Lithos 234–235 (2015) 15–26

Contents lists available at ScienceDirect

Lithos

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

Distinguishing primary and secondary inclusion assemblages in Jack Hills zircons

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ARTICLE INFO

Article history:
Received 25 March 2015
Accepted 28 July 2015
Available online 5 August 2015

Keywords:
Zircon
Mineral inclusion
Early Earth

ABSTRACT

Detrital igneous zircons from Jack Hills, Western Australia, range in age from ~3.0 to nearly 4.4 Ga and contain an inclusion assemblage dominated by quartz and muscovite, cited as evidence of their derivation from peraluminous granitoids. However, some phosphate inclusions in these zircons are known to be secondary from their post-depositional U–Pb ages and manifest mineralization along cracks. We undertook a survey of mineral inclusions in 4.3–3.0 Ga Jack Hills zircons with particular emphasis on their relationship to possible alteration features (e.g., cracks, disturbed internal zonation, and visual turbidity). Mineral inclusions revealed at polished surfaces show variations in modal mineralogy, mostly corresponding to their relationship with cracks. Muscovite is common both on and away from cracks, although the chemistry of muscovite inclusions shows little relationship with other potential alteration features. Inclusions filling cracks (secondary) and inclusions isolated from cracks differ in their modal mineralogy, although both suites are rich in muscovite and quartz. The higher incidence of crack-intersecting inclusions among younger zircons may reflect effects of the (generally larger) inclusion size among younger zircons. Mismatches between the isolated and crack-intersecting populations indicate selective loss of certain phases (e.g., feldspar, apatite) and over-representation of quartz and muscovite along cracks likely due to the effects of larger inclusion size and varying degrees of overpressure following zircon cooling and decompression. Inclusions not associated with cracks in magmatically zoned versus regions with disturbed zoning have similar phase proportions. This indicates only minor inclusion replacement away from cracks (i.e., the isolated assemblage is likely primary). This holds true also for inclusions within visually turbid versus clear volumes of zircon. Phase proportions within the inclusion assemblages differ with age indicating a provenance shift toward fewer mafic phases and apatite in <3.6 Ga relative to Hadean granitoid sources.

1. Introduction

Detrital zircons older than 4 Ga from the Jack Hills locality (Compston and Pidgeon, 1986) in the Narryer Gneiss Complex provide the best known record of Earth's first 500 Ma. In addition to low Ti-in-zircon crystallization temperatures (T^{xlln}), interpreted as showing derivation from near minimum melt conditions (Watson and Harrison, 2005), and elevated $\delta^{18}O$, suggestive of sedimentary input to some precursor magmas (e.g., Cavosie et al., 2005; Harrison et al., 2008; Mojzsis et al., 2001; Peck et al., 2001; Trail et al., 2007), the generally granitic mineral inclusion suite of the zircons has been used to argue for their origin in felsic magmas (e.g., Maas et al., 1992; Mojzsis et al., 2001; Hopkins et al., 2008, 2010, 2012; cf. Rasmussen et al., 2011). However, while most studies show that quartz and muscovite dominate the inclusion assemblages, Rasmussen et al. (2011) concluded that the inclusions largely reflect dissolution of magmatic phases and their replacement with a secondary assemblage during the Neoarchean and later metamorphism of the quartzite hosting the detrital population.

Zircon may be altered by reaction with fluids or recrystallization during metamorphism (Hoskin, 2005). Signs of alteration include disturbed or erased internal zonation (shown by cathodoluminescence, or CL, imaging). CL-bright and -dark regions of zircon transgressing primary zonation may be related to fluid exchange (e.g., Pidgeon et al., 1998; Vavra et al., 1999) and solid-state recrystallization (Hoskin and Black, 2000), respectively. Faded, blurred, and distorted primary zonation may also indicate alteration. Visible turbidity related to the presence of cryptic inclusions also potentially indicates alteration. The effects of various alteration processes on hosted inclusions are uncertain, but fluids present the possibility of chemical exchange with the environment, dissolution of original phases, and precipitation of new phases. The most obvious pathway for fluids to alter zircons and their included minerals is through surface alteration and cracks. Fluid alteration has indeed been suggested as responsible for several aspects of Jack Hills zircon geochemistry, including elevated LREE

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http://dx.doi.org/10.1016/j.lithos.2015.07.014
0024-4937/

and $\delta^{18}O$ (Hoskin, 2005). However, Trail et al. (2007) showed that cracks are instead associated with lower, more mantle-like $\delta^{18}O$ values. Harrison and Schmitt (2007) found elevated Ti and Fe concentrations distinct from the typical unaltered Hadean zircon compositions in and adjacent cracks, suggestive of secondary mineralization. Rasmussen et al. (2011) reported inclusions intersecting and filling cracks and hairline fractures but did not report them as a separate category in their analysis.

Later alteration to the zircons and thus potentially to their inclusions is unsurprising given the long post-depositional thermal history to which they have been exposed and the unknown thermal conditions for Hadean zircons prior to their deposition in the present host quartzite. Several episodes of magmatism and metamorphism occurred in the Jack Hills since 3 Ga and some are reflected in secondary phases and alteration of the quartzite itself. Granitoids intruded the Narryer Gneiss Complex (NGC) at both 3.0 and 2.6 Ga (Myers, 1988; Spagiarri et al., 2007). Fletcher et al. (1988) inferred an episode of hydrothermal alteration in the NGC at ca. 2.9 Ga based on Pb–Pb isotopic resetting, and the 2.6 Ga magmatism was accompanied by widespread deformation and amphibolite facies metamorphism (Myers, 1988). Regional heating from ca. 2 to 1.6 Ga (Fletcher et al., 1988; Myers, 1988) may have resulted from the Capricorn Orogeny or from dike emplacement; Wilde (2010) described ca. 1.8 Ga volcanics in the Jack Hills as well. Finally, ca. 1.2–1.1 Ga basaltic dikes related to the Marnda Moorn and Warakurna large igneous provinces intrude the Jack Hills, some in contact with the Hadean zircon-bearing quartzite unit (Spagiarri et al., 2007). Many of these thermal events are evident in the quartzite itself, which is altered to greenschist facies (Spaggiari et al., 2007). Metamorphic monazite and xenotime in the matrix have ages clustering ca. 2.7, 1.8, and 0.8 Ga (Rasmussen et al., 2010), the former two similar to known NGC thermal disturbances. Rasmussen et al. (2011) found ages of ca. 2.7 and 0.8 Ga for several xenotime and monazite inclusions in the zircons. Monazite-xenotime Gd-exchange thermometry yields temperatures for studied matrix and inclusion phosphates of 418–472 °C (Rasmussen et al., 2011), further suggesting the secondary origin of some phosphate inclusions during metamorphism. In addition, several Jack Hills zircons yielded a radiation damage age of ca. 1 Ga (Pidgeon, 2014), although the nature of radiation damage annealing makes it uncertain whether this age reflects one event or the results of a long history of partial annealing over billions of years of NGC thermal disturbances.

Given the potential role of alteration on mineral inclusion assemblages and the nearly 1.5 Ga age range of this detrital zircon population, we undertook a re-examination of the Jack Hills zircon inclusion population to assess the role that cracks may have played in altering primary inclusions. We examined 1000 Jack Hills zircons ranging in age from 4.2 to 3.0 Ga and incorporated electron imaging and analysis of previously investigated mineral inclusions in >4.0 Ga zircons (Hopkins et al., 2008, 2010) to assess the relationship of inclusions to alteration features and the likelihood of preservation of their primary mineralogy and chemistry.

2. Zircon mineral inclusion records

Zircons commonly contain exotic phases that were either included in the crystal during growth or deposited during later alteration. The inclusion mineralogy in metamorphic zircon can be used to constrain their host rock mineralogy and P–T path (e.g., Liu and Liou, 2011; Liu et al., 2001). Mineral chemistry can provide information about phases present in the magma and constrain the P–T conditions of igneous zircon formation (e.g., Hopkins et al., 2008).

2.1. Primary mineral inclusions in zircon

Whether mineral inclusions in magmatic zircon reflect the phase petrology of the magma in which they grew is dependent on the inclusions' robustness against alteration and whether zircon captures an accurate representation of its host magma. Hadean Jack Hills zircon inclusion assemblages are dominated by granitoid phases (Hopkins et al., 2008; Maas et al., 1992). This has been used to argue a felsic origin for the zircons (Hopkins et al., 2008, 2010; Maas et al., 1992; Mojzsis et al., 2001). Darling et al. (2009) report that zircons grown in intermediate to felsic units within the Sudbury impact melt sheet contain inclusion assemblages proportionately richer in quartz and K-feldspar than their host rocks. They attribute this to late saturation of zircon in residual liquids leading to preferential capture of late-crystallizing phases. Jennings et al. (2011) found that feldspar inclusion compositions in zircons in mafic to felsic plutonic rocks suggest a more evolved melt than feldspar phases in the whole rock and come to similar conclusions. For magmas that are initially undersaturated in zircon, the inclusion population may be biased toward later phases and suggest a more evolved melt composition than the whole rock. Whether zircons grown in magmas that are saturated with respect to zircon for all or most of their history (e.g., granites with voluminous inherited zircon) have more representative inclusion assemblages has not to our knowledge been investigated in detail, but this relationship seems likely.

The likelihood that inclusions (and/or the host zircon) experienced post-crystallization alteration can be assessed in several ways. Textural evidence that an inclusion lies on a crack or is within an altered zone based on cathodoluminescence (CL) imaging of zircon internal zonation, is in most instances clear (Hanchar and Miller, 1993). Inclusions filling cracks are certainly secondary but further evidence is required to make a similar determination for other textures. Furthermore, isolated inclusions cannot be a priori assumed to be primary in all cases since it remains possible, although unlikely, that cracks may have healed without preserving evidence of the prior history (e.g., bubble tracks). However, in many of the zircons examined, fracture-like structures evident only in CL imaging are present and most likely represent annealed fractures and cracks (see Fig. 1E andF). For included minerals conducive to radiometric dating, evidence gained from age determinations is possible. Alternatively, alteration might be suspected if common reaction products or alteration features are observed.

2.2. Jack Hills mineral inclusion suite and implications for provenance

A variety of inclusion phases have been reported for Jack Hills zircons, although most studies identify granitic assemblages including quartz, muscovite, feldspar, and biotite (e.g., Maas et al., 1992; Trail et al., 2007). Bell et al. (2011) briefly report an ilmenite inclusion in a 3.75 Ga zircon and an inclusion assemblage at ca. 3.4 Ga dominated by quartz and K-feldspar with minor muscovite and biotite, but low sample numbers for inclusions inhibit most interpretations. Menneken et al. (2007) surveyed 1000 Jack Hills zircons of all ages and reported the presence of quartz, feldspar, apatite, monazite, xenotime, and Fe oxides, along with relatively abundant diamond which was later found to be contamination from polishing compound (Dobrzhinetskaya et al., 2014). Hopkins et al. (2010) surveyed the inclusion population of 1450 > 4 Ga zircons and found a distribution that was 43% quartz, 36% muscovite, and 12% biotite, with minor apatite, hornblende, Fe–Ti oxides, and other phases. Rasmussen et al. (2011) looked at the inclusion population in 1000 Jack Hills zircons of all ages and found 48% quartz, 24% muscovite, and 10% xenotime, with other minor constituents, and concluded that they were largely secondary. They posited that apatite dominates inclusion assemblages in most magmatic zircons, but since it is only a minor constituent of the Jack Hills inclusion population, it therefore was probably originally present in the Jack Hills igneous zircons but subsequently replaced during alteration. Neoarchean and Proterozoic U–Pb ages of several monazite and xenotime inclusions (Rasmussen et al., 2011) indicate that some portion of the inclusion assemblage dates to after zircon formation and deposition, or was isotopically reset during these times. Harrison et al. (2007) found a peak $^{207}Pb/^{206}Pb$ age of ca. 2.5 Ga in detrital rutiles (and chemical Pb ages