Lunar basaltic meteorites Yamato-793169 and Asuka-881757: Samples of the same low-Ti mare-lava?

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Meteorites Yamato-793169 and Asuka-881757 are basalts from the lunar maria. They are dissimilar in detail to any mare basalts returned by the Apollo or Luna missions, but they are compositionally so similar to each other that they almost certainly are related. Although Y793169 is relatively fine grained and A881757 is coarse grained [11,5,12,13,10], bulk compositional similarities are such that the two rocks can be related by containing slightly different proportions of plagioclase, Fe-Ti oxide, and mesostasis. We suggest that these are related as members of the same thick mare-basaltic pile and were probably ejected by a single impact. This is consistent with their similar ages and exposure histories.

Analysis and Results. We have studied by electron microprobe analysis of fused beads (FB-EMPA, Table 1) [e.g., 2] and instrumental neutron activation analysis (INAA, Tables 2 and 3) splits of the powders prepared for consortium study [13]. For INAA, three 70–80-mg subsamples of the A881757 powder were analyzed in one experiment. These analyses indicate that the powder is uniform in composition for samples ~75 mg in mass (Table 2). In a separate experiment, a single 19-mg sample each of the two meteorites was analyzed by INAA. The composition of the 19-mg subsample of A881757 agrees well with the average of the three 70–80-mg subsamples, except for Cr, which is 2.3% greater in the 19-mg subsample. In Table 3, the mass-weighted mean composition of the four analyzed subsamples of A881757 is presented .

For FB-EMPA, two beads ("A" and "B") were prepared of each meteorite from 10–15 mg of powder. For Y793169, the neutron irradiated powder was used; for A881757, unirradiated material was fused. For elements determined in common by the two techniques, results agree within analytical uncertainty, except that concentrations of Na obtained by FB-EMPA are ~0.93× those obtained by INAA; this is presumably the result of volatilization of Na during fusion.

For A881757, concentrations of some elements obtained for the two beads differ by an amount greater than expected from analytical uncertainty. Bead A has greater concentrations of TiO_2, FeO, and MgO and a lesser concentration of Al_2O_3 than does bead B. These differences correspond to a greater proportion of mafic minerals in bead A, suggesting slight heterogeneity of the powder in the 10-mg mass range.

Table 1. Mean results of electron microprobe analysis of two each (A and B) "fused beads" prepared from powdered meteorites. N = number of analyses averaged.

		Asuka-881757		Yamato-793169	
		A	B	A	B
N		5	4	4	4
SiO_2	%	45.96	46.31	45.89	46.95
TiO_2	%	2.49	2.28	2.08	2.14
Al_2O_3	%	9.68	10.22	11.79	11.71
Cr_2O_3	%	0.31	0.30	0.21	0.23
FeO	%	23.11	22.17	20.96	20.46
MnO	%	0.34	0.34	0.32	0.28
MgO	%	6.11	5.98	5.57	5.59
CaO	%	11.50	11.50	12.01	12.00
Na_2O	%	0.25	0.22	0.26	0.27
K_2O	%	0.037	0.033	0.054	0.055
P_2O_5	%	0.048	0.029	0.055	0.042
Sum	%	99.82	99.38	99.20	99.74

Approximate mass of fused powders: 10–15 mg

Discussion. Compositional similarities between the two meteorites have been noted, particularly the similarity of their unusual TiO_2 concentrations [10,13]. We obtained TiO_2 concentrations of 2.4% for A881757 and 2.1% for Y793169 and an average Ti/Fe ratio of 0.080±0.004 for the four beads (Table 1). Most Apollo mare basalts have Ti/Fe ratios either substantially higher or somewhat lower than this. Samples with similar Ti/Fe ratios (e.g., Apollo 15 pigeonite basalt 15597 with Ti/Fe=0.070) differ in other respects (e.g., 15597 is more magnesian and has different relative REE abundances [see 8]). Of the eight mare basins overflown by the Apollos 15 and 16 orbiting gamma-ray experiments, only two, Cognitum (Ti/Fe: 0.09±0.07) and Crisium (Ti/Fe: 0.03±0.09), have Ti/Fe ratios as low as, and within uncertainty of, the ratio in the meteorites [1]. This comparison speaks to the commonness of high-Ti basalts among near-equatorial mare basins. It also suggests a possible source for A881757 and Y793169, Mare Cognitum, as the VLT (very-low-Ti) basalt from Mare Crisium is compositionally distinct from the two meteorites (e.g., Ti/Fe: 0.041±0.004; [3,7]).

Might these two meteorites be petrogenetically related and, if so, how? They have similar bulk compositions and similar mineral compositions [9], and no isotopic differences are known yet that would preclude a relationship. The small bulk-compositional differences between the two meteorites can be explained by small variations in modal proportions of plagioclase, ulvöspinel, and mesostasis. We can model the composition of Y793169 as consisting of 86–90% material having the composition of bulk A881757, minus ~0.7% ulvöspinel, plus 7.5% plagioclase (mainly An_{96}), plus ~4–8% mesostasis. For these calculations, we use compositions of minerals given by [11] for A881757 and an estimated mesostasis composition from the ITE concentrations of the two meteorites. The slight differences between their compositions could have arisen from slightly different proportions of minerals and different proportions of mesostasis caused by short-range mineral and mesostasis liquid separations during crystallization within a cooling lava (i.e., "short-range unmixing" as discussed by [4]).

Table 2. Relative sample standard deviations (RSD, in %) for some elements determined with high-precision by INAA in three 70–80 mg samples of Asuka-881757 powder.

	RSD
Na	0.79
Sc	0.22
Fe	0.25
Cr	0.28
Co	0.24
La	2.5
Sm	1.2
Eu	3.1
Yb	1.6
Hf	3.8

Can A881757 and Y793169 be members of a differentiation sequence? Because of the coarse-grained texture of A881757 and the finer-grained texture of Y793169, it might be tempting to speculate that the more mafic A881757 is a pyroxene-rich mare cumulate, and Y793169 a corresponding liquid or a slightly more evolved differentiate of a common parent melt. We have considered the compositions of the two meteorites in terms of low-pressure equilibrium liquidus relations using methods developed by [6] and it appears that, in agreement with [9], the coarser-grained A881757 is not a cumulate. Rather, A881757 has a composition nearly that of a low-pressure liquid multiply saturated with plagioclase, pigeonite, augite, and olivine (Fig. 1). The composition of the Y793169 appears to have a small excess quantity of plagioclase relative to the low-P liquidus (Fig. 1). The simplest explanation is that these rocks originated in different levels of a single mare lava, but that they incorporated slightly different proportions of minerals and mesostasis. The compositional differences between the two rocks cannot result from a fractional crystallization mechanism; however, in this scenario, we must presume that the proximity of the A881757 composition to the low-pressure liquidus was either a fortuity or resulted from prior, partial crystallization of its parent melt at low pressure; i.e., it did not originate as a low pressure partial melt.

As an alternative model, we consider relationships that might exist if one of these basalts, presumably the finer-grained Y793169, faithfully records a high pressure composition, unaffected by low-pressure fractionation. Based upon liquidus parameterizations from [6 and previous works], it appears that at intermediate pressures of 5–8 kb, the Y793169 composition is saturated with low-Ca pyroxene and plagioclase. At 10 kb, it is saturated with low-Ca pyroxene and augite. If such a liquid was brought to the surface rapidly, it would have been supersaturated with plagioclase because of expansion of the plagioclase field at low pressure (Fig. 1a). In this model, there is no simple explanation for A881757 as a differentiate of such a liquid, but it is conceivable that deeper in the mare flow, a small amount of early crystallizing (supersaturated) plagioclase might physically have separated (e.g., migrated upward, presumably leading to another, more aluminous basalt layer), at least on a small scale, before the liquid reached low pressure multiple saturation. The lower, more mafic assemblage would then have to expel a small amount of a mesostasis component (residual liquid), as discussed above.

Table 3. Results of instrumental neutron activation analysis, with 1-standard-deviation estimates of analytical uncertainty (±).

		Asuka-881757		Yamato-793169	
		conc.	±	conc.	±
Na_2O	%	0.254	0.003	0.280	0.003
CaO	%	11.9	0.4	12.2	0.4
Sc	μg/g	93.9	0.9	80.7	0.8
Cr_2O_3	%	0.302	0.003	0.231	0.003
FeO(t)	%	23.0	0.2	21.0	0.2
Co	μg/g	24.1	0.2	19.7	0.2
Ni	μg/g	<150		<100	
Rb	μg/g	<15		<7	
Sr	μg/g	140	40	170	40
Zr	μg/g	<150	50	70	30
Cs	μg/g	<0.5		<0.5	
Ba	μg/g	<120		101	10
La	μg/g	3.31	0.05	4.75	0.05
Ce	μg/g	9.1	0.3	13.2	0.3
Nd	μg/g	<30		12	2
Sm	μg/g	3.00	0.03	4.19	0.04
Eu	μg/g	1.02	0.03	1.22	0.02
Tb	μg/g	0.85	0.03	1.10	0.03
Yb	μg/g	3.57	0.05	4.56	0.05
Lu	μg/g	0.534	0.010	0.663	0.008
Hf	μg/g	2.53	0.08	3.19	0.07
Ta	μg/g	0.32	0.04	0.40	0.02
Ir	ng/g	<10		<5	2.1
Au	ng/g	<7		<3	1.2
Th	μg/g	0.45	0.04	0.74	0.04
U	μg/g	<0.5		0.13	0.05
mass	mg	246.3		19.03	

We conclude on compositional and petrologic grounds that these two meteorites could be samples of a single mare lava. Their small compositional differences can be explained by their having incorporated slightly different proportions of very similar mineral and mesostasis components. Whereas they may be related by a high pressure origin and subsequent separation of components during low-pressure crystallization, a simple crystal-fractionation relationship at low pressure, deriving Y793169 from A881757, is not indicated.

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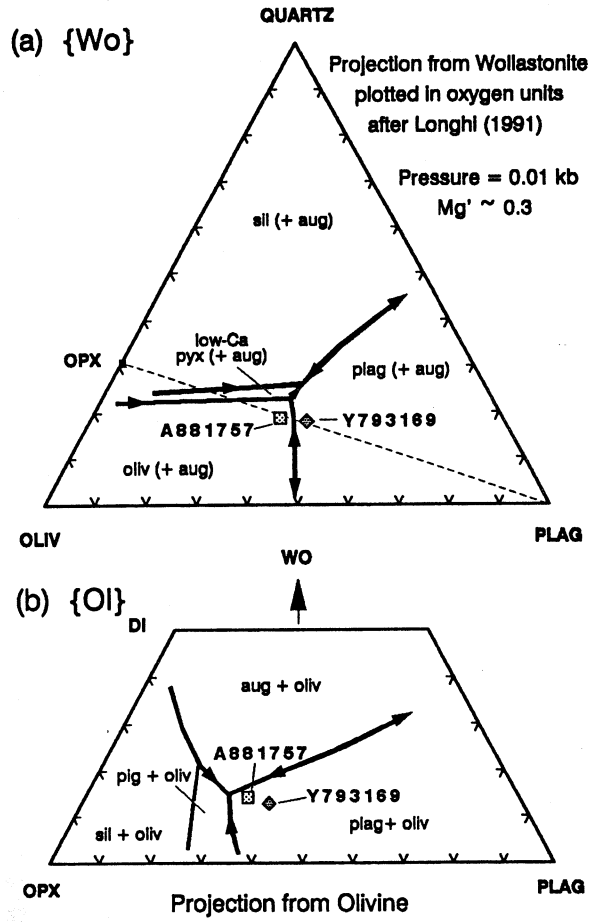

Figure 1. Liquidus surfaces in the pseudoquaternary system olivine-plagioclase-quartz-wollastonite projected onto (a) Oliv-Plag-Quartz and (b) Opx-Plag-Wo planes for conditions relevant to compositions of A881757 and Y793169. Liquidus relationships in proximity to the compositions of A881757 and Y793169 were determined using the computer program MAGPOX (Longhi, 1991), and the general shapes of liquidus projections away from these compositions were inferred from Longhi (1991), esp. his Figs. 3 and 4. Note that although the composition of A881757 apparently lies within the olivine field (a), it is on the pyroxene-plagioclase join, so its major mineralogy, as well as that of Y793169, is dominated by pyroxene and plagioclase.

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