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TRACE ELEMENT GEOCHEMISTRY OF LUNAR METEORITES YAMATO-791197 AND -82192

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Abstract: The lunar meteorites Yamato-791197 and -82192 have been analyzed for up to 36 minor and trace elements. Bulk compositional data are reported as well as data for grain size fractions and individual clasts separated from both meteorites. The data shows clearly that there are some significant chemical differences between Y-791197 and -82192, and also to ALHA81005. Y-82192 shows no sign of a KREEP component at all, and shows a slightly different REE (and incompatible element) pattern than the other two meteorites. Siderophile elements (Ir, Ni, Co, Au) and Se show an admixture of about 1.5% C1 component, but the patterns are quite different for all three lunar meteorites. Y-791197 shows an enrichment in some volatile elements (like Se and Au) already in the bulk composition. Both meteorites contain some volatile-rich clasts, but only Y-791197 has also a volatile rich bulk composition. This is in favor of an earlier suggestion of volcanic contaminations in the lunar source region for Y-791197. The trace element data seems to indicate that there have been at least three individual impacts responsible for the known lunar meteorites.

1. Introduction

Amongst the most valuable discoveries of this decade are the identifications of several lunar meteorites. Meteorites, which are not meteorites in the strict sense, but lunar samples, are rare, and none has been known prior to the return of lunar samples from the moon. The first lunar meteorite, Yamato-791197, was discovered in November 1979 in the Yamato Mountains Meteorite Field by the 20th Japanese Antarctic Research Expedition, but not identified as such until 1983 (Yanai and Kojima, 1984). In the meantime, the U.S. Antarctic Meteorite Search Expedition in the 1981/1982 expedition recovered a meteorite which was unique (Marvin, 1983) and due to chemical and petrological characteristics determined to be of lunar origin (*e.g.*, Warren *et al.*, 1983; Laul *et al.*, 1983). Since then, several more samples of lunar origin have been recovered from the Antarctic ice: Y-82192 (Yanai and Kojima, 1984, 1985), Y-82193 (Yanai *et al.*, 1986), Y-793274 (Yanai and Kojima, 1987), and the newly discovered Y-86032. The first four lunar meteorites are in the 30 gram regime, while Y-793274 weighs only 8.66 g. The new lunar meteorite, Y-86032, discovered by the 1986/87 Japanese Antarctic Research Expedition, weighs in excess of 600 g and thus represents the largest known lunar meteorite to date, and will undoubtedly be of great importance for further lunar studies. The importance of lunar meteorites for lunar research has been discussed by various authors (*e.g.*, Lindstrom *et al.*, 1986; Warren and Kallemeyn, 1986a, 1987a;

TAKEDA *et al.*, 1986) and will not be repeated here. The newly discovered lunar meteorites add to the significance and may represent samples from new and previously unsampled parts of the lunar surface.

One of the most important questions associated with the lunar meteorites is the number of events leading to the ejection of the rocks from the moon. Superfically, the known lunar meteorites look very much alike, and most of them have been recovered from a single meteorite icefield in Antarctica (which contains many thousands of completely different meteorites). All are lunar highlands regolith breccias, which are not so common amongst the Apollo and Luna samples. Thus the question arises if only one impact on the moon was responsible for launching all six lunar meteorites. This has been suggested at least for the first four lunar meteorites that have been investigated so far, but other workers find this difficult to accept (WARREN and KALLEMEYN, 1986c). Petrological and chemical studies are very helpful in dealing with that question. We report here trace element data for two of the lunar meteorites, Y-791197, and -82192. Since no petrological studies have been made, we restrict our discussion to the trace element geochemistry of these meteorites, and try to address the problem of the number of impacts from this viewpoint.

2. Sampling and Analytical Methods

Our sample of Y-791197 (subsample ,98) had an original weight of 218 mg, and our sample of Y-82192 (subsample ,72) had an original weight of 191 mg. These samples have been subdivided in several subsamples. Both chips were gently crushed in an agate mortar, and reasonably sized fragments were used as bulk samples (11.69 mg for Y-791197, and 10.58 mg for Y-82192). Another bulk for each samples was made up from the powder after grinding up the most of the remainder (using an automated agate ball mill). The powdered bulk was 52.60 mg for Y-791197, and 21.32 mg for Y-82192. The objective was to look for probable sampling errors and inhomogeneities, as well as being able to calculate an average bulk composition from two subsamples.

One of the aims of the analyses was the determination of the halogens (see KOEBERL and KIESL, 1986; and KOEBERL and KIESL, in preparation), thus the meteorite powder was divided in different grain size fractions. Due to the limitations of the analytical methods and the limited amount of sample available, only two size fractions for each meteorite were obtained, which we denoted "coarse" and "fine" fraction, the division between the two being at 50 μm. The size fractions obtained in this way have been divided for radiochemical neutron activation analysis (RNAA) for determination of the halogens, and for instrumental neutron activation analysis (INAA; this work). In addition, prior to final grinding, several clasts have been isolated from the bulk of each meteorite. These clasts have been analyzed separately in order to see if there are any unusual compositions present.

The INAA procedures used here follow methods which hvae been described before (see KOEBERL *et al.*, 1986). Shortly, two irradiations have been performed, one short irradiation (1 min) for the determination of Mn and Dy, and a two day irradiation for all other elements. The irradiations have been performed at the TRIGA reactor of the Atominstitut der Österreichischen Universitäten at a flux of approximately $2 \cdot 10^{12}$ n

$cm^{-2}s^{-1}$. The long irradiation was followed by four counting cycles over a period of 5 months. Counting times ranged up to several days for the clast samples in order to obtain good counting statistics. We report here results for 2 major elements and up to 34 trace elements in both meteorites. Analytical uncertainties are usually less than ±5% (see also KOEBERL *et al.*, 1986 a, b), except for Sb, Cs, Ni, Se, Br, Hg, Tm, Rb, Zr, Sr, and U (5–30% uncertainties). Larger errors are possible for small samples (clasts).

Table 1. Trace element data for lunar meteorite Y-791197 (bulk, fractions,

	Y-799197 bulk 1 11.69 mg	Y-791197 bulk 2 52.60 mg	Y-791197 coarse fr. 13.82 mg	Y-791197 fine fr. 28.07 mg	Y-971197 white clast 2.84 mg	Y-791197 ave. bulk (this work)
Na (wt%)	0.25	0.25	0.27	0.26	0.26	0.25
K	240	238	250	235	234	238
Sc	12.6	12.0	12.3	11.6	9.4	12.1
Cr	930	880	860	943	1170	889
Mn	645	680	706	660	589	674
Fe (wt%)	5.10	4.97	4.66	4.82	4.23	4.99
Co	26.2	24.2	24.2	22.5	26.2	24.6
Ni	214	220	305	300	510	218
Ga	—	3.3	—	5.2	3.7	3.3
As	<0.5	0.37	<0.3	0.22	0.098	0.3
Se	0.83	0.50	<0.9	0.19	1	0.56
Br	<0.1	<0.08	<0.1	0.1	<1	<0.08
Rb	<10	8	<14	<10	—	8
Sr	100	171	130	150	<250	158
Zr	35	35	—	—	<300	35
Sb	—	<0.1	—	<0.06	2.0	<0.1
Cs	<0.1	0.08	—	<0.12	0.74	0.08
Ba	30	30	25	36	260	30
La	2.17	2.51	2.19	2.06	1.50	2.45
Ce	4.0	4.65	5.57	5.16	4.18	4.53
Nd	3.5	3.60	3.5	3.72	2.8	3.58
Sm	1.23	1.15	1.17	1.22	0.76	1.17
Eu	0.704	0.720	0.69	0.66	0.73	0.717
Gd	1.65	1.60	1.51	1.61	<4	1.60
Tb	0.28	0.22	0.23	0.27	0.24	0.23
Dy	1.96	1.60	1.76	2.0	0.97	1.67
Tm	0.2	0.15	<0.3	<0.3	<1	0.16
Yb	1.05	1.12	1.23	0.99	1.08	1.11
Lu	0.159	0.138	0.187	0.127	0.15	0.142
Hf	0.92	1.33	0.83	0.92	0.75	1.2
Ta	0.2	0.1	<0.2	0.10	<0.5	0.1
Ir	0.0063	0.0068	0.0067	0.0057	<0.015	0.0067
Au	0.0036	0.0073	—	0.0048	0.0214	0.0066
Hg	<0.2	<0.1	—	—	0.6	<0.1
Th	0.34	0.34	0.29	0.35	0.30	0.34
U	—	0.10	—	0.09	0.09	0.10

All data in ppm, except as noted.

3. Results

The bulk-rock samples of each meteorite appeared to be rather inhomogeneous, with numerous light clasts set in a dark glass-rich matrix. Thus small whole rock samples may be vulnerable to sampling errors due to the inhomogeneity of the meteorites. Tables 1 and 2 give the results of our analyses for bulk, fractions, and clasts of Y-791197 and -82192. The first two columns in each table give the two bulk sam-

and clast), and comparison data for other lunar highland samples.

Y-791197 bulk Ref. 1	Y-791197 bulk Ref. 2	Y-791197 bulk range Ref. 2, 5	Y-791197 bulk ave. Ref. 3	61195 breccia Ref. 4	67075 anorth. Ref. 4	67215 breccia Ref. 2
0.234	0.25	0.23–0.26	0.243	0.34	0.19	0.23
232	200	200–350	221	936	110	100
12.5	13.4	12.5–16.5	13.3	8.53	7.68	15.2
880	935	750–1034	900	680	560	860
660	—	660–740	660	490	490	—
4.43	4.73	4.43–5.30	4.95	3.98	3.07	5.51
18.4	19.7	17.0–21.5	18.7	27.1	7.34	13.5
154	189	110–210	174	410	—	40
3.2	—	3.1–37.4	5.9	3.85	2.33	—
—	—	n.a.	n.a.	0.09	0.002	—
—	—	0.19–0.46	0.3	0.44	—	—
0.16	0.21	n.a.	0.17	0.197	—	—
—	—	0.7–3	1.3	3.86	0.67	—
140	149	90–150	134	166	127	130
26	45	26–45	32	194	—	—
—	—	0.001–0.02	n.a.	—	—	—
0.059	—	0.04–0.2	0.064	0.144	0.03	—
29	33	20–34	31	152	13	18
2.16	2.53	2.16–3.3	2.11	14.6	0.32	1.19
5.0	6.45	5.0–9.1	5.49	34	0.80	3.2
3.0	4.1	3.0–5.2	3.47	23	—	2.4
0.96	1.24	0.96–1.56	1.05	6.3	0.16	0.72
0.72	0.766	0.72–0.77	0.78	1.20	0.63	0.73
—	—	n.a.	n.a.	7.23	0.30	—
0.216	0.29	0.22–0.32	0.253	1.25	0.047	0.20
1.40	—	1.40–2.22	1.53	8.30	0.33	—
—	—	n.a.	0.23	—	—	—
0.95	1.05	0.96–1.34	0.99	4.37	0.25	0.77
0.135	0.156	0.13–0.19	0.146	0.64	0.04	0.125
0.73	0.92	0.73–1.11	0.84	4.58	0.12	0.78
0.078	0.11	0.08–0.16	0.103	0.55	0.011	0.09
0.0064	0.0071	0.0045–0.008	0.0066	0.0113	—	0.001
<0.002	0.0024	0.0013–0.03	0.0051	0.0061	0.00066	—
—	—	—	n.a.	—	—	—
0.28	0.33	0.28–0.45	0.33	2.3	—	0.12
0.079	0.12	0.08–0.13	0.116	0.72	0.0052	—

References: (1) Warren and Kallemeyn (1986a); (2) Lindstrom *et al.* (1986); (3) Warren and Kallemeyn (1986b); (4) Wänke *et al.* (1975); (5) Kaczaral *et al.* (1986)

ples, the first one being the whole-rock sample, and the second one being the bulk obtained from the powdered sample. It is clearly visible that there are only a small and mostly insignificant differences between the two bulk samples for each meteorite. In general, the coarse and fine fractions of each meteorite are very similar to each other and to the bulk meteorite. Several other analyses for Y-791197 and a range of literature data (WARREN and KALLEMEYN, 1986a; LINDSTROM *et al.*, 1986; WARREN and KALLEMEYN, 1986b; KACZARAL *et al.*, 1986) are also given in Table 1. The comparison of our data

Table 2. Trace element data for lunar meteorite Y-82192 (bulk,

	Y-82192 bulk 1 10.58 mg	Y-82192 bulk 2 21.32 mg	Y-82192 coarse fr. 2.33 mg	Y-82192 fine fr. 20.28 mg	Y-82192 clast 1 0.580 mg	Y-82192 clast 2 1.94 mg	Y-82192 clast 3 2.89 mg
Na (wt%)	0.29	0.29	0.27	0.28	0.31	0.29	0.26
K	170	170	180	170	—	—	—
Sc	13.5	14.0	13.8	13.0	8.20	11.7	8.54
Cr	1115	1177	1126	1100	647	950	745
Mn	764	738	752	760	600	620	—
Fe (wt%)	4.99	4.78	5.04	4.43	4.26	4.45	3.50
Co	17.7	19.0	20.6	14.8	13.9	24.3	13.7
Ni	188	145	—	173	<600	<300	<300
Ga	13.2	9.1	—	<8	<26	<20	<10
As	0.024	0.03	0.032	0.035	—	0.033	0.027
Se	—	0.3	—	0.055	—	—	—
Br	—	0.08	—	<0.08	<5	<2	<1
Rb	<5	3	<8	<5	—	—	—
Sr	<200	150	<200	150	<300	<250	<180
Zr	<40	30	<50	28	—	—	—
Sb	—	<0.1	<0.5	0.2	5	2	1
Cs	<0.1	0.08	<0.4	<0.1	—	—	—
Ba	20	20	—	—	—	—	—
La	1.13	1.10	1.12	1.61	1.36	1.39	0.69
Ce	2.83	2.74	3.0	3.35	3.0	4.0	1.7
Nd	2.0	2.1	2.2	2.2	<2.5	2.4	1.3
Sm	0.623	0.629	0.619	0.610	0.65	0.58	0.46
Eu	0.737	0.800	0.81	0.731	1.01	0.98	0.98
Gd	1	1	<3	1	<5	<2	<1.3
Tb	0.19	0.22	—	0.12	0.22	0.18	0.16
Dy	1.01	1.12	—	—	—	—	—
Tm	0.1	0.1	—	0.1	—	—	—
Yb	0.74	0.70	0.72	0.75	0.85	0.80	0.74
Lu	0.11	0.10	0.113	0.10	0.10	0.07	0.11
Hf	0.95	0.92	0.9	0.36	<1.5	0.80	—
Ta	<0.2	<0.1	—	<0.1	—	—	—
Ir	0.0098	0.011	—	0.005	—	—	—
Au	0.0044	0.0025	0.0315	0.0009	0.070	0.0327	0.0181
Hg	<0.1	<0.05	—	—	0.7	—	—
Th	0.25	0.23	<0.5	0.27	—	—	—
U	—	0.066	—	0.065	—	—	—

All data in ppm, except as noted.

with the literature data shows a generally very good agreement. We found slightly higher Co and Ni contents than previous workers, but the differences do not seem to be significant. The agreement for the REE is excellent. The only other element showing a significant difference is Hf, where we find a bulk value of 1.2 ppm, while the literature average is at 0.84 ppm (with a reported range of up to 1.1 ppm). It is not clear, however, if this slight difference is really of importance.

Our data for As and Se seem to be the first As abundances reported at all for

fractions, and clasts), and comparison data from the literature.

Y-82192 ave. bulk (this work)	Y-82192 bulk Ref. 1	Y-82192 bulk Ref. 2	Y-82192 bulk matr. Ref. 3	Y-82192 bulk Ref. 4	Y-82192 bulk Ref. 5	Y-82193 bulk Ref. 3
0.29	0.273	0.265	0.36	0.30	—	0.30
170	173	150	160	—	—	300
13.8	13.5	14.5	8.68	10.9	—	12.2
1156	1010	1020	760	894	—	1050
746	600	657	520	—	—	675
4.85	4.47	4.74	3.8	4.2	—	4.70
18.6	16.7	19.9	14.4	15.8	14.8	19.2
159	122	120	121	140	—	148
10.4	2.8	3.78	—	—	2.86	—
0.028	—	<0.2	—	—	—	—
0.3	—	<0.2	—	—	0.334	—
0.08	<0.17	<0.2	—	—	—	—
3	—	<3	—	—	0.23	—
150	143	136	190	163	—	180
30	24	—	—	37	—	—
<0.1	—	<0.1	—	—	0.004	—
0.08	<0.16	<0.1	—	—	0.02	—
20	22	21	26	29	—	28
1.11	1.54	1.13	1.11	1.18	—	1.27
2.77	3.78	2.98	2.7	2.90	—	3.0
2.1	2.32	1.97	1.5	<6	—	2.0
0.627	0.68	0.631	0.54	0.596	—	0.65
0.779	0.87	0.754	0.94	0.866	—	0.82
1	—	—	0.62	—	—	0.57
0.21	0.174	0.17	0.12	0.140	—	0.14
1.08	1.28	1.13	0.9	—	—	1.0
0.1	—	—	—	—	—	—
0.71	0.79	0.76	0.55	0.59	—	0.73
0.10	0.121	0.115	0.082	0.100	—	0.117
0.92	0.73	0.44	0.36	0.46	—	0.45
<0.1	0.038	—	0.043	0.060	—	0.034
0.010	0.0064	0.0056	0.0029	0.0032	—	0.0057
0.0031	0.0014	0.0011	0.0007	0.0025	0.012	0.0013
<0.05	—	—	—	—	—	—
0.23	0.188	0.2	0.14	0.133	—	0.20
0.066	0.058	0.05	0.031	<0.08	0.051	0.040

References: (1) WARREN and KALLEMEYN (1987a, b); (2) BISCHOFF *et al.* (1987); (3) FUKUOKA *et al.* (1986); (4) LINDSTROM *et al.* (1987); (5) DENNISON *et al.* (1987)

lunar meteorites, and the first Se abundances obtained by INAA. Since As data (as well as Se data) are sparse also for lunar rocks, comparisons are not easily possible. In most cases, As analyses in the different subsamples are in good agreement with each other. It is interesting to note that the average As abundance in Y-791197 is about an order of a magnitude larger than in Y-82192. The abundances found for Y-82192 are in very good agreement with the few As numbers known for highland samples (see Table 1), while the As abundance in Y-791197 is higher by factor of about 3 than the upper limit of the normal lunar range. Se abundances are in very good agreement with lunar highland sample data on one side (*e.g.*, Wänke *et al.*, 1975), and with data obtained by radiochemical neutron activation analysis (Kaczaral *et al.*, 1986) on the other side. For Y-791197, Kaczaral *et al.* (1986) give a range of 0.19–0.46 ppm Se in two subsamples, while we found a range of 0.19–0.83 ppm in four of our subsamples, with a bulk average of 0.56 ppm. For Y-82192, Dennison *et al.* (1987) report a range of 0.33–0.5 ppm Se in three subsamples, while we find 0.3 ppm in our bulk sample. Our Cs result for Y-82192 is higher than the radiochemical result of Dennison *et al.* (1987), but since this is at the limit of the INAA method, we think this difference is not significant.

In general, all our trace element data are in clear support of a lunar origin of the two meteorites, as inferred before by other authors. Comparison data given in Table 1 show a very close similarity to some other lunar highlands samples, although exact fits are rare. This is probably due to the fact that the lunar meteorites have sampled different parts of the lunar surface than the Apollo and Luna missions. The compositions of both, Y-791197 and -82192, are remarkably similar to ALHA81005 (Warren *et al.*, 1983; Laul *et al.*, 1983). Incompatible element concentrations (Zr, Ba, REE, Th, U) are far lower in Y-791197 than in usual lunar regolith samples. Concentrations in Y-82192 are even lower than in Y-791197, making it difficult to find comparable lunar samples. The pattern of incompatible elements, normalized to KREEP (see Warren and Kallemeyn, 1986a, 1987a) is in good agreement with other lunar regolith patterns, just lower. This indicates the absence of a KREEP component for both meteorites, especially for Y-82192.

Results for one white clast from Y-7911 97 and three white or light gray clasts from Y-82192 are also given in Tables 1 and 2. The abundances in these clasts are essentially similar to the bulk abundances, at least for incompatible elements. Some differences seem to be present for volatile elements, as we find higher Se, Sb, Cs, Au, and Hg abundances in some of the clasts.

4. Discussion

Figures 1 and 2 show the chondrite-normlaized REE patterns for Y-791197 and -82192. Plotted are patterns for bulk, grain size fractions, and selected clasts. The patterns for the bulk sample and the size fractions are virtually indistinguishable, while the clast samples show a slightly different pattern. In both cases the clasts have a much more pronounced Eu anomaly than the bulk, which is positive in both meteorites. The abundances are lower than in average lunar highland rocks, but consistent with North Ray crater rocks (Lindstrom and Lindstrom, 1986) or lunar pristine rocks

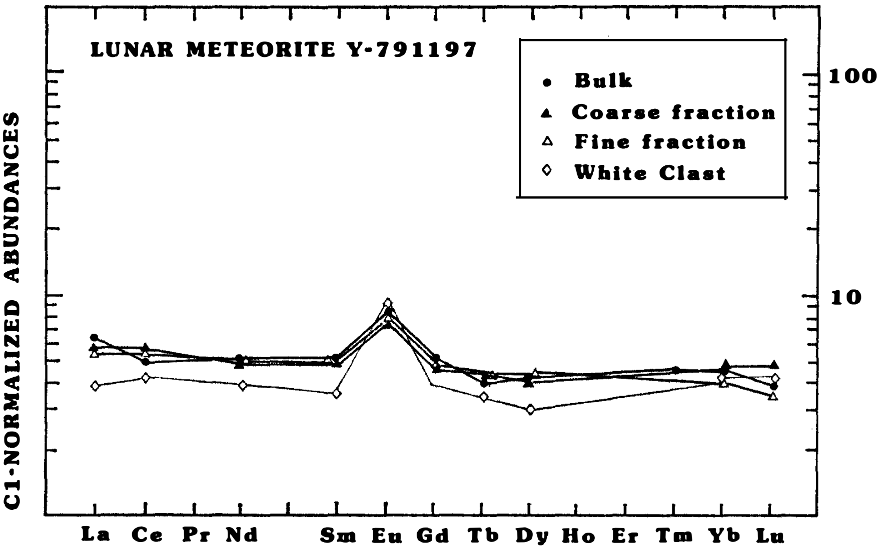

Fig. 1. *Rare earth element pattern for the bulk of Y-791197, a coarse and a fine fraction, and a white clast (2.84 mg). Note the slightly more pronounced Eu anomaly of the white clast. The pattern is similar to ALHA81005, but shows slightly higher REE abundances.*

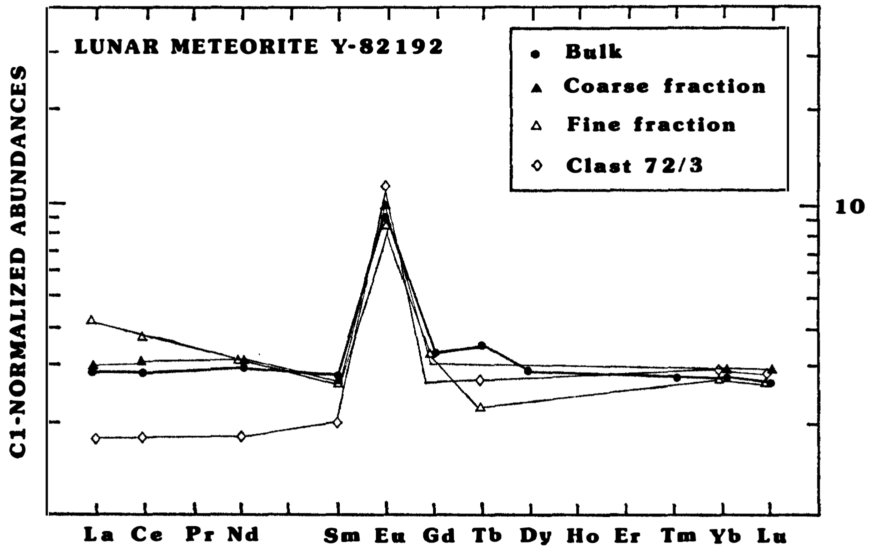

Fig. 2. *Rare earth element pattern for the bulk of lunar meteorite Y-82192, a coarse, and a fine fraction. From the three clasts analyzed one was selected (clast No. 3) and is plotted here. As also observed for Y-791197, the clast has a more pronounced Eu anomaly than the bulk. A KREEP component is completely absent.*

(Warren and Kallemeyn, 1986a; Lindstrom *et al.*, 1986). The Eu anomaly of Y-791197 is smaller than in ALHA81005 or Y-82192, but the average REE abundances are slightly higher. This is the expression of a different stage of differentiation, but probably from the same source melt. The pattern of Y-82192 is essentially flat, while the one for Y-791197 shows a very slight slope from the LREE to the HREE part.

This, and the different Eu anomaly suggests that these samples are probably not closely related.

Other elements are useful in looking for the possibility of further differences between the two samples (and ALHA81005). The lunar meteorites are very similar to each other, so that task is not easy. Figure 3 gives a plot of Th *vs*. Sm. Here, again, the three lunar meteorites plot in different parts of the diagram (clearly within the lunar range). Y-791197 and -82192 are the farthest apart, with ALHA81005 between them. This is about the same trend which we have observed for the REE patterns and is an expression of the very low KREEP content of all of them and the low overall incompatible element content for Y-82192. Some lunar highland samples are given for comparison. Although they exhibit the same trend, they clearly seem to incorporate far more Mare components and KREEP than the lunar meteorites. The separation between the three lunar meteorites in this diagram appears to be not very significant, but clearly points to a different source region on the moon for the meteorites than for the Apollo samples.

Another attempt to look for differences between the lunar meteorites is plotted in Fig. 4. Here we have plotted the pattern for siderophile elements and Se for the three meteorites. OSTERTAG *et al.* (1986) presented a similar diagram for ALHA81005, Y-

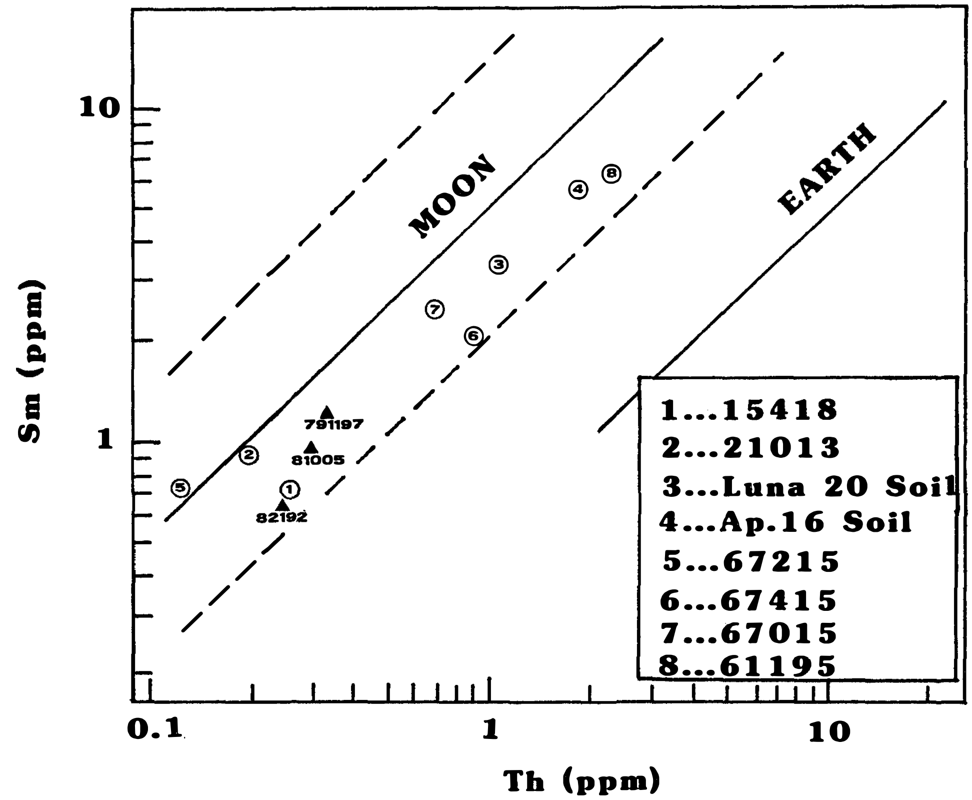

Fig. 3. Th vs. Sm element correlation diagram. The triangles mark the three lunar meteorites ALHA81005, Y-791197, and -82192. Other lunar highlands samples are numbered and identified on the legend on the right side. Data sources: LAUL et al. (1983); PALME et al. (1983); WARREN and KALLEMEYN (1986a), WÄNKE et al. (1975), and LINDSTROM and LINDSTROM (1986). Diagram adapted from KOEBERL et al. (1986b).

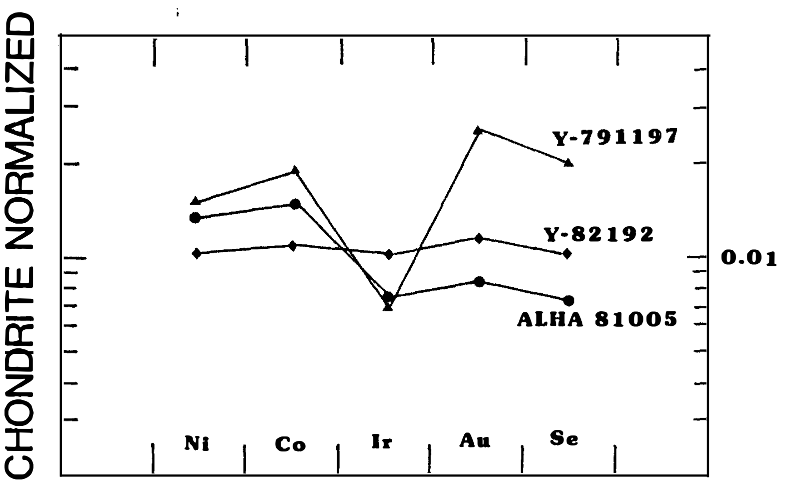

Fig. 4. Chondrite normalized abundances of some siderophile elements and Se. It is clearly visible that all three lunar meteorites considered here have different patterns. Normalizing factors from T*AYLOR (1982), diagram after* P*ALME et al. (1983).*

791197, and some lunar highland samples, resulting in a essentially chondritic pattern at about 1.5% Cl. Due to slightly different normalizing factors (OSTERTAG *et al.* do not give the source of their normalizing factors) the pattern for ALHA81005 looks different here than it does in their diagram, but due to slightly different analytical results we find larger differences between ALHA81005 and Y-791197 than OSTERTAG *et al.* (1986). The incorporation of Se in the siderophile pattern diagram adds further to the significance, and shows differences and trends more clearly. Very often, Se and Au have the same Cl normalized abundances. This can also be observed in Fig. 4, and adds to the significance of our observation that ALHA81005 and Y-791197 have different patterns. Y-82192 has a pattern which is entirely different from both other lunar meteorites, and shows a very flat 1% chondritic pattern. This diagram indicates more pronounced differences between the three lunar meteorites (which would also show up when using other author's data).

Even more interesting is the case of volatile trace elements. KACZARAL *et al.* (1986) have investigated the volatile trace element contents in two sub-samples of Y-791197 and concluded that the enrichment in volatiles present in at least one of their samples is indicative of a marked difference between ALHA81005 and Y-791197 and also the expression of a possible volcanic contamination of the Y-791197 source region. In order to concentrate on the question of the presence of lunar volcanic exhalations in the source region of the Y-791197 meteorite, KOEBERL and KIESL (1986) measured the concentrations of the halogens in size fractions of Y-791197 and -82192, and found that the data are in favor of a volcanic contamination for Y-791197. A comparison with Y-82192 shows higher halogen contents, and a dependence upon the grain size. Our trace element data reported in Tables 1 and 2 add further to the validity of this result. The Se content and the Au content are significantly higher in Y-791197 than in ALHA81005 and Y-82192 (see also Fig. 4). Both elements are rather volatile and seem to be enriched in Y-791197 by a factor of about 1.5 or 2 over the 1.5% Cl content of the meteorite. Also, the As content of Y-791197 is higher than of Y-82192. The Ga contents are far more variable. All this seems to be in favor of a volcanic contamination in the case of Y-791197. WARREN and KALLEMEYN (1986c, 1987b) have presented a number of arguments in favor of different source region for the known lunar meteorites (in our discussion here, we purposely exclude Y-82193, because most of the data point to pairing for Y-82192 and -82193; see *e.g.* EUGSTER, 1987). They based some of their arguments on the difference in the mg ratio, but stated that their own volatile element analyses do not show any significant enrichments. Since we have been able to support the findings of KACZARAL *et al.* (1986) in several aspects we feel that the difference in volatile element content is one more point in agreement with different source regions for the three lunar meteorites.

Another interesting point is the volatile enrichment found in several clasts. BISCHOFF and PALME (1986) reported on volatile rich clasts, which have Zn-rich phases and very high concentrations of Ga, Br, Sb, and Au. They report a Br abundance of 1.39 ppm, which seems extraordinary. Their Sb abundance of 0.11 ppm is considerably higher than the average found by KACZARAL *et al.* (1986), but still lower than our Sb abundances. Some similarities seem to be present, however. While they have rather high Br contents and Ga contents, we find higher Sb and Au abundances, but generally the same elements (only to a different proportion) are enriched. It is interesting to note that we found the same for the Y-82192 clasts, and that there seems to be a size dependence at least for the Sb abundance. This may well be the result of lunar volcanic exhalations, but we should also consider the chance of contamination in a terrestrial environment. If it is terrestrial contamination, it seems unlikely that it occurred in our lab, since we used clean procedures (clean bench) in all preparation steps. But since BISCHOFF and PALME (1986) also found some unusual inclusions we feel that this enrichment may be real and points to a very interesting lunar history of these samples.

5. Conclusions

We have determined up to 34 trace elements and two major elements in several bulk samples of Y-791197 and -82192, as well as in grain size fractions and clasts. The results are generally in very good agreement with previously published data. A close investigation of the differences in trace element abundances between ALHA81005, Y-791197, and -82192 leads to the conclusion that they have not originated from the same source region on the moon. They are different from the bulk of Apollo and Luna samples in having a very low incompatible element abundances, but the fact that there are differences in the abundances between the three meteorites points to different sources. Eu anomalies and REE patterns are slightly different, indicating the complete absence of a KREEP component for Y-82192. Chondrite normalized siderophile and Se patterns also show a marked difference between the three meteorites under consideration. The largest and probably most significant differences are exhibited by the volatile elements. Y-791197 has clearly a significantly higher volatile element content than both other lunar meteorites. In Y-791197 as well as in Y-82192 some volatile rich clasts have been found. In the case of Y-82192, the bulk compositions give no indications of any volatile enrichment (there it seems to be confined to the few volatile rich clasts), while Y-791197 shows some enrichment even in the bulk sample. This would be an independent confirmation of earlier arguments based on petrological considerations (WARREN and KALLEMEYN, 1986c), chemical data (KACZARAL *et al.*, 1986), and is also in agreement with noble age data pointing to different exposure histories at least for ALHA81005 and Y-82192/Y-82193 (EUGSTER *et al.*, 1986; EUGSTER, 1987). We would thus suggest that three different impacts in different source regions on the moon have been responsible for the excavation and delivery of ALHA81005, Y-791197, and Y-82192/3, respectively. The study of the two new lunar meteorites (Y-793274 and -86032) will show if we have five different sample sites, bringing the number already close to the sites sampled by Apollo.

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References

BISCHOFF, A. and PALME, H. (1986): Volatile-rich clasts from lunar meteorite Yamato-791197. Papers Presented to the Eleventh Symposium on Antarctic Meteorites, 25–27 March 1986. Tokyo, Natl Inst. Polar Res., 28–30.

BISCHOFF, A., PALME, H., WEBER, H.W., STÖFFLER, D., BRAUN, O., SPETTEL, B., BEGEMANN, F., WÄNKE, H. and OSTERTAG, R. (1987): Petrography, shock history, chemical composition and noble gas content of the lunar meteorites Yamato-82192 and -82193. Mem. Natl Inst. Polar Res., Spec. Issue, **46**, 21–42.

DENNISON, J. E., KACZARAL, P.W. and LIPSCHUTZ, M.E. (1987): Volatile, chalcolphile, siderophile and lithophile trace elements in lunar meteorite Yamato-82192. Mem. Natl Inst. Polar. Res., Spec. Issue, **46**, 89–95.

EUGSTER, O. (1987): Cosmogenic and trapped noble gas isotopes, exposure age, and terrestrial age of lunar meteorites Yamato-82182 and -82193. Papers Presented to the Twelfth Symposium on Antarctic Meteorites, 8–10 June 1987. Tokyo, Natl Inst. Polar Res., 26–28.

EUGSTER, O., GEISS, J., KRÄHENBÜHL, U. and NIEDERMANN, S. (1986): Noble gas isotopic composition, cosmic ray exposure history, and terrestrial age of the meteorite Allan Hills A81005 from the moon. Earth Planet. Sci. Lett., **78**, 139–147.

FUKUOKA, T., LAUL, J.C., SMITH, M.R. and SCHMITT, R.A. (1986): Chemistry of Yamato-82192 and -82193 Antractic meteorites. Papers Presented to the Eleventh Symposium on Antarctic Meteorites, 25–27 March 1986. Tokyo, Natl Inst. Polar Res., 40–42.

KACZARAL, P.W., DENNISON, J.E. and LIPSCHUTZ, M.E. (1986): Yamato-791197; A volatile trace element rich lunar highlands sample from Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **41**, 76–83.

KOEBERL, C. and KIESL, W. (1986): Lunar meteorites Y-791197 and Y-82192; Geochemistry of halogens and other trace elements. Meteoritics, **21**, 420–421.

KOEBERL, C., KLUGER, F. and KIESL, W. (1986a): Rare earth element determinations at ultratrace abundance levels in geologic materials. Proceedings of the 7th International Conference on Modern Trends in Activation Analysis, Risø Natl. Lab., 399–405.

KOEBERL, C., KLUGER, F. and KIESL, W. (1986b): Trace element correlations as clues to the origin of tektites and impactites. Chem. Erde, **45**, 1–21.

LAUL, J. C., SMITH, M.R. and SCHMITT, R.A. (1983): ALHA81005 meteorite; Chemical evidence for lunar highland origin. Geophys. Res. Lett., **10**, 825–828.

Lindstrom, M.M. and Lindstrom, D.J. (1986): Lunar granulites and their precursor anorthositic norites of the early lunar crust. Proc. Lunar Planet. Sci. Conf., 16th, Pt. 2, D263–D276 (J. Geophys. Res., **91**, B4).

Lindstrom, M. M., Lindstrom, D. J., Korotev, R. L. and Haskin, L. A. (1986); Lunar meteorite Yamato-791197; A polymict anorthositic norite breccia. Mem. Natl Inst. Polar Res., Spec. Issue, **41**, 58–75.

Lindstrom, M. M., Korotev, R. L., Lindstrom, D. J. and Haskin, L. A. (1987): Lunar meteorites Y82192 and Y82193; Geochemical and petrologic comparisons to other lunar breccias. Papers Presented to the Twelfth Symposium on Antarctic Meteorites, 8–10 June 1987, Tokyo, Natl Inst. Polar Res., 19–21.

Marvin, U.B. (1983): The discovery and initial characterization of Allan Hills 81005; The first lunar meteorite. Geophys. Res., Lett., **10**, 775–778.

Ostertag, R., Stöffler, D., Bischoff, A., Palme, H., Schultz, L., Spettel, B., Weber, H., Weckwerth, G. and Wänke, H. (1986): Lunar meteorite Yamato-791197; Petrography, shock history and chemical composition. Mem. Natl Inst. Polar Res., Spec., Issue, **41**, 17–44.

Palme, H., Spettel, B., Weckwerth, G. and Wänke, H. (1983): Antarctic meteorite ALHA81005, a piece from the ancient lunar crust. Geophys. Res. Lett., **10**, 817–820.

Takeda, H., Mori, H. and Tagai, T. (1986): Mineralogy of Antarctic lunar meteorites and differentiated products of the lunar crust. Mem. Natl Inst. Polar Res., Spec. Issue, **41**, 45–57.

Taylor, S.R. (1982): Planetary Science; A Lunar Perspective. Houston, Lunar and Planetary Institute, 481 p.

Wänke, H., Palme, H., Baddenhausen, H., Dreibus, G., Jagoutz, E., Kruse, H., Palme, C., Spettel, B., Teschke, F. and Thacker, R. (1975): New data on the chemistry of lunar samples; Primary matter in the lunar highlands and the bulk composition on the moon. Proc. Sci. Conf., 6th, 1313–1340.

Warren, P.H. and Kallemeyn, G.W. (1986a): Geochemistry of lunar meteorite Yamato-791197; Comparison with ALHA81005 and other lunar samples. Mem. Natl Inst. Polar Res., Spec. Issue, **41**, 3–16.

Warren, P.H. and Kallemeyn, G.W. (1986b): Geochemistry of lunar meteorite Yamato-82192; Comparison with Yamato-791197, and other lunar samples. Papers Presented to the Eleventh Symposum on Antarctic Meteorites, 25–27 March 1986. Tokyo, Natl Inst. Polar Res., 31–33.

Warren. P.H. and Kallemeyn, G.W. (1986c): How many launching sites supplied the lunar meteorites? Meteoritics, **21**, 532.

Warren, P.H. and Kallemeyn, G.W. (1987a): New data for the bulk compositions of four lunar meteorites, and for an Fe-rich basaltic clast of probable VLT-mare affinity from Y-791197. Papers Presented to the Twelfth Symposium on Antarctic Meteorites, 8–10 June 1987. Tokyo, Natl Inst. Polar Res., 22–23.

Warren, P.H. and Kallemeyn, G.W. (1987b): Geochemistry of lunar meteorite Yamato-82192; Comparison with Yamato-791197, ALHA81005, and other lunar samples. Mem. Natl Inst. Polar Res., Spec. Issue, **46**, 3–20.

Warren, P.H., Taylor, G.J. and Keil, K. (1983): Regolith breccia Allan Hills A81005; Evidence of lunar origin, and petrography of pristine and nonpristine clasts. Geophys. Res. Lett., **10**, 779–782.

Yanai, K. and Kojima, H. (1984): Yamato-791197; A lunar meteorite in the Japanese collection of Antarctic meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **35**, 18–34.

Yanai, K. and Kojima, H. (1985): Lunar meteorites; Recovery, curation, and distribution. Papers Presented to the Tenth Symposium on Antarctic Meteorites, 25–27 March 1985. Tokyo, Natl Inst. Polar Res., 87–89.

Yanai, K. and Kojima, H. (1987): New lunar meteorite; Yamato -793274. Papers Presented to the Twelfth Symposium on Antarctic Meteorites, 8–10 June 1987. Tokyo, Natl Inst. Polar Res., 17–18.

Yanai, K., Kojima, H. and Ikadai, S. (1986): Four lunar meteorites including a new specimen Yamato-82193, preliminary examination, curation, and allocation for consortium studies (abstract). Papers Presented to the Eleven Symposium on Antarctic Meteorites, 25–27 March 1986. Tokyo, Natl Inst. Polar Res., 25–27.

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