Precambrian Research 182 (2010) 175–186

Contents lists available at ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

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

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 Ma 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 zircon grains. 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 zircon grains implies a similar crustal source for both sediments in a single, major crustal domain. Age spectra and associated Hf isotopes in the zircon grains 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 zircon grains 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 gneiss (Canada) shows a similar reworking patterns 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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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.

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 metaconglomerate. In combination with published data, these data are used to constrain possible relationships of the three different units, 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, 2009) 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).