Hadean zircons. The major trend starting at 3.8–3.9 Ga defined by the Hf isotopes corresponds to a Lu/Hf that is characteristic for felsic crust and consequently, the primary sources for these zircons presumably had a chemical composition characteristic of continental crust. Reworked Hadean crust appears to have evolved with a similar low Lu/Hf, such that the early crust was probably evolved with respect to Lu–Hf distributions. The co-variation of Hf isotopes vs. age in zircon grains from Mt. Narryer and Jack Hills zircons implies a similar crustal source for both sediments in a single, major crustal domain. Age spectra and associated Hf isotopes in the zircons strongly argue for ongoing magmatic reworking over hundreds of millions of years of the felsic crustal domain in which the zircon grains formed. Late-stage metamorphic zircon grains from the Meeberrie Gneiss unit yield a mean U–Pb age of 3294.5 ± 3.2 Ma with initial Hf isotopes that correspond to the evolutionary trend defined by older NGC zircons and overlap with other detrital zircon grains, proving their genetic relationship. This 'Meeberrie event' is interpret here as the last reworking event in the precursor domain before final deposition. The continuous magmatic activity in one crustal domain during the Archean is recorded by the U–Pb ages and Hf isotope systematics of zircon grains and implies reworking of existing crust. We suspect that the most likely driving force for such reworking of crustal material is ongoing crustal collision and subduction. A comparison of Hf isotope signatures of zircon grains from other Archean terranes shows that similar trends are recognised within all sampled Archean domains. This implies either a global trend in crustal growth and reworking, or a genetic connection of Archean terranes in close paleo-proximity to each other. Notably, The Archean Acasta gneisses (Canada) shows similar reworking pattern to the Yilgarn Craton of Hadean samples implying either a common Hadean source or amalgamation at the Hadean–Archean transition.

1. Introduction

The metasedimentary sequences of the Narryer Gneiss Complex (NGC), Australia, host very old zircon grains with ages ranging from ~4.4 Ga to ~3.2 Ga, representing the only remnants of the Earth's "dark age", the Hadean, and give a continuous record until the early Archean (Compston and Pidgeon, 1986; Froude et al., 1983; Maas et al., 1992; Nelson, 2008; Wilde et al., 2001). This study aims to investigate the relationship between the sedimentary deposits

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0301-9268/$ – see front matter © 2010 Published by Elsevier B.V.
doi:10.1016/j.precamres.2010.07.002

Please cite this article in press as: Nebel-Jacobsen, Y., et al., Reworking of Earth's first crust: Constraints from Hf isotopes in Archean zircons from Mt. Narryer, Australia. Precambrian Res. (2010), doi:10.1016/j.precamres.2010.07.002

from the Jack Hills and Mt. Narryer, using Hf isotopes in detrital and metamorphic zircon grains, and to constrain the nature of crustal reworking in these domains.

Q2 Zircons from the Jack Hills have been intensively studied in recent years, and along with improvements in analytical tools, the study of Hf and O isotopes and Ti-in-zircon thermometry have placed important constraints on the very early Earth's environment (e.g., Amelin et al., 1999; Blichert-Toft and Albarede, 2008; Harrison and Schmitt, 2007; Harrison et al., 2008; Mojzsis et al., 2001; Trail et al., 2007; Watson and Harrison, 2005b). Lu–Hf and U–Pb isotope investigations on a growing number of zircon grains showed that the rocks from which the zircon grains formed represent either juvenile or reworked Hadean crust that may have formed as early as ∼4.4 Ga ago (Amelin et al., 1999; Blichert-Toft and Albarede, 2008; Harrison et al., 2005, 2008). The nature of this crust is still a matter of debate, but integrated investigations of zircon Hf isotopes, Ti contents (Harrison et al., 2008; Trail et al., 2007; Watson and Harrison, 2005a), and investigations on mineral inclusions (Hopkins and Harrison, 2008; Menneken et al., 2007) suggest evolved crustal host rocks with granitic affinities for the zircon grains (e.g., Harrison et al., 2008). Blichert-Toft and Albarede (2008) suggested TTGs as the source of the zircon grains, but the tectonic setting in which these rocks and consequently the oldest zircon grains on Earth formed remains a matter of debate. However, the recent discovery of micro-diamond inclusions in up to 4.25 Ga old Jack Hills zircon grains (Menneken et al., 2007), which could have only formed in a very high pressure environment, imply rapid transport of the zircon grains back to the surface, providing strong support for a subduction-related setting. Although micro-diamond inclusions could not be found in other zircon grains from the NGC, pressure–temperature investigations on hydrous mineral inclusions and Ti-in-zircon thermometry in NGC zircon grains further support a subduction-related origin (Hopkins and Harrison, 2008; Trail et al., 2007).

The NGC comprises two Archean metasedimentary sequences at the Jack Hills and at Mt. Narryer, that were deposited between ∼3.1 and 2.7 Ga (Kinny et al., 1988). The main units are Meeberrie and Dugal Gneiss (Myers and Williams, 1985) and make up ∼90% of the terrane. The metasedimentary units of Mt. Narryer and the adjacent Jack Hills were deposited upon and thrust-stacked into the gneiss units (Nutman et al. 1991). The metamorphic overprint is heterogeneous, with primary sedimentary structures preserved at some sites. The continuous record of old, detrital zircon grains found within the metasedimentary units (4.4–3.2 Ga) can be taken as first-order evidence for magmatic activity over more than 1 Ga. Furthermore, associated low Lu/Hf and time-integrated negative ε_{Hf} values of the zircon grains are arguments for primary felsic host rocks for the zircon grains, implying that tectonic activity and crustal reworking were probably widespread in Archean time (Harrison et al., 2005, 2008; Trail et al., 2007). Studies on Hf isotopes in zircon have so far selectively focussed on Jack Hills zircon grains that yielded U–Pb ages >4 Ga. Nevertheless, Hf isotope evolutionary trends or depleted mantle extraction ages determined on younger zircon populations may provide important information on already reworked reservoirs (e.g., Nebel et al., 2007). Hence, a growing database and associated evolutionary paths of Hf isotopes in zircon grains from sequences younger than 4 Ga and from different depositional areas can give further insights into early crustal evolution (e.g., Zeh et al., 2008).

Here we present combined U–Pb and Lu–Hf isotope data using solution and laser-ablation multiple-collector inductively coupled plasma mass spectrometer (LA-MC-ICPMS) and thermal ionization mass spectrometry (TIMS) on single zircon grains from the Mt. Narryer quartzite ($n = 34$) and the Meeberrie Gneiss Complex ($n = 6$), and two zircon grains from the Jack Hills meta-conglomerate. In combination with published data, these data are used to constrain possible relationships of the three different sedimentary deposits, to evaluate the geochemical nature of the early Earth's crustal domain(s), and to constrain the fate of Earth's first crust.

2. Analytical techniques

Zircon grains were extracted from the rock matrix using magnet separation, heavy liquids, sieving (<180 μm) and final hand picking under a microscope. From the Meeberrie sample, small (<50 μm) idiomorphic zircon grains were selected that all show brownish-greenish colour, matching the description of Kinny et al. (1988) of a secondary, late-stage metamorphic population. Air abrasion of the zircon grains was not performed due to the small amount of sample material, which would have limited a combined U–Pb–Lu–Hf isotope study. Zircon grains were investigated prior to dating and dissolution using back-scattered electron (BSE) images (Fig. 1). U–Pb ages of zircon grains from the Meeberrie Gneiss were determined by isotope dilution thermal ionization mass spectrometry (ID-TIMS). Some zircon grains from the Mt. Narryer metasediment were analysed for their U–Pb isotope systematics using both the TIMS technique and the laser-ablation (LA)-ICPMS (after Gerdes and Zeh, 2006, 2007) in order to compare both techniques (Tables 1 and 3). The two Jack Hills zircon grains were dated using a sensitive high resolution ion microprobe (SHRIMP) at Curtin University, Perth. Lu–Hf isotope systematics of all zircon grains were determined by isotope dilution multiple-collector inductively coupled plasma mass spectrometry (ID-MC-ICPMS) (Table 2) and LA-MC-ICPMS (Table 4). Sample treatment, chemical purification and isotope measurements (ID-TIMS, ID-MC-ICPMS) are similar to those reported in Nebel-Jacobsen et al. (2005). Hafnium isotope analyses using the laser-ablation technique were carried out following the protocol of Gerdes and Zeh (2006). The initial Hf isotope composition of all zircon grains was calculated using the ^{207}Pb/^{206}Pb age (note that ID-TIMS analyses are predominantly discordant ages). For the Meeberrie Gneiss unit, upper concordia intercept ages are used. The Hf isotope compositions of all analysed zircon grains are expressed as a deviation from the chondritic uniform reservoir (CHUR, after Bouvier et al. (2008) in the epsilon units, i.e., parts per 10,000). U–Pb ages were calculated using PbDat and Isoplot (Ludwig, 2001).

Hafnium model ages (Tables 2 and 4) were calculated using a modified equation after Milisenda et al. (1994) for two-stage Sm–Nd model ages. The obtained two-stage Hf model ages for zircon grains are considered here to be more robust compared to the way whole-rock model ages are calculated. This is because of the difference between the Lu–Hf ratio in a zircon and its hosting reservoir at the time of formation; the Hf isotope composition of a crustal domain that separated from the depleted mantle will evolve differently from that of a zircon within it. The application of whole-rock model age calculations on zircon grains in a single step ignores this difference and can result in biased mantle separation ages.

A description of model age calculations is given in Davis et al. (2005) and references therein. In brief, in a first step, the Hf composition of a zircon for the time of its crystallization is calculated using the measured ^{176}Lu/^{177}Hf value, and subsequently the depleted mantle is age-corrected for the time of zircon formation using values of Chauvel and Blichert-Toft (2001). From this point in time backwards, a model age is calculating using the initial Hf isotope composition of the zircon, and a typical ^{176}Lu/^{177}Hf value = 0.0093 for felsic continental crust (Vervoort and Patchett, 1996b). These model ages reflect depleted mantle extraction ages assuming a present day depleted mantle with ^{176}Lu/^{177}Hf = 0.0384 and ^{176}Hf/^{177}Hf = 0.28325 (Chauvel and Blichert-Toft, 2001).

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Table 1
U–Pb results of the NGC zircons analysed by TIMS, LA-MC-ICPMS, and SHRIMP for comparison. All errors refer to the last significant digit, and are two sigma, except for SHRIMP results with 1 sigma.

Sample	Isotope ratios							Age		
	Weight (mg)	ppm U	ppm Pb	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$ (Ma)	$^{207}Pb/^{235}U$ (Ma)	$^{206}Pb/^{238}U$ (Ma)
Meeberrie Gneiss										
TIMS only										
I-10	0.007	64.4	55.0	113.6	0.2596 ± 6	19.739 ± 14	0.55150 ± 395	3244.2	3078.6	2831.4
II-15B	0.02	9.8	5.42	177.2	0.2569 ± 8	16.958 ± 158	0.47874 ± 411	3227.8	2932.5	2521.8
II-11B	0.02	214.0	24.1	122.3	0.05669 ± 52	0.59813 ± 679	0.076525 ± 348	479.42	476.02	475.46
I-06B	0.002	157.6	72.1	176.9	0.2475 ± 6	12.970 ± 116	0.38004 ± 316	3168.9	2677.4	2076.9
II-02B	0.008	94.9	61.4	152.5	0.2474 ± 5	15.217 ± 98	0.44604 ± 280	3168.4	2828.9	2377.6
II-15D	0.028	45.4	26.0	200.2	0.2440 ± 4	14.134 ± 72	0.42018 ± 207	3146.0	2758.7	2261.3
Metasediment										
Mt. Narryer										
TIMS										
I-03	0.002	1601	110	535.6	0.3241 ± 2	23.339 ± 129	0.52227 ± 287	3589.4	3241.2	2708.8
I-09	0.002	2251	1800	1171	0.3981 ± 2	34.077 ± 81	0.62084 ± 144	3901.9	3612.3	3113.3
I-22	0.002	3846	2164	815.5	0.2770 ± 2	18.070 ± 43	0.47318 ± 109	3345.9	2993.5	2497.5
I-01	0.013	541.1	378	330.2	0.2716 ± 2	19.988 ± 50	0.53376 ± 128	3315.3	3090.8	2757.3
I-06	0.002	1174	790	386.4	0.2963 ± 2	21.048 ± 98	0.51530 ± 237	3450.7	3140.8	2679.2
I-11	0.003	1274	936	247.8	0.2683 ± 2	18.473 ± 190	0.49941 ± 514	3296.0	3014.7	2611.3
I-12	0.001	2083	1013	311.2	0.3071 ± 2	14.085 ± 37	0.33263 ± 85	3506.5	2755.5	1851.1
I-08	0.003	1390	797	546.7	0.2864 ± 2	18.023 ± 84	0.45650 ± 210	3397.9	2991.0	2424.1
LA-ICPMS										
I-03	0.002	64	69	13,687	0.3540 ± 43	39.22 ± 186	0.8034 ± 241	3724	3751	3801
I-09	0.002	104	133	14,557	0.4778 ± 48	60.48 ± 375	0.9181 ± 588	4174	4182	4199
I-22	0.002	338	261	17,024	0.2932 ± 41	27.21 ± 196	0.6731 ± 471	3435	3391	3318
I-01	0.013	186	177	4833	0.3304 ± 40	35.85 ± 176	0.7870 ± 283	3619	3662	3743
I-06	0.002	130	92	2240	0.3417 ± 55	25.79 ± 175	0.5475 ± 361	3670	3339	2815
I-11	0.003	212	274	632	0.2691 ± 54	25.31 ± 202	0.6821 ± 518	3301	3320	3353
I-12	0.001	173	158	5361	0.3162 ± 40	30.04 ± 198	0.6892 ± 441	3551	3488	3380
I-08	0.003	119	117	17,281	0.3493 ± 63	35.36 ± 205	0.7341 ± 411	3704	3649	3549
Metasediment										
Jack Hills										
TIMS										
22.1	0.002	310.3	915	29.83	0.3650 ± 8	35.928 ± 197	0.71397 ± 341	3770.7	3664.5	3473.4
08.1	0.001	49.17	175	28.43	0.4085 ± 13	45.904 ± 955	0.81502 ± 1728	3940.6	3907.3	3842.7
SHRIMP				f206%					% Conc.	
22.1	0.002	54	55	0,357	0.44831 ± 288	50.068 ± 1.760	0.8100 ± 274	4080	94	
08.1	0.001	236	239	0,065	0.46262 ± 106	49.763 ± 0.639	0.7802 ± 96	4126	90	

Table 2
Q7 Lu–Hf isotope analyses of zircons by solution MC-ICPMS as listed in Table 1. Initial Hf isotope compositions are calculated with $^{207}Pb/^{206}Pb$ ages and $\lambda^{176}Lu = 1.867 \times 0^{-11}$ yr^{-1} (Scherer et al., 2001; Söderlund et al., 2004); epsilon notions express the deviation from CHUR after (Bouvier et al., 2008) × 10^4. T_{DM} = two-stage zircon mantle extraction model ages from the depleted mantle with values after (Chauvel and Blichert-Toft, 2001). Sol. refers to U–Pb TIMS analyses, in situ refers to laser-ablation (Mt. Narryer), or SHRIMP (Jack Hills) analyses. Initial ε_{Hf} for the Meeberrie unit was calculated using the mean upper intercept age with the concordia.

Sample ID	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	Age (Ma)[a]	$\varepsilon_{Hf}(t)$ in situ	Age (Ma) sol.	$\varepsilon_{Hf}(t)$ sol.	T_{DM} felsic[b]
Mount Narrier—Meeberrie Gneiss							
I-10	0.000724	0.280481	3294	−7.9	3244	–	3988
II-15B	0.000482	0.280469	3294	−7.8	3228	–	3981
I-06B	0.00000136	0.280511	3294	−5.2	3169	–	3849
II-02B	0.000672	0.280513	3294	−6.6	3168	–	3923
II-15D	0.000928	0.280515	3294	−7.1	3146	–	3950
II-11B	0.00133	0.280530	3294	−7.5	479	–	3968
Mount Narrier—Sediment							
MN02 I-03	0.00136	0.280455	3724	−0.4	3589	−3.5	3959
MN02 I-09	0.00105	0.280269	4174	+4.3	3902	−2.1	4088
MN02 I-22	0.00114	0.280570	3435	−2.4	3346	−4.5	3825
MN02 I-01	0.00102	0.280552	3619	+1.5	3315	−5.5	3776
MN02 I-06	0.00139	0.280451	3670	−1.9	3451	−6.9	3989
MN02 I-11	0.00168	0.280567	3301	−6.8	3296	−6.9	3939
MN02 I-12	0.000986	0.280515	3551	−1.3	3506	−2.4	3865
MN02 I-08	0.00130	0.280501	3704	+0.9	3398	−6.1	3875
Jack Hills—Sediment							
JH22.1	0.00122	0.280212	4080	−0.5	3771	−7.6	4256
JH08.1	0.0000339	0.280055	4126	−1.6	3941	−6.1	4352

[a] Meeberrie zircons: upper intercept age, Mt. Narryer zircons: LA-ICPMS age, Jack Hills zircons: SHRIMP age.
[b] Two-stage model ages using a felsic $^{176}Lu/^{177}Hf = 0.0093$.

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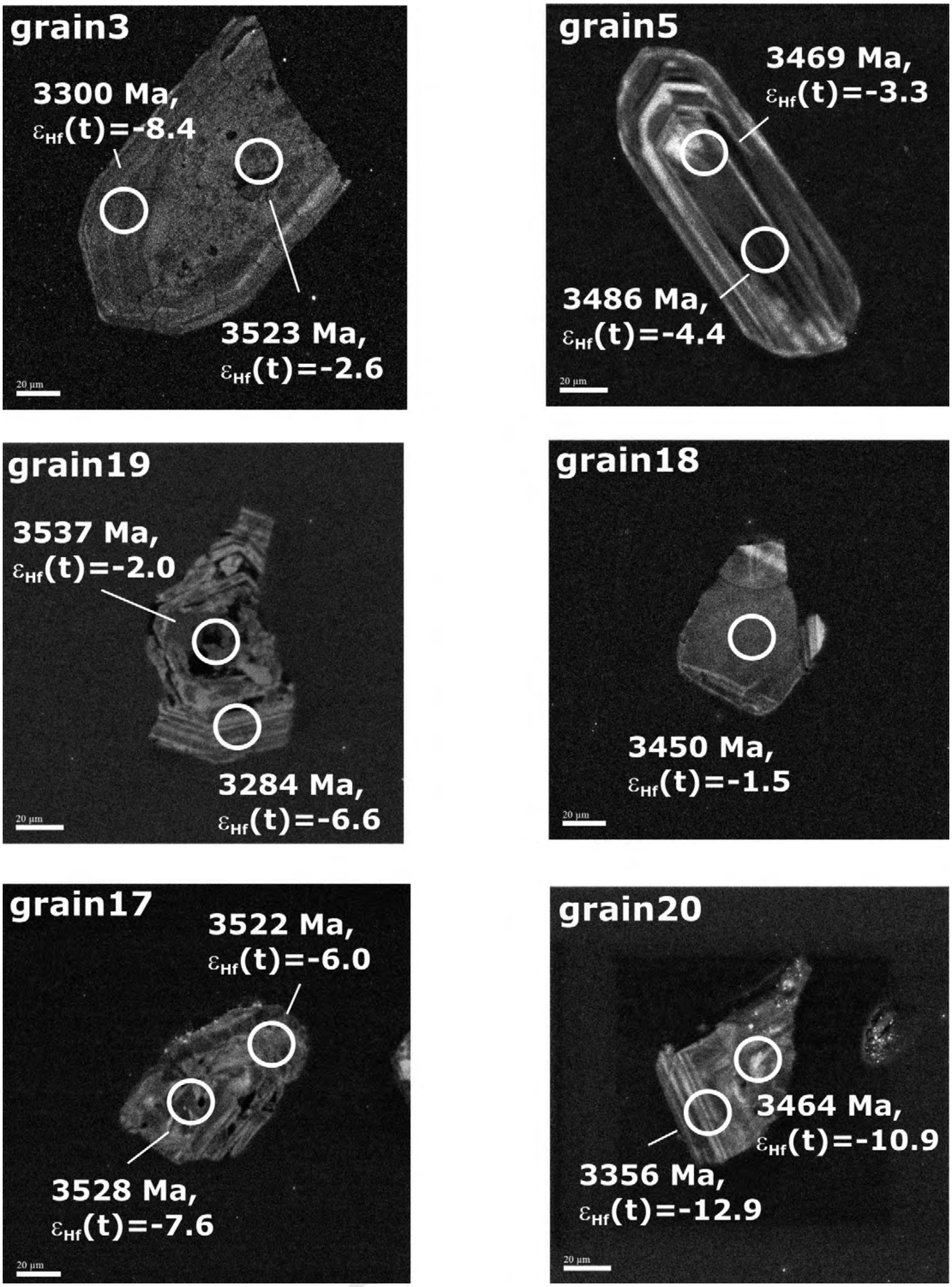

Fig. 1. Back-scattered electron (BSE) images of zircons analysed by laser-ablation. The white circles indicate approximate locations of U–Pb analyses laser spots. Hafnium isotope analyses were placed on top of these spots. Note that grains 3 and 19 host two events with ongoing reworking (∼3.5 Ga) and the last Meeberrie event (∼3.3 Ga). Grains 17 and 20 represent reworked material from the Hadean, as the plot on the lower evolution trend in age vs. Hf isotope space. The size bar indicates 20 μm in all pictures.

The equation for the two-stage Lu–Hf model age is:

$$T_{\mathrm{DM}} = \frac{1}{\lambda} \times \ln\left[\frac{{}^{176}\mathrm{Hf}/{}^{177}\mathrm{Hf}_{\mathrm{DM}} - [({}^{176}\mathrm{Hf}/{}^{177}\mathrm{Hf}_{\mathrm{zircon}} - (e^{\lambda T} - 1))] \times ({}^{176}\mathrm{Lu}/{}^{177}\mathrm{Hf}_{\mathrm{zircon}} - {}^{176}\mathrm{Lu}/{}^{177}\mathrm{Hf}_{\mathrm{crust}})}{{}^{176}\mathrm{Lu}/{}^{177}\mathrm{Hf}_{\mathrm{DM}} - {}^{176}\mathrm{Lu}/{}^{177}\mathrm{Hf}_{\mathrm{crust}}} + 1\right]$$

where t is the crystallization age of the zircon, DM refers to depleted mantle λ to the ^{176}Lu decay constant, and $^{176}\mathrm{Lu}/^{177}\mathrm{Hf}_{\mathrm{crust}}$ to a typical felsic crustal Lu/Hf.

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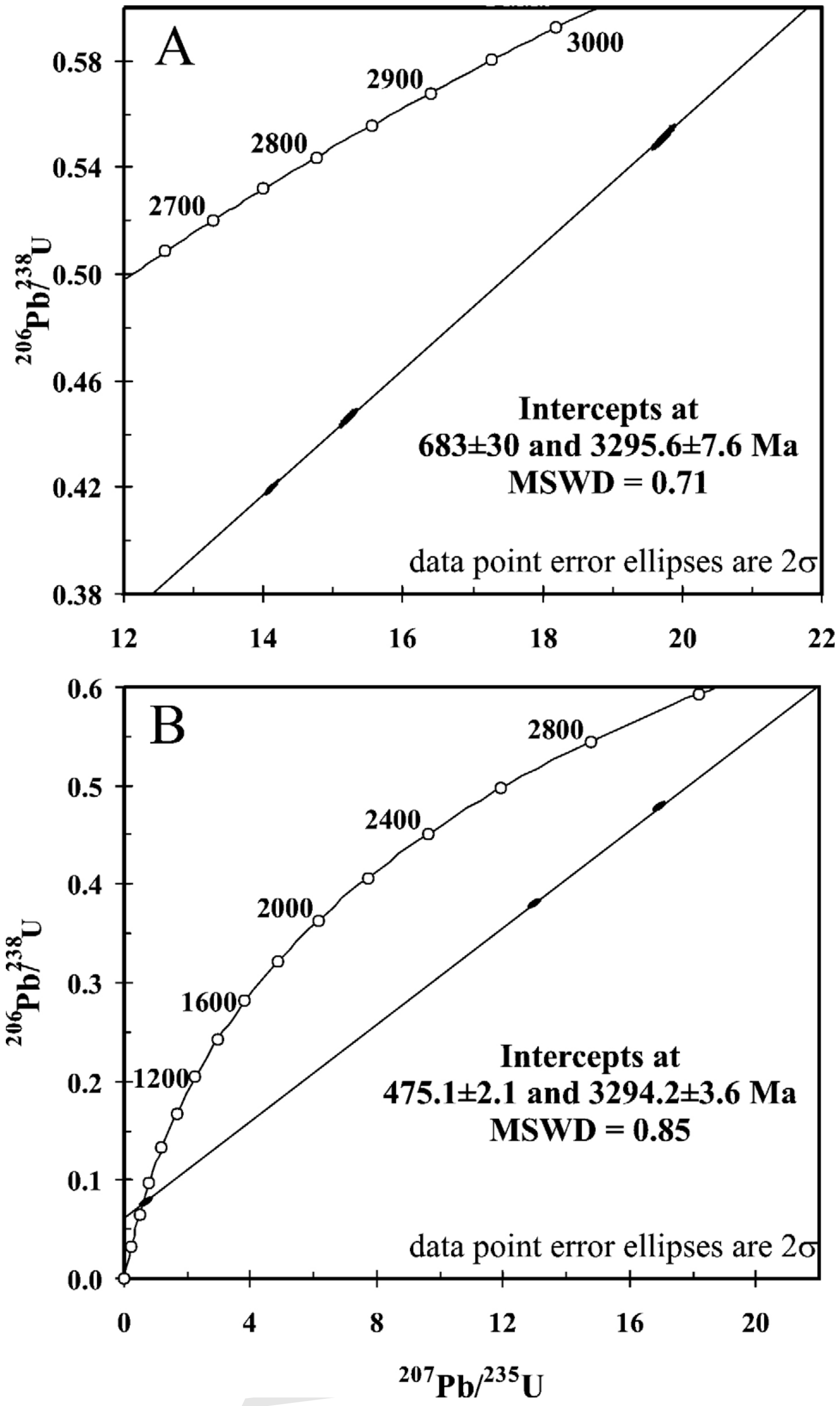

Fig. 2. U–Pb concordia diagrams for the Meeberrie Gneiss. The data are subdivided into two populations with different lower intercepts but similar formation ages. The plot was created using the Isoplot program (Ludwig, 2001).

2.1. U–Pb analyses and age distribution of the zircons

Results of the U–Pb isotope analyses by all techniques are listed in Tables 1 and 3. Analyses of the Meeberrie Gneiss zircon grains are highly discordant, with one concordant analysis indicating a late Phanerozoic age. The mean upper intercept of a discordia line forced though the analyses yields an imprecise age of 3264 ± 33 Ma (MSWD = 151, $n = 6$). However, analyses of the six grains can be subdivided into two distinct groups (three zircon grains each) based on their TIMS U–Pb isotope systematics with each group defining a discordia trend (see Fig. 2) with distinct lower intercepts at 683 ± 30 and 475.1 ± 2.1 Ma, respectively. These lower intercepts

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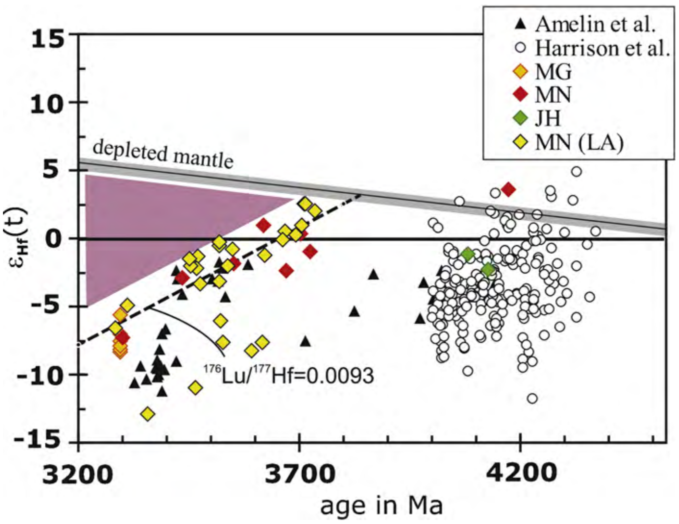

Fig. 3. Hafnium isotope evolution diagram of the Jack Hills (JH), Mt. Narryer (MN) and Meeberrie Gneiss (MG) zircon grains in comparison with published data (Amelin et al., 1999; Harrison et al., 2005; Harrison et al., 2008). Zircons from the Mt. Narryer region show an identical trend in their Hf isotope evolution compared to Jack Hills zircons with a crustal ^{176}Lu/^{177}Hf = 0.0093. CHUR value after Bouvier et al. (2008); depleted mantle is calculated with parameters given in Chauvel and Blichert-Toft (2001) and a decay constant of Scherer et al. (2001).

indicate Pan-African overprinting, as reported elsewhere in Pangea (e.g., Wilde, 1999). The upper intercepts, however, yield indistinguishable ages of 3295.6 ± 7.6 and 3294.2 ± 3.6 Ma, with a mean age calculated from both intercepts of 3294.5 ± 3.2 Ma. This age agrees with an earlier reported U–Pb age of 3296 ± 4 Ma for an event in the Meeberrie unit, and is interpreted as corresponding to the final time of peak metamorphism of the gneiss unit (Kinny et al., 1988). The zircon grains from the Meeberrie Gneiss thus represent a late-stage thermo-tectonic event in the NGC.

Laser-ablation analyses of detrital zircon grains from the Mt. Narryer metasediment yield dominantly concordant ages (Tables 1 and 3) ranging in age from 3299 to 4174 Ma. The two zircon grains from the Jack Hills quartzite yield SHRIMP ^{207}Pb/^{206}Pb ages of 4080 and 4126 Ma. Notably, ID-TIMS analyses of the detrital zircons yield consistently younger ^{207}Pb/^{206}Pb ages when compared to the LA-ICPMS ages. A discordia forced through the ID-TIMS zircon data shows, although very imprecisely, a lower intercept that coincides with the Pan-African lower intercept deduced from the Meeberrie unit. Thus, the TIMS-ages most likely reflect a mixture of an old core and a younger rim. Assuming a Pb loss at ~500–800 Ma (e.g., Dunn et al., 2005; Kinny et al., 1990, this study), the TIMS-ages lie on a discordia with an upper intercept at ~3500 Ma, but with a large uncertainty.

In general, the age distribution of the analysed zircon grains from Mt. Narryer shows a majority of early Archean ages with one zircon of Hadean age. This is in overall agreement with published age distributions for the Jack Hills and the Mt. Narryer sequences with only a small portion of the total sum of all zircon grains being of Hadean age (e.g., Compston and Pidgeon, 1986; Holden et al., in press).

2.2. Hafnium isotope evolution of the NGC

Solution and laser-ablation Hf isotope results are listed in Tables 2 and 4, and displayed in Fig. 3. Most analysed zircon grains from the NGC in the present study yield negative initial $\varepsilon_{Hf}(t)$, which demonstrates that most of the zircon grains formed in an isotopically non-radiogenic reservoir with a low, time-integrated Lu/Hf, typical for continental crust. This observation agrees with previous studies on Jack Hills zircon grains by Amelin et al. (1999), Blichert-Toft and Albarede (2008), Harrison et al. (2005) and Harrison et al. (2008). Analyses of three zircon grains from Mt. Narryer exhibit positive values, with one analysis having a remarkably high value for $\varepsilon_{Hf}(4.2\,Ga) = +4.3$. All zircon grains from Mt. Narryer appear to define two Hf isotopic evolutionary trends. The Hf isotopes of <4 Ga Jack Hills zircon grains reported by Amelin et al. (1999) adjusted using $\lambda^{176}Lu = 1.867 \times 10^{-11}\,yr^{-1}$ (Scherer et al., 2001; Söderlund et al., 2004) lie on similar trends as the zircon grains from the present study (Fig. 3). Two-stage mantle extraction ages (zircon model ages, Tables 2 and 4) calculated using ^{176}Lu/^{177}Hf = 0.0093 (Amelin et al., 1999; Vervoort et al., 1999) are typical of ~3.9 Ga felsic crust and are similar to the major craton-forming event at 3.9 Ga suggested by Shirley et al. (2008) but slightly younger than the major formation event of ~4.1 Ga suggested by Jack Hills zircon grains (Blichert-Toft and Albarede, 2008; Holden et al., in press).

Importantly, the metamorphic Meeberrie unit plots on the same evolutionary trend with all other zircon grains. Three detrital zircon grains have a similar age and Hf isotope composition as the metamorphic Meeberrie zircon grains, suggesting these zircon grains were derived from this unit. Zircon grains were either totally reset at the time of peak metamorphism or newly formed at ~3.3 Ga; nonetheless they still define the same Hf isotope evolutionary trend. Thus, the detrital zircon grains that formed earlier during continuous magmatic or metamorphic activity, as well as Meeberrie zircon grains, can be considered to have formed in one crustal domain and may be genetically related. The depleted mantle extraction age of ~3.8–3.9 Ga can thus be considered as a craton wide event, whereas older zircon grains may have formed in crustal domains with an older pre-history as indicated by their variable Hf isotope composition. Inevitably, the final deposition of the zircon grains after 3.2 Ga included zircon grains that were derived from the Meeberrie Gneiss, implying a partial reworking of this unit. The fact that no younger zircon grains than 3.2 Ga are found is interpreted here as evidence that the 'Meeberrie event' represents the last reworking event in this domain either because of the deposition of the sediment shortly after or because of tectonic and magmatic inactivity.

The second, shallower evolutionary trend defined by the Hf isotope analysed by Amelin et al. (1999) and by our new data suggest that older crust that formed prior to 3.9 Ga was most likely the host for these zircon grains. Hence, in addition to a dominant crust-forming event at 3.9 Ga, reworking of Hadean crust took place throughout the Eo-Archean, such that a Hadean crustal block was subsequently reworked in the Archean and must have survived over hundreds of millions of years.

Until recently, studies on age distributions and trace elements in zircon populations of the NGC metasediments have suggested distinct provenance areas for the sediments of Mt. Narryer and Jack Hills (e.g., Crowley et al., 2005). The study of Pidgeon and Nemchin (2006) revealed a remarkable overlap in age spectra of zircon populations from both locations suggesting similar provenances for these sediments. The combination of zircon Hf isotopes and formation ages provide constraints on source areas of these sediments and their crustal character, i.e., the evolution of the source reservoir from which the zircon grains formed. Fig. 3 illustrates that Hf isotopes in zircon from Mt. Narryer and Jack Hills sediments show no distinction between individual evolutionary paths. Thus, the assumption that Mt. Narryer and Jack Hills sediments has a similar provenance in one crustal domain as argued on the basis of age histograms (Pidgeon and Nemchin, 2006) is supported by the Hf isotope record. Post-depositional histories of the two terranes after 3.2 Ga, however, may have been different, as evident from metamorphic histories preserved in monazites from both localities (Iizuka et al., in press).

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Table 3
U–Pb results of zircons from Mt. Narryer, analysed by LA-ICPMS. Analyses were performed after the method given in Gerdes and Zeh (2007).

Grain	U (ppm)	Pb (ppm)	^{206}Pb/^{204}Pb	^{207}Pb/^{206}Pb	±2s (%)	^{206}Pb/^{238}U	±2s (%)	^{207}Pb/^{235}U	±2s (%)	^{206}Pb/^{238}U	± 2s (Ma)	^{207}Pb/^{235}U	±2s (Ma)	^{207}Pb/^{206}Pb	±2s (Ma)	Conc. (%)
A1	75	80	15,045	0.3263	1.1	0.7649	1.6	34.41	1.9	3662	45	3622	19	3600	16	102
A2	103	107	29,328	0.3250	1.1	0.7700	2.0	34.51	2.3	3681	56	3625	23	3594	17	102
A4	654	571	7927	0.3301	0.6	0.7432	2.3	33.82	2.4	3582	63	3605	24	3617	9	99
A5	589	578	43,535	0.3452	0.6	0.7886	1.8	37.54	1.9	3748	53	3708	19	3686	9	102
A6	230	212	2634	0.3406	1.1	0.7730	1.8	36.30	2.1	3692	51	3675	21	3666	17	101
A7	598	429	8556	0.2997	1.9	0.6209	2.2	25.66	2.9	3113	54	3334	29	3469	30	90
A8	430	354	2833	0.3029	1.0	0.7175	1.9	29.97	2.2	3487	53	3486	22	3485	15	100
A11	315	266	9023	0.3102	1.2	0.7166	1.8	30.65	2.2	3483	49	3508	22	3522	19	99
A12	653	488	16,307	0.2689	0.6	0.6683	1.4	24.78	1.5	3299	36	3299	15	3299	9	100
A13	230	179	13,912	0.3011	0.8	0.6826	1.9	28.34	2.1	3354	50	3431	21	3476	13	96
A14	142	132	18,000	0.3093	0.9	0.7295	2.2	31.11	2.3	3532	59	3523	23	3517	13	100
A15	137	126	4918	0.3094	1.0	0.7240	1.7	30.89	2.0	3511	46	3516	20	3518	15	100
A16	142	119	31,139	0.3001	0.7	0.7155	1.7	29.61	1.9	3479	47	3474	19	3471	11	100
A18	244	219	17,042	0.3153	0.9	0.7267	1.8	31.60	2.0	3521	49	3538	20	3547	13	99
A19	390	326	11,516	0.3093	1.0	0.7141	1.7	30.45	2.0	3474	46	3502	20	3517	16	99
A20	322	247	27,237	0.2709	1.0	0.6715	1.6	25.09	1.9	3312	41	3312	19	3312	16	100
A22	56	54	8016	0.3466	1.0	0.7790	1.9	37.23	2.2	3713	54	3700	22	3692	16	101
A23	168	168	28,818	0.3495	0.8	0.7891	2.1	38.03	2.2	3750	59	3721	22	3705	12	101
A24	194	186	22,235	0.3310	1.1	0.7478	1.9	34.12	2.2	3599	53	3614	22	3622	17	99
A25	282	263	2024	0.3248	1.2	0.7502	1.8	33.59	2.2	3608	50	3598	22	3593	19	100
A26	233	218	7821	0.3297	0.9	0.7370	1.8	33.50	2.0	3559	50	3595	20	3616	13	98
A27	176	171	44,588	0.3409	0.7	0.7765	1.6	36.50	1.8	3704	47	3680	18	3667	10	101
A28	155	138	21,685	0.2994	0.9	0.7155	2.2	29.53	2.4	3479	59	3471	24	3467	15	100
A29	738	639	21,971	0.2968	0.9	0.7070	1.7	28.93	1.9	3447	46	3451	19	3453	14	100
A30	121	144	2408	0.3565	1.2	0.7705	1.7	37.87	2.1	3683	48	3717	21	3735	18	99
A31	257	252	34,279	0.3508	0.9	0.7731	1.7	37.40	1.9	3692	48	3704	19	3711	14	100
A32	61	63	1285	0.3514	1.2	0.7790	1.8	37.74	2.2	3713	50	3713	22	3713	19	100
A34	335	307	13,614	0.3101	0.4	0.7320	1.8	31.30	1.9	3541	50	3529	19	3522	7	101
A35	275	247	2063	0.3114	0.8	0.7162	2.7	30.75	2.9	3482	74	3511	29	3528	13	99
A36	194	163	25,585	0.2960	0.6	0.7225	2.3	29.49	2.4	3505	63	3470	24	3449	10	102
A37	650	572	1047	0.3132	1.0	0.7316	1.7	31.59	1.9	3540	45	3538	19	3537	15	100
A39	703	528	923	0.2662	0.9	0.6620	3.7	24.29	3.8	3275	96	3280	38	3283	14	100
A40	308	264	30,998	0.2987	0.9	0.7274	2.0	29.96	2.2	3524	54	3486	22	3464	15	102
A41	230	188	26,709	0.2786	1.7	0.6819	2.2	26.20	2.8	3352	59	3354	28	3355	26	100
A43	25	26	2972	0.3400	1.5	0.7659	1.8	35.90	2.3	3666	50	3664	23	3663	22	100

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Table 4

Q8 Lu–Hf isotope analyses of Mt. Narryer zircons by LA-MC-ICPMS as listed in Table 2. For details of the isotope analyses see Gerdes and Zeh (2007). Note that the GJ-1 zircon std. is in agreement with solution results reported in Morel et al. (2008). Suffixes ‘gr’ and number refer to grain no. as shown in Fig. 1.

Sample	$^{176}Yb/^{177}Hf^{a}$	$^{176}Lu/^{177}Hf^{a}$	$^{178}Hf/^{177}Hf$	$^{180}Hf/^{177}Hf$	$^{176}Hf/^{177}Hf$	±2s	$^{176}Hf/^{177}Hf_{(t)}$	$\varepsilon_{Hf}(t)$	T_{DM} (Ma)	age (Ma)
A1-gr1	0.0671	0.00127	1.46714	1.88663	0.280551	27	0.280462	0.5	3817	3600
A2-gr1	0.0742	0.00138	1.46702	1.88662	0.280587	27	0.280492	1.4	3765	3594
A4-gr2	0.0561	0.00124	1.46710	1.88650	0.280477	27	0.280391	−1.7	3941	3618
A5-gr7	0.0884	0.00170	1.46710	1.88661	0.280546	26	0.280425	1.2	3849	3687
A6-gr7	0.0552	0.00148	1.46708	1.88675	0.280521	31	0.280416	0.4	3874	3666
A7-gr5	0.0362	0.00084	1.46717	1.88669	0.280500	27	0.280444	−3.3	3903	3469
A8-gr5	0.0325	0.00086	1.46717	1.88675	0.280472	30	0.280414	−4.0	3951	3486
A11-gr3	0.0432	0.00091	1.46703	1.88672	0.280491	28	0.280429	−2.6	3908	3523
A12-gr3	0.0960	0.00204	1.46717	1.88668	0.280544	29	0.280414	−8.4	4023	3300
A13-gr4	0.0685	0.00173	1.46717	1.88645	0.280555	27	0.280439	−3.3	3908	3477
A14-gr4	0.0821	0.00177	1.46704	1.88645	0.280536	33	0.280416	−3.1	3934	3518
A15-gr8	0.0299	0.00060	1.46705	1.88649	0.280529	30	0.280488	−0.6	3803	3519
A16-gr8	0.0354	0.00080	1.46707	1.88658	0.280552	25	0.280499	−1.3	3802	3471
A18-gr9	0.0621	0.00134	1.46697	1.88670	0.280554	29	0.280462	−0.8	3838	3548
A19-gr9	0.0340	0.00076	1.46709	1.88670	0.280547	26	0.280496	−0.3	3789	3518
A20-gr9	0.0343	0.00091	1.46713	1.88660	0.280563	29	0.280505	−4.9	3854	3312
A22-gr10	0.0179	0.00046	1.46710	1.88661	0.280427	30	0.280394	0.3	3904	3693
A23-gr10	0.0277	0.00072	1.46710	1.88654	0.280458	27	0.280406	1.0	3877	3706
A24-gr11	0.0956	0.00209	1.46709	1.88675	0.280547	27	0.280400	−1.2	3921	3622
A25-gr12	0.0359	0.00081	1.46717	1.88641	0.280279	28	0.280223	−8.2	4257	3593
A26-gr12	0.0636	0.00130	1.46702	1.88658	0.280315	28	0.280224	−7.6	4245	3616
A27-gr13	0.0336	0.00060	1.46717	1.88662	0.280457	28	0.280414	2.0	3851	3735
A28-gr14	0.0554	0.00109	1.46711	1.88659	0.280523	24	0.280445	2.5	3803	3711
A29-gr14	0.0309	0.00065	1.46717	1.88649	0.280464	26	0.280418	0.5	3871	3667
A30-gr15	0.0865	0.00176	1.46713	1.88653	0.280594		0.280477	−2.2	3844	3468
A31-gr15	0.0728	0.00144	1.46713	1.88675	0.280587	23	0.280491	−2.0	3823	3454
A32-gr16	0.0371	0.00107	1.46706	1.88662	0.280521	21	0.280444	2.5	3804	3714
A34-gr17	0.0977	0.00262	1.46715	1.88673	0.280510	25	0.280332	−6.0	4086	3522
A35-gr17	0.0781	0.00202	1.46713	1.88648	0.280420	31	0.280283	−7.6	4173	3528
A36-gr18	0.0305	0.00097	1.46710	1.88666	0.280572	28	0.280508	−1.5	3794	3450
A37-gr19	0.0953	0.00235	1.46709	1.88676	0.280596	31	0.280435	−2.0	3892	3537
A39-gr19	0.0894	0.00227	1.46711	1.88672	0.280619	26	0.280475	−6.6	3918	3284
A40-gr20	0.0280	0.00076	1.46714	1.88655	0.280284	29	0.280234	−10.9	4287	3464
A41-gr20	0.0241	0.00070	1.46700	1.88653	0.280297	27	0.280251	−12.9	4297	3356
A43-gr21	0.0372	0.00099	1.46717	1.88682	0.280473	27	0.280403	−0.1	3900	3663
Plesovice ($n=10$)	0.0067	0.00016	1.46714	1.88671	0.282473	21	0.282471	−3.6	1.39	338
GJ-1 ($n=11$)	0.0095	0.00029	1.46711	1.88662	0.282011	21	0.282007	−14.0	2.18	606
JMC 475 ($n=8$)		1.46716	1.88666	0.282159	8					

An important observation is that the 4.2 Ga old zircon with a positive $\varepsilon_{Hf}(t)$ confirms previously reported data by Harrison et al. (2005) of positive ε_{Hf} zircon with Hadean ages and suggests that some of the Hadean zircon grains must have formed in a high Lu/Hf reservoir.

2.3. ID-TIMS vs. LA-ICPMS age corrections for Hf isotopes

Zircon grains that have been analysed by solution ID-TIMS dating have also been dated by LA-ICPMS. For those zircon grains, the Hf isotope character has been determined by solution ID-MC-ICPMS. A second batch of zircon grains have solely been analysed for both U–Pb dating and Hf isotope composition by the laser-ablation technique. Bulk zircon U–Pb dating using ID-TIMS on the same grains that were also dated with LA-ICPMS show predominantly discordant ages using the TIMS technique. Also $^{207}Pb/^{206}Pb$ TIMS-ages are systematically younger than the concordant ages obtained with LA-ICPMS. The reason for this is the spatial resolution of the laser system, which enables sampling only of the cores of the zircon grains. In contrast, the bulk zircon TIMS dating also includes younger overgrowths or altered zircon areas that may or may not reflect recent lead loss. This can have large effects on age distribution patterns of detrital series. Regarding their Hf isotope compositions, the corrections for initial Hf isotopes are rather small due to the low Lu/Hf in zircon grains, and the Hf isotope composition is unaffected by alteration (Gerdes and Zeh, 2007). Nevertheless, different apparent formation ages will result in small variations in the initial ε_{Hf} of the zircon grains. This can result in a shift of a single zircon in an Hf isotope evolution plot, which may result in different geologic interpretations. To illustrate the effect on a zircon population from a single crustal reservoir, we calculated the initial Hf isotope character of each zircon with both the TIMS and the LA-ICPMS dating technique. Fig. 4 presents the offset of each grain in initial Hf isotopes vs. apparent age. As indicated

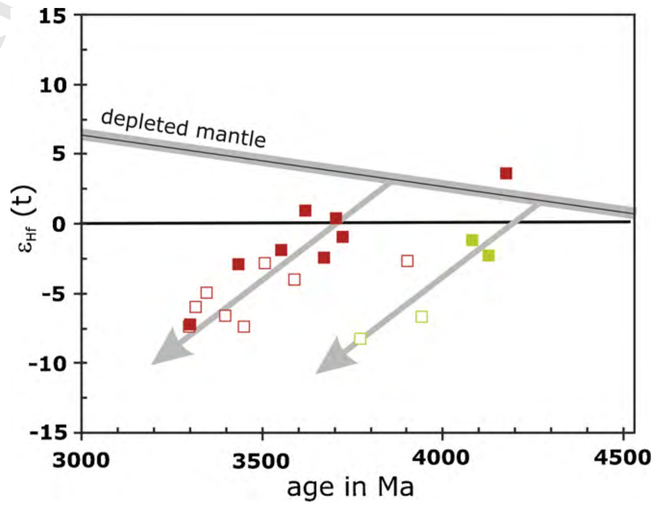

Fig. 4. Comparison of Hf isotope compositions of the Archean zircon grains calculated with core analyses using the laser-ablation and SHRIMP technique (filled symbols) vs. TIMS (open symbols).

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by the figure, the shift of each analysis is following the evolutionary trend of the host reservoir. Consequently, zircon populations that form a trend in Hf isotopes vs. crystallization age will not only exhibit younger ages if minimum $^{207}\text{Pb}/^{206}\text{Pb}$ ages are used, but will also be shifted in the evolution diagram in Hf isotopes *along* the trend. The reason for this is a mixture of core and rim of a zircon (see Fig. 1) that, when displayed in age vs. Hf isotopes, will plot along the same evolutionary trend as obtained by analyses of different growth zones of the same zircon. Therefore, the evolution trend inferred from the zircon population points towards a depleted mantle/BSE extraction model age that is not shifted in time. This, however, is only applicable to zircon grains that experienced Pb loss and no overgrowth with variable U/Hf (Harrison et al., 2005). If these criteria are met, our data imply that geologic interpretation in provenance studies or crustal evolution studies based on Hf isotopes in a zircon that experienced U–Pb isotope disturbance will still yield useful geologic information. Especially within a single population, these zircon grains can potentially be used to constrain an evolutionary trend. For single zircon grains, however, an average crustal or mafic parent-daughter ratio needs to be assumed to calculate mantle extraction model ages (Nebel et al., 2007). The limitations of this technique, as well as the large uncertainties in such trends, should be considered when it comes to geologic interpretations. For small zircon grains, high-precision solution analyses of Hf isotopes are preferred, because the small analytical variability in Hf isotopes compared to the in situ technique may yield more precise model age calculations, i.e., back calculation towards a depleted mantle reservoir shows less scatter. For the Jack Hills population, the pioneering Hf isotope study by Amelin et al. (1999) using the TIMS dating techniques may be biased in a similar way. As a consequence, the analysed zircon grains by Amelin et al. (1999) may in fact be somewhat older. However, as demonstrated here, in an Hf isotope evolution diagram, these zircon analyses fall on a similar crustal evolutionary trend suggesting that the geologic interpretation is correct. The randomly picked zircon population analysed by laser-ablation in this study also falls on the same evolutionary trend as all other zircon analyses, which strongly supports the above approach.

2.4. Implications for the evolution of the early Earth

The Hf isotope evolution trends defined by the populations of zircon analyses can be used to define a Lu/Hf ratio that is representative of the crustal source the zircon grains formed in. The $^{176}\text{Lu}/^{177}\text{Hf}$ of $\leq$0.01 defined by the Hf isotope evolution recorded in the zircon grains from Mt. Narryer and the Jack Hills (Fig. 3) that are <4 Ga are typical for average present day continental crust (Vervoort and Patchett, 1996a). The different aged zircon grains that form this evolutionary trend are attributed to continuous magmatic/tectonic activity over hundreds of millions of years. As such, this continental crustal domain persisted for the time of this magmatic activity. The timing of mantle extraction of this crust, however, is difficult to assess. It is important to note that for zircon grains with ages <4 Ga, each zircon's host reservoir had a potentially different Lu/Hf. Likewise, each individual zircon Hf datum yields different model ages, and the scatter in model ages only broadly constrains the time of mantle extraction of the crust the zircon grains all formed from. Nevertheless, the trend defined by the group of zircon grains and with them the greater crustal domain they formed in appears to have an average formation model age of ~3.8–3.9 Ga. This overall uniform trend with little scatter forming a single trend in age vs. Hf isotope evolution space not only defines the mantle extraction age but also argues for a closed system with internal recycling in one crustal domain or several smaller crustal domains in close proximity to each other. The nature of this recycling, however, is difficult to assess.

It has been argued that Hadean NGC zircon grains either formed by crustal reworking accompanied by subduction activity (e.g., Harrison, 2009) or by re-melting of tonalite-trondjemaite granodiorites (TTG) from deep-rooted mafic successions (Blichert-Toft and Albarede, 2008). From the zircon data alone, both scenarios can explain the Hf isotope record. Based on our data set, we see evidence for continuous magmatic activity that is associated with reworking of existing crust as can be inferred form the evolutionary trends in Hf isotopes. Thus, we favour a scenario with quick subduction in the early Archean Eon. Likewise, in order to explain variable Lu–Hf ratios that are needed for the small deviations from a single trend in the Hf isotopes in Fig. 3, the crustal zircon host rocks probably exhibit a mixture of dominantly older, felsic crust (i.e., low Lu/Hf), and small parts of fresh, mantle-derived mafic (i.e., high Lu/Hf) components, which is typical for subduction-related rocks.

For the two Jack Hills zircon grains analysed here, the zircon Lu–Hf model ages result in ages of 4.26 and 4.35 Ga using a $^{176}\text{Lu}/^{177}\text{Hf} = 0.0093$, in overall agreement with age distributions of Hadean zircon grains. Therefore these early zircon grains must have formed in a reservoir with a similar or even lower Lu/Hf than the younger zircon grains discussed above, i.e., with ages <4 Ga. This is also indicated by the shallow evolutionary trend of reworked Hadean crust as preserved in the Archean zircons <4 Ga. The most likely reason for this feature is that the very early crust on Earth in the first 200–300 Myrs was formed in a different way than the crust that formed afterwards. Possible explanations are much quicker subduction with higher thermal gradients in buoyant subduction zones, such as rapid reworking of existing crust due to early plate tectonic activity (cf. Foley, 2008) and resultant very low Lu/Hf. In addition, crustal formation after early magma ocean crystallization may have been predominantly controlled by melting reservoirs with residual garnet, resulting rocks such as e.g., TTGs (Blichert-Toft and Albarede, 2008), could have provided a reservoir with a very low Lu/Hf in which the NGC zircon grains could have been formed. Details on subduction mechanism to create such low $^{176}\text{Hf}/^{177}\text{Hf}$, however, are yet to be investigated.

An open question remains; was the crust in the early Archean formed by continuous processes or in episodic pulses? Based on the zircon age record between 4.0 and 3.3 Ga, it can be argued that the crustal reservoir in which the zircon grains formed show continuous thermo-tectonic activity. On the other hand, age distributions may be biased by the false assumption that $^{207}\text{Pb}/^{206}\text{Pb}$ ages reflect the actual formation age of these zircon grains. Nevertheless, given the large data set published on early Archean and in particular Hadean ages from the NGC (Amelin et al., 1999; Blichert-Toft and Albarede, 2008; Compston and Pidgeon, 1986; Crowley et al., 2005; Dunn et al., 2005; Froude et al., 1983; Harrison et al., 2005; Kinny et al., 1988; Maas et al., 1992; Nemchin et al., 2006; Pidgeon and Nemchin, 2006; Pidgeon and Wilde, 1998; Wilde et al., 2001), it is unlikely that age gaps can be hidden in the zircon record that represent times of magmatic quiescence. In addition the trends observed in Fig. 3 indicate a continuous process of reworking. Our interpretation of the available data is that the majority of the NGC <4 Ga zircon grains were formed continuously within an isolated, single source, as evident from the single Hf isotope evolution trend that was extracted from the depleted mantle at ~3.9 Ga. In a second isolated reservoir a Hadean component must have been reworked to form the second trend in Hf isotopes. The available data show a gap of newly formed zircon grains with juvenile Hf isotope compositions that fall on the trend in Fig. 3 (see pink field in Fig. 3). (For interpretation of the references to colour in text, the reader is referred to the web version of the article.) This source was thus most likely separated from a slowly evolving depleted mantle by ~3.8–3.9 Ga, and no new crust was extracted from the mantle in this particular domain.

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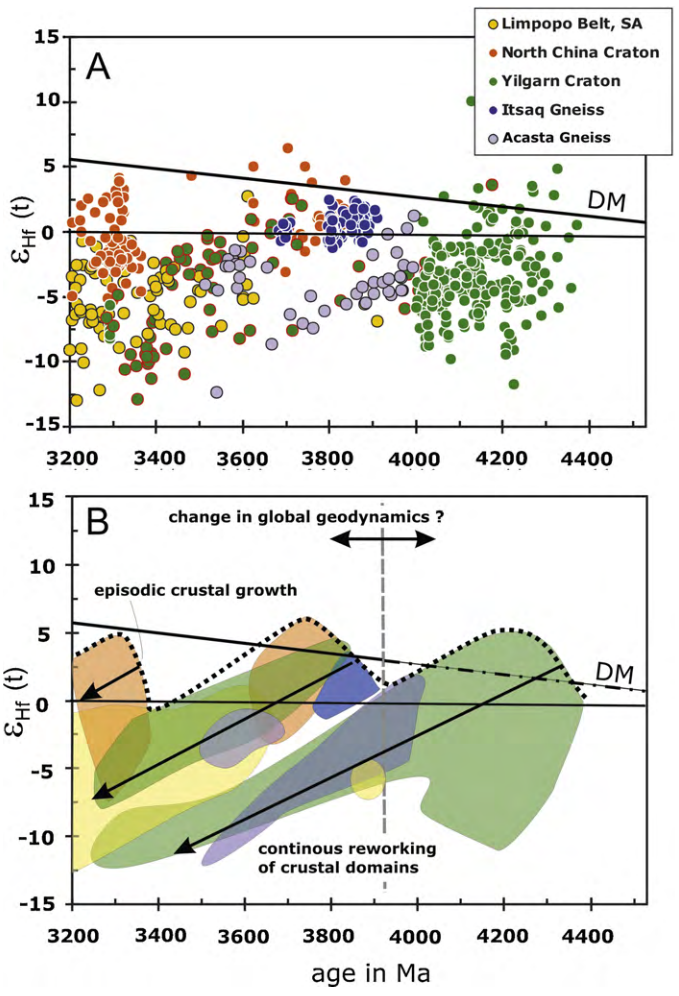

Fig. 5. (A) Compilation of Hf isotopes in Archean and Hadean zircons from global localities. The distribution of zircons indicates the extraction of crustal domains took place at 3.8–3.9 Ga and at 3.2–3.3 Ga. Data source: Acasta: (Iizuka et al., 2009); North China Craton: (Wu et al., 2008); Limpopo Belt: Zeh et al. (2008); Itsaq gneiss: Hiess et al. (2009), Australia: Amelin et al. (1999); Blichert-Toft and Albarede (2008); Harrison et al. (2005), this study. (B) The reworking of Hadean (i.e., >4 Ga old) crust is evident from the trend defined by Archean zircons from Acasta and the Yilgarn craton, indicating either a common history for both regions or amalgamation at ~4.0 Ga. The dashed line indicates the Hf isotope nature of the mantle source from which the domains have been extracted. The difference between the 'chaotic' distribution in Hadean zircons and the more linear trends in post-Archean time indicates a change in global dynamics. Note that the average, age-corrected depleted mantle cannot be extrapolated to the Hadean, and requires a non-linear trend in its infant stadium.

This may indicate that the craton-forming event is constrained to 3.9–3.8 Ga.

One notable feature of Archean vs. Hadean zircon populations is that the Hadean zircons show a chaotic distribution, whereas younger, Archean zircon grains tend to follow evolutionary trends. Even the zircon grains that reflect the reworking of this Hadean component tend to follow a controlled reworking mechanism. If sample bias can be excluded, this points to a major change in crustal dynamics at the end of the Hadean with initial chaotic reworking of early crust in the Hadean eon, and controlled reworking within cratonic domains afterwards (Fig. 5).

3. Comparison with other Archean terranes

The distribution of zircon dates between ~3.7 and 3.3 Ga shows a clear deficit of zircon grains with non-radiogenic (i.e., mantle-like) Hf isotope compositions (see dashed line in Fig. 5 and pink triangle in Fig. 4). A similar distribution with an absence of mantle-derived zircons have been observed by Pietranik et al. (2008) for a large range of global terranes. From this it seems likely that crustal growth took place in episodic pulses of ~400 Myrs, with extraction of these domains from the mantle, and subsequent reworking of these terrains without significant extraction of mantle melts. A comparison with recently published Hf isotopes in zircon from other Archean terranes (Fig. 5) confirms this trend for the Eo-Archean period. Remarkable is the consistency of Hf isotopes along single evolutionary trends within one domain in their initial Hf isotopes vs. time (Fig. 5). Those trends or single clusters within one domain may reveal possible relationships within these terranes. As noted by Zeh et al. (2008), two zircon grains from the Limpopo belt show an overlap with the 'shallow' crustal evolution trend defined by Jack Hills/Mt. Narryer zircon analyses that is interpreted here as a reworking of previous Hadean crust. However, because only two zircon grains plot within this trend, distant transportation of these zircon grains or an independent, single magmatic event are more likely explanations rather than a co-genetic origin. For the trend starting at ~3.9 from the depleted mantle, however, the Limpopo samples appear to share a Hf isotope evolutionary history with the Australian zircon grains, which argues for a formation of the Limpopo craton at ~3.9 Ga. In contrast, the Acasta region in Canada shows a remarkable overlap with the Australia samples for the trend away from the Hadean zircon grains, and a cluster of igneous zircon grains in the mantle extraction trend. From this, a coupled evolution since ~4.0 Ga of both domains is likely, and an older source can predicted for the North Canadian locality. Other craton locations, such as the North China craton, or the Itsaq Gneiss in Greenland show generally similar magmatic activity at 3.9 Ga, with enhanced mantle-derived zircon formation in the North China Craton at ~3.3 Ga. However, the data represent either single igneous events, or are too sparse to allow correlations. Enhanced zircon formation from mantle-derived melts in all Archean localities at least points to a global craton formation event at 3.9 Ga. The difference in Archean terranes can be used to argue that multiple, geographically separated deposition areas existed in the early Archean. Alternatively, these domains were connected at ~3.9 Ga in a larger, single cratonic domain.

4. Conclusions

Combined U–Pb–Lu–Hf isotope investigations of zircons from metasedimentary units from Mt. Narryer and the Jack Hills show that both localities had a similar sedimentary provenance. One 4.2 Ga Mt. Narryer zircon shows a positive $\varepsilon_{\mathrm{Hf}}(t)$, proving the existence of a high Lu/Hf reservoir relative to BSE at this time in Earth's history, in agreement with earlier reported, positive Hadean $\varepsilon_{\mathrm{Hf}}(t)$ values (Harrison et al., 2005).

The Hf isotope evolutionary trend defined by the <4 Ga zircon analyses indicates that this provenance area corresponds to a crustal domain that was separated from a depleted mantle reservoir at ~3.8–3.9 Ga, and further evolved with a time-integrated ^{176}Lu/^{177}Hf of ~0.01, characteristic of continental crust. Uranium–lead upper discordia ages of zircon grains from the Meeberrie Gneiss show an absolute formation age of 3294.5 ± 3.2 Ma and later Pan-African thermal overprints at ~500 and ~700 Ma. Together with Hf isotope data, the 3.3 Ga event marks a major Archean thermo-tectonic event in the NGC terrane, in which the Meeberrie Gneiss formed from previously existing NGC material. Imprecise lower intercepts of discordant ID-TIMS analyses of detrital Mt. Narryer zircon grains coincide with the Pan-African overprints observed for the Meeberrie Gneiss, which argues for Pan-African U–Pb isotope disturbance for most of the NGC zircon grains analysed so far. The effect of age biases among ID-TIMS vs. LA-ICPMS or

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SHRIMP core analyses is negligible because zircons fall on a similar evolutionary trend in Hf isotopes vs. age.

The progressive formation of zircons, which follow a single Hf isotope evolutionary trend over a ~1 Ga period, suggests continuous reworking of crustal material within a single crustal domain. This was a continuous process in early Earth history where zircon formation was coupled to magmatic and/or metamorphic activity within one crustal domain that formed out of the depleted mantle. A second, shallower evolutionary trend shows that a single Hadean crustal domain that provided most of the Hadean zircon grains survived through the Archean and was continuously reworked. Similar trends are only observed from the Limpopo belt (two zircons only) and the Acasta Gneiss in Canada. For the latter, a Hadean protolith is required similar to the Australian source, whereas other Archean domains show no evidence for any Hadean contribution by crustal reworking.

For Hadean (>4 Ga) zircon grains, an even lower Lu/Hf is required to explain their non-radiogenic Hf isotope evolution, assuming these zircons formed from a mantle reservoir. Whether or not zircon host rock formation >4 Ga was triggered by subduction activity throughout the Hadean remains unresolved. However, the chaotic distribution of these zircons in Hf isotopes vs. age argues for prolonged magmatic activity with crustal reworking, possibly related to geotectonic dynamics different from today. In contrast, following the Hf isotopes distribution of zircons <4 Ga, subduction activity and associated crustal reworking similar to present day conditions are most likely.

Q5 Uncited reference

Blichert-Toft and Albarede (1997).

Acknowledgements

Frank Tomaschek is kindly thanked for providing the Mt. Narryer zircons for this study. Heidi Baier is kindly thanked for laboratory assistance. We also thank Kai Klama, who helped with laser-ablation analyses in Frankfurt. Jan Wijbrans is thanked for discussion and Jeremy Wykes is kindly thanked for thoughtful comments on the manuscript. Comments from two anonymous reviewers greatly improved the clarity of our argumentation. Wulf Mueller (deceased) and Peter Cawood are thanked for editorial handling.

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