

GEOCHEMISTRY OF LUNAR METEORITE YAMATO-791197: COMPARISON WITH ALHA81005 AND OTHER LUNAR SAMPLES

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Abstract: Yamato-791197 is a regolith breccia from the Earth's Moon. Because lunar exploration has been of limited scope, lunar meteorites are extremely valuable sources of information about lateral variations in composition and petrology of the Moon's crust. We used INAA to analyze a 197 mg bulk-rock sample, and two 7 mg clasts, from Y-791197. The clasts are both anorthositic impact melt breccias. One of them contains feldspars of unusual "ternary" composition, probably derived from rare lunar granites. It is unclear whether Y-791197 is from the same lunar impact as the first meteorite discovered from the Moon, ALHA81005. In most respects the compositions of these two meteorites are remarkably similar. The source crater(s) must be far from the K, Th, and U-rich region, near the center of the nearside, that supplied the Apollo samples. Volatile element contents are higher in Y-791197 than in ALHA81005, and Y-791197 has a much lower *mg* ratio (0.64) than ALHA81005 (0.73). The *mg* disparity suggests that these two "fossil" soils formed many hundreds of meters apart (for comparison, Apollo 16 traverses spanned points up to 8 km apart, yet the total range in *mg* among 20 analyzed regolith breccias from Apollo 16 is 0.65–0.72), or else the impact responsible for propelling them Earthward happened to occur close to a boundary between compositionally dissimilar terrains (*e.g.*, a mare-highlands boundary). The high aluminum (plagioclase) content of Y-791197 tends to confirm the magmasphere model of earliest lunar evolution.

1. Introduction

Yamato-791197 is a 52.4 g meteorite that was first studied petrographically by YANAI and KOJIMA (1984). These authors concluded from the high FeO/MnO ratios of its mafic silicates as well as its texture and anorthositic bulk composition that Y-791197 is probably a regolith breccia (a mass of lithified former soil) derived from the Earth's Moon.

The importance of this discovery to lunar science can hardly be overstated. The Apollo program sampled the Moon at only six sites. The Soviet Luna landers sampled soils from three additional sites. One other meteorite of lunar origin, ALHA81005 (also a regolith breccia), had previously been discovered (BOGARD, 1983). The Apollo and Luna landings were confined to a small area of the central near side, around which a polyhedron could be drawn covering just 4.7% of the lunar surface (WARREN *et al.*, 1983). Despite a limited amount of horizontal mixing by great impacts, the ancient, nonmare lunar crust manifests considerable lateral heterogeneity (ADLER and TROMBKA,

1977; WARREN and TAYLOR, 1981). Thus, we cannot claim to have samples from enough different regions of the Moon to be even approximately representative of the crust as a whole. Although the exact sources of lunar meteorites can seldom or never be unambiguously determined, the vast majority are presumably not from the small region sampled by the Apollo and Luna programs. Lunar meteorites are therefore extremely valuable sources of information about lateral variations in the composition and petrology of the Moon's crust.

To complicate matters, Y-791197 is so similar to ALHA81005, it seems possible that both meteorites were brought to Earth by a single impact onto the Moon's surface (KEIL, 1985; LINDSTROM *et al.*, 1985; SUTTON, 1985; TAKEDA *et al.*, 1985; WARREN and KALLEMEYN, 1985). One good way to test this hypothesis is to compare precise geochemical data for the two meteorites.

Estimates of the bulk composition and mineralogy of the Moon's nonmare crust will have to be revised based on the new data for Y-791197 (and recent data for ALHA-81005). These revisions, as well as results from petrologic studies of individual clasts in the meteorites, will necessitate at least minor revisions to models of crustal genesis. In turn, constraints on the bulk composition and even the origin of the Moon will be improved by studies of Y-791197. We have analyzed by instrumental neutron activation analysis (INAA) three samples of Y-791197: bulk-rock (matrix) sample Y-791197,75, clast Y-791197,100, and clast Y-791197,103.

2. Analytical Procedures

The INAA procedure was a modified version of that used by KALLEMEYN and WARREN (1983). Results are shown in Table 1. Unless otherwise specified in Table 1, uncertainties from counting statistics are $\leq 5\%$ (relative). Uncertainties and detection limits were far higher for the two clasts than for the bulk-rock sample, mainly because the clasts were much smaller in mass (Table 1). The bulk-rock sample was analyzed as received from Tokyo. The two clast samples were extracted from larger pieces, using stainless steel dental tools. Clean (100%) separations of the clasts from the matrix were achieved, except a tiny bit of orange-brown rind (weathering products?) from the edge of the Y-791197,100 clast was included in the sample of that clast. After being irradiated and counted for INAA, the clasts were made into thin sections and studied petrographically, including mineral analyses by electron microprobe.

3. Petrography

Bulk-rock sample Y-791197,76 appears heterogeneous (Fig. 1), with numerous mm-sized light clasts distributed unevenly within the dark (fine-grained, glass-rich) breccia matrix. OSTERTAG *et al.* (1985b) noted that Y-791197 is a relatively immature (incompletely mixed) regolith sample. Unfortunately, important sampling errors are inevitable when small fragments of such a heterogeneous material are separated for analysis.

Clast Y-791197,100 is a light gray, micropoikilitic impact melt breccia (Figs. 1 and

Table 1. New data for Y-791197 and, for comparison, averaged compositions of other lunar regolith samples.

| | Y-791197 whole- rock 197 mg | ALHA81005 wtd. mean, literature | Luna-20 soil, lit. average | Ap-16 soil, lit. average | Ap-17 Al-rich soil 73141 | Y-791197 Clast ,100 7.0 mg | Y-791197 Clast ,103 7.3 mg |
|---------|--------------------------------------|--|----------------------------------|--------------------------------|--------------------------------|----------------------------------|----------------------------------|
| Na mg/g | 2.34 | 2.24 | 2.45 | 3.50 | 3.12 | 2.21 | 2.56 |
| Mg mg/g | 36±3 | 49.4 | 58 | 35 | 58.8 | 40±16 | 49±15 |
| Al mg/g | 141 | 136 | 121 | 143 | 113 | 131 | 151 |
| K mg/g | 0.232 | 0.194 | 0.59 | 0.92 | 1.17 | 0.23±2 | 0.14±3 |
| Ca mg/g | 108 | 107 | 103 | 112 | 92.9 | 102 | 120 |
| Ti mg/g | 1.7 | 1.57 | 2.8 | 3.4 | 7.3 | — | — |
| Fe mg/g | 44.3 | 42.7 | 60.0 | 41.0 | 62.3 | 155 | 49.5 |
| Sc μg/g | 12.5 | 9.1 | 16.4 | 9.3 | 16.2 | 7.4 | 13.1 |
| V μg/g | 30 | 24.6 | 27 | 20 | 37 | 28±11 | 21±8 |
| Cr μg/g | 880 | 890 | 1500 | 720 | 1480 | 830 | 840 |
| Mn μg/g | 660 | 580 | 800 | 530 | 840 | 480 | 770 |
| Co μg/g | 18.4 | 21.0 | 20.0 | 27.0 | 27.2 | 610 | 15.9 |
| Ni μg/g | 154 | 198 | 260 | 377 | 239 | 14700 | 62±18 |
| Zn μg/g | 21 | 8.7 | 21 | 18 | 16 | — | — |
| Ga μg/g | 3.2 | 2.7 | 3.2 | 5.4 | 2.6 | 4.7±3 | 2.7±3 |
| Br ng/g | 160±40 | 190 | 140 | 140 | 110 | <2000 | <2000 |
| Sr μg/g | 140±10 | 135 | 144 | 163 | 137 | 115±46 | 202±33 |
| Zr μg/g | 26±4 | 26.8 | 120 | 167 | 219 | — | — |
| Cs ng/g | 59±13 | 24 | 70 | 87 | 236 | 0.8±2 | — |
| Ba μg/g | 29±3 | 28.4 | 94 | 127 | 154 | — | 53±16 |
| La μg/g | 2.16 | 1.98 | 6.3 | 12.0 | 15.5 | 1.49 | 1.27 |
| Ce μg/g | 5.0 | 5.2 | 18.0 | 31.0 | 37.8 | 4.9±5 | 3.7±4 |
| Nd μg/g | 3.0±3 | 3.2 | 10.8 | 19.0 | 24.9 | — | — |
| Sm μg/g | 0.96 | 0.95 | 3.1 | 5.7 | 7.0 | 0.70 | 0.73 |
| Eu μg/g | 0.72 | 0.69 | 0.94 | 1.20 | 1.20 | 0.71 | 0.81 |
| Tb μg/g | 0.216 | 0.214 | 0.65 | 1.13 | 1.5 | — | 0.21±3 |
| Dy μg/g | 1.40±23 | 1.33 | 4.1 | 7.4 | 9.3 | 1.11±7 | 1.37±8 |
| Ho μg/g | 0.28±3 | 0.31 | — | — | 2.4 | — | — |
| Yb μg/g | 0.95 | 0.84 | 2.4 | 4.0 | 5.4 | 0.54±5 | 0.82±5 |
| Lu μg/g | 0.135 | 0.124 | 0.39 | 0.59 | 0.80 | 0.087±9 | 0.127±8 |
| Hf μg/g | 0.73 | 0.73 | 2.4 | 4.1 | 5.2 | 0.59±8 | 0.57±4 |
| Ta μg/g | 0.078±5 | 0.093 | 0.30 | 0.51 | 0.75 | — | 0.060±27 |
| Ir ng/g | 6.4 | 6.8 | 9.5 | 11.1 | 12 | 70 | 4.4±1.0 |
| Au ng/g | <2 | 2.2 | 6.4 | 7.3 | 6 | 23±2 | <2 |
| Th μg/g | 0.28 | 0.29 | 1.10 | 1.90 | 2.4 | 0.15±5 | 0.18±5 |
| U μg/g | 0.079±13 | 0.098 | 0.33 | 0.56 | 0.70 | — | — |
| mg | 0.651 | 0.727 | 0.689 | 0.662 | 0.684 | 0.37 | 0.69 |

The ALHA81005 composition is a mass-weighted mean of the analyses of BOYNTON and HILL (1983), KALLEMEYN and WARREN (1983), KOROTEV *et al.* (1983), LAUL *et al.* (1983), PALME *et al.* (1983), and VERKOUTEREN *et al.* (1983); averages of literature data for Luna 20 and Apollo 16 soils are from KALLEMEYN and WARREN (1983); and the 73141 composition is an average of the analyses of MILLER *et al.* (1974), RHODES *et al.* (1974), ROSE *et al.* (1974), and WÄNKE *et al.* (1974).

2). Oikocrysts of mafic silicates, up to 1 mm across, are choked with crystalline debris, up to 0.4 mm across, that apparently escaped complete impact melting. A 1 mm aggregate of anhedral interconnected grains of FeNi metal (with interspersed silicates)

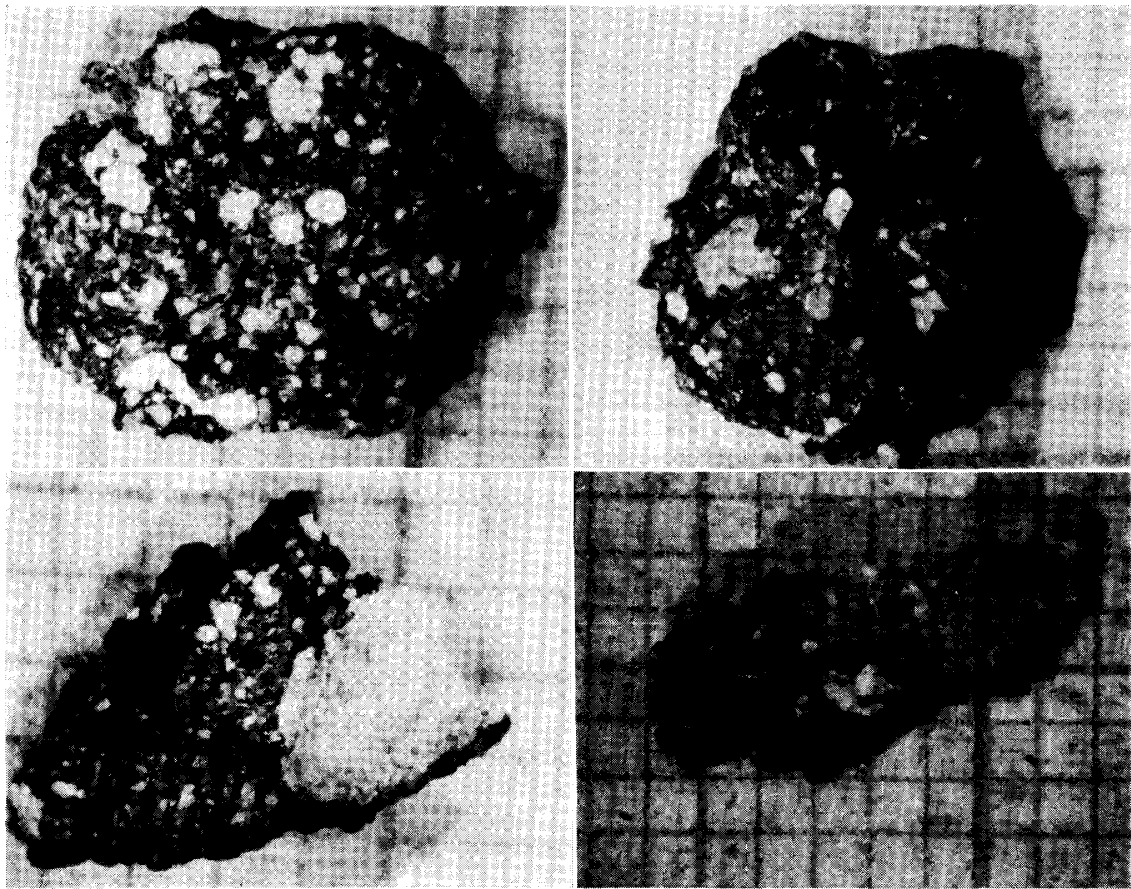


Fig. 1. Macroscopic views of the Y-791197 samples studied by INAA (clockwise from upper left): bulk-rock sample Y-791197,76; the reverse side of Y-791197,76 (note heterogeneity); clast Y-791197,100 (with attached matrix); clast Y-791197,103 (with attached matrix). Divisions in background = mm.

was a major component of the clast. The extremely high Ni content of the bulk-clast analysis (Table 1) implies that a sizeable fraction of the clast was taenite (the high-Ni variety of metallic FeNi). Unfortunately, most of the metal aggregate was absent from the thin section produced after INAA. The metal that is present in the thin section is a 0.4×0.02 mm sliver of kamacite, with uniform composition (in mg/g): Fe 929 ± 9 , Ni 53.1 ± 2.0 , Co 2.4 ± 0.4 , P 2.2 ± 0.2 . The bulk of the metal is presumably of meteoritic origin. Pyroxene compositions are highly non-uniform (Fig. 3). Olivine compositions are similarly non-uniform, with Mg/(Mg+Fe) averaging 65.2 ± 8.9 mol% (range among 6 analyses 56.2–81.1). Plagioclase is uniformly Ca-rich, with Ca/(Ca+Na+K) averaging 96.8 ± 0.8 mol% (range among 17 analyses 95.4–98.5). However, a single grain of feldspar was found to have a “ternary” composition: two analyses gave $An_{54.1}Ab_{21.5}Or_{24.4}$ and $An_{51.9}Ab_{19.3}Or_{28.8}$. Similar feldspar compositions have previously been reported only for lunar granites (RYDER *et al.*, 1975; SHERVAIS and TAYLOR, 1983). Presumably the source lithology of the ternary feldspar in Y-791197,100 was also a granite.

Clast Y-791197,103 is also an impact melt breccia. It appears much lighter in color than the Y-791197,100 impact melt (Fig. 1). The texture of the ,103 clast is es-

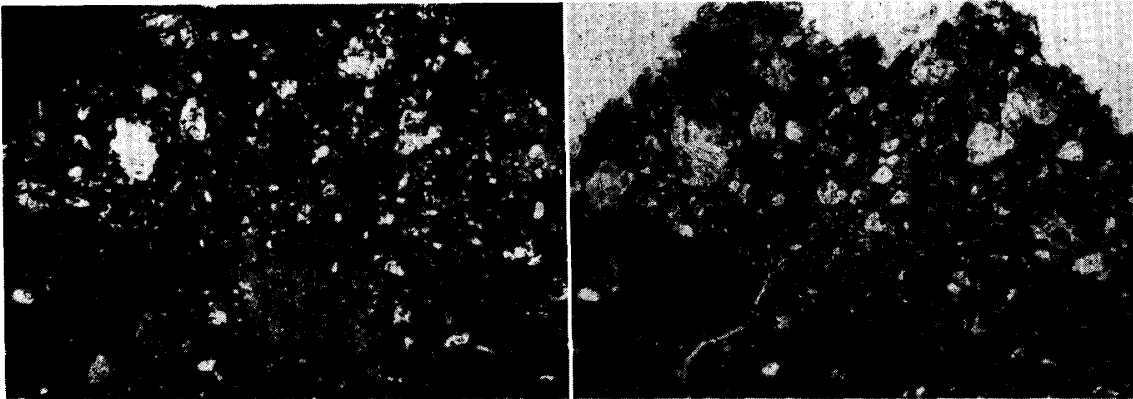


Fig. 2. Transmitted light photomicrographs of clast Y-791197,100, with nicols crossed (left) and uncrossed (right, same view). Dark material along bottom = matrix. View is 2.2 mm long.

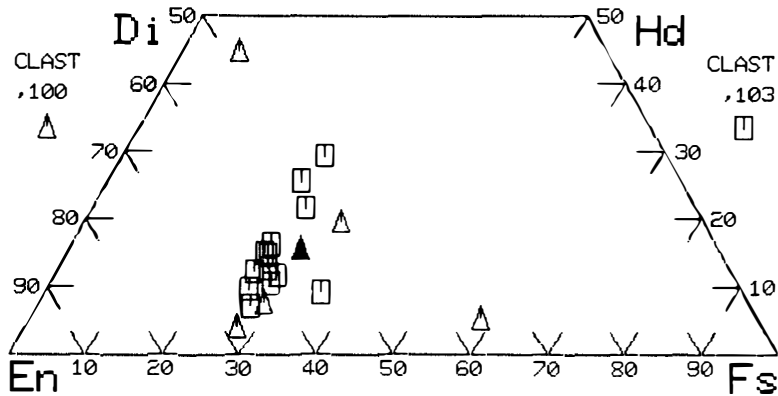


Fig. 3. Pyroxene compositions for clasts Y-791197,100 and Y-791197,103.

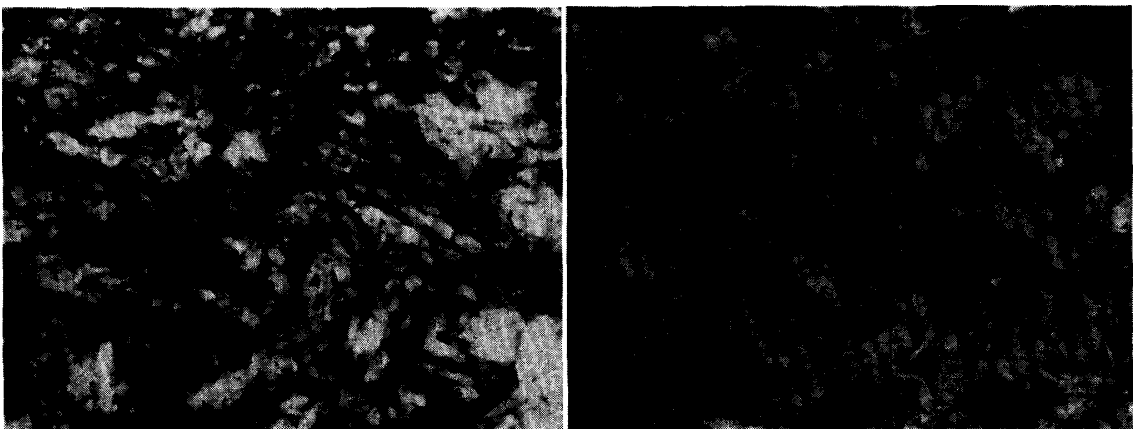


Fig. 4. Transmitted light photomicrographs of clast Y-791197,100, with nicols crossed (left) and uncrossed (right, same view). View is 0.5 mm long.

essentially subophitic, with plagioclase laths up to 0.3 mm long (Fig. 4). The impact melt origin of the clast is apparent from the incongruous presence of equant xenocrysts, up to 0.3 mm across, amidst the thin, lath-shaped crystals of the matrix. Also, the high content of the siderophile Ir (Table 1) indicates that a substantial meteoritic

component is present. Pyroxene compositions are shown in Fig. 3. Olivine compositions are fairly uniform, with Mg/(Mg+Fe) averaging 68.8 ± 1.2 mol% (range among 6 analyses 67.4–70.6). Plagioclase compositions are Ca-rich, with Ca/(Ca+Na+K) averaging 97.3 ± 0.8 mol% (range among 28 analyses 94.2–98.1).

In addition to the two clasts described above, we separated a smaller white clast (0.7 mg) from the matrix portion of Y-791197,100, and used it to produce a tiny (1 mm²) thin section. This lithology is a cataclastic-granulitic breccia, with grains up to 0.4 mm across. As in the other two clasts, the two olivines analyzed are ferroan, Fo_{85.3} and Fo_{66.2}; and the pyroxenes cluster within a few mol% of En₆₂Fs₂₉Wo₉. Plagioclase compositions are less Ca-rich than in the other two clasts, with Ca/(Ca+Na+K) averaging 95.9 ± 0.4 mol% (range among 13 analyses 95.0–96.5). Unlike the other two clasts, it is remotely conceivable that this clast is pristine (*i.e.*, unaffected by meteorite-induced mixing).

4. Discussion: Comparison with ALHA81005 and Other Lunar Regolith Samples

Our INAA data (Table 1) support the conclusion of YANAI and KOJIMA (1984) that Y-791197 is of lunar origin. For example, the Fe/Mn ratio of our bulk-rock analysis (67.1) is typically lunar (LAUL and SCHMITT, 1973), and distinctly higher than the Fe/Mn ratios of nonlunar achondrites: eucrites, howardites, and “SNC” achondrites, all have Fe/Mn ratios close to 40 (*e.g.*, KALLEMEYN and WARREN, 1983). Table 1 also shows averaged literature data for compositions of anorthositic (nonmare) lunar soils and lunar meteorite ALHA81005. Our analysis (KALLEMEYN and WARREN, 1983) of ALHA81005 was essentially identical to the weighted mean of the analyses from six different neutron activation laboratories shown in Table 1. The Luna 20 and Apollo 16 soils are generally considered to be our most representative samples of lunar highlands soil. The Apollo 14 highlands region, with its extraordinarily high abundances of incompatible elements such as Th and K (ADLER and TROMBKA, 1977), certainly does not have a typical lunar highlands composition. But 73141, the most Al-rich soil from Apollo 17 (RHODES *et al.*, 1974), appears to be nearly free of mare material, and may be representative of an appreciable fraction of the central near side highlands.

Bulk-rock Y-791197 incompatible element concentrations (Fig. 5) are remarkably similar to those of ALHA81005, and far lower than those of other lunar regolith samples. The crust in the region(s) that spawned Y-791197 (and ALHA81005) was apparently close to, if not entirely, devoid of KREEP, a trait consistent with orbital spectrometry data (ADLER and TROMBKA, 1977) which indicate that abundant KREEP is found almost exclusively in the region of the central near side. Nonetheless, the pattern of incompatible element ratios is typically lunar.

The similarity between Y-791197 and ALHA81005, and their contrast with other lunar regolith samples, is further illustrated by a plot of “plagiophile” ratios such as Eu/Al vs. Ba/Sr (Fig. 6). As discussed by WARREN and KALLEMEYN (1984), a plagiophile element is one that has a solid/melt distribution coefficient close to 1 for plagioclase, but is incompatible (has distribution coefficients close to 0) with all other high-

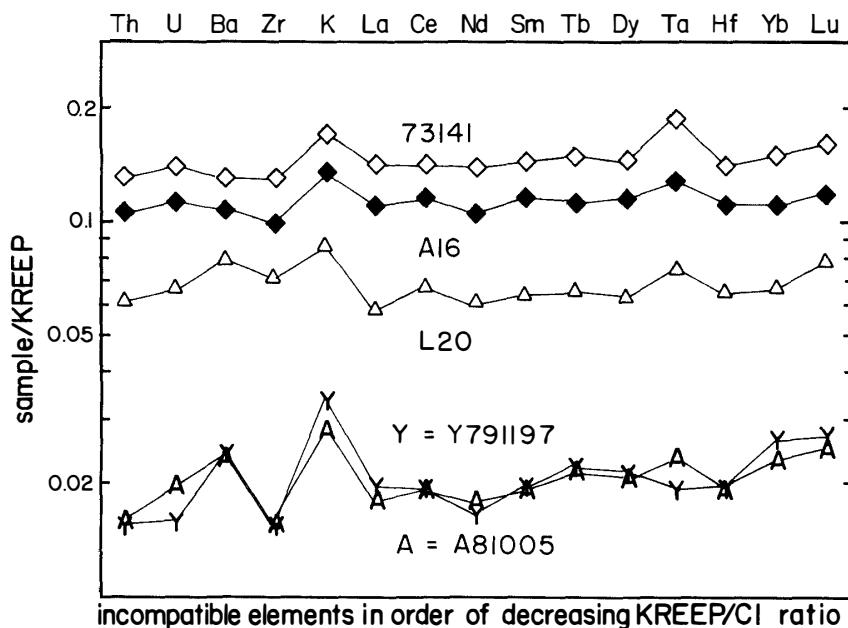


Fig. 5. Incompatible element concentrations in bulk-rock sample Y-791197,76, and literature averages of data for other lunar regolith samples (Table 1), normalized to the composition of high-K KREEP (WARREN and WASSON, 1979).

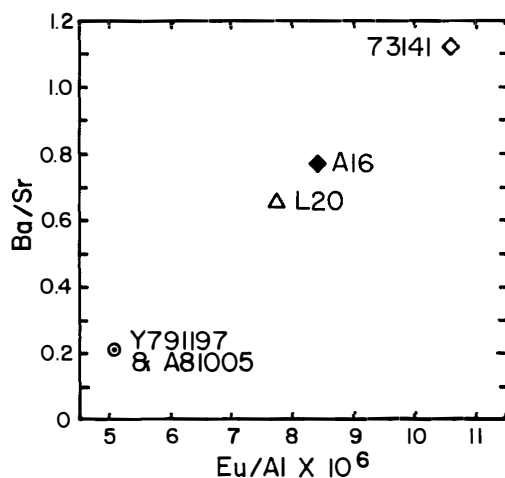


Fig. 6. "Plagiophile" ratios such as Eu/Al and Ba/Sr show a strong similarity between Y-791197,76 and ALHA81005 (averages of literature data for lunar regolith samples are from Table 1).

temperature lunar minerals, namely olivine and several varieties of pyroxene. Because ratios of plagiophile elements tend to evolve in highly systematic ways during igneous differentiation (WARREN and KALLEMEYN, 1984), these ratios are useful for elucidating relationships among lunar samples.

The ratios Sc/Sm and Ti/Sm are also commonly employed to study relationships among lunar rocks (e.g., NORMAN and RYDER, 1980). Scandium and Ti are most compatible with pyroxene and ilmenite, whereas Sm is a typical rare-earth element, incompatible with all major lunar minerals. As Fig. 7 shows, the Ti/Sm ratio of Y-791197

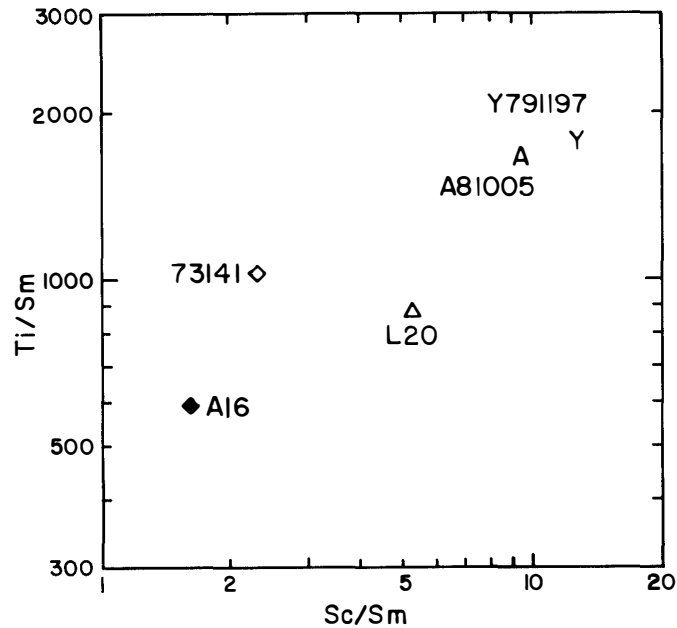


Fig. 7. Ratios Sc/Sm and Ti/Sm are similar in Y-791197 and ALHA81005.

is almost identical to that of ALHA81005. The Sc/Sm ratio of Y-791197 is slightly higher than that of ALHA81005.

There are several noteworthy differences between our analysis of Y-791197 and the mean data for ALHA81005. The Y-791197 bulk-rock Fe/Mn ratio (67.1) is slightly lower than the mean of the ALHA81005 data (73.6, Table 1). Scandium and V are considerably higher in Y-791197. Regarding Sc, FUKUOKA *et al.* (1985), LINDSTROM

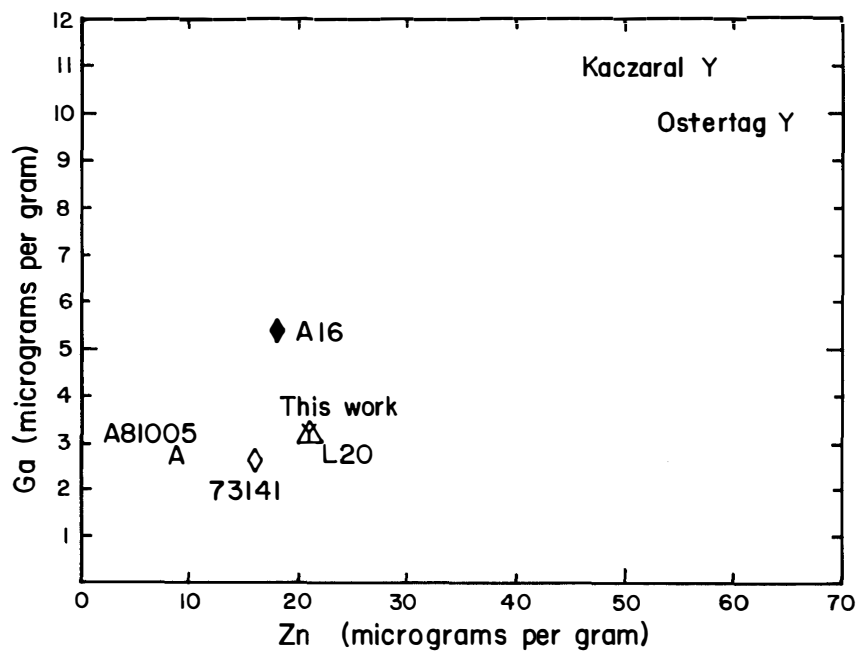


Fig. 8. Data scatter due to sampling problems (see text), but contents of volatile elements such as Zn and Ga appear to be higher in Y-791197 than in ALHA81005. Also shown are averages of literature data for other Al-rich lunar regolith samples (Table 1).

et al. (1985), and OSTERTAG *et al.* (1985b) found the same disparity. Aluminum is slightly higher in Y-791197 (again, FUKUOKA *et al.* (1985) found the same slight disparity).

Zinc content is also far higher in Y-791197 than in ALHA81005 (Fig. 8). Except for Br, Zn is the most volatile of the elements we determine. Comparison between our own analyses (this work; KALLEMEYN and WARREN, 1983) indicates that Br is also roughly $1.8\times$ higher in Y-791197,76, but we note that the *opposite* trend was found by LINDSTROM *et al.* (1985) in their Br data. OSTERTAG *et al.* (1985b) found a similar, but even greater, Zn disparity, and also a commensurate disparity in contents of the volatile Ga. KACZARAL *et al.* (1985) found similar Zn and Ga disparities, as well as commensurate disparities in contents of other volatile elements such as Cd, In, Sb and Te. KACZARAL *et al.* (1985) concluded from these different volatile element contents that Y-791197 and ALHA81005 “did not come from the same lunar region, hence were launched from the Moon in different impacts.”

Our data for Zn, Ga and Br indicate much smaller volatile element disparities between Y-791197 and ALHA81005 than found by OSTERTAG *et al.* (1985b) and KACZARAL *et al.* (1985). There is no reason to suspect a significant interlaboratory bias: Our Y-791197 data for Zn and Ga are in excellent agreement with the data of KACZARAL *et al.* (1985) for the larger of the two pieces they analyzed. Sampling problems are responsible for the discrepancies among the various Y-791197 analyses. The best estimate for the bulk composition of Y-791197 is a mass-weighted mean of all available data. Our bulk-rock sample's mass is 197 mg, as compared with 59 mg for the OSTERTAG *et al.* (1985b) sample, 19 mg for the most volatile-rich of the two KACZARAL *et al.* (1985) samples, and 71 mg for their other sample. Using these analyses, the mass-weighted Zn concentration of Y-791197 is $38\ \mu\text{g/g}$, and the mass-weighted Ga concentration is $6.2\ \mu\text{g/g}$. By lunar regolith standards, these concentrations are uncommonly high. But similar concentrations were observed by WASSON *et al.* (1975) in the undistinguished Apollo 16 regolith sample 61501: $34.6\text{--}36.1\ \mu\text{g/g}$ Zn, $6.16\text{--}6.30\ \mu\text{g/g}$ Ga. The volatile element disparities between Y-791197 and ALHA81005 mildly suggest, but by no means prove, that these two regolith breccias originally formed too far apart to have been launched to Earth by one impact.

Probably the most significant difference between Y-791197 and ALHA81005 is that the former appears to have a lower $\text{Mg}/(\text{Mg}+\text{Fe})$ or “*mg*” ratio. The mass-weighted mean of our three Y-791197 analyses (Table 1) implies an *mg* ratio of 0.636. The analysis of OSTERTAG *et al.* (1985b) implies $mg=0.659$, but analyses reported by YANAI and KOJIMA (1984), FUKUOKA *et al.* (1985), and NAKAMURA *et al.* (1985) imply $mg=0.61$, 0.59 and 0.60 , respectively. Assuming the “true” Y-791197 *mg* ratio is close to the average of these five measurements (0.62), Y-791197 has a far lower *mg* ratio than any other high-Al regolith sample (Table 1). In contrast, the *mg* ratio of the mean ALHA81005 data (0.727 , Table 1) is considerably *higher* than that of any other lunar regolith sample. To put these disparities in perspective, the range in *mg* among 20 regolith breccias analyzed from Apollo 16 is only $0.65\text{--}0.72$ (Fig. 9), even though the traverse stations that provided these samples are as far as 8 km apart, and the landing site was specifically chosen to approximately straddle the boundary between a Cayley Plains region and the Descartes Formation.

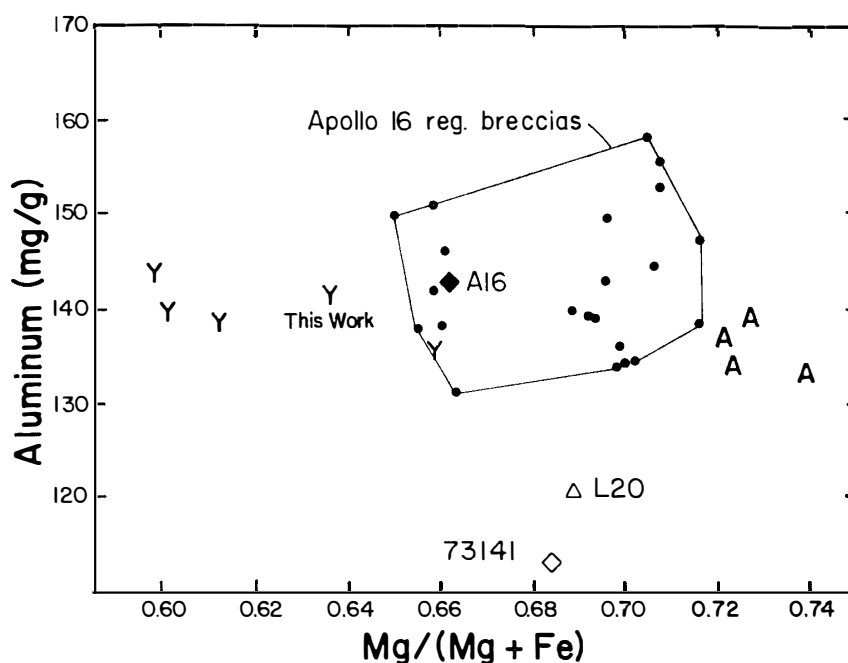


Fig. 9. Analyses from five different laboratories (see text) indicate that Y-791197 (“Y” symbols) has a similar Al content, but a much lower mg ratio than ALHA81005 (“A” symbols: for data sources see Table 1). Also shown are averages of literature data for Al-rich lunar soils (Table 1); and analyses of 20 different Apollo 16 regolith breccias, from MCKAY *et al.* (1986) and other references cited by RYDER and NORMAN (1980).

The distribution of Th in the regolith, as mapped over a sizeable fraction of the lunar highlands by orbital gamma-ray spectrometry (ADLER and TROMBKA, 1977; METZGER *et al.*, 1977), exhibits a striking asymmetry, with Th-rich regions concentrated mainly in the central near side (centered around roughly the same area visited by the Apollo and Luna landings). The low incompatible element contents of Y-791197 and ALHA81005 (Table 1, Fig. 5) imply that neither of these meteorites originated close to the Apollo and Luna regolith samples. Because we can rule out a large fraction of the near side, probability might seem to favor derivation of both these meteorites from the far side of the Moon. OSTERTAG *et al.* (1985a) suggested that Y-791197 is of far side origin. However, it must be realized that Th contents are highly non-uniform on a relatively small scale: the very lowest Th content measured by gamma-ray spectrometry ($0.24 \mu\text{g/g}$, which is marginally lower than the Y-791197 and ALHA81005 Th contents) was found not in the center of the far side, but on the western limb (“region 11”), in the longitude range $100\text{--}110^\circ \text{W}$ (METZGER *et al.*, 1977). The presence of mare basalt clasts in Y-791197 (LINDSTROM *et al.*, 1985) suggests that it formed close to one of the maria, which are strongly concentrated on the near side. Exactly which region(s) of the Moon provided these samples may never be determined to a meaningful degree of confidence. Incidentally, the fact that ALHA81005 also contains a smattering of mare basalt (TREIMAN and DRAKE, 1983) is another striking similarity between these two lunar meteorites.

The average plagioclase (*i.e.*, Al) content of the ancient nonmare crust is the single most important constraint affecting the crucial issue of whether or not a magma

“ocean” (or magmasphere) must be invoked to account for lunar crustal genesis. A magmasphere is probably the only plausible means of producing a crust with an average plagioclase content much greater than that of a basaltic partial melt, *i.e.*, much greater than about 55 wt% (WARREN, 1985). The CIPW norm of our Y-791197 analysis has (assuming $\text{SiO}_2 = 45$ wt%) 74.5 wt% plagioclase. Analyses of Y-791197 by other laboratories indicate similarly high Al contents (Fig. 9). This result strengthens the case for a primordial lunar magmasphere; especially if Y-791197 and ALHA81005 are from separate lunar locations.

5. Conclusions

The overall composition, especially the incompatible element contents, indicate that Y-791197 is definitely lunar, but originated far from the region of the Apollo and Luna samples, probably either on one of the Moon's limbs or on the far side.

The overall compositional similarity between Y-791197 and ALHA81005 strongly suggests that both originated within a single small region, *i.e.*, both were propelled to Earth by a single impact. However, disparities in volatile element contents (Fig. 8) and especially *mg* ratio (Fig. 9) suggest that these two meteorites may have come from separate impacts onto the Moon, their similarity in other respects notwithstanding. Regolith breccias propelled to Earth by a single impact would presumably tend to be compositionally similar, unless either (a) the impact was sufficiently large that the regolith breccias it “sampled” towards the Earth were typically formed far apart; or (b) the impact happened to occur close to a boundary between compositionally dissimilar terrains (in the most extreme case, a mare-highlands boundary). If the impact site was not close to a major crust-composition boundary, the size of the crater would probably (considering Fig. 9) have to be at least comparable to the spread between Apollo 16 sampling sites (8 km). In fact, samples would probably not be transmitted in the same Earthward direction unless both sources were within a relatively thin slice of the total area of the crater. The crater suggested by RYDER and OSTERTAG (1983) as the source of ALHA81005, Giordano Bruno, is 20 km across. Giordano Bruno is also within about 150 km of mare terrains in and around Maxwell and Lomonosov. A crater that is bigger and/or closer to a major crust-composition boundary might be better suited to account for the *mg* disparity between Y-791197 and ALHA81005. But considering the striking overall similarity between these two meteorites, we conclude that both were probably propelled to Earth by a single impact, the *mg* disparity notwithstanding.

The vast majority of lunar highlands rocks are not regolith breccias, but fragmental breccias, impact melt breccias, etc. Only about 10% of the Apollo 16 rocks are regolith breccias (RYDER and NORMAN, 1980). Admittedly our statistics are poor, but both lunar meteorites would probably not be regolith breccias unless the sampling mechanism, *i.e.*, impact ejection off the Moon, favored regolith breccias over other types of highland rocks. It seems unlikely that the impact process discriminates between solid breccias derived from soil and those derived from coarser lithic debris. However, the impact(s) that created these two regolith breccias out of former loose masses of regolith, a process that requires a shock pressure of roughly 100 kbar (KIEFFER, 1975), may have been the same impact(s) that propelled them Earthward. If this model is

correct, it implies that impact ejection from the Moon works most efficiently for materials within a few meters of the surface. Physical modeling of the ejection process (MELOSH, 1985) also indicates that the maximum depth from which an impact can spall material off of the Moon without melting it in the process is probably only a tiny fraction of the depth of the crater.

Both of the clasts we analyzed are anorthositic impact melt breccias. Occurrence of "ternary" feldspar in clast Y-791197,100 suggests that granites may constitute a minor fraction of the crust in the region parental to Y-791197. The high Al (plagioclase) content of Y-791197 tends to confirm the magmasphere hypothesis of earliest lunar evolution.

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