

GEOCHEMICAL INVESTIGATION OF TWO LUNAR MARE METEORITES: YAMATO-793169 AND ASUKA-881757

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Abstract: We report new data for the bulk compositions of two meteorites derived from the mare lava plains of the Earth's Moon: Yamato-793169 and Asuka-881757. These meteorites are remarkably similar to one another, and clearly of lunar origin, but not quite like any previously studied lunar rock. In the Ti-based classification system for mare basalts, Y-793169 and A-881757 are both low-Ti. However, viewed in relation to their extraordinarily low *mg* ratios, their Ti contents are also marginally consistent with kinship to previously-studied VLT (very-low-Ti) mare basalts. In another popular (albeit arbitrary) classification system, A-881757 is low-Al, and Y-793169 is marginally high-Al. Resemblances to VLT mare basalts are also evident from their unfractionated middle-REE/heavy-REE ratios and high Sc/Sm ratios. On a plot of Sc vs. Ti, Y-793169 and A-881757 plot near one another, and well apart from any Apollo/Luna mare basalt. They resemble low-Ti basalts in terms of moderate overall REE contents and V/Sm and Cr/Sm ratios, and they even resemble high-Ti basalts in having high Sc coupled with low V. The high Sc contents probably reflect partial melting of a Sc-rich source (or sources) in the lunar mantle. Neither meteorite shows the enrichments in K and Ge that remain peculiar to mare basalts from Apollo 14, apparently due to assimilation of the K-rich granitic and Ge-rich KREEPy materials that are uncommonly abundant in the Apollo 14 region. A set of remarkable coincidences between Y-793169 and A-881757 (from our data: their bizarrely high Sc despite low Ti, and extraordinarily low *mg*; other workers have demonstrated similar ages, $^{238}\text{U}/^{204}\text{Pb}$, and times of blast-off from the Moon) suggests that these two meteorites might be paired, in the sense of having left the Moon in a single cratering-ejection event. The geochemical contrasts between Y-793169 and A-881757 and previously available mare basalts show that the full diversity of the lunar maria, and the factors that govern variability among mare basalts, are still poorly understood. The diversity and lack of systematics among lunar mare basalt compositions, reinforced by Y-793169 and A-881757, support the magma ocean cumulate model for genesis of the mare source regions. The relationship between geochemistry and age among mare basalts seems more complex than previously supposed, probably because the compositional stratification that develops in the pile of magma ocean cumulates is too disorderly to conform with any model for depth-time-temperature evolution of the lunar interior.

1. Introduction

Mare basalt is a volumetrically minor but nonetheless important lunar rock type, easily distinguished from the nonmare rocks that constitute most of the Moon's crust.

All known mare rocks have textures indicative of uncommonly rapid cooling, by the standards of “pristine” (compositionally endogenous, igneous or monomict-brecciated) lunar rocks. Photogeologic evidence (WILHELMS, 1987) indicates that most (probably all) of the maria formed as series of lava flows, whereas nonmare pristine rocks typically have coarse-grained textures, with equant plagioclase and abundant exsolution in pyroxene, all of which suggest origin deep in the crust. Mare rocks are also compositionally and mineralogically distinctive. They generally have far lower Al (plagioclase) contents than nonmare rocks. Their bulk-rock mg ($= Mg/[Mg + Fe]$) ratios are typically lower than those of all but a tiny percentage of nonmare rocks. Most mare rocks also have uncommonly high Ti (ilmenite) contents.

Having formed relatively late and shallow, mare basalt is the most accessible variety of pristine lunar rock. Mare basalts were sampled in abundance at five Apollo (11, 12, 14, 15 and 17) and two Luna (16 and 24) sites. However, the total diversity of this suite of samples is sufficient, especially in terms of Ti, to attach great interest to any additional sampling of lunar mare basalt. Another cause for concern regarding the representativeness of the Apollo/Luna mare basalt collection stems from the clustering of all these sites in a limited area of the Moon’s central nearside. A polyhedron can be contrived to encompass all of these sites and yet cover only 4.4% of the surface of the Moon (WARREN and KALLEMEYN, 1991a, b).

Lunar meteorites have improved this situation. The total number of lunar meteorites is now twelve (LINDSTROM *et al.*, 1991a), although a few cases of obvious pairing (*i.e.*, Y-82192–Y-82193–Y-86032 and MAC88104–MAC88105) reduce the number of distinct finds to nine. Five of these nine are composed of dominantly highland materials, although they contain a few tiny clasts of apparent mare affinity (*e.g.*, WARREN and KALLEMEYN, 1991a). Yamato-793274 is a breccia composed of mainly mare materials, but it is a moderately mature regolith breccia with no large pure-mare clasts, and the detailed characteristics of its mare component(s) are obscured by the admixed highland component (*e.g.*, KOEBERL *et al.*, 1991). The first meteorite shown to consist of nearly pure mare material, EET87521 (WARREN and KALLEMEYN, 1989, 1991a; DELANEY, 1989), is a polymict breccia with a tiny but problematical highland component.

More recently, YANAI (1990, 1991) and YANAI and KOJIMA (1991) have described two lunar meteorites that are compositionally pristine mare rocks. The larger of these is Asuka-881757 (442.1 g, originally given the tentative name “Asuka-31”), a rock with a fairly typical mare-basaltic mode and major-element bulk composition, despite an exceptionally coarse-grained (by mare standards) texture: blocky pyroxene crystals up to 4 mm across, equant crystals of plagioclase (entirely transformed by shock into maskelynite) up to 3 mm across, and subhedral grains of ilmenite up to 3 mm across (YANAI and KOJIMA, 1991). This texture is so coarse-grained that previous studies of the bulk composition appear to have been seriously impaired by the problem of sampling at a sufficiently large scale to yield a representative composition (YANAI and KOJIMA, 1991; LINDSTROM *et al.*, 1991b), and YANAI (1990) suggested the rock might be a rare mare cumulate. Despite their coarseness (implying a relatively slow cooling rate, at least when the material was at near-liquidus temperature) and their generally intermediate Ca contents, the pyroxenes of A-881757 have undergone very little subsolidus equilibration, with no evidence of exsolution visible at optical-microscopic or

electron-microprobe scale (YANAI, 1991; TAKEDA *et al.*, 1992). Based on the low Ti concentration (1.66 wt% TiO₂) found in a wet-chemical analysis, and on the “remarkably heterogeneous” pyroxene compositions, YANAI (1990, 1991) suggested that A-881757 was a unique rock type, but closely related to the very-low-Ti (VLT) mare rock types found from Luna 24 and Apollo 17.

The other “new” compositionally pristine mare meteorite, Y-793169, has a more typically fine-grained, unbrecciated, although moderately shocked, mare texture, with more lath-shaped silicates, especially plagioclases (typically 1000 × 200 μm), than in A-881757. Even so, this rock is more coarse-grained than many mare basalts, and YANAI and KOJIMA (1991) term it a mare diabase. Pyroxenes in Y-793169 are even more diverse than in A-881757 (the pattern of compositional variation is very similar, but the range in *mg* is significantly greater in Y-793169). A wet-chemical analysis indicates that Y-793169 has an even lower bulk-rock Ti concentration (1.52 wt% TiO₂) than A-881757 (YANAI and KOJIMA, 1991).

TAKEDA *et al.* (1992) show that on a plot of *mg* vs. Ti/(Ti+Cr) for pyroxenes, Y-793169 and A-881757 appear similar to one another and intermediate between Apollo 15 low-Ti mare basalts and Apollo 17 VLT mare basalts.

In this paper, we report the first trace-element data for Y-793169 and A-881757 (excepting the results of LINDSTROM *et al.* (1991b), for a few small (248-mg) and obviously nonrepresentative chips of the coarse-grained A-881757). We confirm the lunar-mare origins of both meteorites, and note many similarities to the previously sampled low-Ti and VLT mare basalts, but also some features, curiously shared by Y-793169 and A-881757, that distinguish these meteorites from all previously sampled mare basalts. The broader implications of these new constraints in terms of the gross evolution of the Moon are also discussed.

2. Analytical Procedures

The two A-881757 samples were aliquots of a widely-distributed powder prepared from a 13-g chip sampled by NIPR personnel, using first boron carbide to grind the chip to sand-sized grains, and then corundum to pulverize a 5.9-g aliquot of the sand (the rest of the sand was mainly allocated for isotopic investigations) (K. YANAI, personal commun., 1992). The Y-793169 sample was originally received as a 119-mg aliquot of sand-sized material (Y-793169,40), ground from a 0.5-g chip sample by NIPR personnel, using boron carbide (K. YANAI, personal commun., 1992). We pulverized Y-793169,40 using an agate mortar and pestle, and then returned it to the NIPR, and from there an aliquot of 20 mg (Y-793169,80) was removed and allocated for this study. These powder samples were first studied by instrumental neutron activation analysis (INAA), using a procedure modified from that of KALLEMEYN *et al.* (1989). After INAA, each powder was split into two aliquots, one 5–10 × larger than the other. The smaller aliquot was used for determination of major elements and Ti with an electron probe, after conversion of the aliquot into a fused bead (we call this technique microprobe fused bead analysis, or MFBA). The larger aliquot was used for RNAA, following our standard procedure (WARREN *et al.*, 1986), to measure siderophile elements Au, Ge, Ir, Ni, Os and Re, along with volatile elements Cd and Zn.

3. Confirmation of Lunar Origin

The bulk-rock compositional results are shown in Table 1. These data distinguish Y-793169 and A-881757 from otherwise similar basaltic achondrites, based on ratios such as Fe/Mn (Table 1), Ga/Al, and Co/Cr. Among lunar bulk-rock samples, Fe/Mn is remarkably constant at ≈ 75 (HASKIN and WARREN, 1991). The Fe/Mn ratios implied by the wet-chemical analyses of YANAI and KOJIMA (1991) are 87 for Y-793169 and 119 for A-881757. If Fe/Mn were truly much greater than 90, we would have to seriously doubt the lunar origin hypothesis. However, our own data indicate Fe/Mn ratios of 66 for Y-793169 and 65 for A-881757. The Ga/Al ratios (in both cases 5×10^{-5}) are high compared to Ga/Al for eucritic or angritic meteorites, and low compared to Ga/Al for shergottites (WARREN and KALLEMEYN, 1989). The Co/Cr ratios (0.012–0.013) are high compared to the range for eucrites. Our new data thus confirm the previous inference based on overall composition, mineralogy, mafic-silicate FeO/MnO ratios, and O-isotopic ratios (YANAI, 1990; YANAI and KOJIMA, 1991): these meteorites are lunar.

4. Brief Review of Mare Basalt Classification

As RYDER (1991) has noted, mare basalt classification has yet to be substantially revised from the completely arbitrary scheme developed, with remarkably confusing nomenclature, in the immediate response to acquisition of the Apollo and Luna samples (1969–1976). Until very recently (NEAL and TAYLOR, 1992), what passed for a classification system was largely based on associating samples with their sites of derivation. With only seven sites as significant sources of mare basalts, and little understanding of the underlying causes of diversity among these rocks, it was expedient, especially in the earliest Apollo times, to “classify” them in relation to type localities (landing sites). At most sites, the mare basalts are fundamentally alike (similar to others from the same site) (NEAL and TAYLOR, 1992). The early emphasis on sites engendered some confusing nomenclature. For example, Apollo 11 “high-K” mare basalts have far lower K concentrations than “medium-K” KREEP basalts from Apollo 15 and 17.

The primary compositional parameter used for mare basalt classification is bulk-rock concentration of Ti. Few important correlations have ever been documented between bulk-rock Ti and other petrologic characteristics of mare materials. The chief merits of this basis of classification seem to be (a) that bulk-rock Ti shows great diversity, and (b) that it is easily measured. The first mare basalts sampled were classified as either “high-Ti” basalts (dominant among Apollo 11 and 17 samples) or “low-Ti” basalts (dominant among Apollo 12, 14 and 15 samples). Actually even “low-Ti” mare basalts are extraordinarily Ti-rich, compared to basalts from other sampled planetary objects—the Earth, the shergottite parent body (Mars?), and the parent asteroids of the eucrite and angrite meteorites. When “very-low-Ti” (VLT) mare basalts were later discovered from Luna 24 and Apollo 17, they should logically have been called low-Ti, with the former “low-Ti” class renamed accordingly (*i.e.*, medium-Ti). But the inertia of the original nomenclature held sway, leaving us with three Ti categories: “very-low” (which is really moderate), “low” (which is really high, and is supposed to be understood to exclude the “very-low” types), and “high”—yet no “medium” class.

Table 1. Concentrations of 38 elements in bulk-rock samples from lunar mare meteorites.

	Na	Mg	Al	Si	K	Ca	Ti	Cr	Mn	Fe	mg	Fe/Mn	Sc	V	Co	Ni	Zn	Ga	Ge	Sr
	mg/g				μg/g		mg/g				mol% wt ratio		μg/g				ng/g	μg/g		
Y-793169*	2.97	34.7	68.2	204	1080	95	9.1	0.75	1.39	167	32.4	119								
Y-793169,80	2.03	34.7	58.8	215	517	86	13.1	1.62	2.50	165	32.6	66	87	53	21.4	7.3(11)	1.35	3.0(13)	2.2(16)	220(20)
A-881757*	3.71	38.7	60.8	212	330	86	10.0	1.16	1.94	169	34.5	87								
A-881757,80a	1.85	37.4	52.7	220	330	82	14.7	2.04	2.65	171	33.4	65	97	88	24.9	13.2	1.72	2.2(8)	3.9	128(11)
A-881757,80b	1.89	38	53	220	310	84	14.7	1.98	2.64	175	33.3	66	96	—	24.3	<35	<16	2.8	—	112(18)
	Zr	Cd	Ba	La	Ce	Nd	Sm	Eu	Tb	Dy	Ho	Yb	Lu	Hf	Ta	Re	Os	Ir	Au	Th
	μg/g	ng/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	pg/g	μg/g	μg/g	μg/g	μg/g
Y-793169,80	190(23)	<180	<81	5.3	15.6	10.2(14)	4.4	1.37	1.10	7.5(11)	1.63(8)	4.8	0.72	3.08	0.33(13)	<60	<0.27	0.050	<0.050	0.75(10)
A-881757,80a	97(19)	6.7(31)	65(12)	3.7	10.0	7.7(13)	3.08	1.08	0.83	5.5(9)	1.24(9)	3.80	0.56	2.26	0.31	16 [▲]	0.38 [▲]	0.31 [▲]	0.14(30) [▲]	0.48
A-881757,80b	<110	—	50(14)	3.3	8.7	7.8	2.96	1.03	0.84	6.0(8)	1.39(14)	3.48	0.54	2.18	0.28	—	—	<2	<3	0.44

* Data of YANAI and KOJIMA (1991; H. HARAMURA, analyst) shown for comparison.

▲ Results for “noble” siderophile elements in A-881757 are surprisingly high, conceivably due to laboratory contamination (see text).

For highest-uncertainty results, 70% confidence limits from counting statistics are shown by values (% relative) in parentheses.

Due to the tendency to rely on sampling site as a classification parameter, there has been little discussion, and even less agreement, as to where the divisions between VLT, low-Ti, and high-Ti should be drawn. The first authors who classified with knowledge of all the major Ti-related groups of Apollo/Luna mare basalts, PAPIKE and VANIMAN (1978), inconsistently suggested “1% TiO₂” (in their abstract) or “1.5 wt% TiO₂” (on page 372) for the division between VLT and low-Ti. Citing only the “1% TiO₂” statement of PAPIKE and VANIMAN (1978), NEAL and TAYLOR (1992) proposed that the VLT/low-Ti division should be 1 wt% TiO₂, with the low-Ti/high-Ti division at 6 wt%. This choice for the VLT/low-Ti division seems very awkward, however. As is well illustrated by Fig. 2 of NEAL and TAYLOR (1992), many of the Luna 24 mare basalts (all of which appear to be of VLT petrologic affinity) have 1.0–1.5 wt% TiO₂, and yet few of the basalts from other sites (except the very distinctive Apollo 17 VLT basalts) have less than 1.5 wt% TiO₂. Thus, we prefer to use 9 mg/g Ti (=1.50 wt% TiO₂) as the VLT/low-Ti division (*cf.* RYDER, 1991). In any case, the new results discussed below underscore the arbitrariness of any Ti-based classification of mare basalts.

Another arbitrary scheme for classifying mare basalts is based on bulk-rock Al (or modal feldspar). Mare basalt Al contents are diverse, but “feldspathic” or “high-Al” mare basalts actually have quite ordinary Al and feldspar contents, by the standards of most other planetary basalt suites, including lunar KREEP basalts. The more numerous ordinary or “low-Al” mare basalts are so feldspar-poor (typically 22–33 vol%: TAYLOR *et al.*, 1991), melts of their compositions are not saturated with feldspar at any lunar interior pressure (LONGHI, 1992), and they are arguably more akin to terrestrial komatiites than to typical terrestrial basalts (the only possibly analogous planetary basalt suite would be the feldspar-poor but broadly diabasic shergottites: MCSWEEN, 1985). In agreement with RYDER (1991), NEAL and TAYLOR (1992) adopted 11 wt% Al₂O₃ (=58 mg/g Al) as the division between low-Al (or normal) and high-Al mare basalts, but to avoid splitting apparently related suites of rocks, they stipulated that some Apollo 12 and Luna 24 basalts with >11 wt% Al₂O₃ would be classed as “low-Al”.

A third parameter that has been used to classify mare basalts is bulk-rock K content. In this case, although the divisions are arbitrary, lunar petrologists believe they know the process responsible for producing the K diversity. It seems clear that some form of assimilation of granite and/or KREEP has affected mare basalts to varying degrees (*e.g.*, NEAL and TAYLOR, 1992). As a division between “low-K” and “high-K” mare basalts, NEAL and TAYLOR (1992) proposed 2 mg/g K.

5. Geochemical Affinities of Y-793169 and A-881757

5.1. Conventional classification schemes: Ti, mg and Al

Probably the most widely-used diagram in mare basalt geochemistry is a plot of bulk-rock *mg* vs. Ti (Fig. 1). PAPIKE and VANIMAN (1978) suggested that among low-Ti basalts *mg* shows a feeble negative correlation with Ti, even though among high-Ti basalts *mg* correlates positively with Ti. Among VLT basalts, Fig. 1 shows a rough trend of inverse correlation between *mg* and Ti—as expected, considering that VLT compositions are far from saturated with ilmenite (LONGHI, 1992), and some of the VLT rocks may be from flows differentiated by fractional crystallization (GROVE and

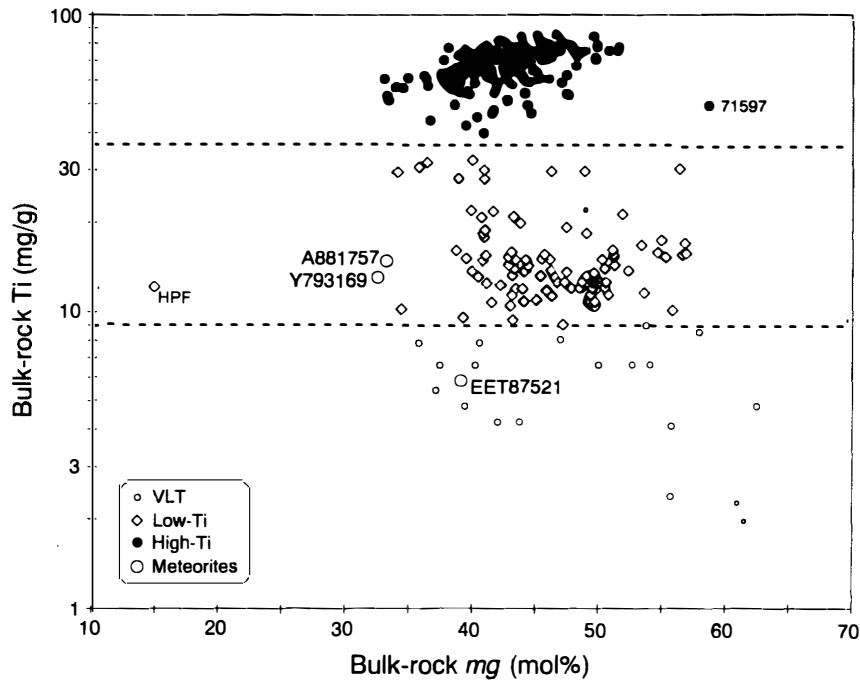


Fig. 1. Bulk-rock mg ($= Mg/[Mg + Fe]$) vs. Ti , showing our new results for Y-793169 and A-881757, and for comparison a large number of Apollo/Luna mare basalts (database of HASKIN and WARREN, 1991), mare-dominated polymict-brecciated lunar meteorite EET87521 (WARREN and KALLEMEYN, 1989), and VLT-mare-like clast "HPF" from lunar highlands meteorite Y-791197 (WARREN and KALLEMEYN, 1991a). The smallest symbols represent mare-volcanic glasses of various petrologic types. Rock 71597 is a rare olivine cumulate variety of high-Ti mare basalt (MURALI *et al.*, 1977). Dashed horizontal lines indicate adopted divisions between VLT, low-Ti, and high-Ti classes.

VANIMAN, 1978). Our results for Y-793169 and A-881757 indicate moderate, "low-Ti" Ti contents, but also extraordinarily low mg , which leaves open the possibility of kinship with the VLT trend.

Figure 2 shows mg vs. Al. If numerous defocused-beam microprobe analyses (DBA) of Luna 16 basalts are included, the mare basalts show an overall trend of increasing Al with decreasing mg (*cf.* Fig. 3a of NEAL and TAYLOR, 1992). However, DBA results are notoriously unreliable, particularly for Al, mainly because most analysts (especially those of the mid-1970s, when the DBAs in question were obtained) fail to correct for the effect of the relatively low density (and thus, enhanced electron beam excitation volume/mass ratio) of feldspar (NAZAROV *et al.*, 1982). Our results suggest that A-881757 is low-Al and Y-793169 is marginally high-Al.

Compared to the bulk-rock results of YANAI and KOJIMA (1991) for both Y-793169 and A-881757, our Ti results are high, and our results for Al, Na, and (to a lesser degree) Ca are low (Table 1). These discrepancies are probably not caused by analytical error at UCLA, because FUKUOKA's (1992) results for aliquots of the same powders demonstrate good agreement. The cause of the discrepancy is probably sampling "error." The YANAI and KOJIMA (1991) analyses appear to reflect comparatively feldspar-rich, and ilmenite-poor, chips. In view of the relatively coarse grain sizes, particularly for

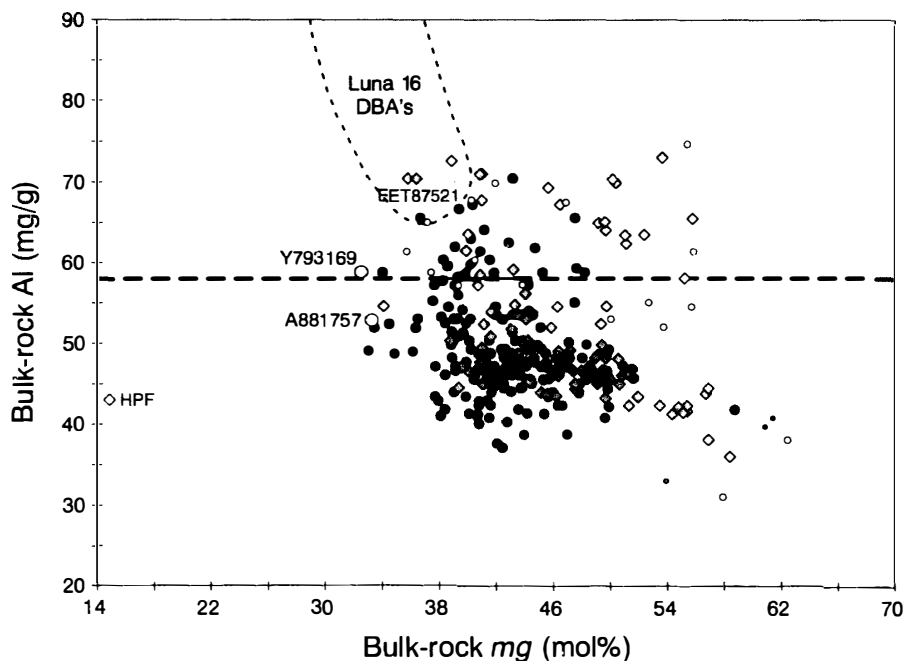


Fig. 2. Bulk-rock mg vs. Al, analogous to Fig. 1. The field of "Luna 16 DBA's" (defocused beam analyses of tiny Luna 16 basalt fragments), based on sources cited in Fig. 2 of NEAL and TAYLOR (1992), may be an artifact of inaccurate data (see text). Dashed horizontal line indicates adopted division between low-Al and high-Al classes.

A-881757, such problems are not unexpected. Our analyses of A-881757 are traceable to a huge sample (13 g), so we suspect they are more representative than the analysis of YANAI and KOJIMA (1991).

In the case of Y-793169, our analysis is based on a relatively small original sampling (0.5 g), and the wet-chemical data of YANAI and KOJIMA (1991) are probably about equally representative. Considering all of these results, Y-793169 is only marginally Ti-rich enough to be classified as low-Ti (as opposed to VLT), but it probably is high-Al. The utility of any "high-Al" classification for mare basalts seems limited, however (for a relative few mare basalts that are vitrophyres, arguably retaining primary compositions unaffected by near-surface differentiation, a high Al content would be suggestive of a mantle source with residual plagioclase, but Y-793169 is hardly vitrophyric).

5.2. Incompatible elements

Results for rare-earth elements (REE) are shown normalized to CI chondrites in Fig. 3. Y-793169 and A-881757 resemble low-Ti basalts in terms of overall REE concentration levels. However, they both have essentially chondritic ratios of middle REE (e.g., Tb) to heaviest REE (Lu). In this respect, they bear little resemblance to previously known low-Ti mare basalts, which have chondrite-normalized Tb/Lu consistently close to 1.4. Based on Tb/Lu, Y-793169 and A-881757 look more like VLT mare basalts.

Among mare basalts, incompatible elements such as La (the lightest REE) show a rough correlation with Ti (Fig. 4). Using La as a classification tool, Y-793169 appears

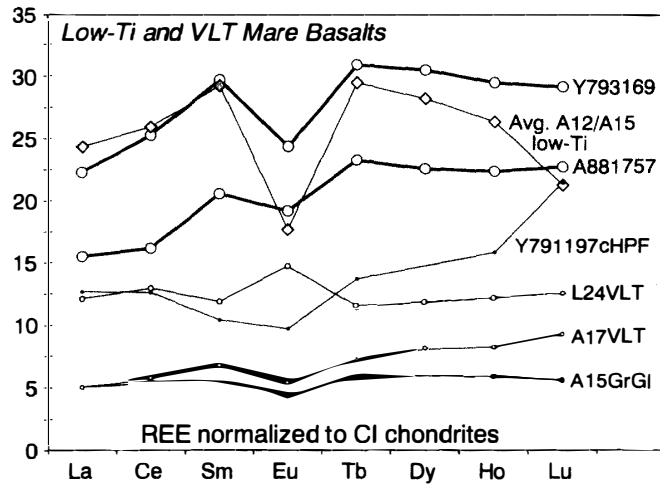


Fig. 3. Bulk-rock REE concentrations normalized to CI chondrites (note linear scale), with literature data included for comparison (sources as for Fig. 1). "A15GrGl" is the Apollo 15 green mare volcanic glass.

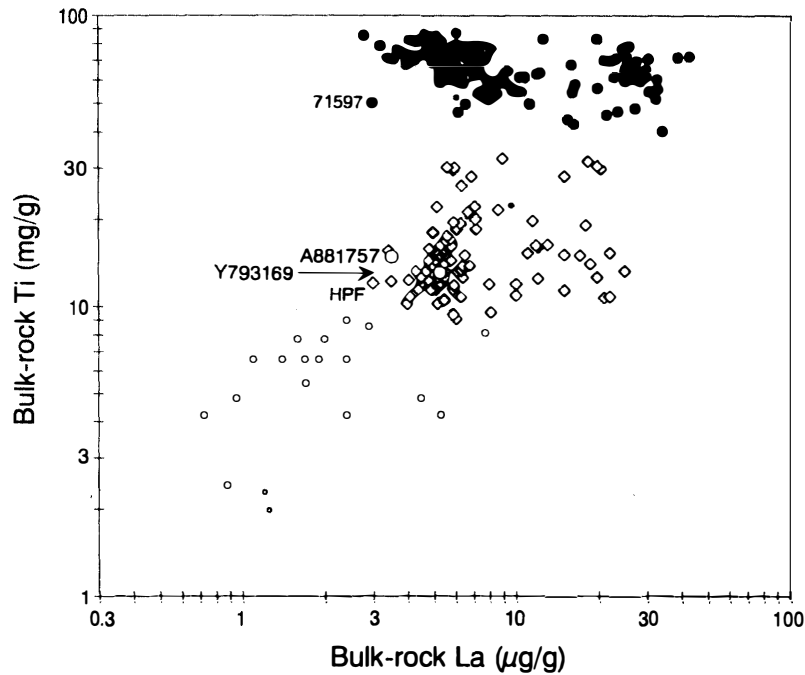


Fig. 4. Bulk-rock La vs. Ti, using the same database and symbols employed for Fig. 1.

to be a fairly typical low-Ti basalt, while A-881757 falls near the division (roughly 3.2 $\mu\text{g/g}$ La) between VLT and low-Ti. However, as noted by YANAI (1990), A-881757 has a texture that may be consistent with origin as a cumulate, in which case, depending on the ratio of cumulus (plus "heteradcumulus") matter to trapped liquid, the La content is expected to be considerably lower than that of the parent basaltic magma (implications of the possible cumulate nature of A-881757 are discussed in detail below).

Figure 5 shows bulk-rock K vs. La. As reviewed by NEAL and TAYLOR (1992), some mare basalts, and especially a subset of the Apollo 14 low-Ti suite, appear to

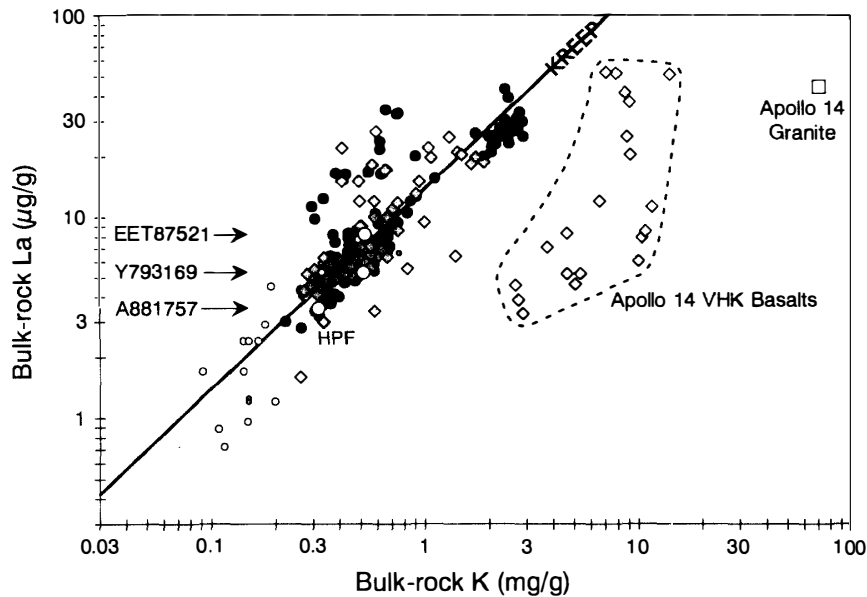


Fig. 5. Bulk-rock K vs. La, using the same symbols and essentially the same database employed for Fig. 1. Also included for completeness are a few analyses of Apollo 14 VHK (very-high-K) basalts from sources cited in Fig. 2 of NEAL and TAYLOR (1992), and for comparison with them, the composition of the largest pristine lunar granite (WARREN *et al.*, 1983).

have K/La ratios enhanced by assimilation of K from granitic rocks. This process apparently did not play any important role in the genesis of the mare meteorites, although the situation for EET87521 is not so clear-cut, due to its minor but possibly significant component of physically admixed KREEP (WARREN and KALLEMEYN, 1989, 1991a).

5.3. Transition elements, including a closer look at Ti

Another element that shows a rough correlation with Ti among mare basalts is Sc (Fig. 6). However, both Y-793169 and A-881757 are much richer in Sc than any other mare basalt of similar Ti content. This dual anomaly is not an artifact of inaccurate analysis, because FUKUOKA (1992) and KOEBERL *et al.* (1992) report very similar Sc contents. The uncommonly high Sc content of A-881757 was originally noted by LINDSTROM *et al.* (1991b). A plot of Sc vs. V for mare basalts displays a rough inverse correlation (Fig. 7). On this diagram, Y-793169 and A-881757 are close to the mainstream, but resemble high-Ti basalts.

Relationships involving transition elements can in many cases be clarified by normalizing the bulk-rock concentrations to an incompatible element such as Sm (a middle REE that is particularly well-determined by INAA). Figure 8 shows a pertinent example, Ti/Sm vs. Sc/Sm, analogous to Fig. 6. On this diagram, the high-Ti mare basalts (*i.e.*, those with >36 mg/g Ti—see Fig. 1) show an excellent correlation. A rougher correlation is displayed by the low-Ti mare basalts (*i.e.*, those with $9 < \text{Ti} < 36$, for Ti in mg/g), but a looser correlation should be expected, considering that the low-Ti basalts range in Ti content over a factor of 3.7, whereas the range for high-Ti basalts is only a factor of 2.2. The VLT mare basalts show even greater scatter (they feature

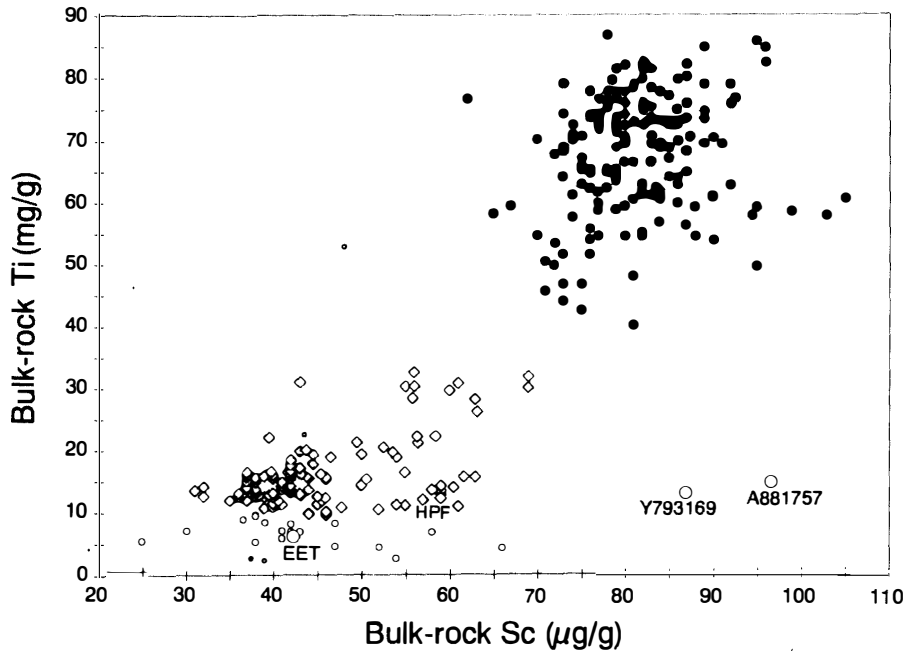


Fig. 6. Bulk-rock Sc vs. Ti, using the same database and symbols employed for Fig. 1.

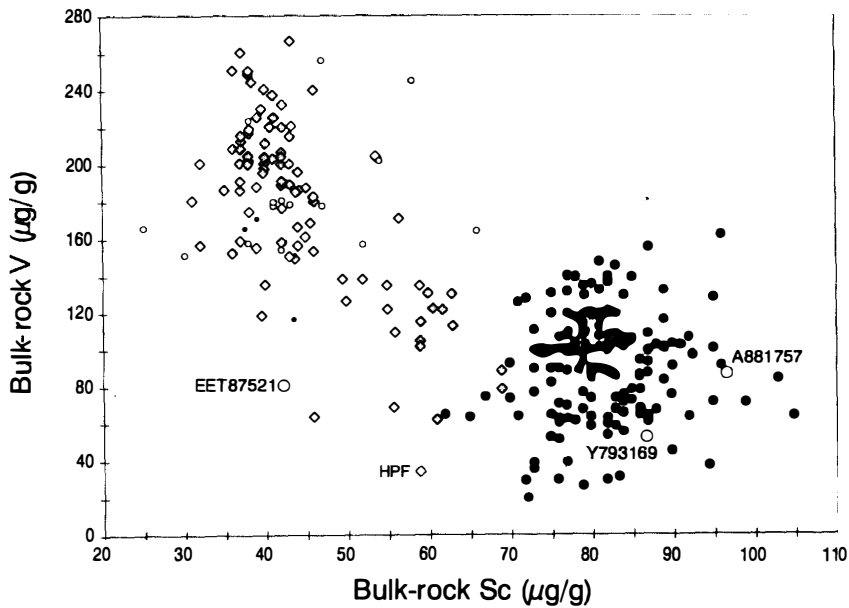


Fig. 7. Bulk-rock Sc vs. V, using the same database and symbols employed for Fig. 1.

a wide range of relative Ti concentrations, and the available samples are generally too small to be fully representative). Nonetheless, the VLT basalts clearly tend to have higher Sc/Sm, at any given Ti/Sm, compared to more “normal” mare basalts. In this respect, both Y-793169 and A-881757 resemble VLT basalts.

Plots of Sc/Sm vs. Co/Sm (Fig. 9) and Sc/Sm vs. Mn/Sm (not shown) are basically similar, but here A-881757 and especially Y-793169 show a greater resemblance to low-Ti basalts than to VLT basalts. On another plot of this general type, V/Sm vs.

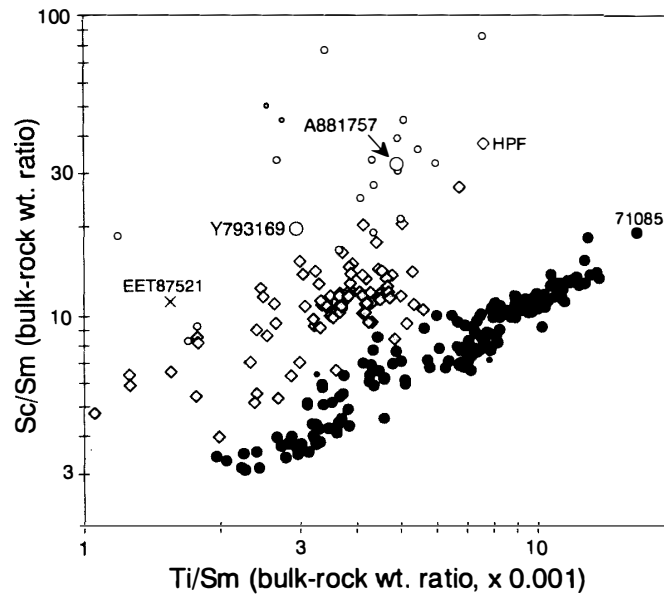


Fig. 8. Bulk-rock Ti/Sm vs. Sc/Sm , using the same database and symbols employed for Fig. 1. The EET (EET87521) meteorite is shown by an "X" symbol because its Sm content has probably been enhanced by physical (impact-brecciation) admixture of KREEP (WARREN and KALLEMEYN, 1989). The basalt with the highest Ti/Sm , 71085, is coarse-grained and extraordinarily rich in Ti, poor in REE, and poor in Al, by Apollo 17 high-Ti standards (WARNER *et al.*, 1979).

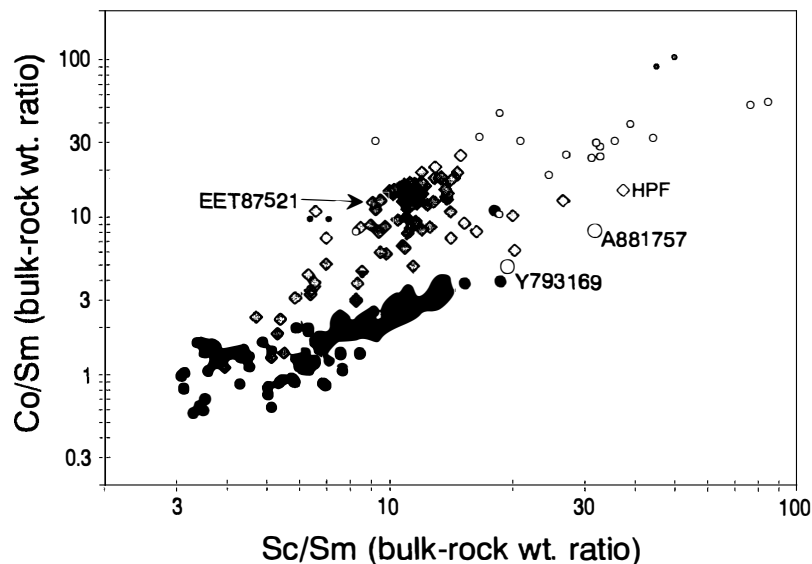


Fig. 9. Bulk-rock Sc/Sm vs. Co/Sm , using the same database and symbols employed for Fig. 8.

Cr/Sm (Fig. 10), A-881757 and especially Y-793169 are further distinguished from Luna 24 and Apollo 17 VLT basalts.

A diagram that has been remarkably successful for delineating relationships among pristine nonmare rocks is a plot of bulk-rock mg vs. Eu/Al (Fig. 11). Fractionation of mafic silicates together with plagioclase acts to diminish mg while enhancing Eu/Al in

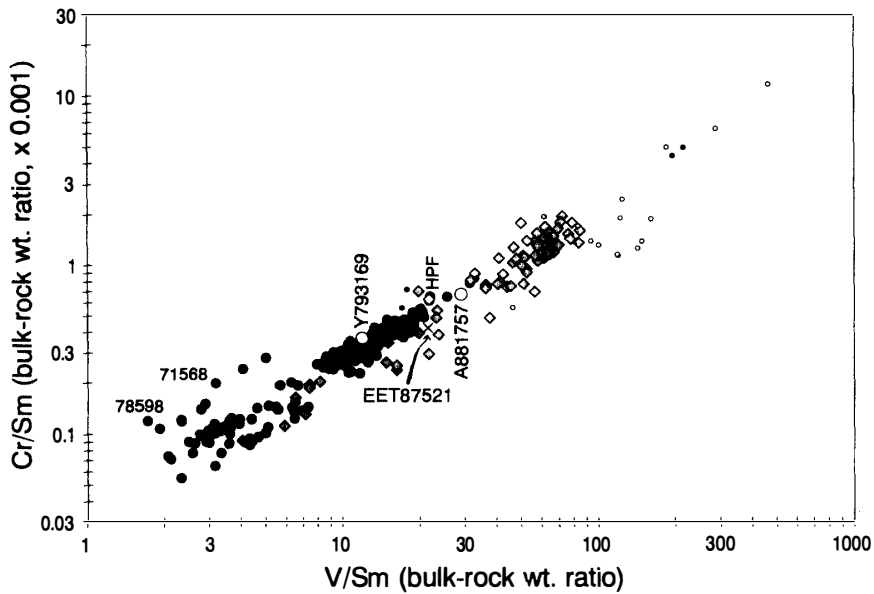


Fig. 10. Bulk-rock V/Sm vs. Cr/Sm, using the same database and symbols employed for Fig. 8.

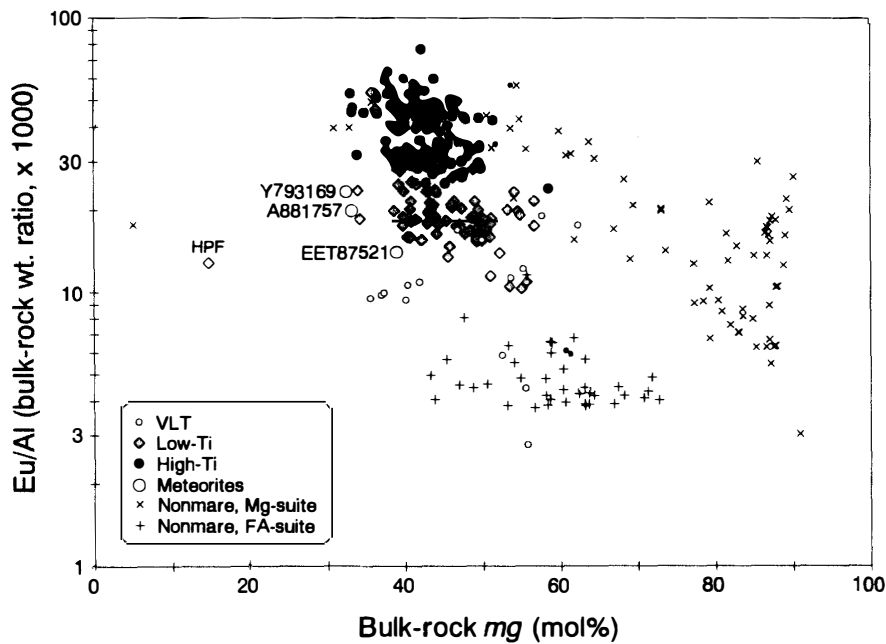


Fig. 11. Bulk-rock mg vs. Eu/Al, using the same database and symbols employed for Fig. 1, with additional data for nonmare pristine rocks from sources given in WARREN and KALLEMEYN (1991a).

residual melts, and consequently will generally yield a negative correlation between mg vs. Eu/Al (WARREN, 1986). Ferroan-anorthositic (FA) suite nonmare rocks have anomalously low Eu/Al, compared to other rocks of low-moderate mg, but this anomaly is a predictable consequence of assuming a magma ocean genesis for the FA suite (the FA rocks reflect a unique sequence of extensive crystallization of mafic silicates without accompanying crystallization of plagioclase), and a more conventional post-

magnasphere (“serial magmatism”) genesis for all of the remaining pristine rocks, *i.e.*, mainly Mg-suite cumulates (WARREN, 1986). As a corollary of this model, the most primitive (lowest-Ti) mare basalts, as products of remelting of sunken cumulates from the main (FA-forming) stage of magnasphere evolution, should show geochemical links with the FA suite; while more evolved (higher-Ti) mare basalts should have lower *mg* and higher Eu/Al. On Fig. 11, the mare basalts show, roughly as predicted, an inverse correlation. Apollo 17 VLT basalts plot amidst the ferroan anorthositic rocks, the high-Ti mare basalts plot at slightly lower *mg* and far higher Eu/Al, and the low-Ti mare basalts cluster in an intermediate region. The positions of Y-793169 and A-881757 also conform to this pattern; as seen from many other geochemical characteristics, they appear similar to both VLT and low-Ti mare basalts, but they resemble few previously known mare basalts as much as they resemble one another.

5.4. Possible cumulate nature of A-881757 as a complication for classification

As noted by YANAI (1990), A-881757 has a coarse-grained texture that might be interpreted to suggest origin as a cumulate. The texture and the marginally high-Al bulk composition (Table 1, Fig. 2) suggest that if a major proportion of the pyroxene is of cumulus (including “heteradcumulus”) origin, a commensurate proportion of the plagioclase is probably also cumulus. Conceivably even some of the ilmenite is cumulus. However, in the opinion of TAKEDA *et al.* (1992), based on such evidence as the abundance of mesostasis-like symplectites and the lack of detectable exsolution in pyroxene, A-881757 “is not a cumulate rock.”

Barring an extremely low-*mg* parent melt, the low bulk-rock *mg* (Fig. 1) is difficult to reconcile with a high degree of crystal accumulation. For example, based on trivial mass balance calculations assuming that the K_D for pigeonite/melt Fe-Mg exchange was ≈ 0.28 (LONGHI, 1992), parent-melt *mg* ratios of 15, 20, or 25 mol% correspond to implications that the final product (A-881757) contains 29, 61, or 81 wt% trapped liquid, respectively. These calculations ignore the significant component of [Fe + Mg] contained in ~ 6 vol% ilmenite (YANAI and KOJIMA, 1991), which may be partly cumulus. However, even assuming that half of the TiO_2 in the bulk rock (Table 1) represents cumulus, MgO-free ilmenite, the *mg* ratio of the remainder of the rock would still be 35 mol%; and parent-melt *mg* ratios of 15, 20, or 25 mol% would correspond to implications that the final product (A-881757) contains 20, 55, or 76 wt% trapped liquid, respectively. Considering that aside from tiny, probably unrepresentative samples such as the HPF clast, mare basalts with *mg* less than 30 mol% are unknown (Fig. 1), it seems unlikely (although by no means inconceivable) that A-881757 contains less than 60 wt% trapped liquid. Moreover, although the A-881757 bulk-rock La content is low, based on the observation that it is $0.15 \times$ as great as that of the most La-rich low-Ti mare basalt, we can infer (assuming as an approximation that La is ideally incompatible) that the content of trapped liquid in A-881757 is at least 15 wt%, and probably much higher; assuming that the La concentration of the parent magma was at least as high as that of an average low-Ti mare basalt ($8 \mu\text{g/g}$), the implied trapped liquid content is at least $3.5/8 = 44$ wt%.

The A-881757 pyroxenes are zoned, and whatever cumulus component they contain must be best represented by their cores (the later-formed rims are more likely affected

by crystallization of intercumulus trapped liquid). According to YANAI (1991), the A-881757 pyroxene cores are pigeonites, relatively Ca-rich (Wo_{15}), but still well within the compositional range suggestive of a $P2_1/c$ structure (Wo_{5-20}) (MORIMOTO *et al.*, 1988). For purposes of estimating the crystal/melt distribution coefficient for the total cumulus component in the rock D_{cum} we assume a roughly 2:1 ratio of pigeonite to plagioclase, and possibly a much smaller proportion of ilmenite. The proportion of ilmenite in the cumulus assemblage is probably low, because the bulk rock has a low V content compared to other low-Ti and VLT mare basalts (Fig. 7), even though $D(V)$ for low-Ca pyroxene is 2.8–3.4, and $D(V)$ for ilmenite is ~ 12 (IRVING, 1978).

For incompatible elements such as REE, the principal effect of a small proportion (<40 wt%) of cumulus pigeonite, plagioclase and ilmenite would be to dilute the concentrations of all such elements by a factor of 0.6–1.0. In terms of diagrams such as Figs. 4, 5, and 8–10, this effect is hardly significant. The effect in terms of Fig. 3 would be to imply a parent melt composition even more similar to the bulk-rock composition of Y-793169. The magnitude of the (–) Eu anomaly is probably diminished by cumulus plagioclase, and the slope of the REE pattern is probably rendered more positive by cumulus pigeonite. Using D 's extrapolated from the experimental constraints of MCKAY *et al.* (1991), the effect of 25–30 wt% cumulus Wo_{15} pigeonite would be to enhance the bulk-rock Lu/La ratio by a factor of ~ 1.2 . However, the observed Lu/La ratio of A-881757 is $1.5 \times CI$ (Fig. 3), so the parent magma is still implied to have a subchondritic La/Lu ratio.

Potentially the most significant effect of cumulus pigeonite would be to enhance the bulk-rock Sc content, and thus conceivably account for the anomaly manifested by Fig. 6. Unfortunately, we know of no direct experimental constraints on $D(Sc)$ for pigeonite. Data reviewed by IRVING (1978) indicate that $D(Sc)$ for $Wo_{\sim 4}$ low-Ca pyroxene is roughly 0.5–1.4, and $D(Sc)$ for high-Ca pyroxene is a complex function of temperature T , oxygen fugacity $f(O_2)$, and probably also melt mg ratio. The log of $D(Sc)$ is proportional to $1/T$, but inversely correlated with $f(O_2)$; and the $D(Sc)$ results for an Fe-free system are systematically high in comparison to the trends for a natural, Fe-bearing basaltic system. By analogy with experimental results for other mare basalt compositions, especially a Luna 24 VLT composition (LONGHI, 1992), the T at which A-881757 accumulated would have been at least 1150°C. The $D(Sc)$ results for the natural system suggest that $D(Sc)$ for high-Ca pyroxene at 1150°C and low $f(O_2)$ would be roughly 2.7. Assuming (in the absence of further constraints) that $D(Sc)$ for Wo_{15} pigeonite would be intermediate between the low-Ca and high-Ca pyroxene values, a value of ~ 2 appears most likely. Based mainly on an analogy to armalcolite, IRVING *et al.* (1978) also inferred that $D(Sc)$ for ilmenite in lunar mare systems is ~ 2 . Given these $D(Sc)$ values, and assuming that no more than 30 wt% of the bulk rock is cumulus pigeonite + ilmenite (accompanied by 10 wt% cumulus plagioclase containing negligible Sc), the bulk-rock Sc content is implied to be enhanced by a factor of ~ 1.2 relative to the parent melt; *i.e.*, instead of 96–97 $\mu g/g$ of Sc, the parent melt might have had 80–97 $\mu g/g$. In terms of Fig. 6, this would still imply a remarkably Sc-rich parent melt, by VLT or low-Ti mare standards.

The experimental constraints on $D(Sc)$ are admittedly imprecise. However, we can look to analogous cumulate rocks from the parent asteroid of the eucrite meteorites,

and from the Apollo 15 mare suite, for independent checks on the possible effect of cumulus pigeonite on Sc. The eucrites formed in an environment so similar to lunar mare basalts (in terms of volatile depletions, oxygen fugacity, etc.) that several of the lunar mare meteorites were originally classified as eucrites. Based on their low incompatible element contents in comparison to noncumulate eucrites, most of the cumulate eucrites are adcumulates with only a few percent trapped liquid. They are essentially biminerally, consisting of 40–60 wt% cumulus pigeonite (now exsolved) and 40–60 wt% cumulus plagioclase, plus a few percent of ilmenite and trapped liquid products. Thus, if $D(\text{Sc})$ for pigeonite in a VLT-like setting is actually $\gg 2$, the average cumulate eucrite would probably have a far higher Sc content than the average noncumulate eucrite. The average Sc content of literature analyses for 25 monomict noncumulate eucrites is $31 \mu\text{g/g}$, compared to an average for 6 monomict cumulate eucrites of $21 \mu\text{g/g}$ (WARREN *et al.*, 1990). This comparison suggests that the actual $D(\text{Sc})$ for pigeonite is roughly 1.3, and certainly $\ll 2$. Most cumulate eucrites contain pigeonite significantly less Ca-rich (Wo_{7-12}) (TAKEDA *et al.*, 1988) than the A-881757 pyroxene cores. However, even Pomozdino, a partial cumulate that appears to contain cumulus pyroxene ranging from Wo_9 to $\text{Wo}_{\sim 30}$, contains only $29 \mu\text{g/g}$ Sc; *i.e.*, about the same as an average noncumulate eucrite (WARREN *et al.*, 1990).

A number of Apollo 15 mare basaltic rocks have been interpreted as orthocumulates. Most of these (*e.g.*, RYDER and STEELE, 1988; VETTER *et al.*, 1988) contain olivine as a major component of the inferred cumulus assemblage, and thus are poor analogs for A-881757. In all such cases, the bulk-rock Sc contents are about the same as, or slightly less than, an average for all Apollo 15 olivine-normative mare basalts ($39 \mu\text{g/g}$), again suggesting that $D(\text{Sc})$ for pigeonite must not be $\gg 1$. Most germane is the one olivine-free example, 15388 (RYDER and STEELE, 1988). The pyroxene/plagioclase ratio of this rock is approximately 2:1, as usual for Apollo 15 mare basalts. The data of RYDER and STEELE (1988), averaged with two previous analyses referenced in their paper, indicate that the bulk-rock Sc content is $44.5 \mu\text{g/g}$, or $\sim 1.02 \times$ the average for Apollo 15 quartz-normative mare basalts, and $\sim 1.15 \times$ the average for Apollo 15 olivine-normative mare basalts. By analogy, we infer that the parent melt of A-881757 probably had a Sc content lower by only a factor of $\sim 0.9 \times$ the observed bulk-rock composition.

In summary, unless the proportion of cumulus matter in A-881757 is far higher than we estimate (≤ 40 wt%, based on admittedly circumstantial evidence), the effect of this cumulus component on the bulk-rock composition is probably not very significant, in terms of classification and interpretation of the petrogenetic affinities of the rock. The high Sc contents of A-881757 as well as Y-793169 probably reflect partial melting of a Sc-rich source (or sources) in the lunar mantle.

5.5. Siderophile and volatile trace elements

We measured six highly siderophile elements (Au, Ge, Ir, Ni, Os and Re; in Y-793169, due primarily to the low mass analyzed, we only determined upper limits for Au, Os and Re). Of these, the most ideally siderophile, at least in the context of lunar petrology, are Ir, Os, Re and Au. As reviewed by HASKIN and WARREN (1991), concentrations of highly siderophile elements in mare basalts show great scatter, but Ir, Os and Re are generally found at $2\text{--}20 \times 10^{-5}$ times CI chondrites; and Au is generally

at $1-10 \times 10^{-4}$ times CI. Our Y-793169 results are consistent with these typical mare basaltic ranges. However, our A-881757 results are consistently higher than “normal”: Ir, Os and Re are at 67×10^{-5} , 87×10^{-5} , and 43×10^{-5} times CI, and Au is at 9.7×10^{-4} times CI. We caution, however, that the pulverization of our A-881757 samples was done at another lab (at the NIPR in Tokyo, using corundum), where conceivably Ir-Os-Re-Au contamination occurred. One speck of dust from a chondritic powder could conceivably account for the differences between A-881757 and a “normal” mare basalt, in terms of Ir, Os, Re and Au.

DICKINSON *et al.* (1989) noted that mare basalts from Apollo 14 (all low-Ti and “high-Al”) are peculiarly enriched in Ge compared to those from all other sites (Fig. 12). The most plausible model to account for this anomaly is to assume that Ge was concentrated into volatile (possibly halogen-rich) phases associated with the same magmasphere residual melts from which KREEP was derived. The Apollo 14 region is extraordinarily rich in KREEP (METZGER *et al.*, 1977) and “evolved” rocks in general (WARREN *et al.*, 1983), and DICKINSON *et al.* (1985) had earlier noted that many of the Apollo 14 mare basalts appear to have assimilated KREEP (*cf.* the evidence for assimilation of granite by another subset of Apollo 14 basalts: Fig. 5). It is probably not mere coincidence that the two most Ge-rich basalts from a site other than Apollo 14 are from Apollo 12, which landed only 180 km to the west of Apollo 14. In this respect, Y-793169 and A-881757 belong to the Ge-poor majority of mare basalts. We infer that KREEP, and probably also other evolved materials, are not concentrated to Apollo-14-like levels in the general region(s) of the Moon that spawned these two meteorites.

Among the other elements determined, the most characteristically volatile are Zn and Cd. The Zn contents of Y-793169 and A-881757 are nearly identical to one another. The Zn and Cd concentrations of these rocks are typical of lunar mare basalts (HASKIN and WARREN, 1991).

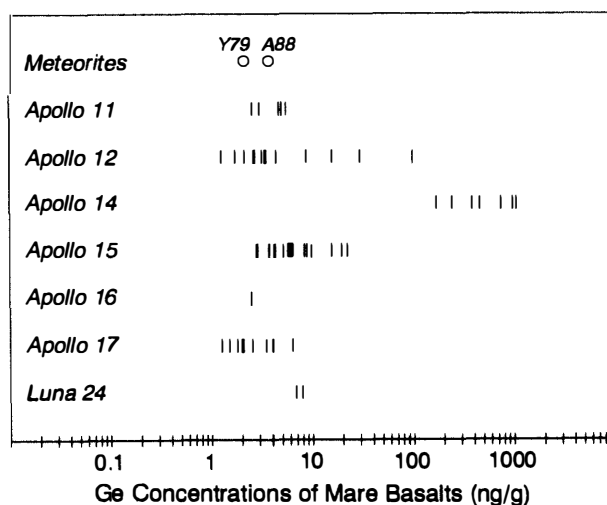


Fig. 12. Bulk-rock Ge contents of mare basalts. Data for Apollo/Luna basalts, from compilation of HASKIN and WARREN (1991) augmented by data of DICKINSON *et al.* (1989), were preaveraged for each basalt before plotting.

6. Discussion: Comparison with Isotopic Results

The crystallization ages of both Y-793169 and A-881757 are uncommonly old, by mare standards. The results of MISAWA *et al.* (1992b) for A-881757 include: 3930 ± 52 Ma based on Pb; 3850 ± 49 Ma based on Nd; 3897 ± 31 Ma based on Sr, assuming $\lambda(^{87}\text{Rb}) = 1.402 \times 10^{-11}$; and 3808 ± 18 Ma based on Ar. Based on a complicated set of Pb data for Y-793169, TORIGOYE *et al.* (1992) infer an age of $\sim 3930 \pm 40$ Ma. Slightly younger ages have been obtained based on K- ^{40}Ar by EUGSTER (1992) and NAGAO and MIURA (1992), and a two-point Sr isochron determined by TAKAHASHI and MASUDA indicates “around 3.7–3.8” Ga. As reviewed by TAYLOR (1982) and NYQUIST and SHIH (1992), most varieties of Apollo/Luna mare basalt are younger than 3800 Ma (the exceptions: most of the Apollo-14 low-Ti, “high-Al” basalts, 3800–4300 Ma; and some of the Apollo 17 high-Ti basalts, 3600–3900 Ma). The high ages of the mare meteorites, coupled with their low bulk-rock Ti and low-moderate bulk-rock Al contents (Fig. 2), nullify a correlation seen in the very limited Apollo/Luna database between low-Al mare Ti content and age, which had been viewed as a significant constraint for models of mare genesis and gross evolution of the Moon (*e.g.*, NEAL and TAYLOR, 1992; NYQUIST and SHIH, 1992).

Another important result has emerged from the studies of MISAWA *et al.* (1992a,b) and TORIGOYE *et al.* (1992). MISAWA *et al.* (1992a) deduce that μ ($^{238}\text{U}/^{204}\text{Pb}$) for the source material of A-881757 was extraordinarily low: < 17 , and most likely ~ 7 . Most mare sources had $\mu > 100$, although a few Apollo 11 low-K mare basalts came from sources with μ of the order 10–20 (NYQUIST and SHIH, 1992), and the source of the Apollo 17 orange pyroclastic glasses had μ of the order 40 (NUNES *et al.*, 1974; TERA and WASSERBURG, 1976). The μ inferred for A-881757 by MISAWA *et al.* (1992a) is comparable to the μ of the Earth’s mantle, and implies a remarkably Pb-rich source, because the U content of A-881757 (Table 1) is quite unexceptional. TORIGOYE *et al.* (1992) tentatively infer that Y-793169 has a similarly low μ , of the order 10. These results imply that volatile elements were at uncommonly high concentrations in both source regions. As discussed above, DICKINSON *et al.* (1989) account for the Ge enrichments among Apollo 14 mare basalts as a consequence of complexing and concentration of Ge by volatile phases such as F, Cl or S. The new results for Y-793169 and A-881757 indicate that volatile enrichments in a mare source region do not correlate with high Ge in the basalts. However, the DICKINSON *et al.* (1989) model assumes that the ultimate source regions of the Apollo 14 mare basalts were “typical” with respect to volatiles; volatile, Ge-rich materials were derived from KREEPy magma ocean residual melts in the vicinity of the crust/mantle boundary, assimilated by slowly rising mare basalts. The lunar meteorite results are consistent with this model, suggesting that the high Ge contents of the Apollo 14 basalts are unrelated to the volatile abundances (including μ) of their mantle source region(s), but are instead by-products of the extraordinarily high KREEP abundance throughout the crust near the Apollo 14 site.

Although Y793169 was collected a great distance (~ 500 km) east of A-881757, conceivably the two are paired, in the sense of having left the Moon in a single cratering-ejection event. They strongly resemble one another in terms of: (1) identical, uncommonly high ages, (2) uncommonly low μ , (3) remarkably high Sc, compared to

other low-Ti, low-V mare basalts, and (4) extraordinarily low *mg*. The isotopic results of NISHIZUMI *et al.* (1992) indicate that the age of ejection of Y-793169 from the Moon (its “blast-off” age) is 1.1 ± 0.2 Ma, and the blast-off age for A-881757 is (within uncertainty) identical: 0.9 ± 0.1 Ma. In contrast, the blast-off age of mare breccia EET87521 is < 0.13 Ma, and that of mare/highlands breccia Y-793274 is < 0.04 Ma (NISHIZUMI *et al.*, 1991). NISHIZUMI *et al.* (1992) found upper limits of 0.05 Ma for the terrestrial ages of both Y-793169 and A-881757. However, coupled with the noble gas results of EUGSTER (1992), NISHIZUMI’s data indicate that Y-793169 and A-881757 probably did not fall to Earth simultaneously (K. NISHIZUMI, personal commun., 1992). Nonetheless, it seems at least possible that the two were blasted off the Moon by a single cratering event. The texture of A-881757 is much coarser-grained than that of Y-793169, but such differences could easily arise within a single thick lava flow.

7. Conclusions

The Y-793169 and A-881757 meteorites are remarkably similar to one another, and yet, although both are clearly of lunar origin, they are not quite like any previously studied lunar rock. Their Ti contents qualify them as low-Ti mare basalts, but viewed in relation to their extraordinarily low *mg* ratios, their Ti contents are also consistent with kinship to previously-studied VLT mare basalts. Resemblances to VLT mare basalts are also evident from their middle-REE/heavy-REE and Sc/Sm ratios. However, they resemble low-Ti basalts in terms of overall REE contents, plus V/Sm and Cr/Sm ratios, and they even resemble high-Ti basalts in having high Sc coupled with low V. The Ti contents that we have measured are substantially higher than those reported earlier (YANAI and KOJIMA, 1991), and the conclusions of WARREN and KALLEMEYN (1991a) regarding the overall abundance of VLT basalts in the lunar maria should be tempered accordingly. However, it remains true that the Ti contents of meteoritic mare basalts (based on a still uncomfortably small number of samples: Y-793169, A-881757, EET87521, the major mare component of Y-793274, and many tiny, poorly-sampled clasts from the highlands meteorites) are consistently far lower than the average of Apollo/Luna mare basalts.

A set of remarkable coincidences between Y-793169 and A-881757 (our data show that both have bizarrely high Sc, by low-Ti mare standards, and extraordinarily low *mg*; other workers have demonstrated similar ages, μ , and times of blast-off from the Moon) suggests that these two meteorites might be paired, in the sense of having left the Moon in a single cratering-ejection event.

The low *mg* and moderate incompatible element contents of A-881757 tend to support the interpretation of TAKEDA *et al.* (1992) that despite its coarse texture this rock is not the product of a high degree of crystal accumulation. The texture of A-881757, pigeonites up to 4 mm across (YANAI, 1991), yet no exsolution at electron-probe-detectable scale (TAKEDA *et al.*, 1992), indicates that coarse-grained rocks have formed on the Moon even in shallow, relatively fast-cooling environments (*e.g.*, a lava pond). Considering the evidence from A-881757, many published claims of “plutonic” affinity for lunar highlands rocks, *e.g.*, with grains only 1–2 mm across (SIMON and PAPIKE, 1985), seem unjustifiable.

The geochemical contrasts between Y-793169 and A-881757 and previously available mare basalts show that the full diversity of the lunar maria, and the factors that govern variability among mare basalts, are still poorly understood. The existing mare basalt classification scheme, based on Ti, is remarkably ineffectual as a predictor of the overall geochemical/petrologic character of mare rocks. However, mare basalts are generally held to be products of remelted cumulates that formed along the bottom of the Moon's primordial magmasphere. Cumulates are notoriously heterogeneous, modally and compositionally, as the proportions of phases (solids as well as trapped liquid) vary almost chaotically, especially in the vertical direction, reflecting turbulence and other complicated processes in the parental magmas. Peridotitic portions of terrestrial intrusions typically contain layers of pyroxenite alternating with layers of dunite (*e.g.*, IRVINE, 1980), and such "modal banding" occurs at all scales from centimeters to kilometers. Assuming these materials were not efficiently stirred by shallow mantle convection (as occurs on the Earth in connection with plate tectonics), any melts produced by reheating them would partly inherit their great compositional diversity. The diversity and general lack of systematics (*e.g.*, *mg*-related) among lunar mare basalt compositions, reinforced by Y-793169 and A-881757, support the magma ocean cumulate model for genesis of the mare source regions. Attempts to link mare geochemistry and age relations in a simple fashion to the time-temperature evolution of the lunar interior (*e.g.*, TAYLOR, 1975, 1982; NEAL and TAYLOR, 1992; NYQUIST and SHIH, 1992) are probably not very useful, because they are probably based on an oversimplified picture of the compositional stratification that develops in the pile of magma ocean cumulates.

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References

- DELANEY, J. S. (1989): Lunar basalt breccia identified among Antarctic meteorites. *Nature*, **342**, 889-890.
- DICKINSON, T., TAYLOR, G. J., KEIL, K. and BILD, R. W. (1989): Germanium abundances in lunar basalts: Evidence of mantle metasomatism? *Proc. Lunar Planet. Sci. Conf.*, 19th, 189-198.
- DICKINSON, T., TAYLOR, G. J., KEIL, K., SCHMITT, R. A., HUGHES, S. S. and SMITH, M. R. (1985): Apollo 14 aluminous mare basalts and their possible relationship to KREEP. *Proc. Lunar Planet. Sci. Conf.*, 15th, Pt. 2, C365-C374 (*J. Geophys. Res.*, **90** Suppl.).
- EUGSTER, O. (1992): Basaltic lunar meteorites Asuka-881757 and Yamato-793169: Comparison with EET87521 and Yamato-793274 (abstract). *Papers Presented to the 17th Symposium on Antarctic Meteorites*, August 19-21, 1992. Tokyo, Natl Inst. Polar Res., 208-210.
- FUKUOKA, T. (1992): Geochemistry of lunar meteorites, Asuka-31 and Yamato-793169 (abstract). *Papers Presented to the 17th Symposium on Antarctic Meteorites*, August 19-21, 1992. Tokyo. Natl Inst. Polar Res., 251-253.
- GROVE, T. L. and VANIMAN, D. T. (1978): Experimental petrology of very low Ti (VLT) basalts. *Mare*

- Crisium: The View from Luna 24, ed. by R. B. MERRILL and J. J. PAPIKE. New York, Pergamon, 445–471.
- HASKIN, L. A. and WARREN, P. H. (1991): Chemistry. Lunar Sourcebook, A User's Guide to the Moon, ed. by G. HEIKEN *et al.* Cambridge, Cambridge Univ. Press, 357–474.
- IRVINE, T. N. (1980): Magmatic infiltration metasomatism, double-diffusive fractional crystallization, and adcumulus growth in the Muskox intrusion and other layered intrusions. *Physics of Magmatic Processes*, ed. by R. B. HARGRAVES. Princeton Univ. Press, 325–383.
- IRVING, A. J. (1978): A review of experimental studies of crystal/liquid trace element partitioning. *Geochim. Cosmochim. Acta*, **42**, 743–770.
- IRVING, A. J., MERRILL, R. B. and SINGLETON, D. E. (1978): Experimental partitioning of rare earth elements and scandium among armalcolite, ilmenite, olivine and mare basalt liquid. *Proc. Lunar Planet. Sci. Conf.*, 9th, 601–612.
- KALLEMEYN, G. W., RUBIN, A. E., WANG, D. and WASSON, J. T. (1989): Ordinary chondrites: Bulk compositions, classification, lithophile-element fractionations, and composition-petrographic type relationships. *Geochim. Cosmochim. Acta*, **53**, 2747–2767.
- KOEBERL, C., KURAT, G. and BRANDSTÄTTER, F. (1991): Lunar meteorite Yamato-793274: Mixture of mare and highland components, and barringerite from the Moon. *Proc. NIPR Symp. Antarct. Meteorites*, **4**, 33–55.
- KOEBERL, C., KURAT, G. and BRANDSTÄTTER, F. (1992): Geochemical and mineralogical study of gabbroic lunar mare meteorites Asuka-881757 (Asuka-31) and Yamato-793169 (abstract). *Papers Presented to the 17th Symposium on Antarctic Meteorites, August 19–21, 1992. Tokyo, Natl Inst. Polar Res.*, 219–222.
- LINDSTROM, M. M., SCHWARZ, C., SCORE, R. and MASON, B. (1991a): MacAlpine Hill 88104 and 88105 lunar highland meteorites: General description and consortium overview. *Geochim. Cosmochim. Acta*, **55**, 2999–3007.
- LINDSTROM, M. M., MITTFELDELDT, D. W. and MARTINEZ, R. R. (1991b): Geochemistry of Asuka-31: Comparison to basaltic lunar meteorites and mare basalts (abstract). *Papers Presented to the 16th Symposium on Antarctic Meteorites, June 5–7, 1991. Tokyo, Natl Inst. Polar Res.*, 102–105.
- LONGHI, J. (1992): Experimental petrology and petrogenesis of mare volcanics. *Geochim. Cosmochim. Acta*, **56**, 2235–2251.
- MCKAY, G., LE, L. and WAGSTAFF, J. (1991): Constraints on the origin of the mare basalt europium anomaly: REE partition coefficients for pigeonite (abstract). *Lunar and Planetary Science XXII. Houston, Lunar Planet. Inst.*, 883–884.
- MCSWEEN, H. Y. (1985): SNC meteorites: Clues to martian petrologic evolution? *Rev. Geophys.*, **23**, 391–416.
- METZGER, A. E., HAINES, E. L., PARKER, R. E. and RADOCINSKI, R. G. (1977): Thorium concentrations in the lunar surface, I, Regional values and crustal content. *Proc. Lunar Sci. Conf.*, 8th, 949–999.
- MISAWA, K., TATSUMOTO, M. and YANAI, K. (1992a): U-Th-Pb isotopic systematics of lunar meteorite Asuka-31. *Proc. NIPR Symp. Antarct. Meteorites*, **5**, 3–22.
- MISAWA, K., TATSUMOTO, M., DALRYMPLE, G. B. and YANAI, K. (1992b): U-Th-Pb, Sm-Nd, and Rb-Sr isotopic systematics and $^{40}\text{Ar}/^{39}\text{Ar}$ age of lunar meteorite Asuka-881757 (abstract). *Papers Presented to the 17th Symposium on Antarctic Meteorites, August 19–21, 1992. Tokyo, Natl Inst. Polar Res.*, 119–121.
- MORIMOTO, N., FABRIES, J., FERGUSON, A. K., GINZBURG, I. V., ROSS, M., SEIFURT, F. A., ZUSSMAN, J., AOKI, K. and GOTTARDI, G. (1988): Nomenclature of pyroxenes. *Am. Mineral.*, **73**, 1123–1133.
- MURALI, A. V., MA, M.-S. and SCHMITT, R. A. (1977): Chemistry of 30 Apollo 17 rake basalts: 71597 a product of partial olivine accumulation (abstract). *Lunar Science VIII. Houston, Lunar Sci. Inst.*, 703–705.
- NAGAO, K. and MIURA, Y. (1992): Noble gases and ^{81}Kr -terrestrial age of Asuka-31. *Papers Presented to the 17th Symposium on Antarctic Meteorites, August 19–21, 1992. Tokyo, Natl Inst. Polar Res.*, 125–128.
- NAZAROV, M. A., IGNATENKO, K. I. and SHEVALEEVSKY, I. D. (1982): Source of errors in defocused beam analysis with the electron probe, revisited (abstract). *Lunar and Planetary Science XXIII. Houston,*

- Lunar Planet. Inst., 582–583.
- NEAL, C. R. and TAYLOR, L. A. (1992): Petrogenesis of mare basalts: A record of lunar volcanism. *Geochim. Cosmochim. Acta*, **56**, 2177–2211.
- NISHIIZUMI, K., ARNOLD, J. R., SHARMA, P., KUBIK, P. W., KLEIN, J. and MIDDLETON, R. (1991): Cosmic ray exposure history of lunar meteorite EET87521 (abstract). *Lunar and Planetary Science XXII*. Houston, Lunar Planet. Inst., 977–978.
- NISHIIZUMI, K., ARNOLD, J. R., CAFFEE, M. W., FINKEL, R. C., SOUTHON, J. and REEDY, R. C. (1992): Cosmic ray exposure histories of lunar meteorites Asuka 881757, Yamato 793169, and Calalong Creek (abstract). *Papers Presented to the 17th Symposium on Antarctic Meteorites, August 19–21, 1992*. Tokyo, Natl Inst. Polar Res., 129–132.
- NUNES, P. D., TATSUMOTO, M. and UNRUH, D. M. (1974): U-Th-Pb systematics of some Apollo 17 basalts and implications for a lunar basin excavation chronology. *Proc. Lunar Sci. Conf.*, 5th, 1487–1514.
- NYQUIST, L. E. and SHIH, C.-Y. (1992): The isotopic record of lunar basaltic volcanism. *Geochim. Cosmochim. Acta*, **56**, 2213–2234.
- PAPIKE, J. J. and VANIMAN, D. T. (1978): Luna 24 ferrobasalts and the mare basalt suite: Comparative chemistry, mineralogy, and petrology. *Mare Crisium: The View from Luna 24*, ed. by R. B. MERRILL and J. J. PAPIKE. New York, Pergamon, 371–401.
- RYDER, G. (1991): Naming lunar mare basalts: Quo vadimus? (abstract). *Lunar and Planetary Science XXII*. Houston, Lunar Planet. Inst., 1157–1158.
- RYDER, G. and STEELE, A. (1988): Chemical dispersion among Apollo 15 olivine-normative mare basalts. *Proc. Lunar Planet. Sci. Conf.*, 18th, 273–282.
- SIMON, S. B. and PAPIKE, J. J. (1985): Petrology of the Apollo 12 highland component. *Proc. Lunar Planet. Sci. Conf.*, 16th, Pt. 1, D47–D60 (*J. Geophys. Res.*, **90** Suppl.).
- TAKAHASHI, K. and MASUDA, A. (1992): Geochemical and chronological studies for Asuka-881757 lunar meteorite (abstract). *Papers Presented to the 17th Symposium on Antarctic Meteorites, August 19–21, 1992*. Tokyo, Natl Inst. Polar Res., 117–118.
- TAKEDA, H., ARAI, T. and SAIKI, K. (1992): Mineralogical studies of lunar meteorite Y-793169, a crystalline basalt (abstract). *Papers Presented to the 17th Symposium on Antarctic Meteorites, August 19–21, 1992*. Tokyo, Natl Inst. Polar Res., 109–112.
- TAKEDA, H., TAGAI, T. and GRAHAM, A. L. (1988): Mineralogy of slowly cooled eucrites and thermal histories of the HED parent body (abstract). *Papers Presented to the 13th Symposium on Antarctic Meteorites, June 7–9, 1988*. Tokyo, Natl Inst. Polar Res., 142–144.
- TAYLOR, G. J., WARREN, P., RYDER, G., DELANO, J., PIETERS, C. and LOFGREN, G. (1991): Lunar rocks. *Lunar Sourcebook: A User's Guide to the Moon*, ed. by G. HEIKEN *et al.* Cambridge, Cambridge Univ. Press, 183–284.
- TAYLOR, S. R. (1975): *Lunar Science: A Post-Apollo View*. New York, Pergamon, 372 p.
- TAYLOR, S. R. (1982): *Planetary Science: A Lunar Perspective*. Houston, Lunar Planet. Inst., 512 p.
- TERA, F. and WASSERBURG, G. J. (1976): Lunar ball games and other sports (abstract). *Lunar Science VII*. Houston, Lunar Sci. Inst., 858–860.
- TORIGOYE, N., MISAWA, K. and TATSUMOTO, M. (1992): U-Th-Pb chronology of Yamato 793169 lunar meteorite (abstract). *Papers Presented to the 17th Symposium on Antarctic Meteorites, August 19–21, 1992*. Tokyo, Natl Inst. Polar Res., 122–124.
- VETTER, S. K., SHERVAIS, J. W. and LINDSTROM, M. M. (1988): Petrology and geochemistry of olivine-normative and quartz-normative basalts from regolith breccia 15498: New diversity in Apollo 15 mare basalts. *Proc. Lunar Planet. Sci. Conf.*, 18th, 255–271.
- WARNER, R. D., TAYLOR, G. J., CONRAD, G. H., NORTHROP, H. R., BARKER, S., KEIL, K., MA, M.-S. and SCHMITT, R. A. (1979): Apollo 17 high-Ti mare basalts: New bulk compositional data, magma types, and petrogenesis. *Proc. Lunar Planet. Sci. Conf.*, 10th, 225–247.
- WARREN, P. H. (1986): Anorthosite assimilation and the origin of the Mg/Fe-related bimodality of pristine Moon rocks: Support for the magmasphere hypothesis. *Proc. Lunar Planet. Sci. Conf.*, 16th, Pt. 2, D331–D343 (*J. Geophys. Res.*, **91**, B4).
- WARREN, P. H. and KALLEMEYN, G. W. (1989): Elephant Moraine 87521: The first lunar meteorite composed of predominantly mare material. *Geochim. Cosmochim. Acta*, **53**, 3323–3330.

- WARREN, P. H. and KALLEMEYN, G. W. (1991a): Geochemical investigations of five lunar meteorites: Implications for the composition, origin and evolution of the lunar crust. *Proc. NIPR Symp. Antarct. Meteorites*, **4**, 91–117.
- WARREN, P. H. and KALLEMEYN, G. W. (1991b): The MacAlpine Hills lunar meteorite, and implications of the lunar meteorites collectively for the composition and origin of the Moon. *Geochim. Cosmochim. Acta*, **55**, 3123–3138.
- WARREN, P. H., TAYLOR, G. J., KEIL, K., SHIRLEY, D. N. and WASSON, J. T. (1983): Petrology and chemistry of two “large” granite clasts from the Moon. *Earth Planet. Sci. Lett.*, **64**, 175–185.
- WARREN, P. H., SHIRLEY, D. N. and KALLEMEYN, G. W. (1986): A potpourri of pristine Moon rocks, including a VHK mare basalt and a unique, augite-rich Apollo 17 anorthosite. *Proc. Lunar Planet. Sci. Conf.*, 16th, Pt. 2, D319–D330 (*J. Geophys. Res.*, **91**, B4).
- WARREN, P. H., JERDE, E. A., MIGDISOVA, L. E. and YAROSHEVSKY, A. A. (1990): Pomozdino: An anomalous, high-MgO/FeO, yet REE-rich eucrite. *Proc. Lunar Planet. Sci. Conf.*, 20th, 281–297.
- WILHELMS, D. E. (1987): The Geologic History of the Moon. U.S., Geol. Surv., Prof. Pap., **1348**, 302 p.
- YANAI, K. (1990): Anorthositic gabbro: Cumulate meteorite from Antarctica (abstract). *Lunar and Planetary Science XXI*. Houston, Lunar Planet. Inst., 1365–1366.
- YANAI, K. (1991): Gabbroic meteorite Asuka-31: Preliminary examination of a new type of lunar meteorite in the Japanese collection of Antarctic meteorites. *Proc. Lunar Planet. Sci.*, **21**, 317–324.
- YANAI, K. and KOJIMA, H. (1991): Varieties of lunar meteorites recovered from Antarctica. *Proc. NIPR Symp. Antarct. Meteorites*, **4**, 70–90.

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