Lithos 190–191 (2014) 313–327

Contents lists available at ScienceDirect

Lithos

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

Invited review article

The role of detrital zircons in Hadean crustal research

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ARTICLE INFO

Article history:
Received 23 August 2013
Accepted 15 December 2013
Available online 22 December 2013

Keywords:
Hadean
Archean
Jack Hills
Narryer
Hf-in-zircon
Crustal formation

ABSTRACT

Meso-Archean sedimentary sequences at Mt. Narryer and the Jack Hills of the Narryer Terrane in Western Australia's Yilgarn Craton contain detrital zircon grains with ages as old as 4.37 Ga, the oldest preserved terrestrial matter. These grains are rare remnants of Hadean (4.5–4.0 Ga) terrestrial crust and their survival stems from the crystallographic properties of zircon during crustal reworking: they are resistant to physical and chemical weathering. Zircons are further suitable for single grain, precise age determinations making them a unique archive of the crustal past. Only a small proportion of all detrital zircons from the Narryer Terrane show Hadean age spectra and younger overgrowth rims on all 'Hadean' grains indicate multiple recycling events. Numerous studies that applied a spectacular range of analytical tools and proxies have been undertaken to decipher the geochemical nature of these zircons' host rocks, in order to place constraints on Hadean geodynamics and the processes responsible for creating the earliest terrestrial crust. Their elemental and isotope budget and mineral inclusions have helped to develop an emerging picture of a water-rich, evolved Hadean crust. However, subsequent studies have challenged this view and it seems that each piece of new evidence indicative of an early, evolved continental crust has non-unique interpretations also permissive of mafic to ultra-mafic crust. In this review we examine these disparate interpretations and their possible implications and conclude that at least parts of the earliest terrestrial crust were hydrated. However, to date there is no conclusive evidence for preserved granitic, continental crust. The protoliths of the Hadean detrital zircons were likely acidic in nature, yet the composition of the greater terrane from which these melts were derived was probably mafic. It remains unclear if the zircons formed in a geodynamic environment that includes Hadean subduction. We suspect that the Hadean crust was an initially homogeneous, thin, mafic layer. It was spiked with minor, low-degree, anatectic melts of granitoid composition formed from material that formerly resided at the surface and was subsequently buried. The process responsible for this was likely sag-subduction triggered by repeated volcanic resurfacing, possibly fed by early mantle plumes. Regional scale granitoid plutonism of the tonalite–trondhjemite–granodiorite suite (TTG) predominates granitoid-generating processes in the Eo-Archean, along with the first appearance of low-Ca (s-type) granites at around 3.9 Ga, evidenced by the first occurrence of detrital monazite in the Narryer Terrane. This coincides with the first addition of juvenile crust as documented by the global detrital zircon record and temperature signatures of the late heavy bombardment in Narryer Terrane zircons. This age probably marks the onset of Archean-style tectonics, likely associated with subduction activity, which lasted until ~3 Ga, when modern style plate tectonics emerged.

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0024-4937/$ – see front matter
http://dx.doi.org/10.1016/j.lithos.2013.12.010

1. Introduction

The Hadean aeon (4.5–4.0 billion years ago) postdates the accretionary period of collisions of asteroids and planetesimals to form the proto-Earth (Gargaud et al., 2013; Goldblatt et al., 2010). Current models and timescales of core formation (Rudge et al., 2010) and magma ocean solidification (Elkins-Tanton, 2008) suggest that these processes were already completed in the Chaotian (>4.5 Ga), predating the Hadean (Goldblatt et al., 2010). During this period, Earth gained most of its present day mass and a first crust covered the early Earth under a faint young sun (e.g., Shaw, 2008). During the Chaotian or shortly after, proto-Earth experienced the putative Moon-forming giant impact (e.g., Halliday, 2008; Touboul et al., 2007) and subsequently, additional extra-terrestrial material was still being delivered by meteorites and asteroid impacts, evidenced by the lunar cataclysm (Tera et al., 1974), including the late veneer (Kimura et al., 1974; Pattou et al., 1996) and the late heavy bombardment (e.g., Gomes et al., 2005). However, the process that dominated the Hadean aeon was crust–mantle differentiation from a primitive mantle (PM/bulk silicate Earth, BSE) reservoir (e.g., Allègre et al., 2008) and along with this the shaping of the first, stable terrestrial crust. Whereas the Earth's mantle preserved the memory of differentiation events in the Hadean in short-lived isotopes as e.g., ^{146}Sm-^{142}Nd (Bennett et al., 2007; Debaille et al., 2013; Rizo et al., 2011) or ^{182}Hf-^{182}W (Touboul et al., 2012; Willbold et al., 2011), and long-lived isotope systems (e.g., ^{176}Lu-^{176}Hf, Blichert-Toft and Arndt, 1999; Blichert-Toft and Puchtel, 2010; Hoffmann et al., 2010; Puchtel et al., 2013), pristine Hadean crustal rocks have not been preserved and to date have only been traced indirectly by isotope inheritance (O'Neil et al., 2008; Rizo et al., 2012; Roth et al., 2013; Tessalina et al., 2010). The only known, direct present-day remnants of this crust are preserved as detrital zircon grains in reworked sedimentary units in Western Australia (Compston and Pidgeon, 1986; Froude et al., 1983; Maas and McCulloch, 1991; Maas et al., 1992; Nutman et al., 1991; Pidgeon and Nemchin, 2006; Pidgeon and Wilde, 1998; Thern and Nelson, 2012; Wilde et al., 2001) and some possible, very rare occurrences elsewhere (Xu et al., 2012). As such, the sedimentary units (in particular the metaconglomerate at the original sampling site W-74, see Fig. 1) at and around the Jack Hills of the Narryer Terrane as part of Australia's Yilgarn Craton are by far the most heavily investigated and most famous detrital suite in search for clues on Hadean geodynamics. To date, the Narryer Terrane zircon suite represents the only available "original" material from which knowledge can be derived of the nature and composition of the first terrestrial crust, the tectonic and magmatic processes that formed it, and its subsequent fate. All of these factors are considered key aspects of the geosciences that may assist in better understanding of, for example, the formation of modern continental crust, the evolution of habitable planets, and the composition of the Hadean exosphere.

Most of our understanding of the Hadean aeon on Earth is based on the Hadean zircon record. However, despite two decades of research on the Jack Hills meta-sediment, there remains confusion and/or uncertainty as to how to interpret the messages revealed by the numerous

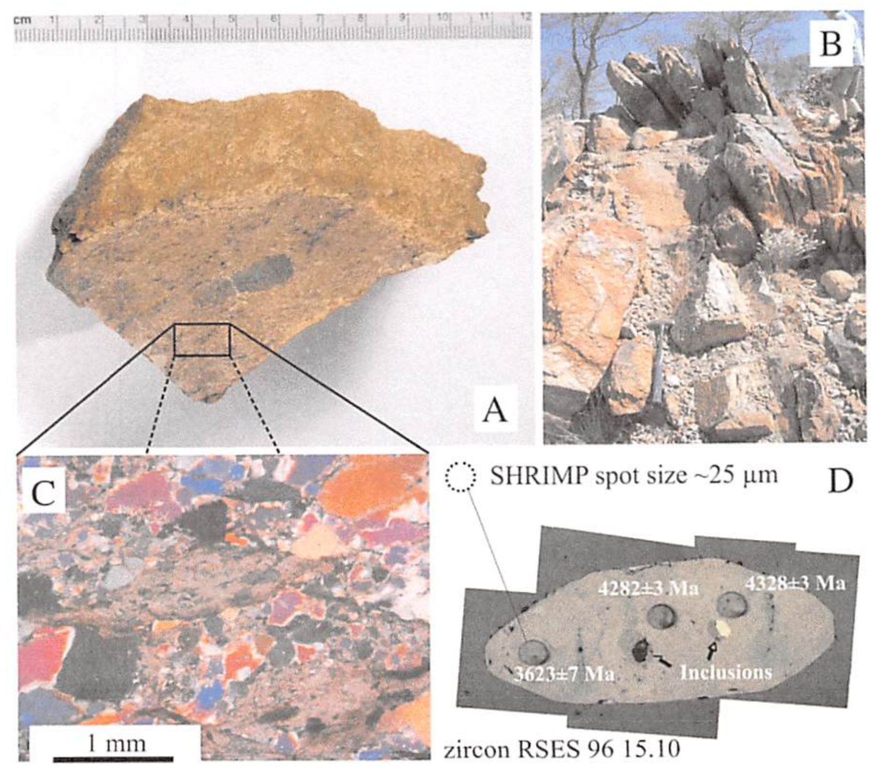

Fig. 1. A: Hand specimen from the Jack Hills with a large quartz pebble in the centre, showing the large variation in grain size; photo courtesy of Charles Tambiah; B: sample site W74 (Compston and Pidgeon, 1986) at the Jack Hills area in Western Australia where Hadean grains were first discovered; photo courtesy of Tim Ivanic; C: thick section picture of elongated quartz pebbles in a matrix of other clasts (quartz, mica) with deformation structures. D: back-scattered electron picture of zircon crystal RSES 96 15.10, showing three distinct ages in a single grain, determined by SHRIMP (see spotsize for scale) at the Australian National University. The crystal contains inclusions that have been subject to intense investigations; image courtesy of Peter Holden.

chemical tools applied to these zircons, and how these observations fit into other, pre-existing models of the Hadean aeon. Consequently a general solution that integrates the numerous interpretations of data into one geodynamic model is desirable. This contribution focusses on literature that addresses the conditions of formation of Hadean zircons, their igneous host rocks and their greater crustal domains. The intention is to give an overview of geochemical proxies applied to the detrital zircons (mainly isotope systems with a focus on Lu–Hf), and to summarize their interpretations. Finally, we assess the implications of these interpretations, gauge their limitations and propose a best-fit solution for placing the available data in a reasonable geodynamic context.

2. Geologic background

Metasedimentary units that contain detrital zircons with Hadean domains crop out in the Jack Hills, part of the Narryer Terrane located in the northwest of the Australian Yilgarn Craton (Myers, 1988; Myers and Williams, 1985). The timing of amalgamation of the Narryer Terrane with the rest of the Yilgarn Craton is constrained by regional tectono-stratigraphic features to be around 2.7–2.6 Ga (Kinny et al., 1990; Myers, 1988). The age of the metasediment is constrained by the youngest detrital zircons in the sequence at ~3 Ga (Cavosie et al., 2007), but no later than 2.65 Ga (Rasmussen et al., 2010), indicating deposition in the Narryer Terrane prior to collision with the rest of the Yilgarn Craton (Spaggiari, 2007). Other important rock units are the mafic Manfred Complex and the felsic Meeberrie Gneiss, both of which are potentially as old as 3.73 Ga (Kinny and Nutman, 1996; Kinny et al., 1988; Pidgeon and Wilde, 1998).

Spaggiari et al. (2007) subdivided the sedimentary successions in the Jack Hills into four units, of which unit 3 is a meta-conglomerate that contains detrital zircons with Hadean ^{207}Pb–^{206}Pb ages. The sample site from which most Hadean zircons were sampled (W-74, Compston and Pidgeon, 1986) is an approximately 4 × 4 m outcrop of rather unspectacular appearance (Fig. 1B). The metasediment comprises conglomerate containing pebbles of large size range, indicating poor sorting in a high-energy, likely shallow water environment. Larger clasts consist of predominantly quartz pebbles embedded in a matrix of finer grained quartz, feldspar, mica (fuchsite), rutile, zircon, monazite and other heavy minerals (Spaggiari et al., 2007). Subsequent metamorphic overprints occurred at ~2.7 Ga, ~800 Ma, ~650 Ma and ~425 Ma (Nebel-Jacobsen et al., 2010; Rasmussen et al., 2010). In close present day proximity, further Hadean grains were reported at Mt. Narryer, with a distinctively smaller Hadean grain population, yet a similar age spectrum (Froude et al., 1983; Kinny et al., 1988; Nutman et al., 1991; Spaggiari, 2007). Other than the Narryer Terrane, only one other location has been reported where detrital zircons with ages >4 Ga have been found in the eastern Yilgarn Craton (Thern and Nelson, 2012). The significance of this finding is yet to be explored, but it suggests that there may be more reworked Hadean provinces buried in the Yilgarn Craton, outside the Narryer Terrane.

3. Hadean zircon mining: ^{207}Pb–^{206}Pb ages and implications

The first discovery of domains in detrital zircons with ages >4 Ga was made using the sensitive high-resolution ion microprobe (SHRIMP-I) located at the ANU. The sample was collected from side 71932 at Mt. Narryer (Froude et al., 1983). This work was followed by dating of zircon grains from the Narryer Terrane in numerous studies, including single zircon analyses by TIMS (thermal ionization mass spectrometry), LA-ICPMS (laser-ablation inductively coupled plasma mass spectrometry), SHRIMP and SIMS (secondary ion mass spectrometry) (Abbott et al., 2012; Amelin, 1998; Amelin et al., 1999, 2000; Bell and Harrison, 2013; Bell et al., 2011; Blichert-Toft and Albarede, 2008; Cavosie et al., 2005, 2006; Compston and Pidgeon, 1986; Crowley et al., 2005; Harrison and Schmitt, 2007; Harrison et al., 2005, 2008; Hopkins et al., 2010; Kemp et al., 2010; Maas et al., 1992; Mojzsis et al., 2001; Nebel-Jacobsen et al., 2010; Nemchin et al., 2006; Nutman et al., 1991; Peck et al., 2001; Trail et al., 2007a; Wilde et al., 2001).

A recent review of the >100,000 individual analyses of Jack Hills zircons carried out at the ANU (Holden et al., 2009) found that out of >7000 grains that yielded near concordant ^{207}Pb/^{206}Pb ages, only 7.3% are >3.8 Ga old. Although the authors note that a 3.8–3.9 Ga population is under-represented (possibly because of analytical procedures), for those grains older than 3.9 Ga, the age distribution peaks at around 4.1 Ga. Similar findings have previously been reported by Cavosie et al. (2004) and later compiled in Cavosie et al. (2007), who found ^{207}Pb/^{206}Pb age spectra for the Jack Hills from a smaller number of analyses that also peak at 4.1 Ga. Notably, part of the compilation presented by Cavosie et al. (2007) was also included by Holden et al. (2009). The extensive dataset of Holden et al. (2009) shows a more or less continuous increase in zircon abundance from the occurrence of the oldest detrital grains dating back to 4.37 Ga towards 4.1 Ga, suggesting a continuously growing source from which these zircon grains were derived. Noteworthy is that grains dating back to 4.36–4.37 Ga have also been reported elsewhere (Harrison et al., 2005, 2008; Nemchin et al., 2006). Based on bulk grain analyses and a smaller data-set, Blichert-Toft and Albarede (2008) interpreted the 4.1 Ga peak in zircon ages as a single event sourcing all Jack Hills zircons, which led these authors to reassess Lu–Hf systematics (see Section 5), assuming zircon formation ages of ~4.1 Ga. The significance of a possible 4.1 Ga event is unclear; the larger dataset employed by other studies as opposed to the limited data available to Blichert-Toft and Albarede (2008), however, is favourable for zircons older than 4.1 Ga and places doubts on the validity of a sole event at 4.1 Ga. Rather, the available data suggests a turning point in Hadean crustal dynamics marked by the largest preserved zircon population at 4.1 Ga. Following the rigorous investigation of Holden et al. (2009), the Jack Hills population shows a first remarkable peak in age populations at 4.34 ± 0.01 Ga in the geologic record, which we adopt here as the first significant "event" in the terrestrial record, noting that older zircons are reported with 4.37 Ga being likely the oldest terrestrial matter found to date. In the hunt for the oldest terrestrial material, Wilde et al. (2001) reported an age of 4.408 ± 0.008 Ga (2σ) for a single zircon domain. However, Parrish and Noble (2003) speculated that the 4.41 Ga age is a relict from ^{231}Pa–^{207}Pb decay, whereas Holden et al. (2009) ascribe the age to an over-estimate attributable to data reduction procedures. Noteworthy is that this age has not been confirmed by dating of >100,000 zircon grains (Holden et al., 2009) and all other domains in the same grain date back to 4.34–4.36 Ga. Thus, an "event" at 4.34 Ga likely marks the onset of the oldest terrestrial stable crustal reservoir, and, excluding the one zircon-domain analysis with 4.41 Ga (Wilde et al., 2001), nothing older than 4.37 Ga has yet been found on Earth.

An important observation is the identification of igneous overgrowth rims on Hadean zircon grains (Cavosie et al., 2006; Froude et al., 1983; Maas et al., 1992; Trail et al., 2007a). This implies the incorporation of older zircons into younger igneous suites does not support preservation of Hadean reservoirs at the time of deposition of the Jack Hills at ~3.0 Ga. In other words, Hadean zircons could have been deposited in sediments derived from reworked Hadean crust, incorporated into yet other magmas some time later, which themselves could have been subsequently reworked. Holden et al. (2009) confirmed this interpretation and recorded up to seven events in a single zircon grain between 4.3 and 3.0 Ga, approximately every 200 Myr. In fact, in their zircon mining approach, they did not find a single Hadean grain without multiple overgrowth zones, suggesting that indeed no primary Hadean crust was present (at least based on the Jack Hills population) at 3.0 Ga when the Jack Hills metaconglomerate was deposited. The record of multiple events within individual grains suggests that the process of recycling may have been repeated a number of times before final deposition at Jack Hills, leaving no trace of the original host rock.

Previous detailed investigations on the geographical distribution of Hadean zircons at the Jack Hills location show that they were almost