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Late accretion to the Moon recorded in zircon (U–Th)/He thermochronometry

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ABSTRACT

We conducted zircon (U–Th)/He (ZHe) analysis of lunar impact-melt breccia 14311 with the aim of leveraging radiation damage accumulated in zircon over extended intervals to detect low-temperature or short-lived impact events that have previously eluded traditional isotopic dating techniques. Our ZHe data record a coherent date vs. effective Uranium concentration (eU) trend characterized by >3500 Ma dates from low (≤75 ppm) eU zircon grains, and *ca.* 110 Ma dates for high (≥100 ppm) eU grains. A progression between these date populations is apparent for intermediate (75–100 ppm) eU grains. Thermal history modeling constrains permissible temperatures and cooling rates during and following impacts. Modeling shows that the data are most simply explained by impact events at *ca.* 3950 Ma and *ca.* 110 Ma, and limits allowable temperatures of heating events between 3950–110 Ma. Modeling of solar cycling thermal effects at the lunar surface precludes this as the explanation for the *ca.* 110 Ma ZHe dates. We propose a sample history characterized by zircon resetting during the *ca.* 3950 Ma Imbrium impact event, with subsequent heating during an impact at *ca.* 110 Ma that ejected the sample to the vicinity of its collection site. Our data show that zircon has the potential to retain ^{4}He over immense timescales (≥3950 Myrs), thus providing a valuable new thermochronometer for probing the impact histories of lunar samples, and martian or asteroidal meteorites.

1. Introduction

Impacts are one of the most important physiochemical processes shaping planetary surfaces. The timing and amplitude of impacts to the inner solar system is, however, debated. This is reflected in differences in long-term cratering estimates ranging from a simple monotonic decline in late accretion impact flux since crust formation, to rapid decline to near current levels followed by little change in the last ∼3000 Myr (e.g., Neukum and Ivanov, 1994; Lowe et al., 2014).

The Moon is our ultimate baseline for a record of late accretion to the inner solar system. This is a consequence of the Moon's proximity to Earth, its absence of effective crustal renewal, and availability of samples collected directly from its surface. Much has been learned from high-temperature chronometers, such as U–Pb in zircon, about the early bombardment history (e.g., lunar crust formation: Nemchin et al., 2008; Taylor et al., 2009; Borg et al., 2014) and major basin-forming impacts inferred to reflect the purported Late Heavy Bombardment, or LHB (e.g., Grange et al., 2009; Hopkins and Mojzsis, 2015; Merle et al., 2017). The subsequent evolution of the impact flux is, however, still poorly constrained. While significant contributions have been made to our understanding of the cratering record from the ^{40}Ar–^{39}Ar dating technique (e.g., Fernandes et al., 2013, and references therein), such studies may provide an integrated view due to the differing susceptibilities to thermal resetting among the constituents of multi-component and multi-generation lunar impact-melt breccias (Turner, 1971; Shuster et al., 2010; Shuster and Cassata, 2015; Boehnke and Harrison, 2016; Mercer et al., 2016).

Alternatively, dating single lunar zircon grains with the (U–Th)/He thermochronometry method (Reiners et al., 2002) holds promise as a means to decipher the history of late accretion to the Moon. Closure to diffusion of ^{4}He, a stable daughter product of U, Th and Sm alpha-decay, occurs at much lower temperatures in zircon (<210 °C: Reiners et al., 2002, 2004; Guenthner et al., 2013) than closure to diffusion of Pb (>1000 °C). Therefore, this tool opens the door to a rich record of less energetic thermal

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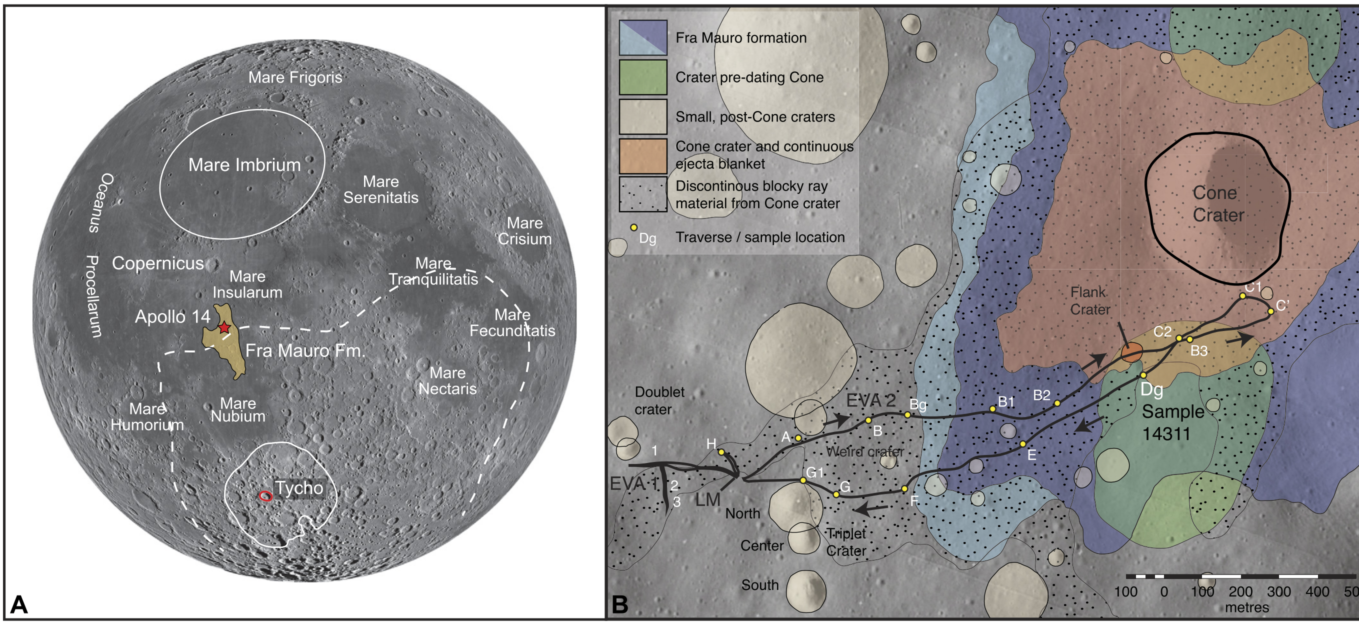

Fig. 1. (a) Location of the Apollo 14 landing site within the Fra Mauro formation (shaded tan area). Image shows extent of the Imbrium basin (solid white line), location of the Tycho impact crater (red oval) with approximate extent of the Tycho continuous ejecta blanket (solid white line) and minimum reach of discontinuous ray deposits (dashed white line) as mapped by Dundas and McEwen (2007). Lunar image collected by the Lunar Rover Orbital Camera and used courtesy of NASA/GSFC/Arizona State University. (b) Map of the Apollo 14 landing site including mapped deposits of the Fra Mauro formation and ejecta associated with the *ca*. 25 Ma Cone Crater (modified from Swann et al., 1977). Location of the two Extravehicular Activity (EVA) traverses and sampling sites are given. 'LM' refers to the location of the Lunar Module. Sample 14311 was collected at site 'Dg'. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

imprints such as those from smaller, late impacts extended over the long tail of accretion (Bottke et al., 2012). Recent advances demonstrate that radiation damage can cause zircon He retentivity to vary widely (~210 to <50 °C; e.g., Guenthner et al., 2013), therefore allowing for multiple events of contrasting energy to be recorded within a single sample. Previous work using phosphate (U–Th)/He thermochronometry on meteorite samples yielded evidence for early events such as the timing of parent body formation (Min et al., 2003), as well as shock metamorphism and ejection times from planetary surfaces (Min et al., 2004). However, ZHe has hitherto not been applied to extraterrestrial samples, nor has (U–Th)/He thermochronometry of any kind been reported on lunar rocks.

Here, we report the first results for zircon grains from Apollo 14 lunar impact-melt breccia 14311. Our goal is to exploit the effects of prolonged radiation damage accumulation (≤3950 Myrs) in lunar zircon grains to constrain a record of multiple impact events of differing peak temperature and cooling rates within a single sample. Results illustrate the power of the ZHe technique to isolate lower temperature impact events inaccessible with other routinely applied dating tools on lunar rocks, allow thermal constraints to be placed on long periods of lunar history, and if integrated with other isotope systems to reveal an impact record that corresponds to the protracted record of accretion to the Moon.

2. Geologic setting and sample information

2.1. Geologic setting of Apollo 14

Impact-melt breccias in the vicinity of the Apollo 14 landing site were sampled from the Fra Mauro formation (Fig. 1a). This formation has been interpreted as a remnant of the ejecta blanket deposited after the impact that formed the Imbrium basin (Warner, 1972; Wilshire and Jackson, 1972; Swann et al., 1977), and includes a mix of impact melt, solid fragments from the impact target, and locally derived material reworked into the ejecta blanket (Oberbeck, 1975; Wilhelms, 1987; Stöffler et al., 1989; Stöffler and Ryder, 2001). The Apollo 14 breccias were sampled in the vicinity of Cone crater (Fig. 1b), a small (340 m wide, 75 m deep) crater estimated to have formed at *ca*. 25-40 Ma in an event that excavated part of the Fra Mauro formation (Turner et al., 1971; Swann et al., 1977).

2.2. Sample description – impact-melt breccia 14311

Lunar sample 14311 was chosen for (U–Th)/He analysis because it provided one of the largest and best-characterized collection of zircon mineral separates from a single sample from the Apollo breccias. The sample was collected at station Dg, at the boundary between the continuous ejecta blanket of Cone crater and discontinuous blocky ray deposits (Swann et al., 1977; Fig. 1b). A number of other small craters that penetrate Cone crater ejecta are also located nearby (e.g., Flank crater). The sample is a melt-poor, polymict impact-melt breccia composed of >75% crystalline matrix (a pyroxene and plagioclase mosaic of 5–10 μm grains), along with mineral clasts (pyroxene, plagioclase, Fe–Ti oxides), and lithic clasts that include igneous rocks and impact breccias, which are suggestive of derivation from multiple precursors that pre-date the Imbrium impact (Carlson and Walton, 1978; Simonds et al., 1977; Swann et al., 1977). Quenched impact melt in the matrix of 14311 is in very low abundance, or absent. The dominant "equant textured" crystalline matrix, however, has been interpreted to result from solid-state recrystallization within a slowly cooling ejecta blanket at temperatures of up to ~1000 °C or more (Warner, 1972).

Previous zircon U–Pb geochronology for this sample (Meyer et al., 1996; Hopkins and Mojzsis, 2015; Merle et al., 2017), documented evidence for three thermal events in the history of 14311: (1) formation of *ca*. 4330 Ma crust; (2) igneous activity or crystallization of a large impact-generated melt sheet at *ca*. 4250 Ma; and, (3) *ca*. 3950 Ma impact-shocked zircon and zircon neoblasts that crystallized from impact melt. The *ca*. 3950 Ma zircon dates correlate with U–Pb phosphate (apatite, merrilite, whitlockite) geochronology obtained for this and other Apollo 14