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Uranium–lead systematics of low-Ti basaltic meteorite Dhofar 287A: Affinity to Apollo 15 green glasses

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ABSTRACT

Dhofar 287 is a lunar meteorite found in Oman in 2001, which consists of a major portion (95%) of low-Ti mare basalt (Dho 287A) and a minor attached part (~5%) of regolith breccia (Dho 287B). Here, we report the U–Pb systematics of Dho 287A using data collected with a Sensitive High Resolution Ion Microprobe (SHRIMP). *In-situ* analyses of five merrillite and three apatite grains, which are resistant to secondary petrologic events, resulted in a total Pb/U isochron age of 3.34±0.20 Ga, in ^{238}U/^{206}Pb–^{207}Pb/^{206}Pb–^{204}Pb/^{206}Pb 3-D space (95% confidence level). The observed Pb–Pb isochron of these eight phosphates coupled with four plagioclase grains also yielded a ^{207}Pb/^{206}Pb age of 3.35±0.13 Ga. This formation age, when considered as the crystallization age of Dho 287A, is similar to crystallization ages of Apollo 15 low-Ti olivine-normative basalts (ONB; 3.3±0.1 Ga). However, the estimated μ-value (^{238}U/^{204}Pb ratio) of Dho 287A is ~18, which is very different from the reported μ-values of ~300 for mare basalts from the Apollo collections, including the Apollo 15 ONBs. These μ-values are still significantly lower than those of Apollo KREEP basalt (500 to 1000), although a possible assimilation with KREEP has been previously proposed for Dho 287A using geochemical criteria. Our U–Pb study of Dho 287A, instead, indicates a closer affinity to Apollo 15 green glasses (^{207}Pb/^{206}Pb age of 3.41 Ga with μ-value of 19 to 55), which are considered to be the most primitive products of lunar volcanism. Combining our U–Pb data with the previously reported Sm–Nd systematics (negative $\varepsilon_{\mathrm{Nd}}$) of Dho 287A clearly distinguishes this meteorite from those of the Yamato 793169 and Asuka 88175 group which have extremely low μ-value of 10–22, old crystallization ages of 3.9 Ga, and high positive $\varepsilon_{\mathrm{Nd},}$ suggesting that Dho 287A may be a representative of an entirely new group of mare basalt derived from previously unsampled source region on the Moon.

1. 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 deserts 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 isotopic "clocks" have been disturbed by subsequent impact events. In this paper, we report Sensitive High Resolution Ion Micro Probe (SHRIMP) U–Pb isotopic analyses of phosphate grains and plagioclase in lunar basaltic meteorite, Dhofar 287 (Taylor et al., 2001).

It is well established that phosphates are one of the main carriers of U in lunar rocks and are also resistant to secondary thermal events, enabling determination of the U–Pb crystallization age of phosphates. In particular, U–Pb dating system has an advantage over other dating systems because even in the case that some disturbance has occurred, both the primary crystallization age and the age of secondary events, can be determined by the assessment of both the ^{238}U and ^{235}U decay series (e.g., Anand et al., 2003a; Terada and Sano 2004; Terada et al., 2006).

Dhofar 287 is a 154 g lunar mare basalt meteorite found in the hot desert of Oman in 2001 (Taylor et al., 2001). The main portion (>95%) of this meteorite (Dho 287A) consists of a lunar mare basalt (Anand et al., 2003b), whereas a smaller portion (<5%) attached on the side consists of an impact breccia (Dho 287B; Demidova et al., 2003). Taylor

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Table 1
Major element compositions of phosphates in thin section of Dhofar 287A

Garin no.	Mineral	CaO (wt%)	Na_2O (wt%)	MgO (wt%)	FeO (wt%)	MnO (wt%)	P_2O_5 (wt%)	Total (wt%)
1	merrillite	43.8	0.4	2.3	4.0	0.1	41.9	92.5
2	apatite	54.8	<0.1	0.7	1.0	<0.1	40.3	96.9
3	merrillite	42.5	0.5	2.5	4.4	0.1	41.7	91.6
5	merrillite	43.1	0.4	0.8	5.6	0.2	42.3	92.4
6	apatite	54.6	<0.1	<0.1	1.0	0.1	40.0	95.7
9	merrillite	43.3	0.6	2.3	4.3	0.1	42.9	93.3
12	apatite	54.9	<0.1	<0.1	1.3	<0.1	40.3	96.6
16	merrillite	42.0	0.6	2.9	4.2	0.1	39.7	89.5

et al. (2001) and Anand et al. (2003b) have reported petrology, mineralogy, and chemistry of the Dho 287A, and have demonstrated that Dho 287A is a low-Ti, olivine-cumulate, mare basalt, which is highly enriched in late-stage mesostasis. Based on the detailed observation of texture and mineralogy, Anand et al. (2003b) demonstrated the similarities of Dho 287A to Apollo 12 and Apollo 15 mare basalts, with close affinities to the olivine-normative basalts (ONB), although the plagioclase feldspar in Dho 287A has been converted to maskelynite by the shock metamorphism during the ejection of this meteorite from the lunar surface. These authors further suggested that the whole-rock composition of Dho 287A displays similarities to Apollo 12 and Apollo 15 mare basalt samples, but requires possible assimilation of KREEP to account for its elevated rare-earth-element (REE) contents.

In order to better understand the petrogenetic history of Dho 287A, we have carried out *in-situ* U–Pb isotopic study of phosphate and plagioclase grains, which in turn provide constraints on the crystallization age of the basaltic lithology in this meteorite. Our *in-situ* analyses, using the SHRIMP installed at the Hiroshima University, attain high sensitivity at a high mass resolution of ~5800 (Sano et al., 1999a,b,c). Although recent, high-precision thermal ionization mass spectrometry (TIMS) analyses have enabled the U–Pb dating from ~10 μg phosphates (Amelin et al., 2005), our *in-situ* analyses have the following advantages in comparison with conventional TIMS techniques: (1) a much smaller amount of sample is required (usually only a polished thin section); (2) the mineralogy and the textural relationships of minerals in the rock can be investigated in their natural setting; and (3) U–Pb systematics in various phases can be independently investigated. This *in-situ* U–Pb dating methodology has been successfully applied to a range of extraterrestrial phosphates, including Martian meteorites (Sano et al., 2000; Terada et al., 2003a, Terada and Sano 2004), ordinary chondrites (Terada and Sano, 2002, 2003), and lunar meteorites (Anand et al., 2003a,b; Terada et al., 2005, 2006; Anand et al., 2006; Terada et al., 2007a,b) as well as terrestrial samples (Sano et al., 1999a, 1999b, 1999c; Sano and Terada, 2001; Nishizawa et al., 2004; Sano et al., 2006). U–Pb studies of meteorites have provided insights into the thermal evolution of their parent bodies. The primary objective of the present work was to investigate the U–Pb systematics of the lunar basalt Dho 287A. The second objective was to compare the crystallization and/or thermal metamorphism of this low-Ti basalt with those of other mare basalts (meteorites and Apollo/Luna mare basalts), and to provide constraints on its possible source region within the lunar mantle.

2. Sample and analytical methods

In this study, we used a polished thin section of Dho 287A, which displayed a coarse-grained texture for mare basalt consisting mainly of phenocrysts of olivine (>1 mm) and pyroxene (up to 0.5 mm), set within a finer-grained matrix composed of elongated pyroxene and plagioclase crystals, the latter of which had been completely converted to maskelynites. This was the very same thin section used by Anand et al. (2003b) for their study; as they had described, the distinctive petrographic feature of this thin section is the unusual abundance (>3%) of late-stage mesostasis, which is composed mainly of fayalite, Si–K–Ba-rich glass, fluorapatite, and merrillite.

We initially obtained back-scattered electron (BSE) images of the thin section, followed by measurements of mineral compositions using an Electron Probe Micro Analyzer (EPMA; JEOL JCMA-733II), in order to identify the location and mineralogy of the phosphate phases. Although about twenty phosphates, with sizes ranging from 10 to 100 μm, occur in this 2.5-inch standard thin section, some of them are severely cracked. For SHRIMP analyses, only areas of the grains without inclusions and cracks were selected. The mineral species and major-element compositions of selected phosphate grains are reported in Table 1. Oxide totals of some grains are low because of the assumed contribution of un-analyzed elements such as F, Cl, SiO_2, Ce_2O_3 and Nd_2O_3, although their abundances were qualitatively confirmed. In order to evaluate the shock processing of Dho 287A, we also carried out the Raman spectroscopy of phosphate grains. In this thin section, we could not recognize the double-peak profiles at 974 and 1000 cm^{-1}, characteristic of high-pressure polymorph of phosphates produced by shock metamorphism (Xie et al., 2002), suggesting that the shock metamorphism of phosphates in Dho 287A might be negligible and that the phosphate grains could retain the intrinsic information of U–Pb systematics.

Following cleaning to minimize surface contaminant Pb by ethanol, the thin section was gold-coated to prevent charging of the sample surface during SHRIMP analyses. In order to further reduce the already very small $^{x-1}PbH^+$ interference on the $^{x}Pb^+$ peaks, the thin section was evacuated in the sample lock overnight. An important final step before the actual analysis, involved the rastering of the primary ion beam over the entire sample surface for 3 min in order to remove any remaining possible contaminants.

An approximately 1 nA O_2^- primary beam with acceleration voltage of 10 kV was focused to sputter an area ~10 μm in diameter on the phosphates. The positive secondary ions were thereby extracted and detected on a single electron multiplier by peak switching. The mass resolution was set to 5800 at ^{208}Pb for U–Pb analyses. For phosphate analyses, the magnet was cyclically peak-stepped from mass 159 ($^{40}Ca_2^{31}P^{16}O_3^+$) to mass 254 ($^{238}U^{16}O^+$), including background, all Pb isotopes, and mass 238 for ^{238}U. 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 $^{40}Ca^{231}P^{16}O^+$ (158.884 AMU) at the mass resolution of 5800). For the phosphate analyses, 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 (1155±20 Ma at 2σ level). Experimental details of the U–Pb analysis and the calibration of the data were presented elsewhere (Sano et al., 1999a, 2006). The U concentration and observed $^{238}U/^{206}Pb$, $^{207}Pb/^{206}Pb$ and $^{204}Pb/^{206}Pb$ ratios are listed in Table 2. For plagioclase

Table 2
U concentrations and $^{238}U/^{206}Pb$, $^{207}Pb/^{206}Pb$, and $^{204}Pb/^{206}Pb$ ratios in phosphates for Dhofar 287A

Spot no.	Mineral	U (ppm)	$^{238}U/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{204}Pb/^{206}Pb$
pho.01	merrillite	27	1.040±0.115	0.3958±0.0177	0.00753±0.00063
pho.02	apatite	24	1.212±0.105	0.4169±0.0138	0.01090±0.00104
pho.03	merrillite	28	1.103±0.140	0.4410±0.0299	0.01384±0.00239
pho.05	merrillite	54	1.139±0.142	0.3446±0.0414	0.00523±0.00132
pho.06	apatite	70	1.136±0.182	0.4113±0.0165	0.00884±0.00075
pho.09	merrillite	31	1.100±0.135	0.4494±0.0211	0.01167±0.00202
pho.12	apatite	95	1.320±0.275	0.3125±0.0109	0.00280±0.00055
pho.16	merrillite	32	0.873±0.164	0.4643±0.0253	0.00963±0.00206

Table 3
$^{238}U^+/^{206}Pb^+$, $^{207}Pb/^{206}Pb$, and $^{204}Pb/^{206}Pb$ ratios in plagioclase for Dhofar 287A

Spot no.	Mineral	$^{238}U^+/^{206}Pb^+$	$^{207}Pb/^{206}Pb$	$^{204}Pb/^{206}Pb$
plag.01	plagioclase	0.291 ± 0.038	0.8953 ± 0.0439	0.04210 ± 0.00454
plag.02	plagioclase	0.009 ± 0.009	1.0407 ± 0.0949	0.06534 ± 0.01099
plag.03	plagioclase	0.160 ± 0.025	0.6895 ± 0.0962	0.03719 ± 0.00596
plag.04	plagioclase	0.541 ± 0.033	0.6146 ± 0.0659	0.02800 ± 0.00390

analyses, the magnet was also cyclically peak-stepped from mass 159 (dummy unknown peak) to mass 254 ($^{238}U^{16}O^+$). No significant isobaric interferences such as hydride and oxide complexes were detected in this mass range. Since we do not have a plagioclase standard for U–Pb calibration, U concentration and elemental ratios of $^{238}U/^{206}Pb$ are not calibrated. As shown in Table 3, there is a negative correlation between $^{238}U^+/^{206}Pb^+$ and $^{204}Pb/^{206}Pb$, and a positive correlation between $^{207}Pb/^{206}Pb$ and $^{204}Pb/^{206}Pb$ as well as those of phosphates, indicating that U–Pb systematics of plagioclase would also retain chronological information.

3. Results

We first investigated the correlation between $^{204}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ for phosphates and plagioclases. As shown in Fig. 1, the trend of phosphates is very similar to that of plagioclase. Assuming that the error correlations are zero, analyses for five merrillites and three apatites give a $^{207}Pb/^{206}Pb$ isochron age of 3.32 ± 0.22 Ga (95% confidence level; MSWD = 0.56, dashed line in Fig. 1). Here, the best-fit isochron (dashed line) is expressed by $^{207}Pb/^{206}Pb = A*^{204}Pb/^{206}Pb + B$, where $A = 15 \pm 4.7$ and $B = 0.272 \pm 0.036$. Next, we calculated a $^{207}Pb/^{206}Pb$ isochron age using both phosphate data and plagioclase data, which show less radiogenic Pb composition. Analyses for five merrilites, three apatites and four plagioclase grains give a $^{207}Pb/^{206}Pb$ isochron age of 3.35 ± 0.13 Ga (95% confidence level; MSWD = 0.48, solid line in Fig. 1). Here, the best-fit isochron can be expressed by $^{207}Pb/^{206}Pb = A*^{204}Pb/^{206}Pb + B$, where $A = 14.0 \pm 2.5$ and $B = 0.278 \pm 0.025$. This equation is very similar to the one for phosphate grains alone.

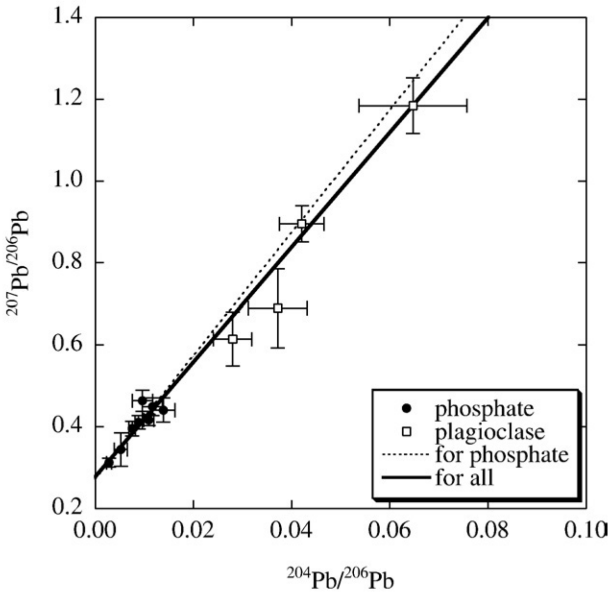

Fig. 1. An inverse $^{204}Pb/^{206}Pb$–$^{207}Pb/^{206}Pb$ isochron diagram for Dho 287A. Uncertainties are portrayed at the 1-sigma level. Analyses of five merrillite and three apatite grains give a $^{207}Pb/^{206}Pb$ age of 3.32 ± 0.22 Ga (95% confidence level; error correlation = 0). On the other hand, analyses of five merrillites, three apatites, and four plagioclases give a $^{207}Pb/^{206}Pb$ age of 3.35 ± 0.13 Ga. The calculation was made using Isoplot/Ex (Ludwig, 2001).

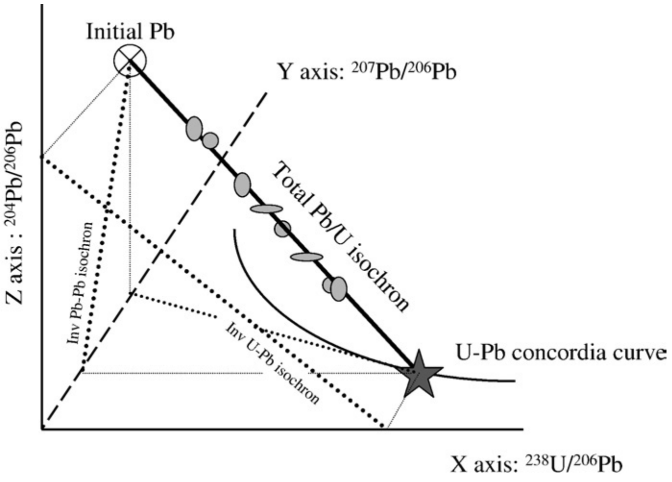

Fig. 2. Schematic diagram of the "Total Pb/U isochron method" in the $^{238}U/^{206}Pb$–$^{207}Pb/^{206}Pb$–$^{204}Pb/^{206}Pb$ three-dimensional space. For the concordia case, the formation age is defined as an intersection of a regression line with the U–Pb concordia curve on the $^{238}U/^{206}Pb$–$^{207}Pb/^{206}Pb$ plane (*X–Y* plane). For details, see Ludwig (1998) and Wendt (1984, 1989).

Finally, 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 Wendt, 1984, 1989; Ludwig 1998). Fig. 2 shows the schematic diagram of a three-dimensional linear regression for the total Pb/U isochron. It is noted that the projections onto the *Z–Y* plane and *X–Z* plane of this three-dimensional plot correspond to the Pb–Pb and the "inverse" U–Pb isochron diagrams, respectively. The projection onto the *X–Y* plane corresponds to the Tera–Wasserburg concordia plot. Here, the formation age is defined as the intersection of the regression line with the U–Pb concordia curve on the $^{238}U/^{206}Pb$–$^{207}Pb/^{206}Pb$ plane (*X–Y* plane). 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 a secondary event affects

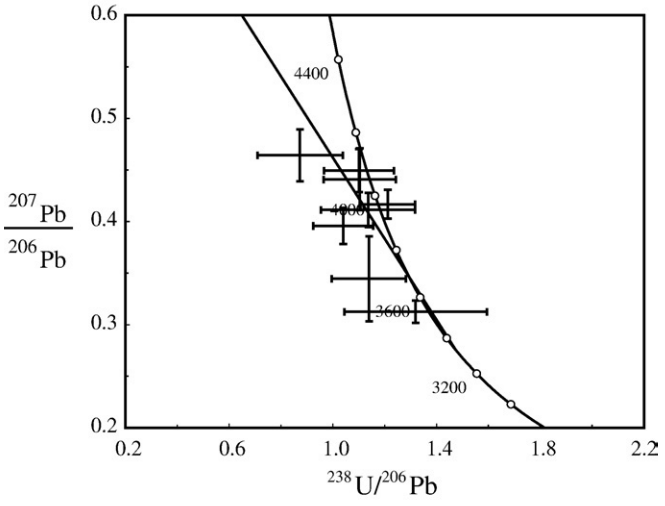

Fig. 3. The results of three-dimensional linear regressions of Dho 287A phosphates in the $^{238}U/^{206}Pb$–$^{207}Pb/^{206}Pb$–$^{204}Pb/^{206}Pb$ three-dimensional space. The data for five merrillite and three apatite grains are projected onto the $^{238}U/^{206}Pb$–$^{207}Pb/^{206}Pb$ plane. The solid curve is an evolution line of the U–Pb system without initial lead (concordia line), and the line is the projected regression line $^{238}U/^{206}Pb$–$^{207}Pb/^{206}Pb$ plane. The total Pb/U isochron age of 3.34 ± 0.20 Ga (95% confidence limit; MSWD = 0.67) was determined as an intersection of the concordia line and the regression line. Uncertainties are portrayed at the 1-sigma level. The calculation was made using Isoplot/Ex (Ludwig, 2001).

the U–Pb systematics slightly, the observed data are scattered on a plane in 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 (see Wendt 1984, 1989). The observed data for the three apatites and five merrilites in Dho 287A are well expressed by a LINEAR regression (MSWD = 0.67), and are not scattered on the plane in 3-D space; this indicates that the disturbance of U–Pb systems, as shown in some systematics of other lunar breccias, does not occur in this case. For the situations with EET 96008 and QUE 94281, both the formation age and the alteration age were obtained by the PLANAR regression (Anand et al., 2003a,b; Terada et al., 2006). Fig. 3 illustrates the linear regression for the total Pb/U isochron giving the isochron age of 3.34 ± 0.20 Ga (95% confidence level) projected onto the $^{238}U/^{206}Pb$–$^{207}Pb/^{206}Pb$ plane. The isotopic compositions of initial lead for the phosphates are $^{206}Pb/^{204}Pb = 25.5 \pm 9.8$ and $^{207}Pb/^{204}Pb = 21.8 \pm 6.0$, which can also be obtained from the intersection of the regression line with the $^{207}Pb/^{206}Pb$–$^{204}Pb/^{206}Pb$ planes, in the three-dimensional correlation plot.

Based on these assessments of U–Pb systematics of Dho 287A, we consider the Pb–Pb mineral isochron age of 3.35 ± 0.13 Ga as a crystallization age for the low-Ti mare basalt component in Dho 287. It should be noted that this Pb–Pb age is consistent with the Sm–Nd age of 3.46 ± 0.03 Ga, obtained by TIMS analyses (Shih et al., 2002).

4. Discussion and remarks

The numerous chronological studies of returned lunar samples of mare basalt and related pyroclastic deposits have been well documented (for summaries, see Nyquist et al., 2001). In general, the high-Ti basalts from the Apollo 11 and Apollo 17 sites are relatively old, generally ranging in age from 3.5 to 3.9 Ga. In contrast, low-Ti mare basalt samples are generally younger, ranging in age from 3.1 to 3.4 Ga for Apollo 15 and from 3.1 to 3.3 Ga for Apollo 12 samples. However, some exceptions exist with Apollo 14 mare basalts, which have ages of 3.9 to 4.2 Ga (Taylor et al., 1983). Whereas, based on the available data of very low-Ti (VLT) basalts, Nyquist et al. (2001) have

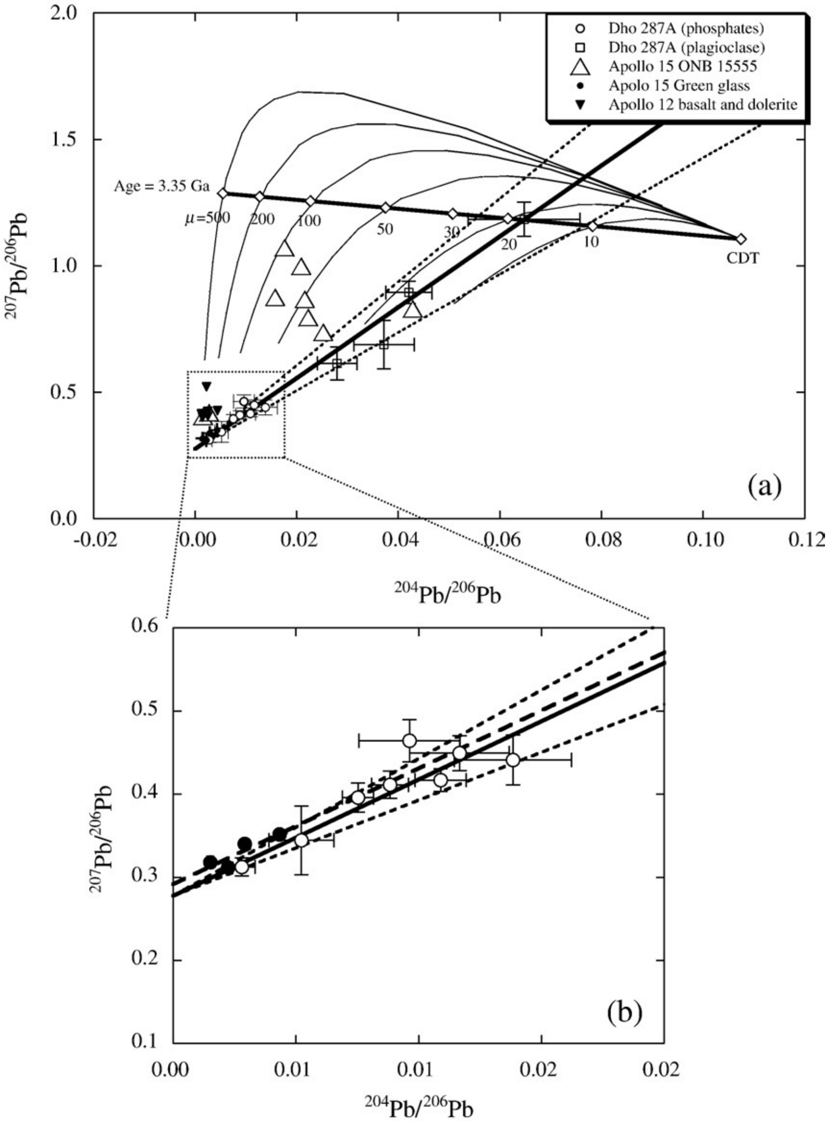

Fig. 4. Tera–Wasserburg Pb–Pb plots for Dho 287A (open circles for phosphates and open squares for plagioclase) and Apollo 15 ONB 15555 (open triangle), Apollo 15 green glasses 15426 (filled circle) and Apollo 12 basalt and dolerite (filled triangle), which are quoted from Tera and Wasserburg (1974), Tatsumoto et al. (1987) and Tatsumoto et al. (1971), respectively. The Pb-growth curve with various μ-values ($= ^{238}U/^{204}Pb$) is also plotted assuming single-stage Pb growth in a reservoir with Canyon Diablo Troilite (CDT) Pb composition at 4.56 Ga. In this diagram, the approximate μ-value of Dho 287A can be estimated by the intersection of Pb–Pb isochron (solid line) and "the various μ-value line" (black solid line), which shows the evolved Pb composition with various μ-values at 3.35 Ga for crystallization age of Dho 287A. The interception of the LINEAR regression line with the error envelope (dashed line) indicates that the magma source of Dho 287A had μ-value of ~ 18 ± 9. The broken line in Fig. 4(b) is the best-fit line for Apollo 15 Green glass, which seems to be identical to that of Dho 287A.

suggested that the formation ages of VLT mare basalts for Luna 24 are much younger at 3.2–3.3 Ga. Radiogenic studies of lunar meteorites have also provide us additional insights into the thermal histories of the lunar interior. For example, a paired group of meteorites, Yamato 793169, Asuka 881757, and MET 01210 and another paired group of meteorites, LAP 02205 and NWA 032, which consist of low-Ti basaltic material, have crystallization ages of 3.9 Ga and 2.7–3.0 Ga, respectively (Misawa et al., 1993; Kita et al., 1995; Fagan et al., 2002; Anand et al. 2003a,b; Fernandes et al., 2003; Nyquist et al., 2005; Rankenburg et al., 2007; Borg et al., 2007; Terada et al., 2007a,b). Similarly, a paired group of meteorites, EET 87521, EET 96008, and probably Yamato 981031 and QUE 94281, which consist of VLT basaltic materials, all have crystallization ages of ~3.5 Ga (Anand et al., 2003a,b; Terada et al., 2005, 2006). Although Shih et al. (2002) reported an age of 3.46± 0.03 Ga for Dho 287A, so far, no lunar basaltic meteorites have been found which has an age of 3.3–3.4 Ga, indicating that there are no meteorites that are paired with Dho 287A at this time. Thus, our result of 3.35±0.13 Ga clearly demonstrates that the thermal activity recorded in Dho 287A is similar to those of Apollo 15 low-Ti mare basalts of 3.1–3.4 Ga, and slightly older than Apollo 12 low-Ti mare basalt of 3.1–3.3 Ga. It is also noted that this age corresponds well to the "peak activity" of mare basalt magmatism in the unexplored areas of the Moon such as Oceanus Procellarum, Mare Nubium, Mare Cognitum and Mare Insularum, inferred from the relative chronology based on recent remote-sensing studies (Hiesinger et al., 2003).

Nearly all of the crystalline mare basalts from the Apollo 15 mission have been assigned to one or two distinct groups on the basis of their petrography and chemistry: an olivine-normative basalts (ONB) and quartz-normative basalts (QNB) (e.g., Rhodes and Hubbard, 1973). While these mare basalt groups were quickly recognized as possibly representing at least two distinct lava flows (Apollo 15 Preliminary Examination team, 1972), they were both extruded at 3.3±0.1 Ga (Nyquist and Shih, 1992), although Snyder et al. (1998) proposed that the QNBs may be slightly older (~3.35 Ga) than the ONBs (~3.25 Ga), although the ages do slightly overlap. Based on the detailed petrographical, mineralogical and geochemical descriptions of mare basalts in Dho 287A, Anand et al. (2003b) suggested that Dho287A is more akin to the Apollo 15 ONBs. In this sense, an obtained age of 3.35 ±0.13 Ga for Dho 287A is also consistent with those of Apollo 15 ONBs; 3.29±0.05 to 3.38±0.08 Ga for 15016 (Evensen et al., 1973; Kirsten et al., 1973); 3.23±0.02 to 3.46±0.09 Ga for 15555 (Chappell et al., 1972; Murthy et al., 1972; Tatsumoto et al., 1972; Andersen and Hinthorne, 1973; Tera and Wasserburg, 1974; Nyquist et al., 1991).

An important point to note is that the U–Pb systematics provide not only the isotopic ages of basalts, but also the μ-values (=^{238}U/^{204}Pb) of parent magma sources. These μ-values place additional constraints on the evolution of the lunar magma source regions. In particular, the μ-value can be used for assessing the fractionation between refractory and volatile elements as an important indicator when considering large-scale planetary differentiation scenarios. (For a review, see Premo et al., 1999). Fig. 4 is a Tera–Wasserburg Pb–Pb diagram, which is essentially same as Fig. 1; however, the Pb-growth curve with various μ-values (=^{238}U/^{204}Pb) are also plotted, assuming single-stage Pb growth in a reservoir with Canyon Diablo Troilite (CDT) Pb composition at 4.56 Ga. In this diagram, the μ-values of Dho 287A can be estimated from the intersection of Pb–Pb isochron and "the various μ-values line" which show the evolved Pb composition with various μ-values at 3.35 Ga (crystallization age of Dho 287A). The interception of LINEAR regression line with error envelope (dashed line) indicates that the magma source of Dho 287A had a μ-value of ~18±9. This extremely low μ-value of ~18 is similar to those of a uniquely paired group of so-called YAMM group (Yamato 793169, Asuka 881757, MET 01210 and probably MIL 05035) whose μ-values are 10±3 to 21.6±3.5 (Misawa et al., 1993; Kita et al., 1995; Terada et al., 2007a,b).

For comparison, the data of Apollo 15 ONB (15555), Apollo 15 green glass (15426) and Apollo 12 basalts and dolerites are also plotted in Fig. 4, as quoted by Tera and Wasserburg (1974), Tatsumoto et al. (1987) and Tatsumoto et al. (1971), respectively. As Tatsumoto et al. (1971, 1974) and Tera and Wasserburg (1974) previously concluded that the low-Ti mare basalts from the Apollo collection samples have high μ-value of 60 to 300, it is obvious that U–Pb systematics of Dho287A is distinct from that for Apollo 15 ONBs and Apollo 12 basalt and dolerites. Moreover, it should be noted that the μ-value of Dho 287A is significantly lower than those for KREEP. If phosphates in KREEPy mesostasis (open circle) were secondary products from an assimilation of a KREEP component, the inclination of the Pb–Pb isochron from the phosphate grains should be much larger, perhaps up to μ-values of more than 500. Anand et al. (2003b) proposed that the whole-rock REE chemistry of Dho 287A is composed of 8% KREEP and 92% of typical low-Ti mare basalt (15119, 19). In contrast, our data suggest a much more primitive source with considerably lower μ-values (<20) are required for the parental magma source of Dho 287A.

Interestingly, these unique features of very low μ-values at an age of 3.4 Ga for Dho 287a are quite similar to those of Apollo 15 Green glass, 15426, as shown in Fig. 4(b). Indeed, Tatsumoto et al. (1987) reported that the U–Pb systematics of the Green glass in 15426 resulted in a ^{207}Pb/^{206}Pb age of 3.41 Ga, with a μ-value of 19 to 55. Although the Green glass gives very radiogenic data, the isochron line for Green glass (broken line in Fig. 4(b)) is identical to that for Dho 287A. Therefore, these results strongly suggest a possible close affinity between the parent magma of Dho 287A and the Green glass source, which is considered to be an early LMO cumulate of orthopyroxene and olivine. Such as affinity to primitive mantle is also supported by the relatively Mg-rich concentration of Dho 287A (Anand et al., 2003b) and the similarity of the chemical composition of the picritic glasses in Dho 287B with those of Apollo 15 green glass.

On the other hand, Shih et al. (2002) reported slightly negative $\varepsilon_{\mathrm{Nd}}$ of −0.63±0.32 for Dho 287A and higher Rb/Sr ratio in comparison with most mare basalts, implying a slight contribution from KREEPy component. Such unique features of low μ-values and slightly negative $\varepsilon_{\mathrm{Nd}}$ for Dho 287A is also different from those of the so-called YAMM group which have extremely low μ-value of 10–22, old crystallization ages of 3.9 Ga but positive $\varepsilon_{\mathrm{Nd}}$ of 0.28 (Misawa et al., 1993; Kita et al., 1995), suggesting that Dho 287A is representative of an entirely new group of mare basalt from an unexplored region on the Moon, probably lying outside the PKT (Procellarum KREEP Terrain).

5. Summary

Detailed SHRIMP *in-situ* analyses of phosphates and plagioclase feldspar in mare basalt Dho 287A yield a crystallization age of ~3.35 Ga. Furthermore, it originated from a low-Ti mantle source region with an extremely low μ-value (around 20). These unique features of a very low μ-value of ~20 with a crystallization age of ~3.4 Ga for Dho 287A basalt are quite similar to those of Apollo 15 Green glass, suggesting a strong affinity of the Dho 287A mantle source region to early LMO cumulates. In addition, Shih et al. (2002) have reported slightly negative $\varepsilon_{\mathrm{Nd}}$ for Dho 287A. Such unique characteristics of U–Pb systematics and Sm–Nd systematics suggest that Dho 287A is representative of an entirely new group of mare basalt from an unexplored region on the Moon.

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