Proc. NIPR Symp. Antarct. Meteorites, **6**, 14–34, 1993

GABBROIC LUNAR MARE METEORITES ASUKA-881757 (ASUKA-31) AND YAMATO-793169: GEOCHEMICAL AND MINERALOGICAL STUDY

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Abstract: Asuka-31 (Asuka-881757) is a new type of gabbroic mare basalt which is similar to VLT mare basalts from Apollo 17 and Luna 24. The small lunar meteorite Yamato-793169 was described to have petrologic characteristics that are similar to those of A-881757; this similarity is confirmed here for trace element compositions. We studied bulk (powder) samples and mineral and rock fragments of A-881757. The mineralogy and mineral chemistry of the separates from A-881757,111 is that of a coarse-grained gabbroic rock of VLT composition; the texture of the mesostases suggests some metamorphic recrystallization with highly unequilibrated mineral compositions. As for mineral phases, we found plagioclase, pyroxene, fayalite, Fe-Ni metal, silica, apatite, and some trace minerals. In addition, we found ulvöspinels associated with Na-rich plagioclase, fayalite, apatite, ilmenite, SiO_2, Fe-sulfide, and a rare metal (0.3 wt% Ni, 2.0 wt% Co) which has a composition unknown so far from any lunar rocks. The trace element contents found in the mineral separates and fragments correspond closely to the mineralogical findings. The chondrite normalized REE patterns for the bulk samples of A-881757 and Y-793169 are relatively flat, with some light REE depletion that is typical of mare basalts. The plagioclase-dominated subsamples A31-CL, A31-CL2, and A31-YC show a distinct positive Eu anomaly. The bulk trace element composition of Y-793169 is almost identical to that of A-881757. Solar-wind derived noble gas and exposure age studies of A-881757 and Y-793169 have indicated marked differences between the two meteorites, indicating that they might have been ejected in different events. These two new gabbroic, VLT-like, mare basalts are therefore valuable new additions to the lunar meteorite collection.

1. Introduction

The collection of lunar meteorites in Antarctica continues to yield more samples every year, and is growing in importance augmenting the presently available lunar sample collection. Eleven lunar meteorites have been recovered so far by Japanese and American expeditions to Antarctica, one more was found in Australia. Following the initial discovery of ALHA81005, the first lunar meteorite (MARVIN, 1983), more samples have been recovered from several geographically quite different locations in Antarctica. The question regarding the number of individual source regions on the moon that are represented by the known lunar meteorites is of great importance. More recently, two

new lunar meteorites were recovered from the MacAlpine Hills (MAC88104/88105; paired). These samples are very similar to other highlands meteorites, such as ALHA81005, Y-791187, and Y-82192/3 (LINDSTROM *et al.*, 1991b, c; KOEBERL *et al.*, 1991a; PALME *et al.*, 1991), but the different finding location and exposure histories preclude pairing with the other samples (*e.g.*, EUGSTER, 1989, 1990; EUGSTER *et al.*, 1991).

Elephant Moraine (EET) 87521 turned out to be the first lunar meteorite predominantly composed of mare components (WARREN and KALLEMEYN, 1989; DELANEY, 1989; DELANEY *et al.*, 1990). Previous to this discovery, anorthositic highland rocks (which were believed not to be a predominant rock type on the lunar surface; ASHWAL, 1992) dominated the lunar meteorite collection. It is interesting to note that the first samples have all originated from the lunar highlands, and are of anorthositic composition (see, *e.g.*, PALME *et al.*, 1983; WARREN and KALLEMEYN, 1986, 1987; KOEBERL, 1988; TAKEDA *et al.*, 1989; KOEBERL *et al.*, 1989; summary by ASHWAL, 1992). This has now changed with the discovery of more mare meteorites; see, *e.g.*, WARREN, 1990; LINDSTROM and MARTINEZ, 1990; TAKEDA *et al.*, 1990; MORI *et al.*, 1990; YANAI and KOJIMA, 1990). After the identification of EET87521 as a mare-dominated meteorite, Y-793274, a very small sample (8.66 g), which was first thought to be of anorthositic (highlands) provenance as well (YANAI and KOJIMA, 1987a), proved to be mare-influenced as well. Detailed consortium studies (KURAT *et al.*, 1990; KOEBERL *et al.*, 1991b; LINDSTROM *et al.*, 1991a; BRANDSTÄTTER *et al.*, 1991) found that it is a mixture of mare and highlands components at a ratio of about 2:1. It may have originated from an impact that occurred at a mare/highlands boundary, or penetrated through a thin mare layer to underlying highland lithologies.

Furthermore, two more lunar meteorites, Y-793169 and Asuka-31, have recently been preliminarily classified as mare rocks, possibly of VLT heritage. The first descriptions of Asuka-31, a gabbroic lunar meteorite, were provided by YANAI (1990a, b, 1991). Y-793169 was first reported to be of lunar origin by YANAI and KOJIMA (1987b). Thus there are now four samples of predominantly mare provenance. These meteorites were the subject of recent studies (started in 1991/2), initiated by the National Institute of Polar Research (leaders: H. TAKEDA and K. YANAI). A consortium study of Asuka-881757 (Asuka-31) and Y-793169 has recently been organized. Due to the small size and preciousness of the samples, only a very limited amount of material was available, and only a small number of consortium members received samples. Samples became available in early 1992. Some preliminary results were reported by LINDSTROM *et al.* (1991d), MISAWA *et al.* (1991), KOEBERL *et al.* (1992), TAKEDA *et al.* (1992), and WARREN and KALLEMEYN (1992).

Asuka-31 was discovered on December 20, 1988, on the northeastern end of the Nansen Ice Field, about 130 km south of the Japanese Asuka Station (YANAI, 1991). It weighed 442.12 g and measured 8.0 × 8.0 × 5.8 cm and seems to be half of the original stone. One side is broken and shows no fusion crust, while the other side has a smoothly rounded surface covered by a shiny black fusion crust (YANAI, 1991). The meteorite was tentatively named Asuka-31 and later, after classification of the 1987 and 1988 collections, renamed Asuka-881757. We usually use the designation Asuka(A)-881757, but in some cases we apply the abbreviation Asuka(A)-31. In this paper we describe our geochemical, petrological, and mineralogical studies of samples of the lunar

Table 1. Major and trace element contents of 2 bulk and 7 mineral samples of A-881757, and two bulk samples of Y-793169. All data in ppm, except as noted.

Weight (mg)	Bulk1 108.3	Bulk2 126.25	A31-Bl 0.56	A31-BL2 2.87	A31-CL 2.09	A31-CL2 4.01	A31-LH 2.81	A31-YC 0.75	A31-OY 0.031	Y793169a 8.39	Y793169b 10.42
Na (%)	0.22	0.21	0.14	0.018	0.73	0.73	0.032	0.78	0.001	0.22	0.234
K	310	320	5300	61	66	150	170	100	<400	542	531
Sc	101	98	141	46.3	3.89	3.15	156	11.7	1.05	92.6	94.5
Cr	1930	1850	1270	36800	62	63	3890	163	19.8	1770	1742
Fe (%)	18.1	17.6	41.1	50.7	1.68	0.96	23.4	2.69	0.27	18.3	19.1
Co	27.9	27.9	53.8	48.6	65.1	3.31	83.3	16.2	1.84	30.5	29.3
Ni	60	45	400	150	<100	20	150	150	13	50	55
Zn	3	2	<50	30	17	15	28	20	638	5	4
Ga	2.5	3	7.5	8	<2	<1.5	3.5	<2	0.04	3.8	3.1
As	0.065	0.06	0.22	0.14	0.07	0.02	0.03	0.13	<0.4	0.21	0.18
Se	<0.7	<0.5	<1.5	0.8	<0.6	<0.6	<3	0.6	219	0.39	0.31
Br	0.1	0.12	0.05	0.06	0.03	0.02	0.02	0.09	0.6	0.14	0.18
Rb	2.3	2.8	6	4	<6	0.95	7	<10	0.26	<4	2.1
Sr	110	120	<200	120	730	750	140	600	<10	70	85
Zr	40	50	<600	260	110	65	<50	280	<10	65	55
Ag	<0.2	<0.2	<1	<0.4	<1	0.09	<0.8	<0.2	<0.1	<0.05	<0.02
Sb	<0.04	<0.03	0.065	0.028	0.01	0.01	0.046	0.01	0.25	0.064	0.049
Cs	0.038	0.037	<0.2	<0.1	0.018	0.012	<0.1	<0.1	n.d.	<0.05	<0.06
Ba	30	25	<20	15	31	20	84	40	11	38	30
La	3.75	3.64	2.57	2.94	0.49	0.25	1.47	0.65	0.22	4.95	4.53
Ce	11.5	10.3	11.9	7.2	1.38	0.85	4.95	2.2	0.51	14.2	15.2

Nd	8.9	7.8	11	5.7	1	0.57	4.6	<2	0.3	12.1	11.7
Sm	2.96	2.81	4.15	1.78	0.23	0.13	1.79	0.58	0.079	4.53	4.11
Eu	1.07	1.12	0.82	0.37	2.29	2.17	0.12	2.57	0.066	1.37	1.26
Gd	3.86	3.35	7.3	1.8	<0.4	0.2	2.4	<1	0.12	5.7	5.4
Tb	0.81	0.72	1.58	0.38	0.07	0.048	0.51	0.13	0.025	1.05	0.99
Dy	5.3	4.5	11.4	3.4	0.35	0.25	3.7	0.8	n.d.	7.1	6.9
Tm	0.49	0.36	1.09	0.52	<0.1	<0.05	0.38	<0.1	<0.03	0.73	0.67
Yb	3.64	2.94	8.15	3.93	0.18	0.13	2.65	0.49	0.07	4.71	4.49
Lu	0.56	0.49	1.24	0.61	0.012	0.013	0.41	0.062	0.009	0.68	0.64
Hf	2.37	2.05	5.41	5.74	0.13	0.045	0.92	0.19	0.02	2.89	3.10
Ta	0.23	0.22	1.61	0.78	0.09	0.06	0.21	0.16	0.02	0.29	0.32
W	0.084	0.073	0.2	0.1	0.07	0.06	0.21	0.38	n.d.	0.12	0.09
Ir (ppb)	<1	0.3	31	15	<4	<2	<3	<5	0.4	<2	1.1
Au (ppb)	0.3	0.2	1.4	0.8	0.4	0.6	1.5	0.2	0.8	0.9	1.3
Hg	<2	<2	<8	<4	<9	<3	10	<12	n.d.	<0.2	<0.1
Th	0.43	0.42	2.93	2.64	0.3	0.21	0.21	0.28	0.029	0.69	0.67
U	0.21	0.11	0.55	0.095	0.09	0.03	0.09	0.11	<0.05	0.12	0.07
K/U	1476	2909	9636	642	733	5000	1889	909		4517	7586
Zr/Hf	16.88	24.39		45.30	846	1444		1474		22.49	17.74
La/Th	8.72	8.67	0.88	1.11	1.63	1.19	7.00	2.32	7.59	7.17	6.67
Hf/Ta	10.30	9.32	3.36	7.36	1.44	0.75	4.38	1.19	1.00	9.97	9.69
Th/U	2.05	3.82	5.33	27.79	3.33	7.00	2.33	2.55		5.75	9.57
La_N/Yb_N	0.70	0.84	0.21	0.51	1.84	1.30	0.37	0.90	2.12	0.71	0.68
Eu/Eu*	0.97	1.12	0.46	0.63		41.13	0.18		2.07	0.82	0.82

meteorites Asuka-881757 (Asuka-31) and Yamato(Y)-793169.

2. Samples and Analytical Methods

We have received sample A-881757 (Asuka-31) in two forms, first (,81) as a homogeneous powder, which cannot be used for any petrological or mineralogical studies, and later split ,111, a coarse-grained crushed sample remaining from crushing the original samples, which was intended to allow some petrological studies. Unfortunately, Y-793169 was received only as a homogeneous powder, prepared at the NIPR in Tokyo and UCLA (P. H. WARREN), thus not enabling us to do any mineralogical and petrological studies.

Nine individual samples of A-881757 (Asuka-31) were analyzed by neutron activation analysis. Two splits of sample A-881757,81 were used for bulk trace element analyses by instrumental neutron activation analysis (INAA). Most of the INAA methods have been described previously (see, *e.g.*, KOEBERL *et al.*, 1991a, b). The sample bulk1 weighed 108.30 mg, sample bulk2 126.25 mg. Our allocation of Y-793169 was split in two subsamples of 8.39 and 10.42 mg, which were used for bulk trace element analysis. In order to obtain more information than just the bulk composition, the coarse grained sample ,111 was screened for subsamples to perform INAA and petrographical analyses as well.

From the sample A-881757,111, we therefore selected a number of crystals and fragments by hand picking under the stereo microscope. We selected two batches of clear crystals (CL, CL2), one of yellowish crystals (YC), two black samples (BL, BL2), and one grayish lithology (LH). Sample weights are given in Table 1. One additional sample, a small enigmatic orange sphere (OY), which was obviously unique, was also retrieved from the crushed sample. Because it was so small (31 μg), this sample was irradiated separately at a high flux reactor (Forschungszentrum Seibersdorf near Vienna) at a neutron flux of 6×10^{13} n cm^{-2} s^{-1} for about 120 hours. Most of the INAA procedures have been described before; see, *e.g.*, KOEBERL (1988, 1993) and KOEBERL *et al.* (1989).

After the INAA measurements were completed and several months cooling time had passed, polished sections of samples CL, CL2, BL, BL2, YC, LH, and OY were prepared and subsequently studied by optical microscopy, electron microscopy, and electron probe microanalysis. The crystals, fragments, and lithologies were analyzed with an ARL-SEMQ electron microprobe following routine procedures. SEM studies and BSE images were obtained with a JEOL JSM-6400 scanning electron microscope.

3. Results and Discussion

3.1. Mineralogy, phase compositions, and chemical composition of fragments

The broken interior of A-881757 is very coarse-grained, consisting of brownish pyroxenes, translucent plagioclase, and black ilmenites. Some adhering brownish and greenish glassy melts (impact derived?) were observed in the hand specimen when one of the authors (CK) examined it at the NIPR. Unfortunately, these possible impact glasses were not available for analysis.

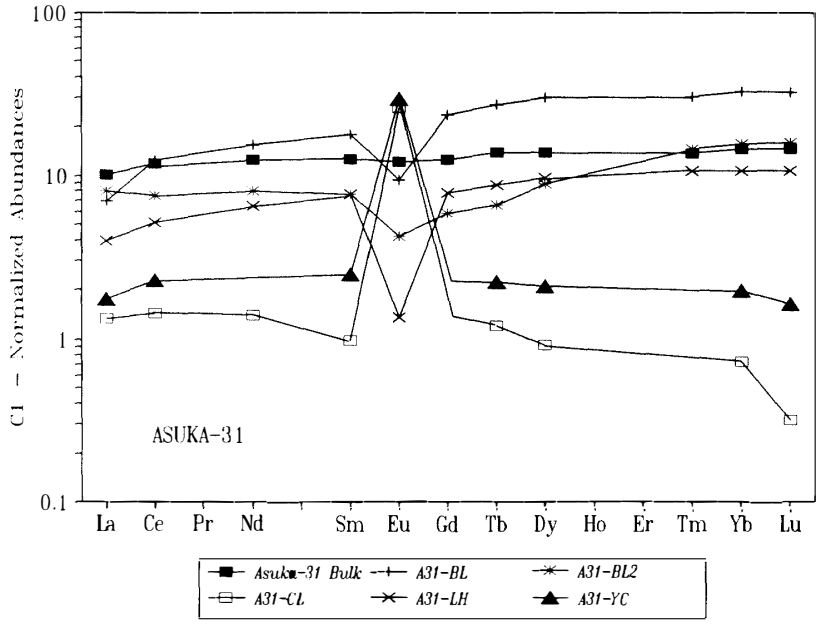

Fig. 1. Chondrite-normalized REE abundance patterns for A-881757: bulk sample and selected mineral fragments (normalization factors from TAYLOR, 1982).

Table 2. Typical mineral compositions of fragments in sample A31-CL.

	An	An	An	Px	Px	Px	Fa
SiO_2	43.1	43.8	47.9	49.1	49.5	46.9	29.9
TiO_2	0.02	0.02	0.03	0.77	0.75	1.00	0.11
Al_2O_3	35.7	35.6	33.3	1.54	1.51	1.15	0.02
Cr_2O_3	0.05	<0.02	<0.02	0.62	0.41	0.15	0.02
FeO	0.65	0.41	0.78	21.6	22.7	29.7	62.0
MnO	<0.02	<0.02	<0.02	0.49	0.40	0.52	0.74
MgO	0.05	0.11	0.05	12.5	12.8	4.40	4.20
CaO	18.6	18.5	15.8	12.3	10.8	14.4	0.42
Na_2O	0.42	0.54	1.63	0.04	0.02	0.04	<0.02
K_2O	0.02	0.02	0.23	<0.02	<0.02	<0.02	<0.02
Total	98.61	99.00	99.72	98.96	98.89	98.26	97.41
An	95.9	94.8	83.1				
Fe/Fe+Mg	0.885	0.676	0.900	0.492	0.500	0.791	0.888

As described in the previous section, we isolated several subsamples of A-881757 by handpicking, and analyzed them by INAA. Most of these subsamples consisted of several fragments or crystals that had an identical optical appearance. This was necessary to obtain samples with reasonable weights. After completion of the INAA measurements, the samples were mounted on petrographic sections and studied by optical and electron microscopy. In the following paragraphs we discuss the results of the chemical and mineralogical studies on the fragments and crystals of the subsamples. The results of the INAA analyses for selected major elements, and the complete trace element data, are given in Table 1. This table also gives the individual bulk analyses of two samples from A-881757 and Y-793169; the bulk chemical composition will be discussed in Sec-

Fig. 2a. Back-scatter electron (BSE) image of sample A31-CL: Ca-rich pyroxene with lamellae, attached to a large plagioclase fragment (gray).

Fig. 2b. Back-scatter electron (BSE) image of sample A31-CL: Fayalite (white)–pyroxene (gray) symplectite attached to plagioclase.

tion 3.2. Figure 1 shows the condrite-normalized REE patterns for a bulk sample and selected mineral fragments of A-881757.

The following fragment and crystal samples were studied:

3.1.1. Sample A31-CL

This sample consists of 3 translucent (clear) fragments of shocked plagioclase (maskelynite). They are highly anorthitic (An 95) and contain a few small grains of heterogeneous, Fe-rich pyroxene and some patches of mesostasis (very Fe-rich pyroxene with about 39 wt% FeO, ilmenite, fayalite, and silica). Some pyroxenes show lamellae (Fig. 2a). The plagioclase that is co-existing with fayalite and silica is clearly richer in Na (An 83) and K than the other plagioclase. Some fayalite/pyroxene symplectite was observed (Fig. 2b), similar to observations reported by YANAI (1991). Typical mineral compositions from the A31-CL subsample are given in Table 2. The trace element composition is dominated by that of lunar pyroxene (*e.g.*, PALME *et al.*, 1984), with

generally low rare earth element (REE) contents, a relatively flat chondrite-normalized REE pattern, with a typical positive Eu anomaly (Fig. 1).

3.1.2. Sample A31-CL2

The subsample is very similar to A31-CL. It consists of 4 highly anorthitic maskelynites (An 92–95) with similar inclusions of pyroxene, fayalite, ilmenite, and silica. Na_2O contents of maskelynite range from 0.4–1.8 wt%. FeO contents of the plagioclases are usually low (0.3–0.4 wt%) and increase with increasing Ab content. Typical mineral compositions are given in Table 3. Trace element contents are very similar to A31-CL except for the pyroxene-compatible elements which reflect different plagioclase-pyroxene mixing proportions for these two samples. A31-CL2 also has even slightly lower REE abundances than A31-CL, but shows a positive Eu anomaly of similar magnitude.

3.1.3. Sample A31-BL

This sample consists of 2 irregular black fragments of which one is mainly ilmenite

Table 3. Typical mineral compositions of fragments in sample A31-CL2.

	Plag	Plag	Plag	Plag	Plag	Px	Fa
SiO_2	43.8	44.1	44.9	46.2	47.2	47.7	29.7
TiO_2	<0.02	0.03	0.05	0.05	0.05	0.87	0.11
Al_2O_3	35.3	35.0	35.2	34.2	32.8	1.00	0.03
Cr_2O_3	<0.02	<0.02	<0.02	<0.02	<0.02	0.15	<0.02
FeO	0.38	0.34	0.39	0.63	0.76	30.4	66.6
MnO	<0.02	<0.02	<0.02	<0.02	<0.02	0.48	0.85
MgO	0.13	0.18	0.12	0.09	0.04	9.50	1.72
CaO	18.7	18.4	18.3	17.3	16.1	8.30	0.58
Na_2O	0.52	0.62	0.83	1.22	1.72	0.02	<0.02
K_2O	0.03	0.02	0.02	0.05	0.22	<0.02	<0.02
Total	98.86	98.69	99.81	99.74	98.89	98.42	99.59
An	95.1	94.1	92.3	88.4	82.7		
Fe/Fe+Mg	0.625	0.513	0.643	0.793	0.918	0.642	0.956

Table 4. Typical mineral compositions of 2 fragments (ilmenite and mesostasis) in sample A31-BL.

	Ilmenite fragment					Meta-mesostasis			
	An	Px	Px	Fa	Ilm	Px	Px	Px	Fa
SiO_2	45.3	46.0	45.5	29.9	0.02	46.8	45.8	45.9	29.6
TiO_2	0.02	1.17	0.87	0.13	52.2	0.83	0.94	0.93	0.06
Al_2O_3	34.00	1.00	0.93	<0.02	0.04	0.92	0.97	1.07	0.02
Cr_2O_3	0.02	0.09	0.11	0.02	0.20	0.11	0.11	0.06	<0.02
FeO	0.68	28.9	35.2	65.0	45.3	33.7	33.0	29.6	64.5
MnO	<0.02	0.31	0.45	0.74	0.32	0.61	0.53	0.5	0.68
MgO	0.04	3.0	4.3	3.2	0.40	5.9	4.8	3.9	3.2
CaO	16.8	17.2	9.7	0.31	<0.02	8.7	12.2	15.5	0.24
Na_2O	1.28	0.02	0.06	<0.02	<0.02	0.04	0.03	0.04	<0.02
K_2O	0.09	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Total	98.23	97.69	97.12	99.30	98.48	97.61	98.38	97.50	98.30
An	87.4								
Fe/Fe+Mg	0.909	0.844	0.821	0.919	0.984	0.762	0.794	0.810	0.919

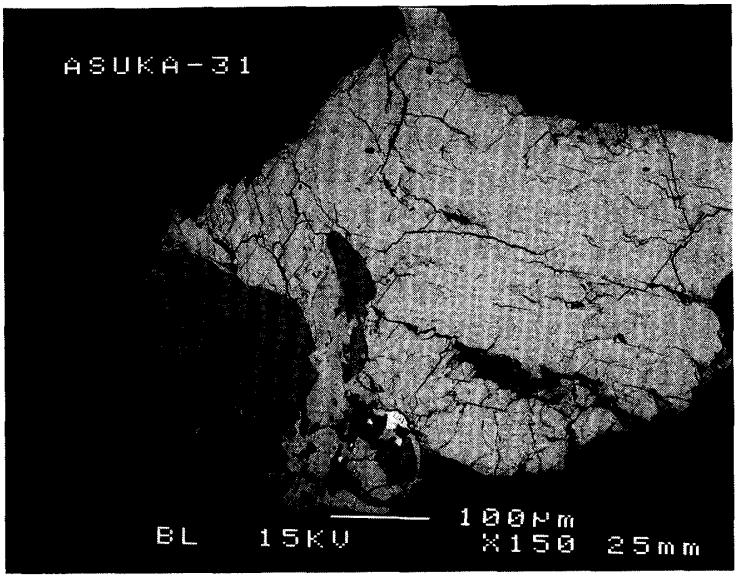

Fig. 3a. Back-scatter electron (BSE) image of sample A31-BL: Large ilmenite (gray) with fayalite and Fe-rich pyroxene (both gray), plagioclase (darker gray), silica (dark gray), and sulfide (white).

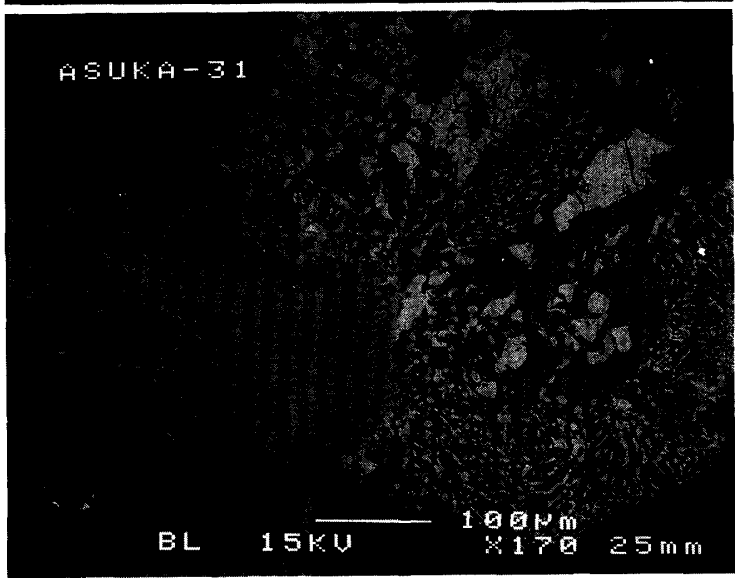

Fig. 3b. Back-scatter electron (BSE) image of sample A31-BL: Sample of symplectitic mesostasis consisting of fayalite (white), pyroxene (gray), and silica (dark gray), attached to pyroxene (left side). Small white specks are Fe-sulfides.

with some pyroxene, Na-rich maskelynite, fayalite, and troilite attached (Fig. 3a). The second fragment consists of medium-grained mesostasis (with meta-igneous texture) consisting of fayalite, ilmenite, silica, and FeO-rich pyroxene with small inclusions of troilite (Fig. 3b). Mineral compositions of the ilmenite and mesostasis fragments are given in Table 4. Because these fragments represent mainly mesostasis their mineral compositions are appropriately FeO-rich (pyroxene, olivine) and Na_2O-rich (plagioclase). Trace element contents are correspondingly high (Table 1) with REE contents in A31-BL above those of the bulk samples. A slight negative Eu anomaly is present (Fig. 1), representing mainly the mesostasis. Remarkable are the high contents of Ni (400 ppm) and Ir (31 ppb) which may either indicate an indigenous component, or contamination from impact melts.

3.1.4. Sample A31-BL2

This batch consists of 7 black, irregular fragments of up to 1.5 mm longest

Fig. 4a. Back-scatter electron (BSE) image of sample A31-BL2: Coarse-grained mesostasis consisting of fayalite (gray), ulvöspinel (light gray), ilmenite (light gray), apatite (gray, center and upper left), plagioclase (darker gray), and silica (dark gray). Bright specks are Fe-sulfides.

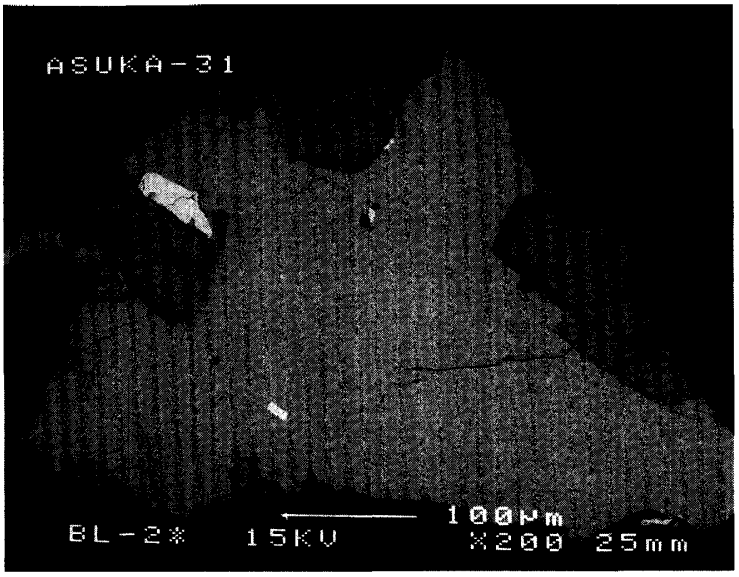

Fig. 4b. Back-scatter electron (BSE) image of sample A31-BL2: Ulvöspinel grain containing ilmenite (gray), Fe-sulfide (white, large), Ni-poor metal (white, small), and titaniferous fayalite (between ilmenite and ulvöspinel).

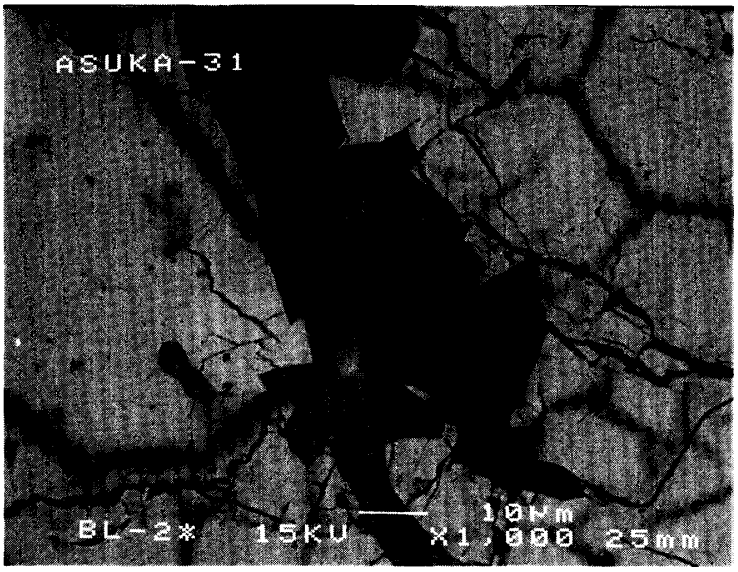

Fig. 4c. Back-scatter electron (BSE) image of sample A31-BL2: Plagioclase (dark gray) and K-rich phase X (gray) from a small inclusion in a large fayalite grain.

Table 5. Typical mineral compositions of 3 fragments in sample A31-BL2. Note the enigmatic phase X.

	Gabbroic fragment					Ulvöspinel fragment						Ilmenite fragment	
	Plag	Plag	Fa	Ulv	Phosp	Ulv	Ulv	Fa	Ti-Fa	X	Ilm	Ilm	Fa
SiO_2	49.4	49.6	29.8	0.02	1.52	0.05	0.15	29.5	30.4	53.4	<0.02	0.03	29.1
TiO_2	0.05	0.07	0.31	30.6	0.05	38.6	30.3	0.14	1.19	0.62	52.5	53.1	1.04
Al_2O_3	30.1	28.5	<0.02	2.79	0.03	2.58	2.75	0.02	0.04	21.2	0.05	0.05	0.02
Cr_2O_3	<0.02	<0.02	0.11	4.5	<0.02	9.2	5.8	0.07	0.17	<0.02	0.12	0.13	0.05
FeO	0.95	1.59	63.6	60.0	2.70	58.0	59.7	65.9	62.9	1.50	45.6	45.8	63.2
MnO	<0.02	<0.04	0.77	0.41	<0.02	0.34	0.28	0.78	0.62	0.07	0.35	0.45	0.67
MgO	0.04	0.06	3.2	0.26	<0.02	0.36	0.39	1.81	5.3	<0.02	0.45	0.44	4.3
CaO	15.4	14.3	0.50	<0.02	48.2	<0.02	<0.02	0.67	0.35	0.42	0.02	<0.02	0.19
Na_2O	1.54	2.24	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.35	<0.02	<0.02	<0.02
K_2O	0.62	0.68	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	9.50	<0.02	<0.02	<0.02
Total	98.10	97.04	98.29	98.58	52.50	99.13	99.37	98.89	100.97	87.06	99.09	100.00	98.57
An	81.4	74.6											
Fe/Fe+Mg	0.933	0.936	0.918	0.992		0.989	0.988	0.953	0.870				0.892

Table 6. Typical mineral compositions of fragments in sample A31-LH.

	Px	Px	Px	Ulv	Glass
SiO_2	48.3	48.1	48.3	0.14	45.3
TiO_2	0.69	0.88	1.04	27.5	0.75
Al_2O_3	1.18	1.48	1.81	6.00	5.10
Cr_2O_3	0.30	0.47	0.48	7.00	0.05
FeO	29.2	23.7	20.1	54.8	30.3
MnO	0.54	0.42	0.32	0.39	0.38
MgO	11.6	11.0	10.8	1.33	2.58
CaO	7.00	12.3	15.5	0.26	10.3
Na_2O	0.04	0.03	0.06	<0.02	0.27
K_2O	<0.02	<0.02	<0.02	<0.02	0.05
Total	98.85	98.38	98.41	97.42	95.08
An					
Fe/Fe+Mg	0.586	0.547	0.511	0.959	

dimension. They are very similar to sample BL and consist mainly of fayalite, ilmenite, maskelynite (1.5–2.2 wt% Na_2O), silica, and a coarse-grained Ca-phosphate (probably apatite) (Fig. 4a). A relatively high proportion of ulvöspinel was found in the fragments of this sample (Fig. 4b). The occurrence of some ulvöspinel in A-881757 as an accessory phase with ilmenite has also been mentioned by YANAI (1991). We also found titaniferous fayalite. Representative mineral analyses are given in Table 5. An unknown phase ("X"; see Table 5; Fig. 4c) was encountered. Phase X is a K-Al-silicate enclosed in fayalite together with some plagioclase. A31-BL2 has lower REE contents than A31-BL, which is probably because of the larger fraction of ilmenite and ulvöspinel, which dilute the REE abundances. The same applies also for most other trace element contents, which are lower in A31-BL2 (Table 1). The high Cr content is due to the high ulvöspinel abundance.

3.1.5. Sample A31-LH

This sample consists of two irregular, reddish-brown translucent fragments of 1–1.5 mm size; the fragments are similar to those of sample BL but consist mostly of pyroxene with few troilite and some metal inclusions. Rare ulvöspinel was also found. Typical mineral compositions are given in Table 6. A small batch of glassy melt, presumably of local origin, is attached to one of the fragments. Some metal droplets have been found in this melt (Fig. 5). The metal has a very unusual composition, with 2.0 wt% Co and 0.26 wt% Ni. This composition is outside any range reported for metal grains from lunar rocks (*e.g.*, WARREN *et al.*, 1981; HEIKEN *et al.*, 1991), and also unlike chondritic metal particles (*e.g.*, AFIATTALAB and WASSON, 1980) or the relatively Co-rich taenite grain (1.8 wt%, but with 42.0 wt% Ni) found in lunar meteorite MAC88105 (KOEBERL *et al.*, 1991a). The REE are stronger fractionated (Fig. 1) with a negative Eu anomaly.

3.1.6. Sample A31-YC

This sample consists of 3 mostly clear to yellowish transparent maskelynite fragments which contain a few pyroxenes. The yellow color stems from colored cracks. Typical mineral compositions are given in Table 7. One fragment is a glass of feldspathic

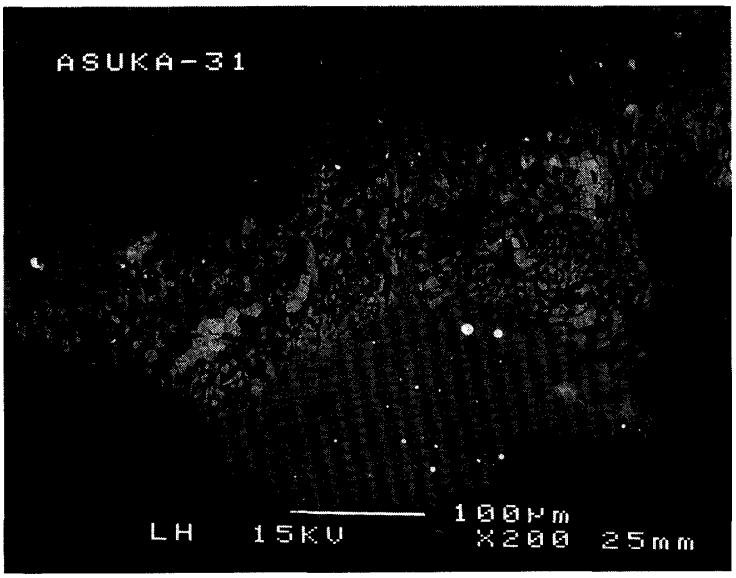

Fig. 5. Back-scatter electron (BSE) image of sample A31-LH: Contact of pyroxene with mesostasis consisting of Fe-rich pyroxene, fayalite, plagioclase, and ilmenite. Lower portion is glass produced (presumably) by shock melting containing spheres of the unique Co-rich (Ni-poor) metal.

Table 7. Typical mineral compositions of fragments in sample A31-YC.

	Plag	Plag	Plag	Plag	Px	Px
SiO_2	44.9	45.3	45.3	46.2	49.0	47.7
TiO_2	<0.02	<0.02	0.02	0.02	0.87	0.99
Al_2O_3	36.7	35.4	35.6	34.0	1.79	1.18
Cr_2O_3	<0.02	0.13	<0.02	0.03	0.59	0.21
FeO	0.44	0.47	0.62	0.69	18.4	29.8
MnO	<0.02	<0.02	<0.02	<0.02	0.35	0.46
MgO	0.10	0.07	0.07	0.06	12.2	8.70
CaO	18.2	17.2	17.2	16.2	14.9	9.3
Na_2O	0.53	0.98	1.14	1.42	0.04	<0.02
K_2O	0.03	0.07	0.05	0.10	<0.02	<0.02
Total	100.9	99.62	100.00	98.72	98.14	98.34
An	94.8	90.3	89.0	85.8		
Fe/Fe+Mg	0.714	0.794	0.837	0.868	0.458	0.658

composition which devitrified from the surface and along cracks. Totals of EMP analyses are low (not shown in Table), indicating the possibility of hydration, presumably during weathering in Antarctica. This is the plagioclase-rich sample that has the highest REE contents. Other trace elements (Sc, Cr, Fe, Ni, Zr) also indicate a higher degree of contamination as compared to A31-CL and A31-CL2, possibly because of the contribution from the glass fragment.

3.1.7. Sample A31-OY

This unusual orange fragment, which turned dark under irradiation, is of reddish-brown color under the microscope; it is optically isotropic and soft. EDX analyses show that is composed predominantly of carbon. The trace element data are very puzzling: high selenium, but rare earth elements near chondritic values. The origin of this object is not clear, but we cannot exclude contamination (from whatever source) during the sample preparation at the NIPR. However, this does not readily explain the

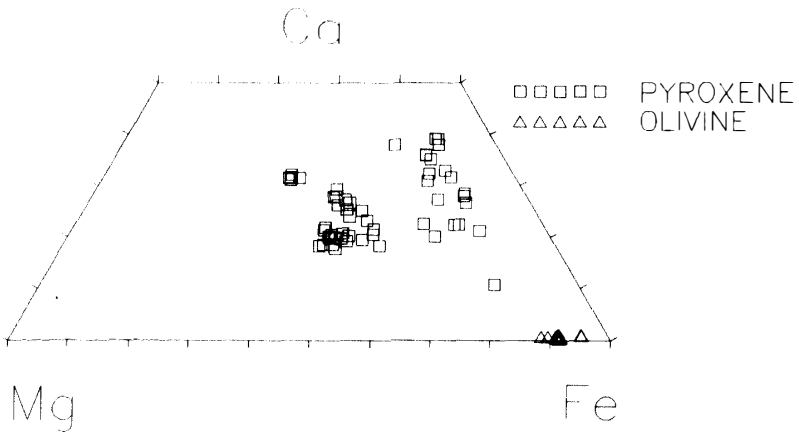

Fig. 6. Pyroxene quadrilateral showing all pyroxene and olivine analyses obtained for A-881757 minerals.

trace element composition, so the origin of this fragment remains an open question.

3.1.8. General

The complete pyroxene and olivine compositions for A-881757 are shown in Fig. 6, demonstrating the existence of some primitive pyroxenes with higher Cr, but lower Ti contents. The plagioclase compositions are typical for LT (Apollo 12) and VLT (Luna 24, Apollo 17) basalts (*e.g.*, CRAWFORD, 1973; KURAT and KRACHER, 1981; VANIMAN and PAPIKE, 1977). However, the FeO content is on average considerably lower in A-881757 plagioclase as compare to the plagioclases in the mare basalts mentioned above. This could reflect slower crystallization of the melt, indicating a hypabyssal nature of the A-881757 gabbro. The REE contents of the plagioclase crystals correspond to a REE content in the liquid from which the plagioclase crystallized of about $10 \times$ Cl. The Cl-normalized REE patterns with the strong positive Eu anomalies are typical for lunar plagioclase (*e.g.*, PALME *et al.*, 1984; BASALTIC VOLCANISM STUDY PROJECT, 1981; HEIKEN *et al.*, 1991).

3.2. Bulk and trace element composition

Table 1 also gives the trace element composition of the subsamples selected from A-881757,111 as well as the trace element composition of two bulk samples of A-881757 and two bulk samples of Y-793169. Figure 7 shows the provenance of the sample from bulk Fe/Mn contents, clearly confirming a lunar origin for A-881757. In addition, the figure shows a comparison to other lunar meteorites. According to YANAI (1991), the whole rock petrography shows that A-881757 consists mainly of plagioclase (maskelynitized) and pyroxene, and some ilmenite and troilite, with traces of olivine, apatite, and Ni-Fe metal; it shows gabbroic texture. The petrology and bulk chemical data support this view; A-881757 is clearly an unusual lunar mare basalt, unlike most samples retrieved by the Apollo and Luna missions. Its bulk Fe content is higher than that of any other lunar meteorites; the bulk chemical composition is compatible with (but not identical to) that of a VLT marebasalt. This is demonstrated in Fig. 8, where A-881757 is compared with Y-793274 (KURAT *et al.*, 1990; KOEBERL *et al.*, 1991b). Regarding the mg-number, the two samples differ mainly in Fe content.

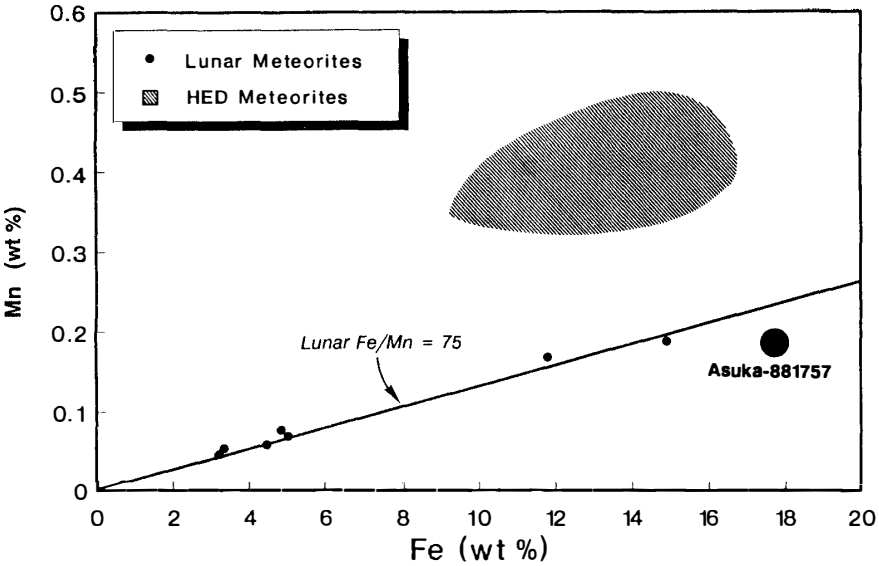

Fig. 7. Fe-Mn ratio in lunar meteorites compared to basaltic meteorites. The group of lunar meteorites plotting between about 3–5 wt% Fe are the highland meteorites; the two dots at higher Fe and Mn contents represent the two mare-dominated meteorites EET87521 and Y-793274.

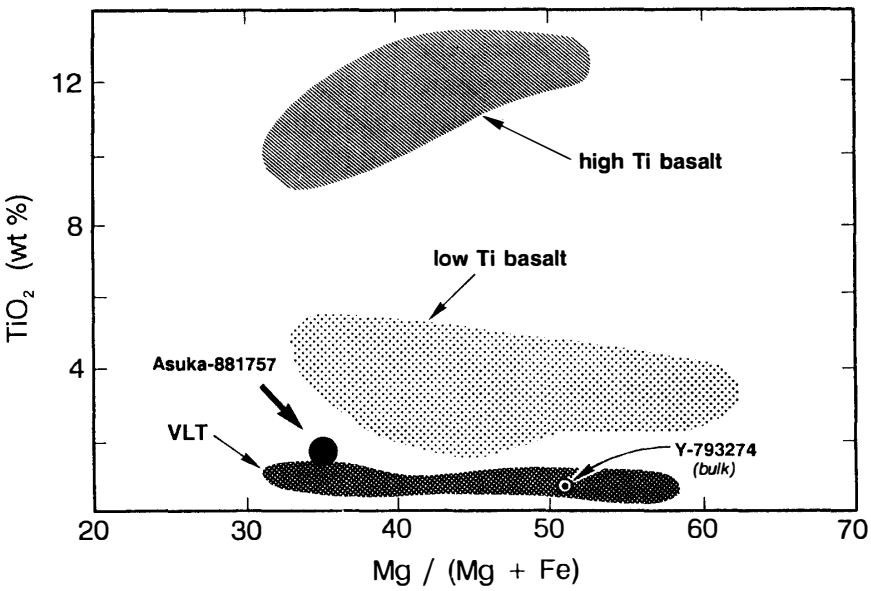

Fig. 8. Bulk characterization of A-881757 as a VLT mare meteorite (after KOEBERL et al., 1991b).

Table 8 gives weighted averages for the trace element contents in A-881757 and Y-793169 in comparison with data from other lunar meteorites, especially the two meteorites (Y-793274 and EET87521) that are dominated by mare lithologies. A comparison of our data with preliminary data reported by LINDSTROM *et al.* (1991d) shows that although some abundances are similar (*e.g.*, Sc, Cr, Co, Hf, U), especially Na, K, the light REEs (Fig. 9), and Th have lower abundances in their samples compared

Table 8. Major and trace element contents for the bulk weighted averages samples of A-881757, and two bulk samples of Y-793169. Also given are data for Asuka-31 from LINDSTROM *et al. (1991d). All data in ppm, except as noted.*

	A-881757 wt av.	Y-793169 wt av.	A-881757 bulk Ref. 1	Y-793274 bulk Ref. 2	EET87521 bulk Ref. 3	Y-86032 bulk Ref. 4
Na (%)	0.215	0.228	0.11	0.34	0.31	0.32
K	315	536	200	550	570	135
Sc	99.4	93.7	111.8	31.9	44	7.26
Cr	1887	1754	1840	2010	1470	660
Fe (%)	17.8	18.7	20.8	11.8	14.9	390
Co	27.9	29.8	27.6	41.4	46	13.2
Ni	52	53		100	29	150
Zn	2.5	4.4		49	3.1	10
Ga	2.8	3.4		4.04	5.27	4.8
As	0.06	0.19		0.053		0.27
Se	<0.5	0.35		0.28		0.3
Br	0.11	0.16		0.21	<0.4	<0.2
Rb	2.6	2.1		<2	<4	<10
Sr	115	78		100	104	118
Zr	45	59		81	140	25
Ag	<0.2	<0.02				<0.02
Sb	<0.04	0.056		0.048		<0.05
Cs	0.037	<0.05		0.1	0.041	0.5
Ba	27	34		97	88	·30
La	3.69	4.72	2.35	7	8.3	1.00
Ce	10.9	14.8	7.4	17.9	20.9	2.60
Nd	8.31	11.88		12	13	1.73
Sm	2.88	4.30	2.43	3.56	3.86	0.57
Eu	1.10	1.31	0.58	0.96	0.98	0.87
Gd	3.59	5.53		4.19		1.1
Tb	0.76	1.02	0.72	0.76	0.8	0.21
Dy	4.87	6.99		4.64	4.8	1.1
Tm	0.42	0.70				0.1
Yb	3.26	4.59	3.3	2.72	3.19	0.596
Lu	0.52	0.66	0.48	0.376	0.48	0.089
Hf	2.20	3.01	2.06	2.96	2.88	0.54
Ta	0.22	0.31	0.42	0.34	0.37	0.07
W	0.08	0.10		0.19		0.3
Ir (ppb)	0.3	1.1	3.1	6.2	0.51	0.0085
Au (ppb)	0.2	1.1		3	0.22	0.006
Hg	<2	<0.1				<0.07
Th	0.42	0.68	0.31	1.05	0.95	0.22
U	0.16	0.09	0.09	0.26	0.23	0.07
K/U	2019	5806	2222	2115	2478	1929
Zr/Hf	20.65	19.78	0.00	27.36	48.61	46.30
La/Th	8.69	6.95	7.58	6.67	8.74	4.55
Hf/Ta	9.78	9.80	4.90	8.71	7.78	7.71
Th/U	2.72	7.36	3.44	4.04	4.13	3.14
La_N/Yb_N	0.76	0.69	0.48	1.74	1.76	1.13
Eu/Eu*	1.04	0.82		0.76		3.36

References for comparison data are: (1) LINDSTROM *et al.* (1991d); (2) KOEBERL *et al.* (1991b); (3) WARREN and KALLEMEYN (1989); (4) KOEBERL *et al.* (1990).

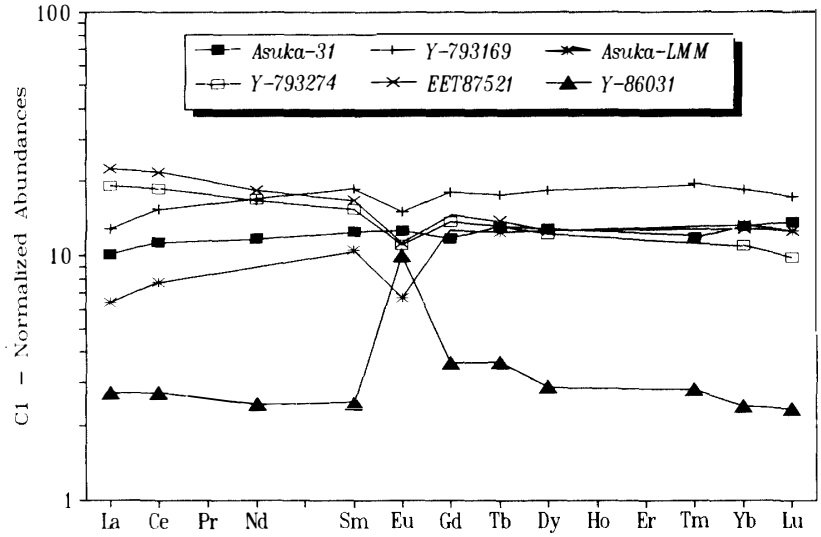

Fig. 9. Chondrite-normalized REE abundance patterns for averages of A-881757, Y-793169, EET87521, Y-793274, and Y-86032. (For data sources see Table 8; normalization factors from TAYLOR, *1982).*

to ours. LINDSTROM *et al.* (1991d) also note differences between their analyses and those of YANAI (1991). They conclude that these differences originate from variations in the modal amounts of ilmenite, plagioclase, and pyroxene due to the heterogeneity of the meteorite. The lower light REEs in their sample may be due to dilution by a higher amount of ilmenite.

A comparison of the REE patterns between A-881757 and Y- 793169 and other lunar meteorites is shown in Fig. 9. The patterns of A-881757 and Y-793169 are essentially identical (parallel), with Y-793169 having slightly higher total REE abundances and a slight negative Eu anomaly. Within the range demonstrated by sample heterogeneities in A-881757, no significant differences exist between the trace element compositions of A-881757 and Y-793169, indicating that they are essentially composed of similar lithologies. The other mare meteorites, EET87521 and Y-793274, have higher LREE contents and steeper La/Yb slopes, but similar HREE abundances, while the highlands meteorites (represented by Y-86032) show very different REE patterns. Incompatible trace elements are higher in Y-793274 and EET87521, indicating some KREEP contribution for these meteorites. The higher LREE of Y-793274 and ETT87521 are typical for a KREEP component, while the lower LREE are characteristic of mare basalts (*e.g.*, BASALTIC VOLCANISM STUDY PROJECT, 1981; HEIKEN *et al.*, 1991).

As for bulk trace element contents, both A-881757 and Y-793169 have compositions that are similar to those reported from VLT mare basalts (*e.g.*, BASALTIC VOLCANISM STUDY PROJECT, 1981; HEIKEN *et al.*, 1991). However, some differences exist. While the basic elemental ratios and patterns are similar, the absolute abundances of some incompatible elements (Sc, Zr, Ba, Hf, Th, U) show differences of up to a factor of 2 (but not necessarily in the same direction). Regarding siderophile elements, A-881757 and Y-793169 have the usual Co enrichment that is typical for lunar rocks, and depletions in Ni, Ir, and Au, indicating the absence of any extraterrestrial contamination

(or significant regolith component).

4. Conclusions

The mineralogy and mineral chemistry of the separates from A- 881757,111 is that of a coarse-grained gabbroic rock close to VLT composition as described by YANAI (1991). The texture of the mesostases suggests mild metamorphic (autometamorphic?) recrystallization. Mineral compositions are therefore still highly unequilibrated. Compositional ranges found by us correspond to those found by YANAI (1991). We found fayalite, Fe-Ni metal, silica, apatite (in sample A31-CL and -LH as symplectitic intergrowths, as also reported by YANAI, 1991). In addition we found ulvöspinels associated with Na-rich plagioclase, fayalite, apatite, ilmenite, SiO_2, Fe-sulfide, and a rare metal (0.3 wt% Ni, 2.0 wt% Co) which has a composition unknown so far from any lunar rocks and which may have originated from *in situ* reduction.

The trace element contents found in the mineral separates and fragments correspond closely to the mineralogical findings. The chondrite normalized REE patterns for the bulk samples of A-881757 and Y-793169 are relatively flat with no clear Eu anomaly (A-881757) or only a small negative Eu anomaly (Y-793169). The subsamples A31-CL, A31-CL2, and A31-YC are, however, dominated by a distinct positive Eu anomaly, in agreement with their plagioclase-dominated mineralogy. The trace element compositions of the plagioclases correspond to those known for other lunar plagioclases (PALME *et al.*, 1984). The trace element composition of the bulk of Y-793169 is essentially similar to those of A-881757; no studies of mineral separates were possible for Y-793169. Differences between some trace element contents exist between our samples and samples analyzed by LINDSTROM *et al.* (1991d), which is due to the coarse-grained, heterogeneous, nature of the meteorite.

A-881757 and Y-793169 are new valuable additions to the lunar meteorite collection. They represent a lunar rock type that was previously underrepresented in the Apollo and Luna collections. Studies of solar-wind derived noble gases and exposure ages in A-881757 and Y-793169 show that both never resided on or near the lunar surface; there are marked differences between the cosmic-ray exposure histories of the two meteorites (EUGSTER, 1992), indicating that they might have been ejected in different events. Their exposure history is also different from those of other lunar meteorites (*e.g.*, EUGSTER, 1989, 1990; EUGSTER *et al.*, 1991). The study of lunar meteorites continues to contribute essential details towards a better understanding of the composition and history of the lunar surface.

Acknowledgments

We are grateful to the NIPR, particularly Dr. K. YANAI, and to Prof. H. TAKEDA, for samples and discussion. We appreciate perceptive reviews by N. NAKAMURA and K. TAKAHASHI.

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(Received August 18, 1992; Revised manuscript received December 1, 1992)