NOBLE GASES IN YAMATO-791197: EVIDENCE FOR LUNAR HIGHLAND ORIGIN

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Abstract: Concentrations and isotopic compositions of five stable noble gases were determined for a whole rock sample and a white clast prepared from the Yamato-791197 breccia. The whole rock contains large amounts of trapped gases originating from solar wind implantation. Relative elemental abundances and isotopic compositions of trapped gases indicate the possible origin of the Y-791197 meteorite from lunar highland regolith. The high concentrations of both trapped and spallogenic gases in the whole rock and the cosmogenic $^{131}Xe/^{126}Xe$ ratio in the white clast suggest that the meteorite resided at a low average cosmic-ray shielding less than 65 g/cm^2. An exposure age of 910 ± 60 Ma is tentatively estimated for the whole rock, whereas the exposure age for the white clast is shorter by a factor of about three.

1. Introduction

The Yamato-791197 meteorite (hereafter Y-791197) is an anorthositic regolith breccia collected in the bare ice field near the Yamato Mountains, Antarctica, during the 1979–1980 field season. Its texture and mineral chemistry are similar to lunar highland rocks (YANAI and KOJIMA, 1984a, b). Recently, the Allan Hills A81005 meteorite (hereafter ALHA81005) collected from the Victoria Land in 1981 has been confirmed to be of lunar highland origin (*e.g.* Collected papers in Geophys. Res. Lett., **10**, 773–840, 1983). The identification of lunar meteorites is of great importance because their existence indicates the possibility of an acceleration mechanism by which lunar surface materials can be ejected towards the earth's orbit. Furthermore, the identification of lunar meteorites in the antarctic meteorite collections is important because new types of lunar materials may be found among the great number of antarctic meteorites that have been collected so far and will be collected by future expeditions. The escape velocity from Martian gravity is twice that from lunar gravity. The existence of lunar meteorites makes a Mars-origin hypothesis of the so-called SNC meteorites (*e.g.* SMITH *et al.*, 1984) more plausible.

Samples used in the present work are small chips of whole rock (10.14 mg) taken from a 150 mg chip (Y-791197,105) and a white clast (10.52 mg), separated from a large clast (about 3 mm in diameter) in a 140 mg chip (Y-791197,95). They were heated in vacuum at about 100°C for 15 h to remove an adsorbed atmospheric component. Noble gases were extracted by heating the sample at 1750°C for 20 min in an electric vacuum furnace. Techniques used for noble gas analysis are standard ones and have been given elsewhere (TAKAOKA, 1976; TAKAOKA and NAGAO, 1978).

2. Results and Discussion

Concentrations and isotopic ratios of all five stable noble gases were determined. Results are given in Tables 1–3. The whole rock sample contains large amounts of trapped gases originating from solar wind ions implanted into grain surfaces. Figure 1 is a plot of elemental abundances for the whole rock sample, ALHA81005 (Bogard and Johnson, 1983), Apollo 16 fines 65501 (Bogard and Nyquist, 1973), and the solar gas-rich meteorite Pesyanoe (Schultz and Kruse, 1983; Marti, 1969). Except ^{4}He, the elemental abundances in Y-791197 are 1.9–2.8 times enriched over those for ALHA-81005; agreement with lunar highland soil 65501 is better. A considerable part of the ^{4}He seems to have been lost from Y-791197. In comparison with solar gas-rich meteorites, Y-791197 is more depleted in lighter elements, *i.e.* more mass-fractionated. The ^{20}Ne/^{36}Ar ratio (2.74) for the whole rock is in the range (2.1–2.9) for Apollo 16 highland soils, but out of the range (3.7–8.3) for mare soils (Kirsten *et al.*, 1973).

Table 1. Isotopic abundances (cc/g) of noble gases in Y-791197,105 whole rock and in Y-791197, 95 clast.

Isotope	Whole rock	Clast	ALHA81005*	Y-791197WR / ALHA81005
^{3}He (10^{-5})	0.200	0.00219	0.169	1.18
^{4}He (10^{-5})	446	2.38	440	1.01
^{4}He/^{3}He	2227±15	1085±28	2604	—
^{20}Ne (10^{-5})	92.8	0.566	50.0	1.86
^{21}Ne (10^{-5})	0.304	0.0139	0.160	1.90
^{22}Ne (10^{-5})	7.55	0.0596	3.99	1.89
^{20}Ne/^{22}Ne	12.30±0.08	9.50±0.06	12.53	—
^{21}Ne/^{22}Ne	0.0403±0.0003	0.234±0.002	0.0401	—
^{36}Ar (10^{-5})	33.9	0.304	15.8	2.15
^{38}Ar (10^{-5})	6.41	0.0869	2.98	2.15
^{40}Ar (10^{-5})	86.0	0.796	28.4	3.03
^{38}Ar/^{36}Ar	0.189±0.002	0.286±0.003	0.189	—
^{40}Ar/^{36}Ar	2.536±0.028	2.62±0.05	1.80	—
^{84}Kr (10^{-10})	1700	21.0	612	2.78
^{132}Xe (10^{-10})	245	3.19	115	2.13

Errors cited to isotopic ratios are statistical ones (1σ), and uncertainty for concentrations is within 10%.

* Bogard and Johnson (1983).

The white clast sample is a separate from a large clast consisting mainly of plagioclase. It contains appreciable amounts of trapped gases as well as spallogenic ones. The trapped gas abundances in the clast are lower by factors of 190 for ^{4}He to 78 for ^{132}Xe compared with those in the whole rock, and progressively become more deficient in the lighter gases relative to the whole rock (Table 4). The following isotopic ratios were assumed for decomposition into trapped and spallogenic components: $(^{3}\mathrm{He}/^{4}\mathrm{He})_{\mathrm{sp}}=0.2$, $(^{3}\mathrm{He}/^{4}\mathrm{He})_{\mathrm{t}}=3.80\times10^{-4}$, $(^{20}\mathrm{Ne}/^{21}\mathrm{Ne}/^{22}\mathrm{Ne})_{\mathrm{sp}}=0.74/0.83/1$, $(^{21}\mathrm{Ne}/^{22}\mathrm{Ne})_{\mathrm{t}}=0.0317$, $(^{38}\mathrm{Ar}/^{36}\mathrm{Ar})_{\mathrm{sp}}=1.55$, $(^{38}\mathrm{Ar}/^{36}\mathrm{Ar})_{\mathrm{t}}=0.189$, $(^{40}\mathrm{Ar}/^{36}\mathrm{Ar})_{\mathrm{sp}}=0$; for solar Kr and Xe, isotopic ratios of surface correlated Kr (BEOC-12) given by Eberhardt *et al.*

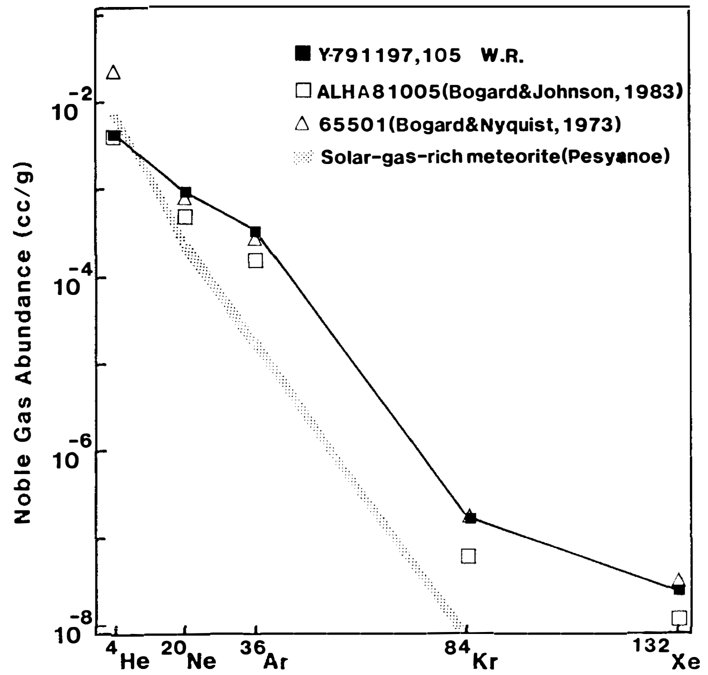

Fig. 1. Noble gas abundances in Y-791197,105 whole rock are compared with those in the lunar meteorite ALHA-81005, Apollo 16 soil 65501 and solar gas-rich meteorite Pesyanoe. Abundance pattern is suppressed in light gases, especially in He, relative to solar gas-rich meteorite. The same trend of mass fractionation is found for ALHA-81005 lunar meteorite. The ^{20}Ne/^{36}Ar ratio for Y-791197 falls in the range of typical values for lunar highland regolith (see text).

(1972) and surface correlated Xe (SUCOR-Xe) given by Podosek *et al.* (1971) respectively are used. The progressive depletion in the light gases suggests diffusive loss of the trapped gases from plagioclase grains, probably by impact shock.

The ^{4}He/^{3}He ratio for the whole rock is 2227, slightly lower than the ratio for ALHA-81005 but it is a typical value for lunar highland soils (Kirsten *et al.*, 1973; Bogard and Nyquist, 1973; Walton *et al.*, 1973). Helium in the clast is a mixture of the trapped and spallogenic components. The ratio of spallogenic ^{3}He in the whole rock to that in the clast is >15. The ^{20}Ne/^{22}Ne ratio for the whole rock is similar to that for ALHA81005 (Bogard and Johnson, 1983) and Ne-B (Black, 1972), but slightly lower than that for lunar soil Ne (Eberhardt *et al.*, 1972). This can be attributed to the mass fractionation effect accompanied by the diffusive gas loss. Approximately 89% of ^{21}Ne determined in the clast is of spallation origin. The ratio of spallogenic ^{21}Ne in the whole rock to that in the clast is 5.4 As shown in Table 4, the difference in this ratio between spallogenic ^{3}He and ^{21}Ne indicates that spallogenic ^{3}He loss occurred preferentially in the clast. The preferential loss is also found of the light trapped gases in the clast because plagioclase is less retentive for He and Ne (Megrue, 1966).

The ^{38}Ar/^{36}Ar ratio in the whole rock is indistinguishable from that for both ALHA81005 (Bogard and Johnson, 1983) and lunar soil (Eberhardt *et al.*, 1972). The ^{40}Ar/^{36}Ar ratio for the whole rock is higher by a factor of 1.4 than for ALHA81005, and falls in a range of typical ratios observed in highland soils (Bogard and Nyquist, 1973; Kirsten *et al.*, 1973; Walton *et al.*, 1973). The ^{40}Ar-^{39}Ar age of a white clast separated from Y-791197,96 has been determined to be 4065 Ma (KANEOKA and TAKAOKA, 1986). If the whole rock has the same gas-retention age as the clast (,96), radiogenic ^{40}Ar produced by the *in-situ* decay of ^{40}K would be 1.5×10^{-5} cm^3 STP/g, only 1.8% of total ^{40}Ar determined in the whole rock with an average K content of 250 ppm (FUKUOKA *et al.*, 1985; LINDSTROM *et al.*, 1985; OSTERTAG *et al.*, 1985; WARREN and KALLEMEYN, 1985). This means that the whole rock of Y-791197 contains large excess of ^{40}Ar, as most lunar regolith materials do. Correction for radiogenic ^{40}Ar gives 2.49 for the ^{40}Ar/^{36}Ar ratio of trapped Ar.

Ar in the clast is relatively enriched in the spallogenic component. 7.1% of ^{36}Ar and 39% of ^{38}Ar are spallogenic. The ^{40}Ar/^{36}Ar ratio is 2.82 after correction for the spallogenic component. This ratio is very similar to that of trapped Ar in the whole rock. Since no data are available on the K content for the present sample (,95), we consider two extreme cases. If the ^{40}Ar/^{36}Ar ratio of trapped Ar in the clast is the same as that of trapped Ar in the whole rock, we have 9.3×10^{-7} cm^3 STP/g for radiogenic ^{40}Ar. The K content to produce this quantity of ^{40}Ar by the *in-situ* decay in 4065 Ma is as low as only 15 ppm. This is considerably lower compared with the K content of 140 ppm reported for a small white clast separated from matrix of Y-791197,76 (WARREN and KALLEMEYN, 1985). Otherwise, a great portion of radiogenic ^{40}Ar might have been lost from the clast (,95). On the other hand, without any large loss of radiogenic ^{40}Ar, the trapped ^{40}Ar/^{36}Ar ratio in the clast should be considerably lower than that in the whole rock. Sample heterogeneity is common in breccia as *e.g.* found in the ^{40}Ar/^{36}Ar ratio for the white clast (,96), which is an order of magnitude higher than that for the clast (,95) (KANEOKA and TAKAOKA, 1986).

The isotopic ratio of Kr for the whole rock is identical with that for ALHA81005 bulk (BOGARD and JOHNSON, 1983). It is enriched in the light isotopes relative to solar Kr (EBERHARDT *et al.*, 1972), as shown in Fig. 2. This enrichment is attributed to spallogenic Kr produced by cosmic-ray irradiation. Approximately 12% of ^{78}Kr is spallogenic. The proportion of spallation Kr is quite remarkable in the clast, 80% of ^{78}Kr being of spallogenic origin. The isotopic ratios of spallation Kr in the clast are: ^{78}Kr/^{80}Kr/^{82}Kr/^{83}Kr/^{84}Kr/^{86}Kr $= 0.180 \pm 0.020/0.582 \pm 0.058/0.756 \pm 0.081/ = 1/0.683 \pm 0.192/ = 0.015$, and are also plotted in Fig. 2.

The isotopic composition of Xe for the whole rock is in good agreement with that for the ALHA81005 bulk (Fig. 3). However, Y-791197 Xe is apparently richer in the spallogenic component compared with solar Xe (PODOSEK *et al.*, 1971). As in the case of Kr, the spallation component is relatively enriched in the clast, about 90% of ^{126}Xe

Table 2. Isotopic ratios of Kr in Yamato-791197 meteorite. Istotopic ratio of solar Kr (EBERHARDT et al., 1972) is also given for comparison.

Isotope	Whole rock	Clast	Solar Kr (BEOC-12)
^{78}Kr	2.21 ± 0.06	9.6 ± 0.7	1.944 ± 0.016
^{80}Kr	13.61 ± 0.09	37.3 ± 1.9	12.75 ± 0.07
^{82}Kr	66.40 ± 0.30	97.4 ± 2.8	65.74 ± 0.26
^{83}Kr	66.78 ± 0.42	108.26 ± 2.6	65.87 ± 0.23
^{84}Kr	326.6 ± 1.8	354.9 ± 8.0	327.9 ± 0.8
^{86}Kr	$=100$	$=100$	$=100$

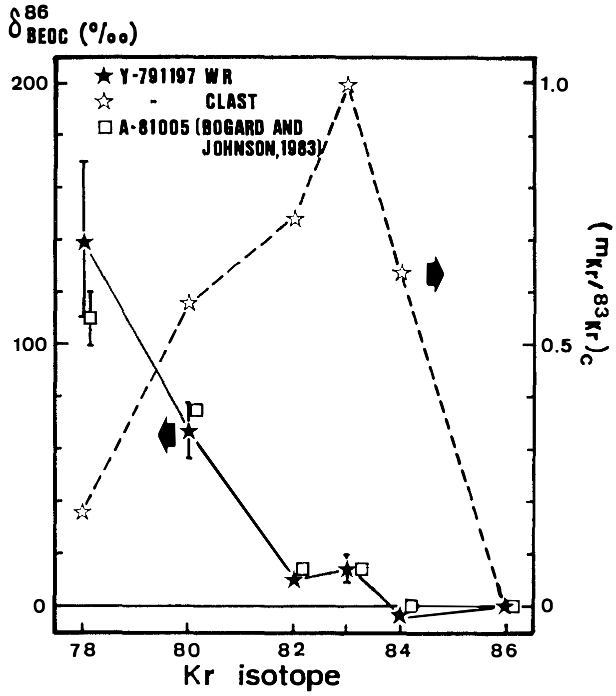

Fig. 2. Isotopic composition of Kr for whole rock relative to solar Kr (BEOC-Kr, EBERHARDT et al., 1972) and isotopic ratio of spallation Kr in the clast

being spallogenic. The isotopic ratios of spallation Xe are: ^{124}Xe/^{126}Xe/^{128}Xe/^{129}Xe/^{130}Xe/^{131}Xe/^{132}Xe/^{134}Xe/^{136}Xe$=0.55\pm0.11/=1/1.53\pm0.29/3.24\pm0.45/0.89\pm0.32/4.48\pm0.88/0.53\pm0.74/0.03\pm0.44/=0$. These ratios agree well with those for lunar soils except ^{129}Xe (BASFORD *et al.*, 1973). The ratio of spallogenic ^{126}Xe between the whole rock and the clast is 2.3. The ^{131}Xe/^{126}Xe ratio is an indicator for shielding depth because ^{131}Xe is produced not only by the spallation reactions of Ba and REE but also by the ^{130}Ba (n, γ) reaction, whereas ^{126}Xe is produced by the spallation reaction. The cosmogenic ^{131}Xe/^{126}Xe ratio for the clast (,95) is 4.48 ± 0.88. Comparison between the observed and the predicted ^{131}Xe/^{126}Xe ratios (HOHENBERG *et al.*, 1978) indicates that the clast resided near the moon surface (<65 g/cm^2) with the assumed Ba/La ratio between 10 and 70. Spallogenic and trapped gases are more enriched in the whole rock than in the clast. This suggests that the whole rock resided at a low average

Table 3. Isotopic ratios of Xe for whole rock and clast of Y-791197. Solar Xe (SUCOR-Xe) (PODOSEK et al., 1971) is given for comparison.

Isotope	Whole rock	Clast	SUCOR-Xe
^{124}Xe	0.543 ± 0.011	2.6 ± 0.4	0.476
^{126}Xe	0.552 ± 0.012	4.3 ± 0.4	0.434
^{128}Xe	$8.57\ \pm0.14$	14.2 ± 1.0	8.39
^{129}Xe	$102.9\ \pm1.8$	117.3 ± 1.3	105.0
^{130}Xe	$16.73\ \pm0.15$	19.6 ± 1.2	16.49
^{131}Xe	$82.4\ \pm0.8$	98.0 ± 3.0	82.26
^{132}Xe	=100	=100	=100
^{134}Xe	$37.2\ \pm0.4$	36.5 ± 1.7	37.12
^{136}Xe	$30.2\ \pm0.2$	29.5 ± 1.2	30.10

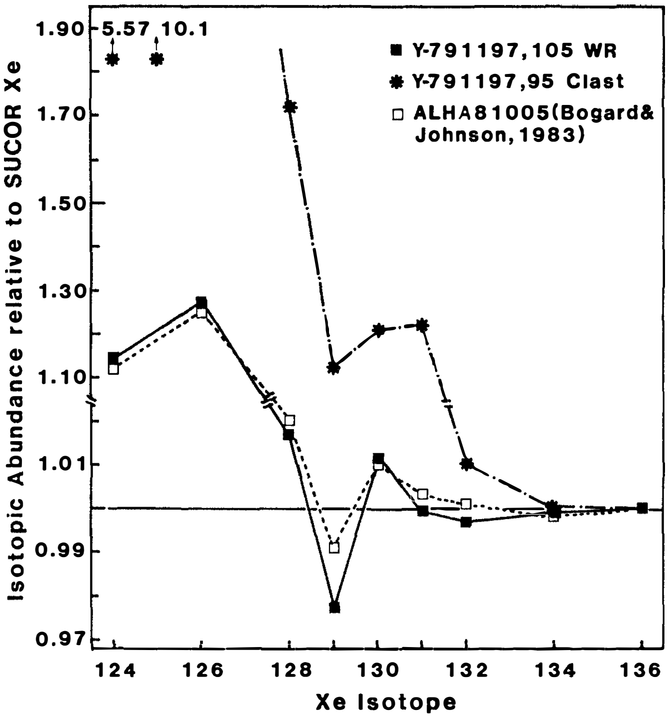

Fig. 3. Isotopic composition of Xe for whole rock and clast relative to solar Xe (SUCOR-Xe, PODOSEK *et al., 1971).*

cosmic-ray shielding less than 65 g/cm^2.

Cosmic-ray exposure ages for the whole rock range from 400, 970 and 850 Ma to 640, 1740 and 1300 Ma for spallogenic ^{21}Ne, ^{83}Kr and ^{126}Xe, respectively, with production rates of these spallogenic nuclides at two shielding depths: One g/cm^2 and 65 g/cm^2 (HOHENBERG *et al.*, 1978; REGNIER *et al.*, 1979). In this calculation, we used the average chemical composition (Table 5) of the Y-791197 whole rock given by FUKUOKA *et al.* (1985), LINDSTROM *et al.* (1985), OSTERTAG *et al.* (1985), and WARREN and KALLEMEYN (1985). The ^{21}Ne age is considerably younger than the ^{83}Kr and ^{126}Xe ages. This is a general tendency found in lunar regolith samples resulting from diffusive loss of Ne during soil maturation. A concordant age for the ^{83}Kr and ^{126}Xe ages is obtained at very shallow shielding depths, and discrepancy between them is enhanced for deeper shielding. Therefore, we tentatively estimate the exposure age for Y-791197 to be 910±60 Ma. From the concordant ages for very shallow shielding and the enhanced discrepancy of the exposure ages for deeper shielding, we suppose that Y-791197 came from an uppermost part of the lunar highland regolith. This is in agreement with the recent measurements of cosmic-ray produced nuclides (NISHIIZUMI and ELMORE, 1985) and thermoluminescence analyses (SUTTON, 1985).

The cosmic-ray exposure history of the clast seems to differ from that of the whole rock. The clast (,95) contains only about 50% of spallogenic ^{83}Kr and ^{126}Xe compared with the whole rock concentrations (Table 4). The shielding depth estimated from the cosmogenic ^{131}Xe/^{126}Xe ratio is less than 65 g/cm^2. Although no data are available for the chemical composition of the clast (,95), concentrations of target nuclides such as Sr and Ba in the white clast which consists mainly of plagioclase are supposed to be

Table 4. Comparison of trapped and spallogenic gases between whole rock and clast of Y-791197.

Isotope	Whole rock	Clast	Whole rock / Clast
$(^{4}\text{He})_t$ (10^{-3})	4.46	0.0238	187
$(^{20}\text{Ne})_t$ (10^{-4})	9.28	0.0556	167
$(^{36}\text{Ar})_t$ (10^{-4})	3.39	0.0282	120
$(^{84}\text{Kr})_t$ (10^{-7})	1.70	0.0194	87.6
$(^{132}\text{Xe})_t$ (10^{-8})	2.45	0.0312	78.6
$(^{3}\text{He})_s$ (10^{-8})	32	<2.2	>15
$(^{21}\text{Ne})^{\#}_s$ (10^{-8})	67.1	12.5	5.4
$(^{83}\text{Kr})_s$ (10^{-10})	4.74	2.52	1.9
$(^{126}\text{Xe})_s$ (10^{-10})	0.289	0.124	2.3

Concentration is given in cm^3 STP/g.

Table 5. Chemical composition assumed for estimation of production rates of cosmogenic nuclides.

Element	Whole rock	Reference	Clast	Reference
Na (%)	0.24	a, b, c, d		
Mg (%)	3.6	a, b		
Al (%)	14.2	a, b		
Si (%)	21.5	b, c		
K (%)	0.024	a, b, c, d	0.023	a, b
Ca (%)	11.0	a, b, c, d	11.7	a, b
Ti (%)	0.18	a, b	0.09	b
Fe (%)	4.9	a, b, c, d	5.16	a, b
Rb (ppm)	2	c		
Sr (ppm)	136	a, c, d		
Y (ppm)	9.5	e		
Zr (ppm)	38	a, c, d		
Ba (ppm)	30	a, c, d	53	a
La (ppm)	2.5	a, c, d	1.3	a

(a) WARREN and KALLEMEYN (1985), (b) FUKUOKA *et al.* (1985), (c) OSTERTAG *et al* (1985), (d) LINDSTROM *et al.* (1985), (e) Zr/Y=4 was assumed.

similar to or larger than those in the whole rock sample, because both Sr and Ba are chemically compatible with Ca. Assuming the chemical composition as given in Table 5, the ^{38}Ar age ranges 120 Ma at 1 g/cm^2 to 250 Ma at 65 g/cm^2 with a maximum age of 300 Ma at 10 g/cm^2. The ^{126}Xe and ^{131}Xe ages are in a narrow range between 290 and 400 Ma. Discrepancy between the ^{38}Ar age and the Xe ages is largest on the surface, and decreases to a minimum around 30 g/cm^2. Therefore, we tentatively estimate the cosmic-ray exposure age for the white clast (,95) to be 310±30 Ma at 30 g/cm^2. This short age means that the white clast which had been resided in depth of large cosmic-ray shielding was thrown out to a regolith layer 310 Ma ago by the collisional impact of an interplanetary body such as meteorites.

In summary, the large concentrations of solar wind gases, the relative elemental abundances and the isotopic compositions of noble gases in the Y-791197 anorthositic breccia are all compatible with the origin from lunar highland regolith. The concordant cosmic-ray age of 910±60 Ma is estimated tentatively for the whole rock sample from the ^{83}Kr and ^{126}Xe ages calculated at the shielding depth of 1 g/cm^2. The white clast may be one of ejecta thrown out 310±30 Ma ago. From the cosmogenic ^{131}Xe/^{126}Xe ratio, the concordance of the cosmic-ray ages, and the enrichment of both solar and spallogenic gases in the whole rock sample, we suppose that the Y-791197 meteorite resided at low average cosmic-ray shielding. Whether or not the antarctic meteorites were ejected by a single impact is an open question. A clue to answer the question could be given by study of Y-82192 and -82193, new lunar meteorites (YANAI and KOJIMA, 1985), as well as further studies of clasts and composite minerals of Y-791197 and ALHA81005.

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