CHEMISTRY OF YAMATO-791197 ANTARCTIC METEORITE: EVIDENCE FOR ITS LUNAR HIGHLAND ORIGIN

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Abstract: We report chemical data for 33 major, minor and trace elements in one clast, two matrices and two bulk samples of the Yamato-791197 meteorite by instrumental neutron activation analysis (INAA). Based on the well-established characteristic lunar and meteoritic ratios of FeO/MnO, Cr_2O_3/V and K/La, and the large-ion lithophile (LIL) element patterns, the Y-791197 meteorite is undoubtedly an anorthositic gabbro breccia of lunar highland origin. The similarity of chemical compositions of the Y-791197 and ALHA81005 meteorites suggests that both meteorites may have been ejected from the same lunar region. Based on the overall chemical abundances and the very low K_2O content, it is suggested that both meteorites originated from the far side of the moon. The similar Ir/Ni/Au ratios of the Y-791197 and ALHA81005 meteorites suggest that they may be related to one and the same impact event.

1. Introduction

Two unique meteorites, Yamato-791197 (Y-791197) and Allan Hills A81005 (ALHA81005), were collected from the bare ice area near the Yamato Mountains in November 1979 and from the bare ice in the Allan Hills region, Antarctica, on January 18, 1982, respectively. Both meteorites have similar textures (YANAI and KOJIMA, 1984). Two years ago, the ALHA81005 meteorite was recognized as a lunar breccia. Evidence for its lunar origin has been published in the Geophys. Res. Lett., **10** (9) (1983) which contains 18 special papers devoted to the study of this meteorite.

The Y-791197 meteorite has major chemical, mineralogical, and textural features that are characteristic of lunar breccias (YANAI and KOJIMA, 1984). The oxygen isotopic data of Y-791197 support a lunar origin for this meteorite (CLAYTON *et al.*, 1984). In the present study, we have carried out a detailed chemical study of the Y-791197 meteorite. Based on our results, a lunar highland origin for this meteorite is confirmed. From a comparison with the ALHA81005 data, we discuss source regions and the impact origin for these two lunar breccias.

2. Samples and Experimental

Two whole rock samples (sub. nos. 107 and 148) and one white clast sample with a dark matrix (sub. no. 99) were provided from the National Institute of Polar Research of Japan. We separated two matrix chips, which were denoted as matrix-A (148-1) and matrix-B (148-2), and one bulk sample, denoted as bulk-A (148-3), from a whole rock sample (sub. no. 148). Bulk-A (148-3) sample consisted of a large number of fragments of 0.2 to 1 mm grain size. A white clast (99-1) was purified with exclusion of the dark matrix prior to analysis. Bulk-B (107-1) sample consisted of many matrix grains, less than 3 mm in size; the sample also included a small grayish clast.

The abundances of 33 major, minor and trace elements in five samples have been determined by instrumental neutron activation analysis (INAA). Matrix-A and -B and bulk-A samples were activated with thermal neutrons for 4 min at 500 kW (4×10^{12} n/cm^{2}s) in the Oregon State University (OSU), TRIGA II reactor for measurement of short-lived radionuclides. Then the samples were reactivated with thermal neutrons for 7 h at 1 MW (3×10^{12} n/cm^{2}s) in the OSU reactor for measurement of long-lived radionuclides. The γ-ray spectrometry for these samples was carried out by the OSU and Battelle counting systems. The clast and bulk-B samples were activated with thermal neutrons for 2 min at 100 kW (1.5×10^{12} n/cm^{2}s) in the Musashi Institute of Technology (MIT), TRIGA II reactor for measurement of short-lived radionuclides. Then the samples were reactivated with thermal neutrons for 5 h at 3.5 MW (5.5×10^{13} n/cm^{2}s) in JRR-4 reactor of the Japan Atomic Energy Research Institute for measurement of long-lived radionuclides. The γ-ray spectrometry for these samples was carried out by the MIT, Gakushuin University and Battelle counting systems. G. S. J. standard rocks, JB-1, JR-2 and U.S.G.S. standard rocks, BCR-1, GSP-1, and PCC-1 were also activated as standard and/or control samples.

3. Results

Analytical results are shown in Table 1 together with the results for standard rocks, BCR-1 and JB-1. The chemical abundances of the clast, matrix and bulk samples of ALHA81005 (LAUL *et al.*, 1983) and the chemical abundances of the Apollo 16 65055 highland rock (TAYLOR, 1982) are compiled in Table 1 for comparison.

Analytical results for the bulk and matrix of Y-791197 agree well with each other within the error, although the Cr, Sc and La values indicate small discrepancies which imply sample heterogeneity. Therefore, we calculated the mass-weighted mean of the chemical abundances of the two matrices and two bulk samples for overall chemical abundances of the bulk Y-791197 meteorite (Table 1). These mean values agree well with the analytical results reported by WARREN and KALLEMEYN (1985) and OSTERTAG *et al.* (1985). The analytical values of Co, Ni and Au for the bulk-B sample of Y-791197 are remarkably high compared with those for the two matrices and the bulk-A sample. Although the Au value of the bulk-B agrees with that reported by KACZARAL *et al.* (1986), the Co value obtained by them does not agree with that of the bulk-B but agrees well with that of the bulk-A. We suspect that these high Co, Ni and Au values were caused by some contamination, although the origin of the contamination is not

Table 1. Chemical abundances by INAA.

		Y-791197						ALHA81005			Apollo 16	Controls		
		Clast 99-1	Matrix-A 148-1	Matrix-B 148-2	Bulk-A 148-3	Bulk-B 107-1	Wtd. mean matrix & bulk	Clast (LAUL *et al.* (1983))	Matrix (LAUL *et al.* (1983))	Bulk (LAUL *et al.* (1983))	65055 TAYLOR (1982)	BCR-1*	JB-1*	Error** %
Wt	mg	5.39	5.65	6.57	21.4	23.2		9.3	23.0	20.5		10.8, 26.0	20.6, 21.7	
TiO_2	%	0.15	0.36	0.35	0.30	0.32	0.30	0.30	0.30	0.30	0.28	2.15	1.31	10–20[1)]
Al_2O_3	%	24.7	28.9	27.8	27.7	26.0	27.1	25.9	25.6	26.3	28.5	13.5	14.8	0.5–1
FeO	%	6.9	6.6	6.6	6.7	6.8	6.7	5.9	5.6	5.6	3.90	=12.2	8.6	0.5–1
MgO	%	12.3	5.1	4.5	5.8	7.7	6.4	9.0	8.0	8.0	4.81	3.5	7.8	5–10
CaO	%	16.1	15.0	14.5	15.3	15.5	15.3	16.7	15.2	15.2	16.1	6.9	9.7	2–5
Na_2O	%	0.30	0.35	0.36	0.34	0.32	0.34	0.31	0.31	0.31	0.44	=3.20	2.84	0.5–1
K_2O	%	0.038	0.032	0.037	0.028	0.026	0.029	0.02	0.025	0.025	0.13	=1.70	1.49	3–10
MnO	%	0.111	0.083	0.083	0.087	0.084	0.085	0.074	0.070	0.069	0.05	0.185	0.152	1–2
Cr_2O_3	%	0.188	0.125	0.125	0.125	0.114	0.120	0.120	0.120	0.125	0.83	0.0019	=0.067	0.5–2
Sr	ppm	150	120	130	130	150	137	130	140	140	140	=330	432	5–8
Ba	ppm	78	40	40	40	38	39	25	30	30	80	=670	528	5–10
Sc	ppm	14.5	12.1	12.6	13.5	12.7	12.9	9.0	9.0	9.5	7.2	=32.0	29.0	0.5
V	ppm	27	30	30	30	24	28	25	25	25	35	387	215	2–10[2)]
La	ppm	5.07	2.16	2.58	2.16	2.06	2.17	1.7	2.0	2.0	6.2	=25.5	40.5	1–3
Ce	ppm	13.0	5.3	5.6	5.6	5.2	5.4	4.0	4.8	5.0	16.0	=54.0	68.0	1–5
Nd	ppm	7.3	3.5	4.0	3.5	3.2	3.4	3.0	3.5	3.3	—	=30	28	3–10

Sm	ppm	2.25	1.03	1.04	1.08	1.01	1.04	0.85	1.0	1.0	2.6	=6.70	5.50	0.5–2
Eu	ppm	0.81	0.80	0.75	0.80	0.76	0.78	0.70	0.73	0.75	1.0	=2.00	1.58	1–3
Gd	ppm	2.7	1.3	1.2	1.3	1.3	1.3	—	—	—	—	=7.0	7.4	6–10
Tb	ppm	0.52	0.26	0.25	0.26	0.21	0.24	0.18	0.20	0.20	0.55	=1.1	0.69	2–5
Dy	ppm	3.3	1.7	1.5	1.6	1.45	1.5	1.2	1.3	1.3	—	6.3	3.9	3–8
Tm	ppm	0.39	0.13	0.16	0.16	0.16	0.16	0.12	0.13	0.13	—	=0.60	0.42	6–10
Yb	ppm	2.02	1.03	1.05	1.12	0.95	1.03	0.74	0.84	0.86	2.1	=3.40	2.32	2–5
Lu	ppm	0.30	0.14	0.15	0.17	0.14	0.15	0.11	0.13	0.13	0.29	=0.52	0.34	2–6
Zr	ppm	65	25	30	30	35	32	25	30	30	72	175	140	7–15
Hf	ppm	1.66	0.78	0.79	0.78	0.85	0.81	0.55	0.70	0.70	2.1	=4.7	3.7	1–5
Th	ppm	1.08	0.35	0.40	0.39	0.29	0.35	0.25	0.30	0.32	1.18	=6.0	9.3	2–10
U	ppm	0.26	0.09	0.09	0.10	0.09	0.09	—	—	—	0.31	=1.74	1.82	9–15[3]
Ta	ppm	0.25	0.10	0.10	0.10	0.12	0.11	0.075	0.10	0.10	0.3	=0.80	2.73	2–9
Co	ppm	28.2	19.0	20.5	19.8	(173)	19.8	19.0	20.0	20.0	29	=36.0	38.8	0.5–1
Ni	ppm	430	170	210	170	(1940)	180	160	190	190	390	n.d.	148	2–10
Ir	ppb	18.3	6.0	8.0	6.0	6.6	6.5	6.0	6.2	6.1	10	n.d.	n.d.	6–10
Au	ppb	6.4	2.3	2.5	2.5	(37)	2.5	1.4	2.4	2.4	5.0	n.d.	n.d.	2–10

Values in parenthesis may be contaminated.
Their values were excluded for the calculations of the mass weighted mean of the matrix and bulk.
* Values are averages of two analyses.
** Errors for INAA are due to counting statistics.
[1] Except for clast, 99-1 (53%), BCR-1 (4%) and JB-1 (5%).
[2] Except for clast, 99-1 (22%) and bulk-B, 107-1 (17%).
[3] Except for bulk-B, 107-1 (22%) and JB-1 (3%).

clear. Therefore, these high values were excluded in the calculations of the mass-weighted mean for the matrix and bulk of Y-791197.

4. Discussion

The strongest chemical evidence for lunar origin of Y-791197 is the observed FeO/MnO ratio of 79 for the bulk of this meteorite (hereafter, the bulk of Y-791197 means the weighted mean of the overall four matrix and bulk samples of Y-791197). In a MnO *vs.* FeO correlation diagram shown in Fig. 1, the FeO/MnO ratio of 80 ± 5 for a wide variety of lunar samples is clearly distinguished from the low ratios (30–50) for eucrites, howardites and SNC achondrites. Our analytical results for K and La of Y-791197 fall on the lunar line in a K *vs.* La correlation diagram shown in Fig. 2. The diagram shows a strong correlation between K and La for KREEP, igneous and metaigneous rocks from all Apollo and Luna sites. KREEP and VLT basalts from Luna 24 are the two end members. In this diagram, the lunar line is clearly distinct from the lines of the eucrites and howardites, earth and SNC achondrites (Fig. 2). These two evidences suggest strongly that Y-791197 is of lunar origin. This conclusion is supported by oxygen isotopic study (CLAYTON *et al.*, 1984).

The Cr_2O_3/V ratio of 43 for the bulk of Y-791197 falls on the lunar highland line (45 ± 5) in a V *vs.* Cr_2O_3 correlation diagram (Fig. 3). In this diagram, howardites and

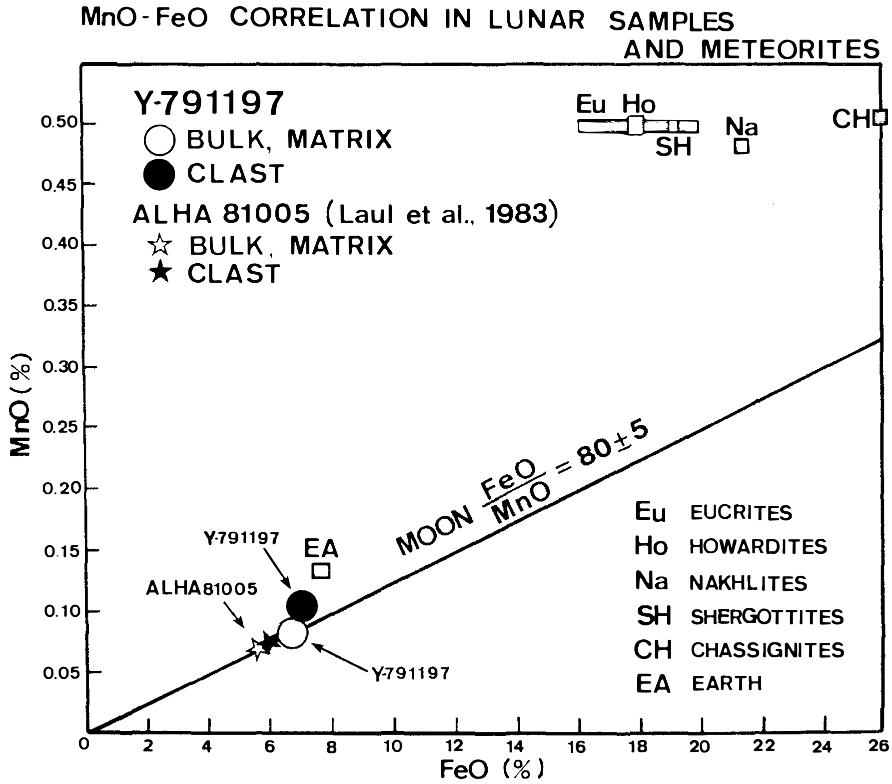

Fig. 1. MnO vs. FeO correlation in moon, earth and achondrite bodies. The lunar FeO/MnO ratio of 80±5 first noted by LAUL et al. (1972) is characteristic of the moon and provides strong evidence in favor of a lunar origin for Y-791197.

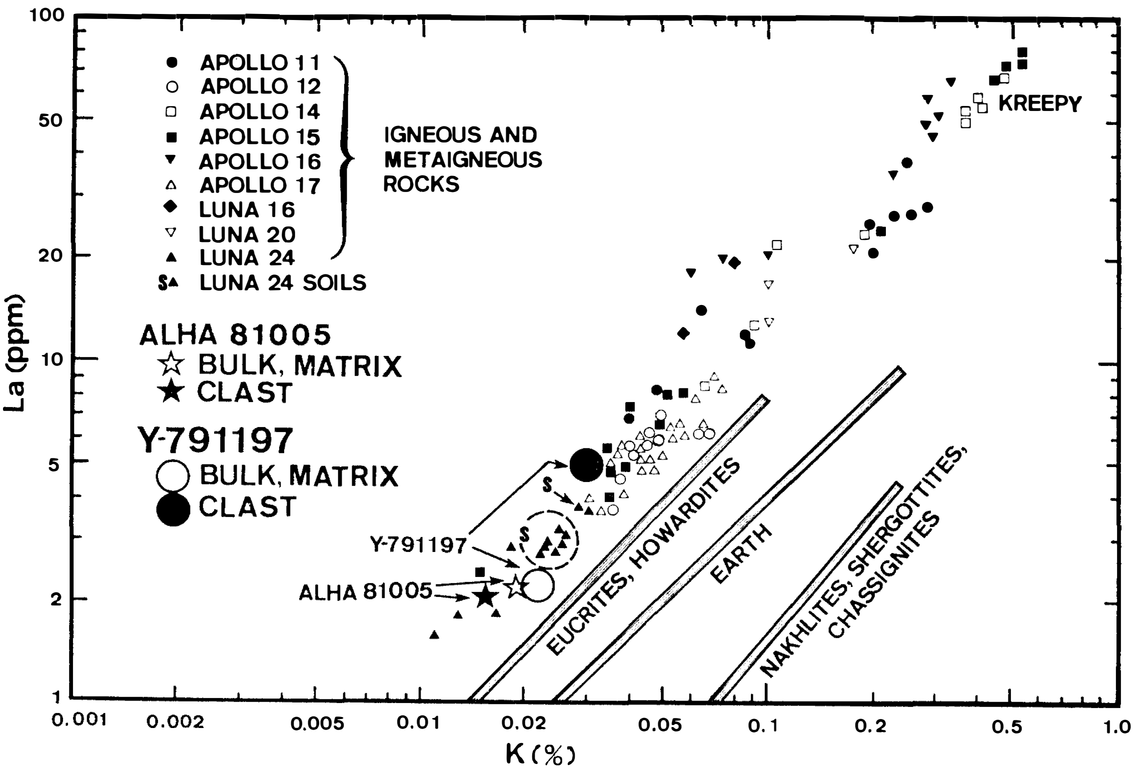

Fig. 2. K vs. La correlation in moon, earth and achondrite bodies. This correlation was first noted by WÄNKE et al. (1973). The data for earth and achondrites are taken from WÄNKE and DREIBUS (1982).

SNC lie far away from the lunar line. As first noted by LAUL *et al.* (1972) and later pointed out by DREIBUS *et al.* (1978), the Cr_2O_3/V ratio is different for mare and highland samples. The chemical compositions of Y-791197 (including white clast) are consistent with those of anorthositic gabbro.

The large-ion-lithophile (LIL) element abundances of matrix, clast and bulk samples of Y-791197, normalized to volatile-free Cl chondritic abundances (ANDERS and EBIHARA, 1982), are plotted in Fig. 4 with those of ALHA81005 and Apollo 16 65055 highland rock. The LIL element pattern of the bulk of Y-791197 is typical of lunar anorthositic gabbros with a positive Eu anomaly (Eu/Eu*=2.0, relative to Cl chondrites value). Among known lunar samples without an Eu anomaly, the Apollo 16 65055 anorthositic gabbro pattern resembles the pattern of the white clast (99-1) (Fig. 4). The white clast (99-1) pattern is more than two times higher than most LIL elements except for Sr and Eu relative to those of the matrix and bulk (Table 1). Most other elements of the clast are also higher than those of the matrix and bulk (more MgO compared with the matrix and bulk). This indicates a different lithology for the clast. Whereas our analytical results for the bulk of Y-791197 agree well with literature values as mentioned before, our data for the clast (99-1) do not agree with the data reported for other clasts (WARREN and KALLEMEYN, 1985; NAKAMURA *et al.*, 1985; TAKAHASHI *et al.*, 1985). As expected, these observations indicate that Y-791197 is a very complex breccia. This is consistent with the petrographic observations by YANAI and KOJIMA (1984), OSTERTAG *et al.* (1985), and LINDSTROM *et al.* (1985).

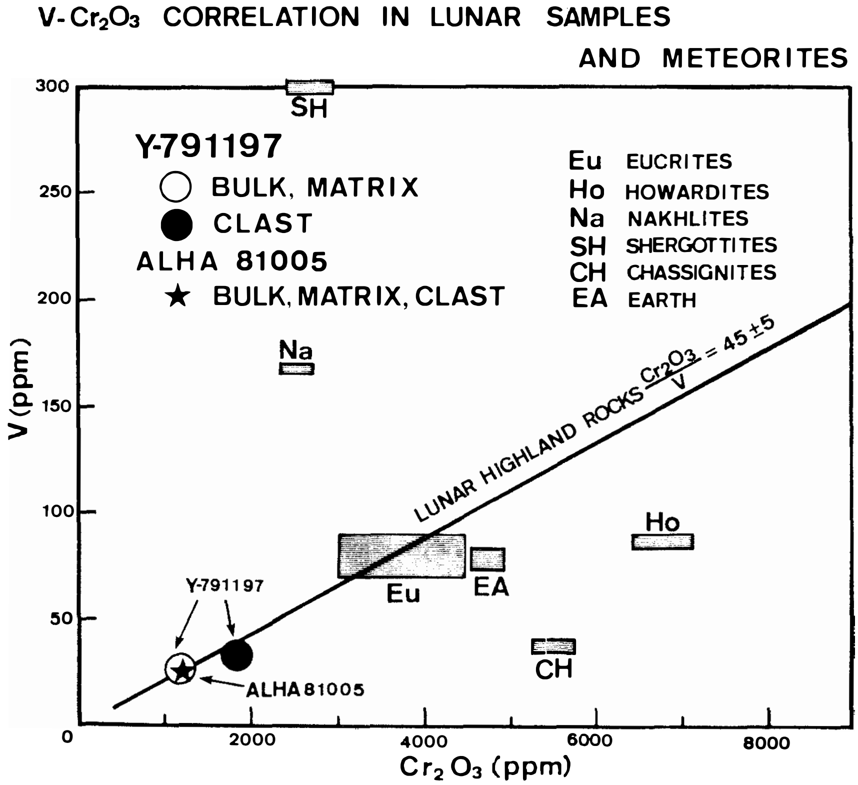

Fig. 3. *V vs. Cr_2O_3 correlation in moon, earth and achondrite bodies. The data are taken from* DREIBUS *et al.* (*1978*), SMITH (*1982*), LAUL *et al.* (*1972, 1983*). *The Y-791197 data fall on the lunar highland line. This correlation for the moon samples was first noted by* LAUL *et al.* (*1972*).

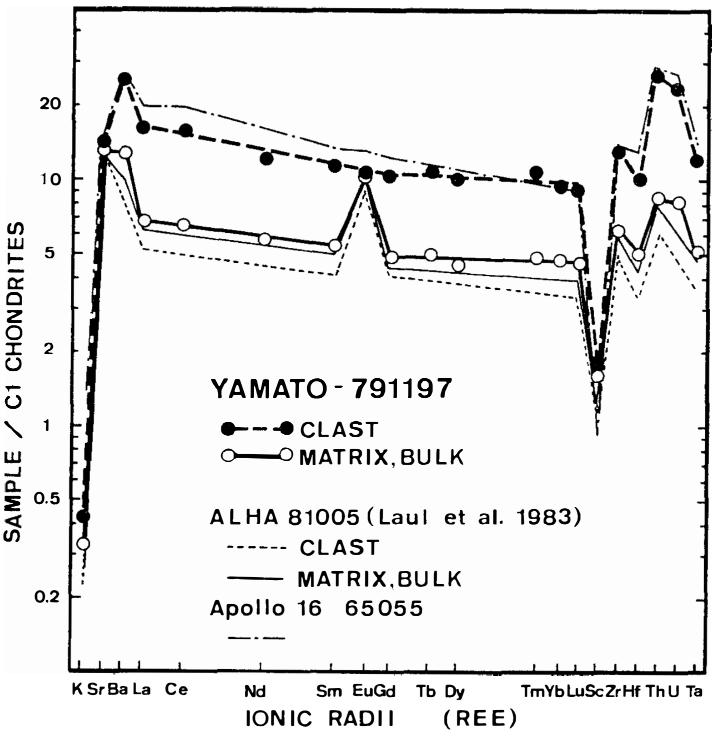

Fig. 4. *C1 chondrites* (*non-volatile*) *normalized abundance patterns of the large-ion lithophile* (*LIL*) *elements in bulk, matrix and clast of Y-791197 and ALHA81005 meteorites, and Apollo 16 65055 highland rock. The 65055 data are taken from* TAYLOR (*1982*).

Based on evidence of Cl chondrites normalized LIL element patterns and the Cr_2O_3/V ratio, the Y-791197 meteorite is undoubtedly of lunar highland origin. This conclusion is supported by noble gases (TAKAOKA, 1985), mineralogic and petrographic observations (YANAI and KOJIMA, 1984; OSTERTAG *et al.*, 1985; TAKEDA *et al.*, 1985); and other studies (*e.g.* NAKAMURA *et al.*, 1985; KANEOKA and TAKAOKA, 1985; MCFADDEN *et al.*, 1985; NAGATA and FUNAKI, 1985).

The similarity of the chemical compositions of the Y-791197 and ALHA81005 meteorites suggests that the two meteorites were possibly paired and/or originated from the same general lunar region. Reiterating, we note that the matrix and bulk of Y-791197 plot near the points for ALHA81005 on the elemental correlations of MnO *vs.* FeO (Fig. 1), K *vs.* La (Fig. 2) and V *vs.* Cr_2O_3 (Fig. 3). Most chemical abundances of the bulk of Y-791197 match closely with those of ALHA81005 (see Table 1 and Figs. 4 and 5). The FeO and MnO contents of the bulk of Y-791197 are about 20% higher relative to those of the matrix and bulk of ALHA81005, whereas the MgO content of ALHA81005 is about 30% higher than that of Y-791197. The concentrations of LIL elements are about 20% higher in Y-791197 than those in ALHA81005, except the Sc content of Y-791197 being about 40% higher than that observed in ALHA81005. Sample heterogeneity of the two breccias may explain the small chemical discrepancies which are attributed to their polymict character and to the small sample size (about 60 mg). LINDSTROM *et al.* (1985) pointed out the same kind of chemical discrepancy between Y-791197 and ALHA81005. Based on their petrographic study, they explained the compositional differences by a different proportion of clast types in the two lunar meteorite breccias. Although there are small chemical discrepancies between these lunar breccias, their chemical similarity implies that they may have been paired (although the sites of collection in Antarctica were separated by more than 3000 km) and/or originated from the same general lunar region. In our chemical study, we cannot distinguish between the two.

SUTTON (1985) indicates that the Y-791197 lunar breccia resided by orders of meters nearer to the lunar surface relative to the ALHA81005 breccia. Because of the relatively small dimensions of Y-791197 and ALHA81005, $4.5 \times 4.2 \times 2.8$ cm and $3 \times 2.5 \times 3$ cm, respectively (YANAI and KOJIMA, 1984; MARVIN, 1983), the paired nature of these two breccias may be ruled out, although the meteorites possibly originated from the same region of the moon.

The lack of an appreciable KREEP component in the Y-791197 and ALHA81005 lunar breccias implies a far side origin of both meteorites. One of the chemical features of both meteorites is their low K contents (see Fig. 2). The Cl chondrites normalized REE pattern of Y-791197 bulk (Fig. 4) monotonously decreases from La to Lu; La $7.0 \times$(Cl chondrite), Sm $5.3 \times$ and Lu $4.6 \times$, which is not typical of a KREEP pattern. The Cl chondrites normalized $(La/Lu)_{CN}$ ratio of Y-791197 bulk is 1.5, whereas the ratio of KREEP is 2.1. Although the pattern of the white clast (99-1) of Y-791197 is similar to that of Apollo 16 65055 rock (Fig. 4), the light-REE are enriched in 65055 compared with the clast (99-1). The $(La/Lu)_{CN}$ ratio of 65055 is 2.1, the same as KREEP, but that of the clast is 1.8. The K content of the clast (99-1) is a factor of 3.4 times lower than that in 65055 (Fig. 4). These observations suggest that Y-791197 was derived from an unsampled and unsurveyed highland area, probably from the far side. Both Y-791197 and ALHA81005 meteorites contain minor amounts of mare basalt clasts (TREIMAN and DRAKE, 1983; LINDSTROM *et al.*, 1985). Because mare basalts are essentially absent on the lunar far side, the possibility of a near-side origin for them may not be excluded completely. PIETERS *et al.* (1983) suggest that the source region for ALHA81005 was the near side limb or the far side of the moon based on remote sensing data by X-ray, γ-ray and infrared reflectance measurements. This conclusion is supported by the absence of appreciable KREEP based on the trace element studies (*e.g.* PALME *et al.*, 1983; KALLEMEYN and WARREN, 1983). Furthermore, the lack of appreciable KREEP in Y-791197 supports a far-side origin for both meteorites. This conclusion is consistent with WARREN and KALLEMEYN (1985) and OSTERTAG *et al.* (1985).

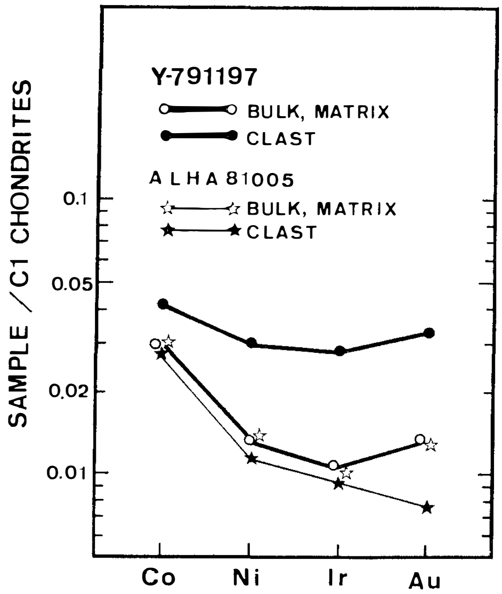

Fig. 5. C1 chondrites (non-volatile) normalized abundance patterns of siderophiles in bulk, matrix and clast of Y-791197 and ALHA81005 meteorites. The later data are taken from LAUL *et al. (1983).*

Siderophile element (Co, Ni, Ir and Au) contents of the Y-791197 bulk and the ALHA81005 bulk are almost the same (Table 1); their Cl chondrites (non-volatile) normalized patterns are shown in Fig. 5. The Ni/Ir/Au ratios of the clast and the matrix and bulk-A for Y-791197 are similar to those of the matrix and bulk for ALHA-81005 (Fig. 5). Appreciable amounts of siderophile elements were derived from ancient meteoritic components on the moon's surface (MORGAN *et al.*, 1972; GANAPATHY *et al.*, 1974). Similar ratios of siderophile elements in lunar breccias imply that the lunar surfaces as their provenance experienced contamination by chemically similar impacting meteorites or planetesimals. This suggests that the Y-791197 and ALHA-81005 samples may have been ejected from the moon by one and the same impact event. Two possible explanations may be invoked for a single impact origin for both meteorites. One is that both meteorites were ejected as fragments from the moon by a single impact event and then simultaneously reached the earth. Another possibility is that both meteorites arrived at the earth at different times from unique earth parking orbits (see ARNOLD, 1965a, b) after simultaneously ejected from the moon. In the former case, both meteorites should have the same space exposure age (earth transit time) and the same terrestrial age. In the latter case, the total ages of the earth transit times and the terrestrial ages for both meteorites will be the same. SUTTON (1985) reported that the space exposure age of Y-791197 is less than 2000 years by thermoluminescence (TL) measurements. This age is similar to the 2500 years upper limit obtained from ALHA81005 (SUTTON and CROZAZ, 1983). The TL results indicate that the two meteorites experienced similar short earth transit times (SUTTON, 1985; SUTTON and CROZAZ, 1983). The terrestrial age of ALHA81005 is $(1.8\pm0.7)\times10^5$ y and that of Y-791197 is less than 1×10^5 y (NISHIIZUMI and ELMORE, 1985). A small difference between the two terrestrial ages may exist, but because of large uncertainties, more precise dating is required to examine the terrestrial age problem.

5. Concluding Remarks

Based on the results of our chemical study, the conclusions are as follows.

(1) Y-791197 is undoubtedly of lunar highland origin and it is an anorthositic gabbro.

(2) Y-791197 is a heterogeneous lunar regolith breccia. One clast has a different chemistry from that of the matrix and bulk.

(3) Bacause of the very low K_2O content and the chemical similarity, Y-791197 and ALHA81005 may have originated from the same far side of the moon.

(4) Based on similar Ir/Ni/Au ratios, the Y-791197 and ALHA81005 meteorites are probably related to the same lunar impact event.

For confirmation of conclusion 3, remote geochemical sensing data are required for a wide lunar surface area, especially for the far side. Of course, future missions for sample recovery from the far side of the moon are needed. Determinations of precise terrestrial ages and earth transit times of both meteorites are required to verify conclusion 4.

Our chemical study confirms that the Y-791197 meteorite is indeed the second lunar breccia. To test whether this lunar meteorite is a common type, two additional meteorites, Y-82192 and 82193, are waiting for investigation as possible lunar meteorites (YANAI and KOJIMA, 1984, 1985).

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