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Re-evaluation of the origin and evolution of >4.2 Ga zircons from the Jack Hills metasedimentary rocks

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Abstract

New data are presented on internal structures, U–Pb systematics and oxygen isotope compositions of eight detrital zircons with ages greater than 4.2 Ga, from the Jack Hills metasedimentary belt, Australia. Cathodoluminescence imaging, ion-microprobe U–Pb and oxygen isotope results show evidence for an extensive period of complex zircon growth, secondary reaction and U–Pb isotopic disturbance from 4.36 to 3.90 Ga. In addition many of the zircons have discordant U–Pb systems and excess common Pb indicating a superimposed, relatively recent, reaction between radiation damaged zircon and low temperature fluids. The significance of oxygen isotope compositions for zircons with complex internal structures and U–Pb systems is complicated by uncertainty in the origin of the grains and the unknown effect of later reactions. However, a minority of grains with sharp oscillatory zoning, uniform and concordant U–Pb systems, igneous Th–U ratios and low common Pb contents, are interpreted as undisturbed primary magmatic zircons. The oldest identified, oscillatory zoned, magmatic grain, with an age 4363 ± 20 Ma, is one of a few reported magmatic grains with this age, which is interpreted as the oldest reliable age for Hadean magmatic zircons. Mantle $\delta^{18}O$ values are reported for these zircons. Younger oscillatory zoned zircon, including oscillatory zoned cores in complex grains, have $\delta^{18}O$ values lower than 6.5‰, which are within the range of ion microprobe analysed $\delta^{18}O$ values for zircons in high temperature equilibrium with the normal mantle rocks of 5.3 ± 0.6‰ (2 standard deviations). These values are also within the range of $\delta^{18}O$ values found in lunar zircons. The absence of heavy oxygen in the grains that can be interpreted as primary magmatic zircons and the complex history over the period from 4.36 to 3.9 Ga, seen in all other Jack Hills zircons and reflected in the internal structures and U–Pb isotopic systems, questions the model for the early Earth involving long intervals of relatively temperate conditions from 4.4 to 4.0 Ga that were conducive to oceans and possibly life.
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Keywords: Jack Hills; zircon; internal structures; U–Pb ages; Oxygen isotopes

1. Introduction

The reports by Wilde et al. [1] and Mojzsis et al. [2] of heavy oxygen in >4 Ga (Hadean) detrital zircons from metaconglomerate sample W74 from the Jack Hills in Western Australia, and their interpretation of

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these data as evidence for continental crust and possibly oceans on the surface of the Earth as old as 4.4 billion years ago, has significantly changed perceptions of early Earth processes. In particular the hypothesis of a cool early Earth [3] has profound implications for ideas on the timing of cooling and core formation of the early Earth, the onset of mantle convection and the history of meteorite bombardment (e.g. [3–6]). Specifically Watson and Harrison [6] suggest that within 100 Ma of formation the Earth had settled into a pattern of crust production, erosion and sedimentary recycling, similar to that common during the known era of plate tectonics.

Underlying this interpretation is the widely accepted relationship that δ^{18}O values greater than 5.3±0.6‰ (2 sigma) determined for mantle zircon [7] result from crystallisation in a magma contaminated by, or generated from, surface material that has reacted with water at low temperatures [8]. Valley et al. [9] comment that "values above 6‰ cannot be explained as pristine differentiates from mantle magmas and to be conservative, the lower limit of the non-magmatic supracrustal field is set at 6.5%, when poorer precision ion microprobe data is discussed". Based on this, the high δ^{18}O values (6.5–7.5‰) of >4 Ga detrital zircons from the Jack Hills metaconglomerate have been interpreted as forming from magmas whose parent rocks were subjected to low-temperature alteration, weathering or diagenesis.

However, questions have been raised as to whether the heavy δ^{18}O in the >4 Ga zircons (and attendant light-REE enrichment) truly represents a primary magmatic signature or results from secondary alteration [10,11]. Hoskin [11] proposed that the high δ^{18}O signature could be the result of localised exchange with a light-REE-bearing, high δ^{18}O (6–10‰ or higher) fluid and that a complex explanation involving permanent liquid water in the Early Archaean is not necessary as the zircon textures and compositions are simply explained by exchange between partially metamict zircon and a low-volume ephemeral fluid. This raises fundamental questions as to what are primary and what are secondary features in the ancient zircons.

In view of these questions on the significance of the heavy oxygen, it is imperative that further detailed studies are made to clarify the meaning of the isotopic relationships of the very old zircons from the Jack Hills metasediments. To this end, we have undertaken a combined SHRIMP U–Pb, cathodoluminescence, and oxygen isotope study of eight >4.2 Ga zircons from the same metaconglomerate outcrop (W74) from the Jack Hills. The purpose of this contribution is to present our results and discuss their implications for models of the evolution of the early Earth.

2. Samples and analytical technique

Detrital zircons were separated from two separate samples (jh14 and jh17) collected from the conglomerate outcrop in the Jack Hills originally studied by Compston and Pidgeon [12].

U–Pb analyses on zircons from these samples were made using the Western Australian consortium SHRIMP II at Curtin University of Technology. Initial analysis of the grains extracted from the samples was done using short one scan runs aimed at identifying zircons older than 3.9 Ga. These old grains were later reanalysed using full seven scan analyses following procedure described by Compston et al. [13] and Kennedy and de Laeter [14]. U–Pb ratios were calibrated against the Sri-Lankan zircon CZ3 (Pidgeon et al. [15]). The data reduction was done using SQUID AddIn for Microsoft Excel [16] and Isoplot [17] was applied for further age calculations. All errors for individual analyses in Table 1 and concordia plots are presented at 2σ level. The errors in average ages and concordia intercepts are calculated at the 95% confidence level. Cathodoluminescence images of all zircon grains described in this paper were made using a Phillips Electron Microscope.

Prior to oxygen analyses all SHRIMP spots were removed from the surface of the sample by repolishing. Oxygen isotopes were measured using a CAMECA IMS1270 ion microprobe (NordSIMS Facility, Swedish Museum of Natural History) using a method similar to that described by Nemchin et al. [18] with the exception that, for this study, only ^{16}O and ^{18}O were measured. Briefly, a 20 keV Cs+ primary beam (+10 kV primary, −10 kV secondary) of ca. 5 nA was used in aperture illumination mode to sputter a ca. 15 µm sample area, with a normal incidence electron gun providing charge compensation. Fully automated runs comprised a 180-s pre-sputter period with a raster of 25 µm, field aperture, entrance slit and mass centring, using the ^{16}O signal, followed by 240 s of data acquisition using two Faraday detectors in the multicollector system operating at a common mass resolution of ca. 2500. Data were normalised to measurements of the Geostandards zircon 91500, assuming a δ^{18}O value of +9.86‰ determined by laser fluorination (reported in [19]). Data from Jack Hills zircons and 91500 are presented in Table 2 with external uncertainties reported at the 2σ level, including propagated external reproducibility on the 91500 standard which ranged between ±0.44‰ and ±0.56‰

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