Where did the oldest lunar mare sample come from?

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Introduction: Kalahari 009 is a lunar meteorite classified as a very-low-titanium (VLT) mare basalt breccia and known as one of the oldest mare basalts with the U-Pb age of 4.35 ±0.15 Gyr (Terada et al., 2007). This meteorite provides the information of the lunar oldest mare magmatism prior to the Late Heavy Bombardment around 3.8-4.1 Gyr ago and potentially facilitates understanding of the origin of lunar mare magma activity. Here we report search for the source crater of the Kalahari 009 meteorite and shock products in the meteorite.
Analytical Methods: The source crater of Kalahari 009 was searched in a region from northern latitude of 60 degree to southern latitude of 60 degree using data of the Multiband Imager (MI) and Gamma Ray Spectrometer (GRS) obtained by the lunar explorer SELENE (KAGUYA). We selected candidates of the source crater, of which FeO, TiO2 and Th concentrations are comparable to those in Kalahari 009 (16 wt% of FeO, 0.45 wt% of TiO2 and 0.09 ppm of Th) (Sokol et al., 2008). To estimate the compositions of FeO and TiO2 we used the algorithms for deriving the abundances of FeO and TiO2 based on MI image data (Otake et al., 2012). At the same time, optical maturity parameter (OMAT), which is an index of relative surface age of craters, was also calculated to search for the source crater of Kalahari 009 using the method in Lucey et al. (2000).
To reveal the impact history of Kalahari 009, we observed the thin section of the meteorite using the field emission scanning electron microscope (JEOL 7001F) and Raman spectrometer (JASCO NRS-2000).
Result and Discussion: 254 craters with concentrations of FeO (14-17 wt%), TiO2 (≤ 1 wt%) and Th (≤ 1 ppm) were identified. It was suggested that Kalahari 009 was ejected together with the Kalahari 008 highland breccia (Sokol et al., 2008), and therefore the source crater may be located in a region of cryptomare. 92 out of 254 craters are located in cryptomare. The cosmic exposure age of Kalahari 009 is from 220 ±40 yr to ~0.3 Myr (Nishiizumi et al., 2005), which means that the craters with relatively high OMAT are candidates of the source crater. Thus, the source crater of Kalahari 009 is probably one of 92 craters in cryptomare having relatively high OMAT.
In the thin section of Kalahari 009, shock products such as coesite, ringwoodite, partly mosaicism and planar fracturing in plagioclase and olivine were observed. According to the shock classification in Stöffler et al. (1991), the shock pressure is estimated as 30-35 GPa. The presence of ringwoodite suggests the shock pressure of ~ 7-14 GPa based on the Fe2SiO4 phase diagram (Ohtani, 1979). Thus, it is inferred that Kalahari 009 experienced the shock pressure of ~ 7-35 GPa. The Ar-Ar dating of Kalahari 009 showed that the meteorite experienced significant loss of radiogenic Ar at 1.7 Gyr (Fernandes et al., 2007). Thus, Kalahari 009 has experienced at least one impact which caused loss of radiogenic Ar and/or produced shock-induced minerals.
In summary, we describe a possible ejection scenario of Kalahari 009 based on the results of the present and previous studies. An impact event occurred at 1.7 Gyr, but the ancient basalt clast remained in the impact crater as a breccia. Then, the 2nd impact produced a small crater inside the large crater between ~0.3 Myr and 220 ±40 yr and ejected the meteorite from the small crater.
In the presentation, we will discuss the source crater of Kalahari 009 in conjunction with the impact history of the meteorite.

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