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Geochemical signatures and magmatic stability of terrestrial impact produced zircon

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ABSTRACT

Understanding the role of impacts on early Earth has major implications to near surface conditions, but the apparent lack of preserved terrestrial craters >2 Ga does not allow a direct sampling of such events. Ion microprobe U–Pb ages, REE abundances and Ti-in-zircon thermometry for impact produced zircon are reported here. These results from terrestrial impactites, ranging in age from ~35 Ma to ~2 Ga, are compared with the detrital Hadean zircon population from Western Australia. Such comparisons may provide the only terrestrial constraints on the role of impacts during the Hadean and early Archean, a time predicted to have a high bolide flux. Ti-in-zircon thermometry indicates an average of 773 °C for impact-produced zircon, ~100 °C higher than the average for Hadean zircon crystals. The agreement between whole-rock based zircon saturation temperatures for impactites and Ti-in-zircon thermometry (at $a_{TiO2}=1$) implies that Ti-in-zircon thermometry record actual crystallization temperatures for impact melts. Zircon saturation modeling of Archean crustal rock compositions undergoing thermal excursions associated with the Late Heavy Bombardment predicts equally high zircon crystallization temperatures. The lack of such thermal signatures in the Hadean zircon record implies that impacts were not a dominant mechanism of producing the preserved Hadean detrital zircon record.

1. Introduction

Extraterrestrial impacts are thought to have led to lunar formation (ca. 4.5 Ga; Canup and Asphaug, 2001), substantially resurfaced inner solar system bodies at ca. 3.85–3.95 Ga (i.e., the Late Heavy Bombardment 'LHB'; Tera et al., 1974), and profoundly influenced the habitability of early Earth (e.g., Grieve et al., 2006). However, their role in early Earth petrogenesis remains poorly understood. Although rare on Earth, due to constant resurfacing, impact craters preserved on other terrestrial planets (Mercury, Mars) and the Moon yield crater size–frequency distributions suggesting similar early impact histories in the inner solar system (the Venusian impact record is partially obscured by recent volcanism; Neukum et al., 2001). Because of the much greater gravitational cross-section of the Earth relative to the Moon, it is expected to receive ca. 20 times higher impact flux (e.g., Grieve et al., 2006).

The search for ancient terrestrial impacts has largely focused on shock features in minerals or impact melt spherules (e.g., Cavosie et al., 2010; Lowe et al., 2003). We are, however, unaware of any report of such features in Hadean or Archean detritus. Although low energy impacts do not produce thick melt sheets, those that result in widespread decompression melting of the middle crust (Grieve et al., 2006) should persist over time-scales sufficient for crystallization of zircon, provided target rock composition and Zr-content are conducive to zircon formation, with dimensions of >10 μm (Harrison and Watson, 1983; Watson, 1996) permitting geochemical and geochronological analysis. Many well-preserved terrestrial impact sites have now been dated using U–Pb geochronology of impact produced zircon (e.g., Hart et al., 1997; Kamo et al., 1996; Krogh et al., 1984; Moser, 1997), but using zircon to constrain the thermal (Ferry and Watson, 2007; Gibson et al., 1997; Watson and Harrison, 2005) or compositional (Grimes et al., 2007; Maas and McCulloch, 1991) evolution of impact melt sheet magmas is in its infancy. Such information could provide a baseline for understanding conditions on early Earth and permit comparison with the Hadean zircon record (see review in Harrison, 2009) to assess the hypothesis that Hadean detrital zircon formed in impact environments.

2. Background

The long-standing, popular conception that the near-surface Hadean Earth was an uninhabitable, hellish world (Kaula, 1979; Solomon, 1980; Wetherill, 1980) has been challenged by the discovery (Compston and Pidgeon, 1986; Froude et al., 1983) and geochemical characterization (see review in Harrison, 2009) of >4 Ga zircon grains from Mt. Narryer and Jack Hills, Western Australia. Hadean zircon crystals may preserve environmental information regarding their formation and thus provide a rare window into conditions on early Earth. Isotopic and

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petrologic analyses of these ancient grains have been interpreted to suggest that early Earth was more habitable than previously envisioned, with water oceans, continental crust, and possibly even plate tectonics (Harrison, 2009; Hopkins et al., 2010).

Alternatively, diamonds apparently included in these ancient zircon grains have been suggested as evidence of their formation under ultra-high pressure conditions (Menneken et al., 2007; Williams, 2007). Diamonds (usually sub-μm) have been found within rocks associated with terrestrial impact events (Masaitis, 1998) and the assumed high bolide flux during the Hadean (Koeberl, 2006) might warrant investigation into the possibility of an impact origin for the Hadean zircon population if the existence of diamond inclusions can be substantiated.

In this paper, we present U–Pb zircon geochronology, Ti-in-zircon thermometry, and trace-element geochemistry from four of the best-preserved terrestrial impactites to assess the role of impacts in the formation of the Hadean detrital zircon. These data reveal a limited range of formation conditions that strongly contrast with that documented for Hadean detrital zircon. To further generalize these empirical results which are necessarily limited by the scarcity of preserved impactites, we developed a thermochemical model to obtain a first order estimate of the abundance and temperature spectrum of impact produced zircon that could be expected from a detrital zircon population following an LHB-era impact episode on different crustal compositions (Archean vs. modern crust).

3. Methods

Analysis of zircon was accomplished both in thin section and as separated grains. For all hand samples thin-sections were obtained and examined via electron imaging using a LEO 1430 VP scanning electron microscope (SEM) to assess zircon crystal size and abundance. Mineral separates were obtained from bulk rock samples by standard heavy liquid separation procedures. Separated zircon crystals were handpicked and mounted in 1 in. diameter epoxy mounts together with AS3 zircon standard (Paces and Miller, 1993).

Ion microprobe analyses were conducted with a CAMECA ims1270 using an ~8–12 nA mass-filtered $^{16}O^{-}$ beam focused to spots between ~20 and 35 μm. We initially screened zircon grains for U–Pb dating to discriminate between inherited zircon (i.e., those older than the accepted impact age) and those formed within the impact melt. Zircon crystals with U–Pb ages similar to those of previously published impact dates (i.e., impact produced zircon) were then re-analyzed for trace elements (all rare earth elements REE, Ti, and Hf) within the same area as the U–Pb analysis, ensuring that the data acquired is from the same crystal domain. The trace element protocol also included mass/charge stations at ^{26}Mg, ^{55}Mn, and ^{57}Fe permitting monitoring of beam overlap onto inclusions in zircon that could overwhelm the low abundances of some critical trace elements in zircon (e.g., Ti). Conditions for trace element analyses were broadly similar to those of U–Pb dating, with a ~10–15 nA mass-filtered $^{16}O^{-}$ beam focused to a ~25–35 μm spot. Analysis yielding high Ti and Fe were re-imaged by SEM to make sure no visible cracks were within the spot. When cracks were identified grains were re-analyzed on fresh clean surfaces to avoid contamination of Ti associated with crystal defects (Harrison and Schmitt, 2007). NIST 610 glass was used as a primary REE standard (Pearce et al., 1997), checked against 91500 zircon (Harrison and Schmitt, 2007; Wiedenbeck et al., 2004). We used SL13 (6.32 ± 0.3 ppm Ti) and AS3 (21.6 ± 1.6 ppm Ti) as titanium standards (Aikman, 2007). For reconnaissance analysis, we also used a rapid analysis protocol for $^{48}Ti^{+}$ and SiO^{+} (excluding other trace elements) by multi-collection with dual electron multipliers which yield equivalent results. The U–Th–Pb, Ti, and REE data are individually tabulated in the Supplementary online materials.

4. Zircon from preserved terrestrial impactites

4.1. Vredefort, South Africa

The Vredefort impact structure in South Africa is the largest known terrestrial impact site (Earth Impact Database, 2011) and represents the deeply eroded remnant of an originally ~300 km wide crater (Reimold and Gibson, 1996). Although the melt sheet has been eroded due to post-impact uplift, pseudotachylite breccia and granophyre veins remain. U–Pb dating (isotope dilution thermal ionization mass spectrometry ID-TIMS) of zircon isolated from a 45 cm pseudotachylite breccia vein at ~140 m depth within a borehole near the center of the remnant crater yield an impact age of 2023 ± 4 Ma (Kamo et al., 1996). Similar analysis of zircon extracted from a syn- to post-impact norite dike also yield an age of 2019 ± 2 Ma (Moser, 1997). The target rocks of the Vredefort impact were the 2.7–3.6 Ga Kaapvaal craton granite–greenstone terrane (Schmitz et al., 2004) and sediments and volcanic rocks of the Witwatersrand basin.

We obtained zircon and whole rock samples of Vredefort impactite from three different sources: (1) pseudotachylite breccia collected near the quarry at Leeukop, just west of Parys was used for mineral separation (VD_PB) as well as in-situ thin section analysis (VD_PB_1A and VD_PB_1B; Fig. 1); (2) granophyre (VD_G; Fig. 1) from the Kommandonek Nature Preserve (provided by Roger Gibson, University of Witwatersrand); and (3) zircon from the INL borehole (VD_INL; Fig. 1) collected just south of the geographical center of the Vredefort Dome (provided by Sandra Kamo, University of Toronto).

Pseudotachylite breccia sample VD_PB consists of 1–3 cm clasts of Archean granite to granodioritic gneiss target material within a fine grained crystalline matrix (Reimold and Gibson, 2006). The separated zircon crystals (~35 grains isolated) range in length from 20 to 100 μm and exhibit igneous textures (i.e., elongate faceted faces, high axial ratio, pyramidal terminations; Corfu et al., 2003) and show no planar deformation features. Thin sections (VD_PB_1A and VD_PB_1B) were also imaged via SEM to identify zircon (~8 grains) within the melt fraction in-situ and avoid inherited grains associated with target rock clasts.

Granophyre sample VD_G consists of fine-grained crystalline quartz, plagioclase and alkali feldspar with long laths of hypersthene and small grains of magnetite (Reimold and Gibson, 2006). Zircon grains (~20 grains isolated) average ~100 μm and are fractured. Crystals lack igneous oscillatory zoning and are generally intimately intergrown with a Mg-rich pyroxene phase identified by energy dispersive X-ray analysis.

INL borehole (VD_INL) sample was taken at 139.10 m depth, a few cm below the top contact of a ~45 cm wide intersection of pseudotachylitic breccia (Kamo et al., 1996). We obtained a zircon mineral separate of two optically distinct populations of zircon crystals (13 grains total): larger, dark, sub-rounded grains which appear to have younger overgrowths on old shocked grains, and smaller, clear, multi-faceted grains that appear to represent new impact produced zircon.

4.2. Sudbury impact, Canada

The Sudbury Igneous Complex (SIC; ~250 km; Earth Impact Database, 2011) is a 2.5–3.0 km thick, elliptical igneous body with four major subunits from surface to base: granophyre, quartz gabbro, norite, contact sublayer (Therriault et al., 2002). U–Pb dating of zircon from the norite member yield an impact age of 1849.5 ± 0.2 Ma (TIMS; Davis, 2008). Target rocks are a mix of Archean granite–greenstone terrains (~2.7 Ga; Krogh et al., 1996) with a small component of supracrustal Huronian rocks (Grieve, 1991).

Zircon mineral separates (provided by Don Davis) were obtained from both the mafic (SUD_ M) and felsic norite (SUD_ F) members (Fig. 1) along a transect of the southern exposed limb of the melt