Ion Microprobe U-Pb Dating of Phosphates in Lunar Basaltic Meteorites. K. Terada[1,] Y. Sasaki[1], Y. Oka[1], A. Tanabe[1], N. Fujikawa[1], S. Tanikawa[1], Y. Sano[2], M. Anand[3] and L. A. Taylor[4], [1]Department of Earth and Planetary Systems Science, Hiroshima University, Higashi-Hiroshima 739-8526, JAPAN (terada@sci.hiroshima-u.ac.jp), [2]Center for Advanced Marine Research, Ocean Research Institute, The University of Tokyo, Nakano-ku 164-8639, JAPAN, [3]Department of Earth Sciences, CEPSAR, Walton Hall, The Open University,Milton Keynes, MK7 6AA, U.K.,[4]Planetary Geosciences Institute, University of Tennessee, Knoxville, Tennessee 37996, USA

Introduction: Most studies of lunar rocks and soils have been conducted on samples collected by the Apollo and Luna missions, but these represent samples from near-equatorial regions of the near side of the Moon. However, recent discoveries of lunar meteorites, which have been blasted off the Moon only to land in the hot desserts and Antarctic ice fields of Earth, have provided great impetus to lunar science. These meteorites provide potentially new insights into the petrologic history of unexplored regions of the Moon, including some as distant as the far-side. In spite of their scientific value, chronological studies of lunar meteorites have been difficult, since most of them are complex breccias, and in some cases, their radiometric "clocks" typically have been disturbed by subsequent impact events.

In order to better understand the petrogenetic history of lunar meteorites, we have developed *in-situ* U-Pb age dating of phosphates grains using Sensitive High-Resolution Ion MicroProbe (SHRIMP) installed at Hiroshima University [1]. Our *in-situ* analyses attain high sensitivity at high mass resolution of ~5800. Although recent high-precision Thermal Ionization Mass Spectrometry (TIMS) analyses have enabled the U-Pb dating from ~10 microgram phosphates [e.g. 2], our *in-situ* analyses have the following advantages in comparison with conventional TIMS techniques: (1) a much smaller amount of sample (usually a thin polished section) is required, (2) the mineralogy of phosphates and their textural relationships with other minerals in the rock can be investigated in their natural setting, (3) U-Pb systematics in various phases are independently investigated. This *in-situ* U-Pb dating method has been successfully applied to the lunar basaltic meteorites [3-10] and has enabled us to unravel the lunar evolution such as Cryptomare magmatism 4.35 Gyr ago [8] and an extremely low μ-value (= $^{238}U/^{204}Pb$) of magma sources [7, 9, 10].

This paper will illustrate the advantages of in-situ U-Pb of phosphate in lunar mateorites and the recent new findings

Advantages of U-Pb dating of phosphates: It is well established that phosphates are one of the main carriers of U in lunar samples and are also resistant to secondary thermal events due to relatively high closure temperatures [~500 °C, 11]. In the series of studies, we calculated a "total Pb/U isochron age" in the $^{238}U/^{206}Pb$-$^{207}Pb/^{206}Pb$- $^{204}Pb/^{206}Pb$ three-dimensional space (for details see [12-13]). The crucial advantages of this method are: (1) it is not necessary to know the isotopic composition of initial lead; (2) both ^{238}U and ^{235}U decay schemes are used at the same time, yielding a smaller justifiable age uncertainty for the U-Pb systematics; and (3) if the secondary event affect U-Pb systematics slightly, the observed data are scattered on a plane in the 3-D space, and two intersections of PLANAR regression with Concordia curve give two kinds of chronological information, such as formation age and alteration age in principle [12-13]. For the situations with EET 96008 and QUE 94281, both the formation age and the alteration age were obtained by the PLANAR regression [3, 6].

Analytical Methods: A 0.3-1 nA O_2^- primary beam with acceleration voltage of 10 kV was focused to sputter an area 5~ 10 μm in diameter on the phosphate grains and positive secondary ions were extracted and detected on a single electron multiplier by peak switching. The mass resolution was set at 5800 at ^{208}Pb for U-Pb analyses. No significant isobaric interferences were detected in this mass range for the phosphates (e.g., the mass peak of ^{159}Tb (158.925 AMU) is clearly separated from that of $^{40}Ca^{231}P^{16}O_3^+$ (158.884 AMU) at the mass resolution of 5800). The abundance ratio of ^{238}U to ^{206}Pb was obtained from the observed $^{238}U^+/^{206}Pb^+$ ratio; this was done using the following empirical relationship between the $^{206}Pb^+/^{238}U^+$ and $^{238}U^{16}O^+/^{238}U^+$ ratios of the standard apatite (PRAP) derived from an alkaline rock of the Prairie Lake circular complex in the Canadian Shield (1156 ± 45 Ma (2σ)[3]).

Results and Discussion: Chronological studies of numerous returned samples of mare basalt and related pyroclastic deposits from the Moon have been well documented (for summaries, [13-14]). In general, the high-Ti basalts from the Apollo 11 and Apollo 17 sites are relatively old; commonly ranging in age from 3.5 to 3.9 Ga. In contrast, low-Ti mare basalt samples are generally younger; they range in age from 3.1 to 3.4 Ga, although some exceptions exist (Apollo 14 mare-basalts have ages from 3.9 to 4.2 Ga [15-16]). Based on the available data for VLT basalts, Nyquist *et al.*

[15] have suggested that the formation ages of VLT mare-basalts for Luna 24 are younger at 3.2-3.3 Ga.

Figure illustrates the age distribution of the basaltic lunar meteorites coupled with the data determined by the conventional methods, which have been reported. Here, the red and blue data are obtained by Hiroshima-SHRIMP and the conventional methods [17-20]. On the whole, in spite that these meteorites are possibly derived from unexplored regions of the Moon, they are mainly the products of later magmatic activity, spanning a billion year, from 3.9 to 2.8 Ga, consisting with those of the Apollo and Lunar collection. However, each trend of age distribution of LT and VLT basalts are different from those of collected samples. Especially for the VLT basalt magmatism, our results clearly demonstrate that the thermal activities recorded in VLT basaltic meteorites are quite different from those of the regions of the Moon explored by the Luna mission (3.2-3.3 Ga.), and indicate protracted VLT basalt volcanism on the Moon seems to have spanned from 4.35 Ga to 2.9 Ga ago. It should be noted that the ancient age of 4.35 ± 0.15 Ga for Kalahari 009 suggests that the basaltic volcanism on the Moon started relatively soon after its formation and differentiation [8].

Recent remote-sensing observations have provided some constraints on the relative chronology of the unexplored regions of the Moon, indicating that mare basalt magmatism peaked between 4.0 and 3.8 Ga and extended to approximately 1.2-0.9 Ga [14, 21]. Subsequently, Head and Wilson [22] identified these hidden mafic deposits, which they termed as "cryptomaria". Based on a global study of all previously identified and suspected hidden mafic deposits, Antonenko [23] estimated possible age ranges from 3.2 to 4.1 Ga, suggesting that mare-basalt magmatism had started by at least 4.1 Ga on the Moon, as previously proposed on the basis of radiometric age dating of Apollo samples [15-16]. Recently, based on the spectral and chemical data obtained for dark-haloed craters that are believed to have excavated mare basalts, Giguere *et al.*[24] and Hawke *et al.*[25-26] have suggested that mare basalts in cryptomaria tend to be of VLT type, consistent with Kalahari 009 data. Therefore, on the basis of ancient crystallization age and bulk-rock geochemical characteristics of Kalahari 009, we conclude that it represents our first sample from such VLT type cryptomaria on the Moon [8].

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