Pb–Pb dating of Yamato 86032

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Introduction:

The Moon exhibits significant differences between the nearside and farside hemispheres in elemental distributions[1], mare volcanic activity[2], and crustal thickness[3]. The origin of this dichotomy has been considered to be either:

1. lunar magma ocean (LMO) solidification[4] or
2. secondary process(es) (a large impact[5], mantle overturn[6]).

Based on recent observations of elemental distribution on the lunar surface, especially Mg# in mafic minerals of primitive crustal highland rocks, asymmetric crustal growth where crystallization progresses from the farside toward the nearside (direct link to 1.LMO solidification) is proposed as a model for the origin of the dichotomy[7].

If this model is correct, there should be a clear gap in the formation age between the lunar nearside and farside floatation crust. The pyroxene Pb–Pb age of the Ferroan Anorthosite (FAN) 60025 gives a precise age of 4359.2 ± 2.4 [Ma][8] for the nearside crust formation. On the other hand, no high-precision age constraints have been obtained for the formation of the lunar farside crust. In this study, we conducted high-precision pyroxene Pb–Pb dating of the Yamato 86032 meteorite, which is considered to have originated on the farside, to test the validity of the asymmetric crustal growth model and toward a more detailed understanding of LMO crystallization style.

Sample & experimental procedure:

Yamato 86032 (Y-86032) is a lunar anorthositic breccia found in 1986. The clasts are considered to be derived from the region far from the Procellarum KREEP Terrane (PKT) (possibly farside) because of the following unique features[9,10]:

1. The low bulk FeO (< 5wt.%), REEs, Th (<0.2 ppm), and U abundances,
2. The high Na contents in anorthite and high Mg# [=100×molar Mg/(Fe+Mg)] in mafic minerals (Magnesian anorthosite),
3. Anorthositic clasts in this meteorite retain old Ar–Ar ages compared to Apollo anorthosites.

Based on the Sm–Nd system, the formation age is estimated to be between 4.43-4.31 billion years ago[9,10].

A fragment of Y-86032 was crushed in ethanol using an agate mortar and pestle. Pyroxenes were concentrated by hand-picking under an optical microscope. We analyzed 3 pyroxene fractions from 2 different lithology (Y-86032, 138: 2 fractions, Y-86032, 144: 1 fraction) (Figure 1). Following Iizuka et al. (2014)[11], all sample fractions were leached four times in 1.5 mL of 0.5 M HNO_3 with ultrasonic agitation for 10 min, twice in 1.5 mL of hot 6 M HNO_3 for 1 h, and twice in 1.5 mL of hot 6 M HCl for 1h (Table 1). The acid residues were digested in a mixture of 25 M HF (25 drops) and 12 M HNO_3 (10 drops) at 120 °C for 2 overnights, followed by conversion to a soluble form by repeated evaporation with 12 M HNO_3 and 6 M HCl. Finally, the residues were evaporated and re-dissolved in 0.5 M HBr. The separation of Pb was performed using 0.05 ml of anion exchange resin AG1x8 200–400 mesh (Eichrom Technologies, U.S.A.). The Pb isotopes were measured using a Thermo Scientific TRITON plus at the University of California, Davis. Pb isotopic data were plotted using the Isoplot R software[12].

Table 1. Sequential acid leaching & digestion method.

	type of acid	duration	temperature
Wash 1 (W1)	0.5 M HNO_3	10 min × 4	25 ℃
Wash 2 (W2)	6 M HNO_3	1 hour × 2	110 ℃
Wash 3 (W3)	6 M HCl	1 hour × 2	110 ℃
Residue (R)	25 M HF + 12 M HNO_3	48 hours	120 ℃

Table 2. Amounts of Pb [unit: pg] eluted from each fraction.

	Px1	Px2	Px3
lithology	Y-86032, 138	Y-86032, 138	Y-86032, 144
Weight [mg]	1.13	2.71	1.19
Wash 1 (W1)	12.6	114.0	15.7
Wash 2 (W2)	27.9	205.4	14.7
Wash 3 (W3)	4.5	5.6	13.6
Residue (R)	19.1	21.1	26.8

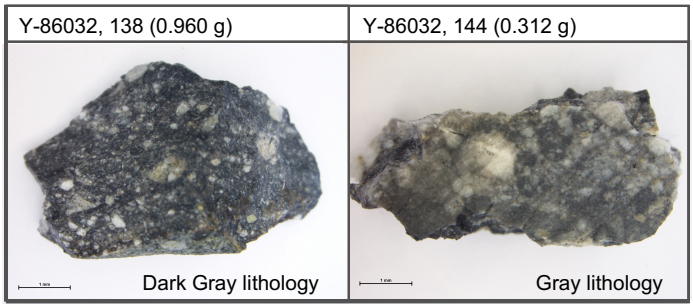

Figure 1. Optical images of Yamato 86032 used for this study.

Results & discussions:

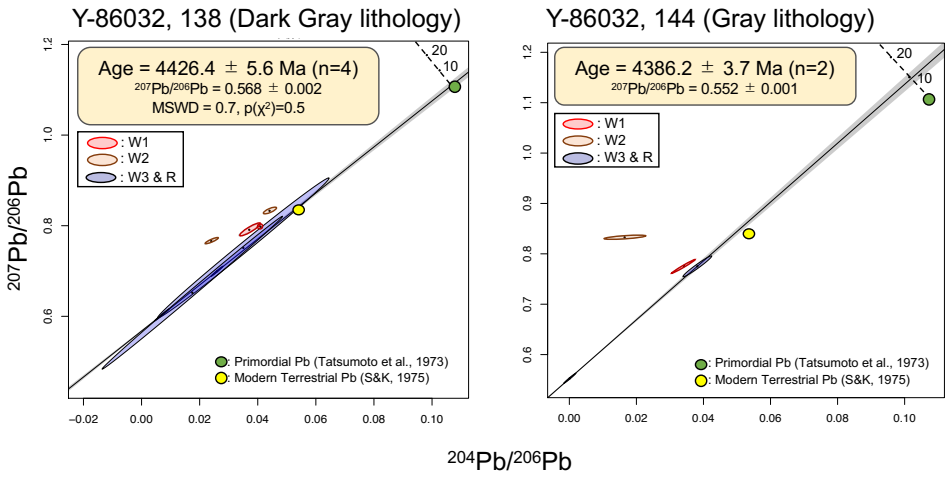

Figure 2. Inverse Pb–Pb isochrons of acid leachates & residues of Y-86032 pyroxene fractions. Data points used for isochrons are described as blue points (W3 & R). The yellow circle is modern day terrestrial Pb and the green circle is primordial Pb. The numbers in the figure represent the μ value ($^{238}U/^{204}Pb$) and each isochron pass through the initial Pb.

Pb concentrations in pyroxenes & Pb–Pb dating:

The Pb concentrations in pyroxenes estimated from the residue ranged from 7-22 ppb (Table 2). The high Pb amounts in W1 and W2 suggest that Pb from terrestrial contaminants and plagioclase in the meteorite have been dissolved from the pyroxene fractions. Because these washes are considered to have sufficiently removed common Pb, and 6 M HCl is considered to have caused the partial dissolution of pyroxene as in the previous study[8], both W3 and R are used for isochrons in this study.

Pyroxenes in two different fragments yielded different Pb-Pb dates: 4426.4 ± 5.6 [Ma] (n=4, MSWD = 0.7) from Y-86032, 138 (Dark Gray lithology), and 4386.2 ± 3.7 [Ma] (n = 2) from Y-86032, 144 (Gray lithology) , indicating that the pyroxene in each fragment has different formation timing.

Pb–Pb dates comparison to FAN60025:

The Pb–Pb dates of the Y-86032 are 27-67 [Ma] older than the Pb–Pb age of lunar nearside crust FAN60025, supporting the asymmetric crustal growth model that the lunar farside crust (or a region far enough from the PKT) is older than the nearside. There are two possible interpretations of the two different Pb–Pb dates obtained in this study. First, the Pb–Pb dates obtained here have a positive correlation with Mg# in mafic minerals and thus imply a cooling history of LMO. Mg# for each fragment in Y-86032 is higher than that of FAN nearside crust. The Mg# of olivine in FAN60025 and Y-86032 are compared here because it is difficult to determine the accurate estimation of Mg# in pyroxenes by their exsolution. The Mg# in FAN60025 olivine has a range of compositions (Fo_{42-66}: Fo#[＝100 × molar Mg/(Mg+Fe)])[13]. On the other hand, Mg# in Y-86032 olivine is Fo_{60-80} for those in the Dark Gray lithology, $Fo_{60.2-72.7}$ for those in the Gray lithology[10]. In this case, it is possible to consider that 4426 [Ma] of Y-86032 records the first stage of crust formation from the LMO, while 4359 [Ma] of FAN60025 records the last stage crystallization from the LMO. The second is that Y-86032 has experienced at least two shock metamorphisms[10] or thermal metamorphism because it contains some granulitic breccia[10], and the age obtained from Y-86032, 144 may record the timing of such metamorphisms.

This is the first report of a high-precision dating derived from a source other than the lunar central nearside crust. Further studies on the correlation between Mg# of mafic minerals in lunar pristine rocks and their high-precision formation ages are needed in the future.

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