SUPPORT FOR A PROLONGED KREEP MAGMATISM: U-PB AGE DATING OF ZIRCON AND BADDELEYITE IN LUNAR METEORITE NWA 4485.

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Introduction: The duration, distribution, and nature of pre-mare magmatism of the Moon remains loosely constrained. The extensive late basin-forming events around 3.9 Ga and subsequent mare basalt eruption erased most of the record of the early lunar history. Fragments of rocks and individual minerals within breccias and impact-melt rocks predating the basin-forming events hold clues to understanding the pre-mare magmatism. Except highly feldspathic rocks, i.e. ferroan anorthosites, breccias returned from the non-mare regions generally contain high concentrations of incompatible trace elements (ITEs), which are referred to as KREEP [1]. The KREEP materials are considered to be related to the last dreg of the magma ocean [1] and to the local enrichment of ITEs in the Procellarum KREEP Terrane (PKT) [2]. Rock/mineral fragments in the breccias likely suffer from multiple shock and heating events. The U-Pb system within refractory zircon is the most reliable isotopic chronometers to date the pre-mare volcanism, because its robustness in the event of isotopic disturbance. Zircons crystallize in the melt rich in ITEs and often occur in the KREEP-rich rocks and breccias. U-Pb isotopic studies of zircons in the Apollo non-mare samples provide constraints on the timing of zircon-forming KREEP magmatism [e.g., 3-5]. Lunar meteorite NWA 4485 is a KREEP-rich polymict regolith breccias with high Th content [6], implying a derivation from the PKT. Here, we date zircons from NWA 4485 to further constrain the timing of pre-mare KREEP magmatism.

Sample and method: Isolated grains of zircon and baddeleyite in the breccias matrix and zircons associated with lithic clasts from one thick section of NWA 4485 were analyzed. *In situ* U-Pb and Pb-Pb age dating of zircon and baddeleyite were conducted by a sensitive high mass-resolution ion microprobe (SHRIMP II) at National Institute of Polar Research (NIPR). Mineralogical analyses were performed with JEOL JXA8200 electron microprobe, and back-scattered electron images and cathodoluminescence images were obtained using JEOL JSM-5600LV scanning electron microscope at NIPR. Analyses of raman spectra of zircons were done with Jasco NRS-1000 micro-Raman spectrometer at NIPR.

Results: Totally thirty analyses on twelve zircon grains and one baddeleyite grain were made. All the analyzed grains but one are a few tens micron in size.

Zircons associated with the KREEP basalt clast: Three zircon grains co-existing with pyroxene and plagioclase in the degraded portions of a medium-grained, intersertal KREEP basalt [7] were analyzed. $^{207}Pb/^{206}Pb$ ages of the three zircons are 4154 ± 4 Ma, 4170 ± 26 Ma, and 4173 ± 6 Ma, respectively, showing a small discordance of U-Pb system (5–10%). Their uranium content ranges from 91 ppm to 131 ppm.

Isolated zircon grain with an overgrowth: The largest (200×120 μm) euhedral zircon grain in the breccia matrix shows an overgrowth, which is clearly seen in the cathodoluminescence image (Fig. 1). Four points analyzed in the core yielded an average $^{207}Pb/^{206}Pb$ age of 4211 ± 7 Ma (2σ) and have a U-Pb concordia age of 4208 ± 11 Ma (2σ) (Fig. 2). Two analyse in the overgrowth rim were concordant and gave an average $^{207}Pb/^{206}Pb$ age of 3927 ± 23 Ma (2σ) (Fig. 2). The uranium content of the core is 24-43 ppm, and that of the rim is 11-30 ppm. Raman spectra of the core and the overgrowth rim show little evidence for pressure-induced transformation of zircon.

Zircon and Baddeleyite grains in the matrix: Analyses of discrete two grains of zircons show an average $^{207}Pb/^{206}Pb$ age of 3929 ± 10 Ma (2σ) and have a U-Pb concordia age of 3931 ± 18 Ma (2σ). The U content is 176-219 ppm. An analysis in one zircon grain yielded a $^{207}Pb/^{206}Pb$ age of 4352 ± 10 Ma. The U content is 28 ppm. $^{207}Pb/^{206}Pb$ age of one baddeleyite grain is 3922 ± 12 Ma.

Discussions: The zircons intergrown with other minerals in the degraded KREEP basalt clast imply that the age (~4170 Ma) represents the timing of crystallization of the rock. The euhedral shape and the relatively large grain size of the largest zircon suggest that the age determined (~4210 Ma) for the core is the timing of crystallization of the parent rock. The age of the overgrowth (3927 Ma) probably represents the timing of the later thermal event, either due to shock metamorphism by meteoroid impact(s) or contact metamorphism by an large-scale intrusion into the nearby crust. Interestingly, isolated fragments of two zircons and a baddeleyite in the matrix show ages (3933 Ma) remarkably similar to that of the overgrowth rim of the largest zircon. They may have recorded the same thermal pulse, although their distinct U content by one order of magnitude implies different magmatic origins.

The core and overgrowth of the largest zircon do not show much difference in the U content. The U content of zircons ranges from 11 to 219 ppm among grains, showing a neagative correlation with the ages. They are within the range of those of the Apollo zircons [8].

Ages obtained from analyses of zircons and a baddeleyite range from 4352 Ma to 3922 Ma. The range of the ages are consistent with those determined from ion probe analyses of phosphates in NWA 4472 (4344−3937 Ma) [9], which is paired with NWA 4485. Note that the age of apatite in the “evolved basalt clast” which we expect is related to the “KREEP basalt clast” in our sample is much younger age (3937 Ma) than that of the zircons in the KREEP basalt clast (~4170 Ma). The age difference may have resulted from a greater susceptibility of apatite to the isotopic disturbance relative to zircon [10, 11]. The U-Pb system of zircon and baddeleyite as well as that of phosphates [9] has not been affected by younger thermal event(s) that was recorded as Ar-Ar age (3200−2850 Ma) [9].

Note that the age spectrum obtained from zircon and baddeyeite in the “single” paired meteorite NWA 4472/4485 (total 252 gram) [12] broadly covers that defined by U-Pb and Pb-Pb ages of zircons in the Apollo non-mare samples from multiple landing sites (Apollo 12, 14, 15, and 17) (4320-3880 Ma) [e.g., 4, 13-15], except the oldest one (4417 Ma) [5]. While the youngest age (~3930 Ma) dated from the overgrowth of the largest zircon and other discrete zircon fragments likely represents an episode of intense meteoritic bombardment at 3.8-3.9 Ga, the older ages (4352 Ma, ~4210 Ma, and ~4170 Ma) may preserve their primary ages. A cluster of zircons in Apollo 17 breccia 73235 have a 4310 Ma-aged core enclosed by an overgrowth of 4187 ± 11 Ma [15, 16]. The overgrowth implies a secondary thermal event at ~4187 Ma, which is marginally close to the age of the KREEP basalt clast (~4170 Ma). The heat source to generate the parent magma of the KREEP basalt could be either the internal heating due to radioactive decay and/or the external heating by impact.

The U-Pb and Pb-Pb age spectrum constrained from analyses of zircons in a KREEP-rich lunar meteorite NWA 4485 supports a prolonged KREEP magmatism, which has been suggested from U-Pb isotopic studies of zircons in the Apollo non-mare samples [4]. Yet, the origin of the zircons and their parent magma, and the heat source are still matters of debate, either a final episode of the primordial magma ocean crystallization, or late-stage crystallization of plutons intruded into the crust, or crystallization of large-scale impact melt pools which formed by basin-forming impact events.

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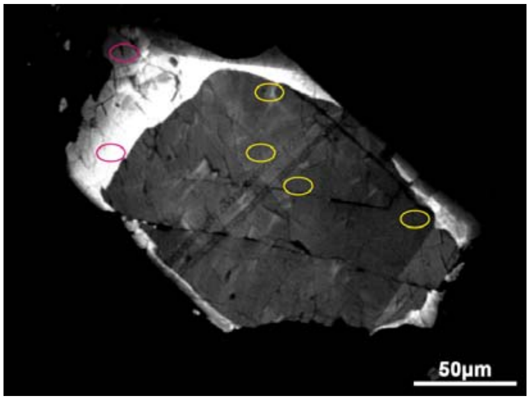

Fig. 1. Cathodoluminescence image of the largest zircon grain with a core (light grey to dark grey) and an overgrowth rim (white). Analyzed points are shown with circles.

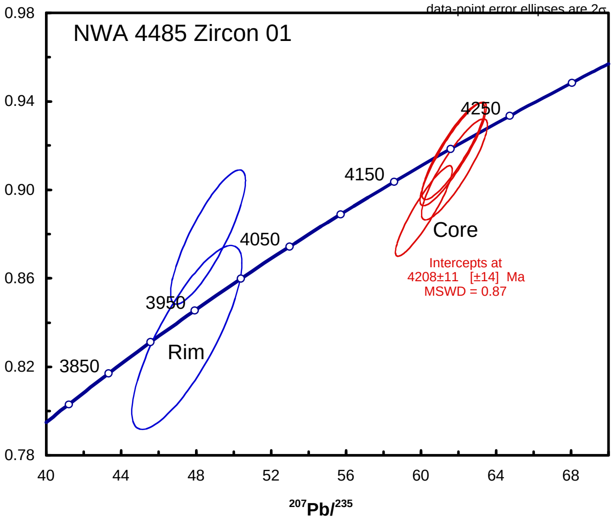

Fig. 2. U-Pb concordia plot for the largest zircon grain showing the clearly resolved ages of the core and the overgrowth rim.