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Hadean crustal evolution revisited: New constraints from Pb–Hf isotope systematics of the Jack Hills zircons

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ABSTRACT

Detrital zircon crystals from the Jack Hills metasedimentary belt, Western Australia, are the only surviving vestiges of Hadean crust and represent an extraordinary archive into the nature of the early Earth. We report the results of an in situ isotopic study of 68 Jack Hills zircons in which the Hf and Pb isotope ratios were measured concurrently, allowing a better integration of isotope tracer information ($^{176}Hf/^{177}Hf$) with crystallization age ($^{207}Pb/^{206}Pb$). These data are augmented by Hf isotope data from zircons of the surrounding Narryer gneisses (3.65–3.30 Ga) and from Neoarchaean granites that intrude the Jack Hills belt. The detrital zircons define a subchondritic ε_{Hf}–time array that attests to a far simpler evolution for the Hadean Earth than claimed by recent studies. This evolution is consistent with the protracted intra-crustal reworking of an enriched, dominantly mafic protolith that was extracted from primordial mantle at 4.4–4.5 Ga, perhaps during the solidification of a terrestrial magma ocean. There is no evidence for the existence of strongly depleted Hadean mantle, or for juvenile input into the parental magmas to the Jack Hills zircons. This simple Hf isotope evolution is difficult to reconcile with modern plate tectonic processes. Strongly unradiogenic Hf isotope compositions of zircons from several Archaean gneiss terranes, including the Narryer and Acasta gneisses, suggest that Hadean source reservoirs were tapped by granitic magmas throughout the Archaean. This supports the notion of a long-lived and globally extensive Hadean protocrust that may have comprised the nuclei of some Archaean cratons.

1. Introduction

There is mounting evidence for extensive differentiation of the terrestrial planets within the first few million years of their accretion. This process generated crustal material as seen in some meteorite suites (Tera et al., 1997), on the moon (Norman et al. 2003; Nemchin et al., 2008; Edmunson, et al. 2009), and on Mars (Borg et al., 1997). Evidence for early differentiation of the silicate Earth is largely in the form of elevated $^{142}Nd/^{144}Nd$ ratios detected in a range of crustal and mantle-derived rocks (Caro et al., 2003; Boyet and Carlson, 2005; Bennett et al., 2007). These ^{142}Nd anomalies may signal the formation of an incompatible element depleted mantle with superchondritic Sm/Nd within the first 30–75 million years of Earth history (Boyet and Carlson, 2005; Bennett et al., 2007), which predates the extant rock record by 500 million years. The generally unradiogenic hafnium isotope composition of the oldest terrestrial minerals, detrital zircon crystals from the Jack Hills of Western Australia (Froude et al. 1983; Compston and Pidgeon, 1986; Wilde et al., 2001), point to the existence of a complementary 'enriched' reservoir by 4.3 Ga (Amelin et al., 1999) or even earlier (Harrison et al., 2005, 2008; Blichert-Toft and Albarède, 2008). An ancient 'protocrust' formed at or before 4.3 Ga has also been invoked to explain the Pb isotope variability of Archaean cratons (Kamber et al., 2003). Yet, the volume and composition of the Hadean crust, how long it persisted, and under what geodynamic conditions it formed, all remain enigmatic and contentious issues. Scenarios range from a voluminous granitic continental crust shaped by plate tectonics (Armstrong, 1981; Bowring and Housh, 1995; Harrison et al., 2005, 2008), to a single-plate basaltic 'protocrust' (Kamber et al., 2005; Nemchin et al., 2006) that accumulated after solidification of a global magma ocean (Kramers, 2007). Hafnium isotope systematics of the Hadean zircons can help constrain the composition of their protoliths (e.g. Amelin et al., 1999), but this approach is clouded by complex age distributions in the grains and the difficulty of reliably associating Hf isotope ratios with the time of zircon crystallisation. Debate continues

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Table 1
A summary of the concurrent Pb–Hf isotope data for the Jack Hills detrital zircons analysed during this study (OZ, oscillatory zoning; SZ, sector zoning). Analyses with asterisks were used for the regression in Fig. 6. Analytical uncertainties for $\varepsilon_{Hf}(t)$ combine the within-run errors in interference-corrected $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ and uncertainties in $\lambda^{176}Lu$ and $^{207}Pb/^{206}Pb$ age, the latter also incorporating the reproducibility of bracketing NIST610 analyses and the uncertainty in the Pb isotope composition of this material. No common lead corrections were made. Epsilon Hf values are calculated using the 176Lu decay constant of Söderlund et al. (2004) and relative to the chondritic parameters of Bouvier et al. (2008); these yield ε_{Hf} values for the oldest Jack Hills zircons that are 0.7 units higher than those derived with the CHUR values of Blichert-Toft and Albarède (1997). Full analyses are listed in supplementary Table 2.

Grain/spot	CL zoning	Age (Ma)	±2σ	$\varepsilon_{Hf(t)}$	±2σ
JH17					
1.1	Planar, contorted	4112	8	−3.8	0.9
1.2	Dk, contorted	4078	13	−3.9	1.1
2.1	Dk, vague OZ	4102	21	−1.6	1.1
3.1	Light, OZ**	4101	2	−4.3	0.9
5.1	Contorted	3926	10	−7.2	0.9
6.1	OZ core**	4090	5	−3.8	0.8
6.2	OZ core**	4084	2	−4.1	0.8
6.3	OZ overgrowth**	4090	8	−3.8	0.7
7.1	Light, contorted	3931	23	−7.7	0.9
7.2	Unzoned	3991	17	−7.0	0.7
7.3	Unzoned	4067	3	−4.3	0.7
8.1	Dk, contorted	3967	26	−6.5	0.8
8.2	Dk, contorted	3889	30	−9.1	1.1
9.1	Vague fir−tree	4090	3	−1.9	0.8
9.2	Vague fir-tree	4068	3	−3.2	1.0
10.1	Irreg., contortion	3944	9	−7.6	1.1
10.2	Irregular planar	3873	20	−10.4	0.8
11.1	OZ, SZ**	4073	5	−4.7	0.9
11.2	OZ, SZ**	4061	4	−5.3	0.7
13.1	Dk, contorted	4134	2	−4.5	0.7
13.2	Broad irregular	4129	3	−3.6	0.9
14.1	Dk banded core	4106	1	−2.9	0.6
14.2	Rim, broad zoning	4065	7	−3.9	0.8
15.1	Dk, broad banding	4089	1	−4.0	0.8
16.1	Dk, irreg. banding	3932	6	−5.6	0.8
17.1	Dk, patchy	3869	1	−4.3	0.8
17.2	Dk, patchy	3838	6	−5.4	0.9
18.1	OZ core**	4296	35	−1.4	2.0
18.2	OZ core**	4236	5	−3.0	1.7
19.1	Dk OZ core**	4063	2	−3.8	0.9
19.2	Broad banding	3989	16	−4.0	1.6
20.1	Irreg dk banding	4083	2	−2.0	0.9
20.2	Irreg dk banding	4082	4	−2.7	0.6
21.1	Faint OZ	3957	6	−5.9	0.7
21.2	Unzoned	3910	10	−7.8	1.1
22.1	OZ**	4021	2	−2.8	0.7
23.1	OZ**	4018	8	−3.2	0.8
24.1	Dk, contorted	4102	4	−3.5	0.7
24.2	Contorted zoning	4063	9	−4.3	0.6
25.1	Vague, irreg OZ	3934	9	−7.3	0.7
26.1	Irreg. OZ rim	4015	45	−6.2	0.9
26.2	Dk core, contorted	3841	7	−9.9	0.9
28-1	OZ core**	4139	9	−3.2	0.6
30	Dk, OZ tip**	3886	7	−4.6	0.7
32.1	Dk, OZ fragment**	4153	6	−3.2	1.1
33.1	Irreg OZ rim	4011	4	−3.4	0.6
35.1	OZ core, contorted	4013	9	−5.8	0.6
35.2	Unzoned rim	3982	6	−4.1	1.0
36.1	Dk, relict OZ	4021	3	−3.9	0.9
37.1	Irreg. broad banding	3950	6	−8.1	0.8
38.1	Dk, faint relict OZ	4064	10	−5.7	1.3
39.1	Unzoned	4002	8	−7.4	1.2
40.1	Sharp OZ**	4263	6	−3.6	0.7
40.2	Sharp OZ**	4240	7	−3.8	0.9
40.3	Sharp OZ**	4277	1	−3.0	0.7
41	OZ core, some irreg.**	3910	25	−6.7	0.7
42	Unzoned	3965	32	−7.8	0.9
43	Unzoned	4039	8	−1.8	0.9
44.1	Dark, irregular	4019	3	−1.3	0.7
44.2	OZ rim, patchy	4042	3	−2.2	0.9
JH14					
190.1	Dk core, planar	4295	12	−3.8	1.6
190.2	Unzoned overgrowth	4171	5	−4.1	0.8
159.1	Dk OZ core	4174	21	−3.9	2.2
159.2	OZ rim	3414	9	−10.8	0.5
175.1	Sharp OZ, core**	4098	12	−4.0	1.1
155.1	Broad OZ core**	4015	4	−2.9	1.1
94.1	Dk core, convolute	3938	25	−5.3	1.2
91.1	Faint OZ	4071	11	−3.2	0.9
84.1	Broad banding	4122	7	−3.8	2.7
82.1	Broad banding	3929	24	−5.9	0.4
102.1	Dk, irreg zoned	4138	11	−3.4	0.8
117.1	Remant OZ core	4255	11	−2.8	1.8
117.2	Dk overgrowth	3930	45	−4.6	0.7
117.3	Tip, irregular zoning	4010	20	−5.9	0.7
118.1	Bright, irreg. zoning	3986	4	−4.3	1.1
149.1	Broad banding	4065	4	−2.5	1.3
113	Broad, irreg. banding	4004	4	−4.2	0.8
8	Irreg. OZ	4100	30	−6.4	1.0
33	Remnant, irreg. OZ	4225	4	−3.2	0.5
206.2	Broadly OZ rim	3369	51	−9.1	2.0
292.1	Dark, OZ**	4053	6	−2.3	1.3
128	Broad banding	3744	19	−6.8	2.3
148	Broad irreg banding	3989	19	−4.2	0.7
79	Irreg broad banding	4094	4	−3.7	0.7
32	Unzoned	3960	3	−7.8	0.6
68	Broad, irreg banding	3998	13	−6.0	1.0
218	Dark, OZ**	4017	1	−4.2	1.2
216	Bright, core	4017	1	−5.3	0.8
310	Dark core, contorted	4004	4	−5.0	0.8
309	Core, remant OZ	3801	50	−5.7	0.8
206	OZ core	3750	93	−10.3	2.3
234	Dark, fine OZ**	3903	11	−5.9	0.9
247	Faint, fine OZ	3981	3	−2.9	0.8
305	Irreg. planar zoning	3866	23	−5.1	1.3
276-1	OZ core**	4069	3	−2.3	0.9
276-2	OZ core**	4026	5	−4.5	0.9

on whether the extreme Hf isotope heterogeneity reported for the Jack Hills zircons reflects complex crust–mantle interaction and recycling processes consistent with plate tectonics (Harrison et al., 2005, 2008) or is simply an artefact of incorrect age assignment (Valley et al., 2006).

Here, we report the results of an isotopic study of the Jack Hills detrital zircons where the Pb and Hf isotope ratios are measured by laser ablation MC-ICP-MS concurrently with high spatial resolution (40–50 µm spots), allowing a more robust integration of age and isotope tracer information (Woodhead et al., 2004; Kemp et al., 2009a). These data are augmented by the first Hf isotope data, obtained by both laser ablation and on purified solutions, from zircons of meta-igneous rocks (3.65–2.65 Ga) that surround the Jack Hills belt. The goal is to evaluate the degree of Hf isotope heterogeneity in the Hadean Earth, constrain the timing of crust formation and the composition of this crust, and to test whether Hadean crustal sources were sampled by younger magmas. The new data define a much simpler Hf isotope evolution than seen in previous studies of the Jack Hills zircons. These data attest to the formation of a dominantly mafic protocrust at 4.4–4.5 Ga that underwent repeated remelting during the Hadean period.

2. Sample details

The ~70 km-long Jack Hills metasedimentary belt lies within the Narryer terrane near the northern periphery of the Archaean Yilgarn Craton, Western Australia (Wilde and Spaggiari, 2007). The belt comprises a multiply deformed succession of clastic metasedimentary rocks, chert and banded iron formations and mafic–ultramafic lenses overprinted by greenschist to low amphibolite facies metamorphism (Spaggiari et al., 2007). These units are in tectonic contact with Eo- to Mesoarchaean granitic gneisses (the Narryer Gneiss Complex, Kinny et al., 1988; Pidgeon and Wilde, 1998), and are intruded to the south