



Petrogenesis of lunar highlands meteorites: Dhofar 025, Dhofar 081, Dar al Gani 262, and Dar al Gani 400

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Abstract—The petrogenesis of four lunar highlands meteorites, Dhofar 025 (Dho 025), Dhofar 081 (Dho 081), Dar al Gani 262 (DaG 262), and Dar al Gani 400 (DaG 400) were studied. For Dho 025, measured oxygen isotopic values and Fe-Mn ratios for mafic minerals provide corroboratory evidence that it originated on the Moon. Similarly, Fe-Mn ratios in the mafic minerals of Dho 081 indicate lunar origin.

Lithologies in Dho 025 and Dho 081 include lithic clasts, granulites, and mineral fragments. A large number of lithic clasts have plagioclase AN# and coexisting mafic mineral Mg# that plot within the “gap” separating ferroan anorthosite suite (FAN) and high-magnesium suite (HMS) rocks. This is consistent with whole rock Ti-Sm ratios for Dho 025, Dho 081, and DaG 262, which are also intermediate compared to FAN and HMS lithologies. Although ion microprobe analyses performed on Dho 025, Dho 081, DaG 262, and DaG 400 clasts and minerals show far stronger FAN affinities than whole rock data suggest, most clasts indicate admixture of $\leq 12\%$ HMS component based on geochemical modeling. In addition, coexisting plagioclase-pyroxene REE concentration ratios in several clasts were compared to experimentally determined plagioclase-pyroxene REE distribution coefficient ratios. Two Dho 025 clasts have concordant plagioclase-pyroxene profiles, indicating that equilibrium between these minerals has been sustained despite shock metamorphism. One clast has an intermediate FAN-HMS composition.

These lunar meteorites appear to represent a type of highland terrain that differs substantially from the KREEP-signatured impact breccias that dominate the lunar database. From remote sensing data, it is inferred that the lunar far side appears to have appropriate geochemical signatures and lithologies to be the source regions for these rocks; although, the near side cannot be completely excluded as a possibility. If these rocks are, indeed, from the far side, their geochemical characteristics may have far-reaching implications for our current scientific understanding of the Moon.

INTRODUCTION

Despite contributions from the Apollo and Luna missions, two-thirds of the mare regions and the entire far side of the Moon are not represented in the lunar database (Pieters 1978). Furthermore, Clementine and Lunar Prospector remote sensing data indicate that the near and far sides are substantially different in terms of inferred chemical composition and lithologies (Spudis et al. 2000, 2002). Thus, it is likely that our understanding of the lunar geologic processes and history is incomplete. However, newly

discovered lunar meteorites could potentially supply the samples necessary to characterize previously unsampled terrains of the Moon. Recent meteorite finds from the Dhofar region of Oman (which account for nearly half of the 30 known lunar meteorites) may represent such samples.

In this study, we have examined the mineralogy and petrology of the four highland breccia meteorites Dhofar 025 (Dho 025), Dhofar 081 (Dho 081), Dar al Gani 262 (DaG 262), and Dar al Gani 400 (DaG 400). We have used geochemical (major, minor, and trace element) analyses of bulk rock and individual mineral grains to: 1) provide

evidence for the lunar origin of these rocks; 2) distinguish between mare and highland clasts; 3) identify the clasts least affected by shock metamorphism; 4) infer near or far side origins for these rocks; and 5) determine how this information can further improve our current understanding of the Moon.

ANALYTICAL TECHNIQUES

Thin sections of each meteorite were examined with an optical microscope using transmitted and reflected light. Major and minor element mineral compositions of plagioclase, olivine, and pyroxene in Dho 025 and Dho 081 were determined on a fully automated CAMECA SX-50 electron microprobe at the University of Tennessee using an accelerating voltage of 15 kV. For plagioclase analyses, a beam current of 20 nA and a spot size of 5 μm was used. Other minerals were analyzed with a beam current of 30 nA and a 2 μm spot size. The counting times were 20 sec for all elements analyzed in plagioclase and 30 sec for elements in all other minerals. Standard online matrix corrections (PAP) were applied to all analyses.

The oxygen isotopic composition of Dho 025 was determined at the University of Chicago. Separate splits weighing ~ 10 mg were analyzed using the procedure outlined by Clayton and Mayeda (1983, 1996). The whole rock chemical composition of Dho 025 was determined at the Vernadsky Institute, Moscow, Russia. An aliquot of a 1-g sample was powdered in an agate mortar to obtain homogeneous material for whole rock analyses. Silicon, Ti, Al, Cr, Fe, Mn, Mg, and Ca were determined by XRF and ICP. Sodium and K were measured by atomic absorption. Trace elements were analyzed by instrumental neutron activation analysis (INAA).

Minor and trace element (including REE) concentrations were determined for selected mineral grains and clasts in Dho 025, Dho 081, DaG 262, and DaG 400 using the modified CAMECA IMS 3f ion-microprobe at Washington University, St. Louis following the methods outlined by Zinner and Crozaz (1986a). Analyses were obtained using an O^- beam with an accelerating voltage of 12.5 kV. Secondary ions were collected at low mass resolution using energy filtering (100 V offset) to remove complex molecular interferences. Simple interferences not removed by this method were corrected by deconvolution of major molecular interferences in the mass regions K-Ca-Ti, Rb-Sr-Y-Zr, and Ba-REEs (Alexander 1994). Concentrations were obtained using sensitivity factors reported by Floss and Jolliff (1998), Hzu (1995), and Zinner and Crozaz (1986b) for the REE and by Hsu (1995) for other elements. All mineral analyses were normalized to the reference element, Si, using SiO_2 concentrations determined by electron microprobe.

Polymineralic clast analyses were normalized using an SiO_2 concentration of 50 wt%, a value that should be fairly representative of the average SiO_2 concentrations of the clasts, based on the abundances of the minerals present

(plagioclase, pyroxene, and olivine) and their average SiO_2 concentrations (44 wt%, 50 wt%, and 35 wt%, respectively). This approach may overestimate the trace element concentrations of clasts with high proportions of plagioclase and olivine, but the effect should be less than 15% in most clasts. Some error may also be introduced by the fact that different minerals in the matrices of polymineralic clasts have different ion yields, but it is difficult to estimate the magnitude of this effect. However, we note that the difference in relative sensitivity factors between various REE is $<30\%$ for a wide variety of standards (including oxides, silicates, and glass) and, thus, relative REE concentrations (i.e., the shapes of the patterns) are not affected by this approach.

PETROGRAPHY AND MINERAL CHEMISTRY

Dho 025, an anorthositic regolith breccia weighing 751 g, was found in Dhofar, Oman in January of 2000 (Grossman 2000). Dho 081, a shocked, feldspathic fragmental highlands breccia, was discovered a year earlier. The cosmogenic exposure age for Dho 025 is between 13–20 Myr (Nishiizumi et al. 2002). However, for Dho 081, the transition time between the Moon and the Earth was too short for detectable amounts of long-lived nuclides to be produced (Nishiizumi et al. 2002). The lithologies present in these two meteorites include: 1) lithic clasts, 2) granulites, and 3) mineral fragments. A summary of clast types and their mineral compositions is listed in Table A1.

Lithic clasts are the dominant lithology in Dho 025 (Figs. 1a–1b). These clasts are partially recrystallized monomict and polymict rocks with anorthositic to troctolitic-anorthositic compositions. Monomict rocks consist of single-crystal plagioclase with subhedral to spherical mafic inclusions (Figs. 1c–1d), similar to rocks from North Ray Crater (Norman 1981). These clasts are 100–200 μm in size and are predominantly plagioclase (AN# 96–98) with olivine inclusions of homogenous composition (Fo 69–80). Polymict rocks range from recrystallized anorthosites to microporphyritic crystalline melt-rocks. They consist mainly of plagioclase (AN# 94–98), with minor amounts of mafic minerals (Mg# 64–83) (Fig. 2a). Mafic minerals in these clasts have subhedral shapes due to interaction with an impact melt.

Only one granulitic troctolite clast was observed in Dho 025 (Fig. 1e). It has a granoblastic texture (Cushing et al. 1999) and consists of plagioclase (AN# 96) and olivine (Fo 79) grains. Mineral fragments (Fig. 1f) present in the breccia matrix include plagioclase (AN# 95–98), orthopyroxene (Mg# ~ 75), pigeonite (Mg# 65–69), and augite (Mg# 66–80). Accessory minerals include spinel, ilmenite, FeNi metal, troilite, and silica. Akaganéite ($\beta\text{-FeOOH}$) occurs as rims on FeNi metal grains and is most likely of terrestrial origin. Other terrestrial alteration products (calcite, celestite, and gypsum) are also present in the meteorite, mainly filling cracks.

Compared to Dho 025, Dho 081 is poor in mafic mineral

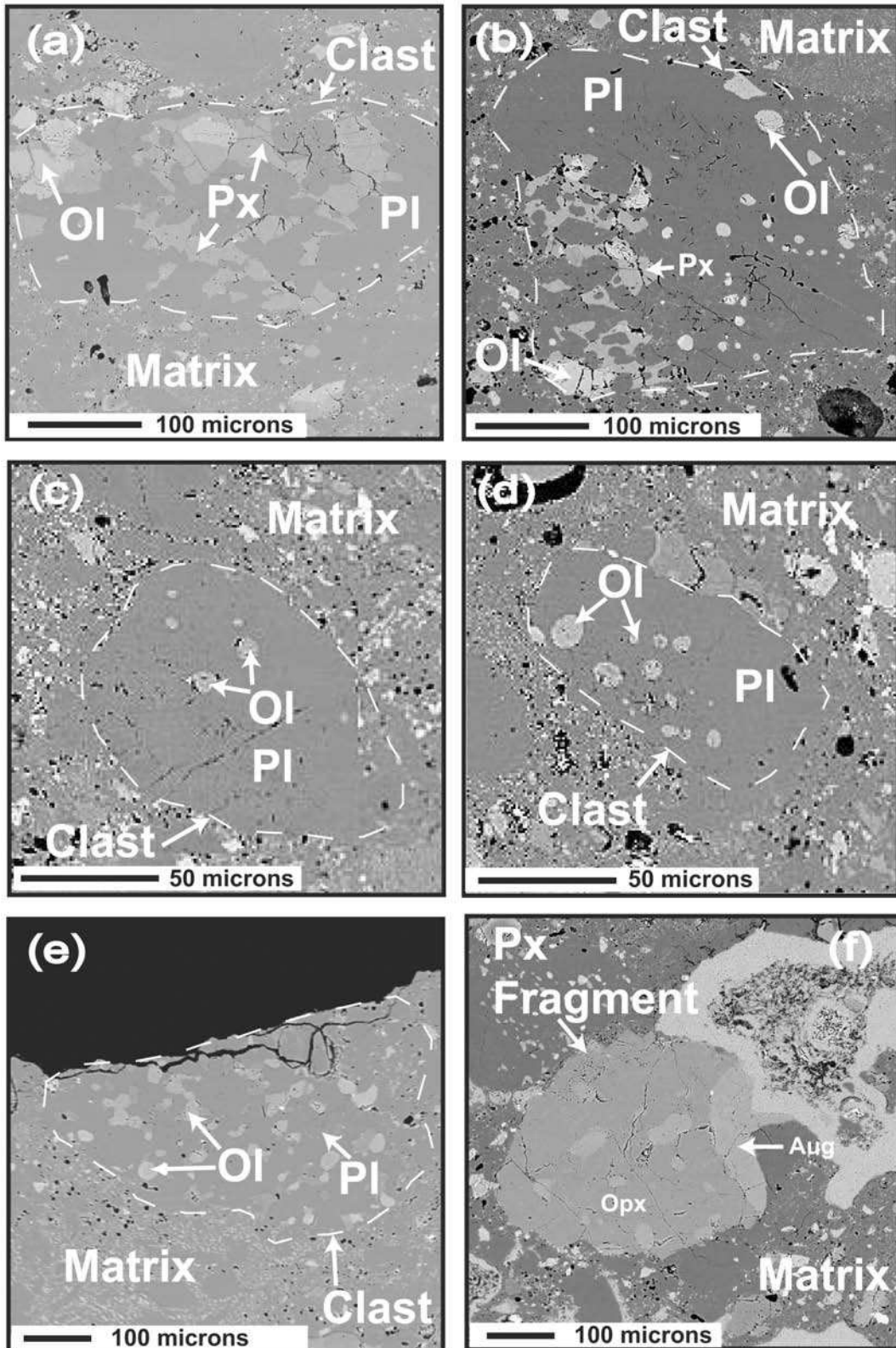


Fig. 1. Backscattered electron images of lunar meteorite Dho 025: a and b) lithic clasts with embayed mafic minerals resulting from interaction with impact melt. These clasts are surrounded by a fine-grained and glassy meteorite matrix; c and d) two single-crystal plagioclase clasts with spherical olivine inclusions; e) granulite clast consisting of plagioclase and olivine mineralogy and exhibiting a granoblastic texture; f) biminerally pyroxene fragment consisting of augite and orthopyroxene.

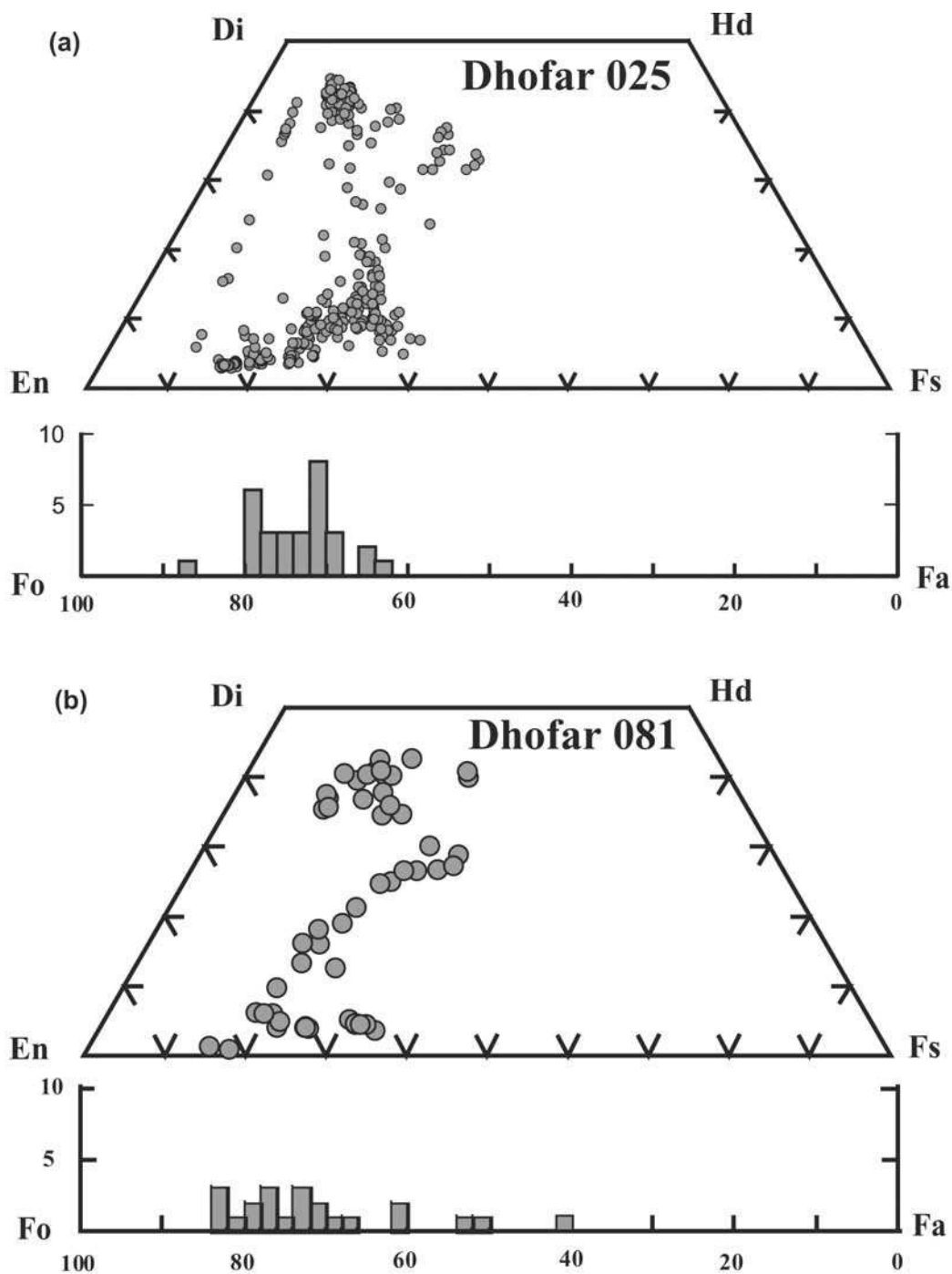


Fig. 2. Pyroxene and olivine major element compositions for lunar meteorites (a) Dho 025 and (b) Dho 081.

constituents. Lithic clasts in this breccia are partially recrystallized anorthosites that dominantly consist of plagioclase (AN# 94–97), with embayed and/or zoned mafic minerals (Figs. 3a–3c). Olivine is the most abundant mafic mineral (Fo 56–83), while pyroxene (Mg# 58–78) is a minor constituent in these clasts (Fig. 2b). Granulite lithologies in Dho 081 range from 200–500 μm in size and have granoblastic textures (Fig. 3d). Though consisting mostly of

plagioclase (AN# 96–97), these clasts also contain fine-grained olivines with compositions of Fo 70–75. The majority of Dho 081 clasts are individual mineral fragments (Figs. 3e–3f). Plagioclase fragments (AN# 94–98) are most abundant, while mafic mineral fragments are mainly olivine, often with pyroxene rims. Olivine fragments commonly exhibit reverse zoning (e.g., core: Fo ~71 versus rim: Fo ~80). One olivine grain (~350 μm ; Fig. 3e) in particular is characterized by a

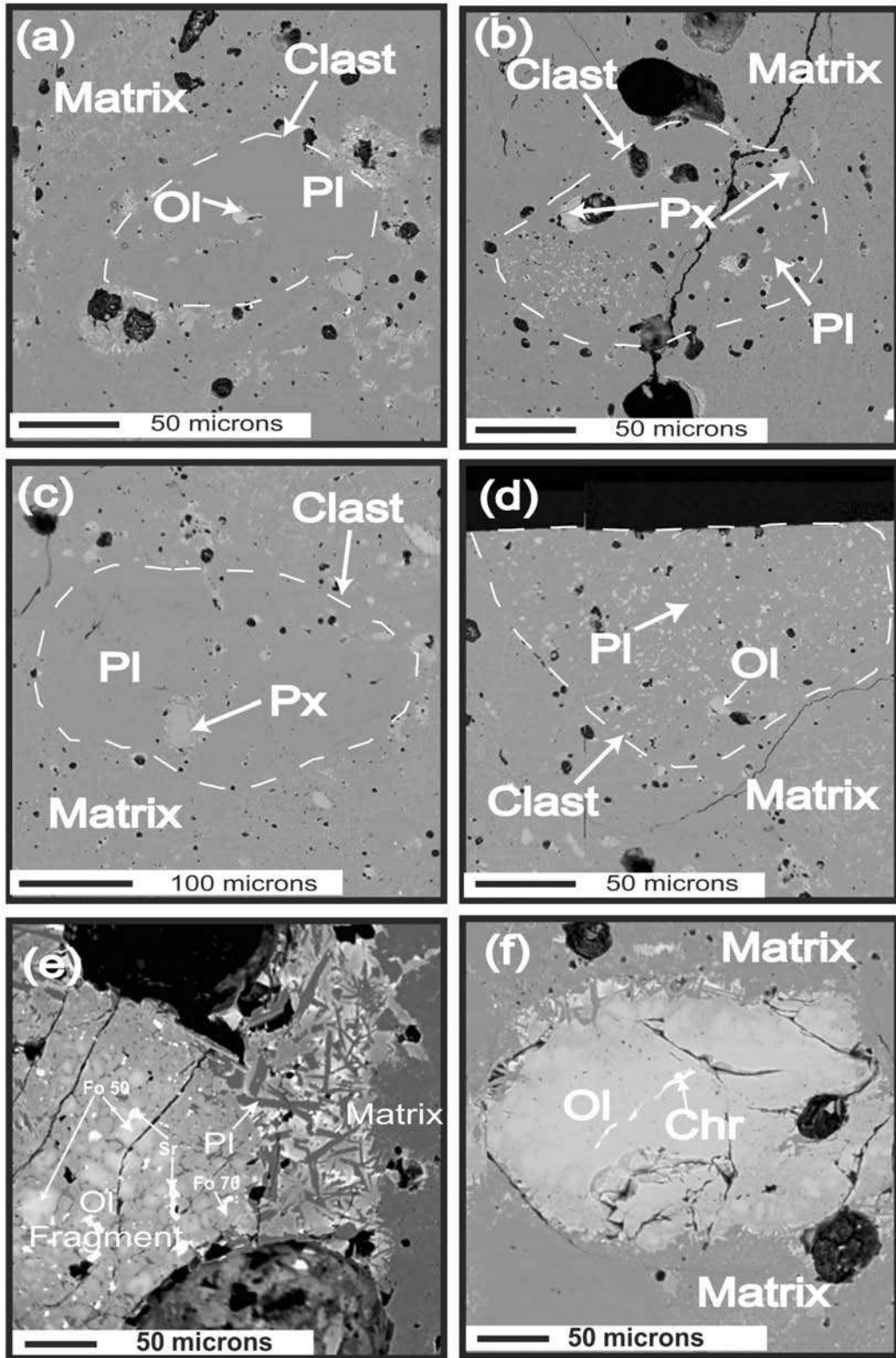


Fig. 3. Backscattered electron images of lunar meteorite Dho 081: a–c) mafic-poor lithic clasts; d) granoblastic granulite with fine-grained olivine mineralogy; e) backscattered electron image of a heavily melted and embayed relic olivine mineral fragment with several vesicles in and around the edges. This olivine fragment has reverse zonation (core: Fo ~50; rims: Fo ~70) probably due to re-equilibration with the impact melt matrix; f) olivine mineral fragment with chromite vein.

compositional variance of Fo ~20 from core to rim (i.e., Fo ~50 to Fo ~70). Reverse zoning is likely due to interaction with an impact melt. Monomineralic pyroxene grains are also compositionally variable (Mg# 41–72). Accessory minerals in the meteorite matrix include Cr-spinel, Ti-chromite, and troilite.

Lunar meteorites DaG 262 and DaG 400 are also anorthositic breccias (Bischoff et al. 1998; Zipfel et al. 1998). In the present study, we have only made trace element measurements in a number of DaG 262 and DaG 400 clasts. Bischoff et al. (1998) carried out a detailed characterization of the types of clasts present in DaG 262 and their mineral chemistries and note that this meteorite is dominated by feldspathic, fine-grained to microporphyritic crystalline melt clasts. Granulitic clasts, as well as recrystallized and cataclastic anorthosites, are also present, but mafic mineral-rich clasts are rare. Plagioclase is highly anorthitic (AN# ≥ 95), and mafic minerals (olivine and pyroxene) have Mg#s ranging from 50 to 70 (Jolliff et al. 1999), suggesting an affinity to the ferroan anorthosite (FAN) suite for much of the material in this meteorite. Similarly, DaG 400 is dominated by anorthositic clasts, most of which are fine-grained to microporphyritic impact melt clasts (Zipfel et al. 1998). Recrystallized anorthosites, granulites, and mineral fragments are also present, but as in DaG 262 and Dho 081, mafic lithologies are rare. Plagioclase in all DaG 400 lithologies ranges from AN 94–98 (Semenova et al. 2000). Mafic minerals associated with anorthosites (which make up 95% of all clasts) have more ferroan compositions (in the FAN range) than anorthositic norites and troctolites, which fall in the FAN-high magnesium suite (HMS) “gap” (Semenova et al. 2000).

Like DaG 400, Dho 025 and Dho 081 have lithologies with strong FAN affinities, but some clasts plot within the FAN-HMS gap (Figs. 4 and 5). Traditionally, pristine Apollo and Luna rocks, as well as other lunar meteorites have plotted within the FAN and HMS envelopes. Rocks that plot in between (i.e., in the FAN-HMS gap) have been classified under the general term “lunar granulites” (Bickel and Warner 1978; Lindstrom and Lindstrom 1986; Norman 1981). Several other recent characterizations of minerals in lunar meteorites have revealed clast compositions plotting regularly in this gap but without textures typical of granulites (Cushing et al. 1999). Meteorites that display these gap compositions without characteristic granulitic textures include three of the four lunar meteorites in this study (DaG 400, Dho 025, and Dho 081) and several other Dhofar meteorites (Dho 280, Dho 301, Dho 302, and Dho 303) (Anand et al. 2002; Nazarov et al. 2002; Semanova et al. 2000). Since the clasts in these meteorites show neither pristine nor granulitic textures, we have classified them as mixed impactites. This designation denotes the possibility that these clasts are mixtures of FAN and HMS components created by impact melting. However, the possibility exists that these clasts may retain information from pristine crustal

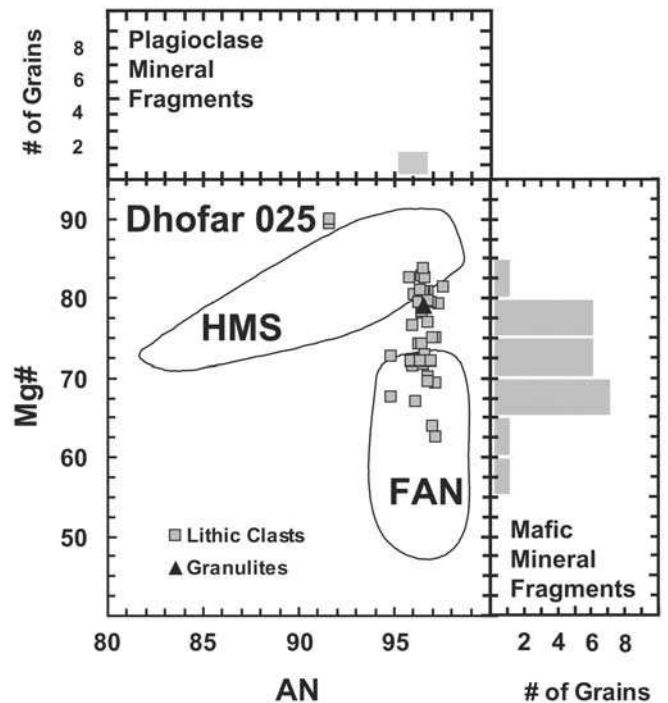


Fig. 4. Mafic phase (olivine and pyroxenes) Mg# versus AN# in plagioclase for Dho 025 clasts. Compositional fields for FAN and HMS rock suites are shown for comparison (Warren 1985). Mg# for mafic mineral fragments that lack coexisting plagioclase grains are shown on the right portion of the diagram, and AN# for plagioclase fragments lacking coexisting mafic mineral grains are shown on the top portion of the diagram.

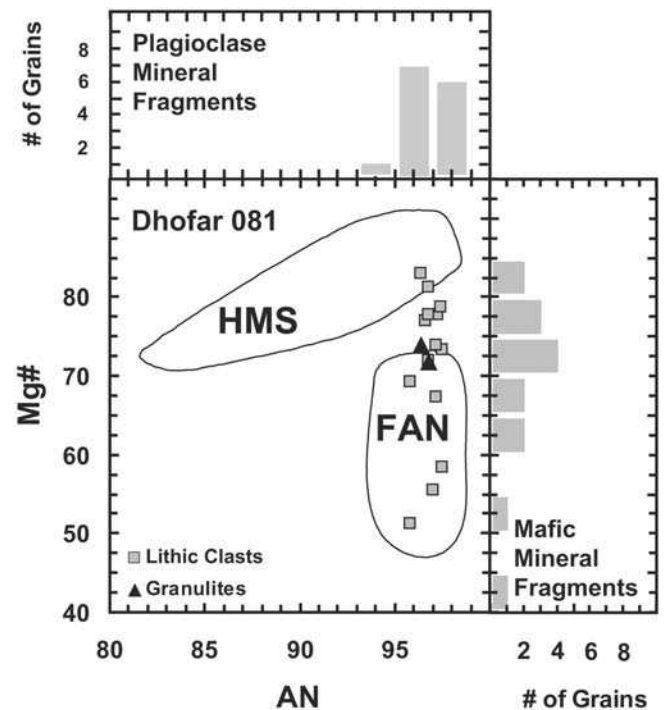


Fig. 5. Mg# versus AN# plot for Dho 081 clasts. The symbols and fields are the same as in Fig. 4.

lithologies. Therefore, both possibilities were investigated further using whole rock, clast, and mineral composition data.

EVIDENCE FOR LUNAR ORIGIN

Fe-Mn Ratios

It is well known that Fe and Mn distributions in some minerals are diagnostic of their parent bodies (Laul et al. 1972). Conditions of the initial accreted material, the extent of core formation, and the oxygen fugacity of a particular body constrain the Fe-Mn ratios of the parent body (Papike 1998). In the case of the Moon, an additional factor affecting Fe-Mn distributions among minerals may have been the loss of relatively volatile Mn during the Moon-forming impact event (Papike 1998; Papike et al. 2003).

Figure 6 shows the Fe-Mn ratios of olivines and pyroxenes from Dho 025 and Dho 081. Although olivines from both meteorites plot along the lunar trend, pyroxenes appear to have slightly elevated Mn with average pyroxene Fe-Mn ratios in Dho 025 and Dho 081 of 49.7 and 52.3, respectively. These observations may indicate that fractionation of Fe and Mn in olivine differs slightly from that of pyroxene. However, this is difficult to determine considering the low concentrations of both Fe and Mn in these

minerals. A simpler explanation may be that the observed variations are due to the difference in lithologies analyzed in this study compared to that by Papike (1998) (i.e., anorthosite versus basalt), which established the basis for such discriminations. Differences between these two rock types in starting bulk composition or subsequent crystallization sequences may account for the elevated levels of Mn. Nonetheless, the average Fe-Mn ratios in the olivine and pyroxene of Dho 025 and Dho 081 (86.0 and 87.9, respectively) are consistent with Apollo and Luna rocks. Furthermore, the whole rock Fe-Mn ratio for Dho 025 is 65.7, similar to the lunar meteorite average of 70 (Palme et al. 1991).

Oxygen Isotopes

The Dho 025 oxygen isotope composition is $\delta^{18}\text{O} = +5.47\text{‰}$ and $\delta^{17}\text{O} = +2.81\text{‰}$ (Taylor et al. 2001). This composition lies along the terrestrial-lunar fractionation line (TLFL) (Fig. 7) and is consistent with results for other lunar meteorites including DaG 262 and DaG 400. In addition, the oxygen isotope data also agree with those of Apollo mare basalts and highlands rocks. Minor deviations from the TLFL are attributed to desert weathering influences (Stelzner et al. 1999).

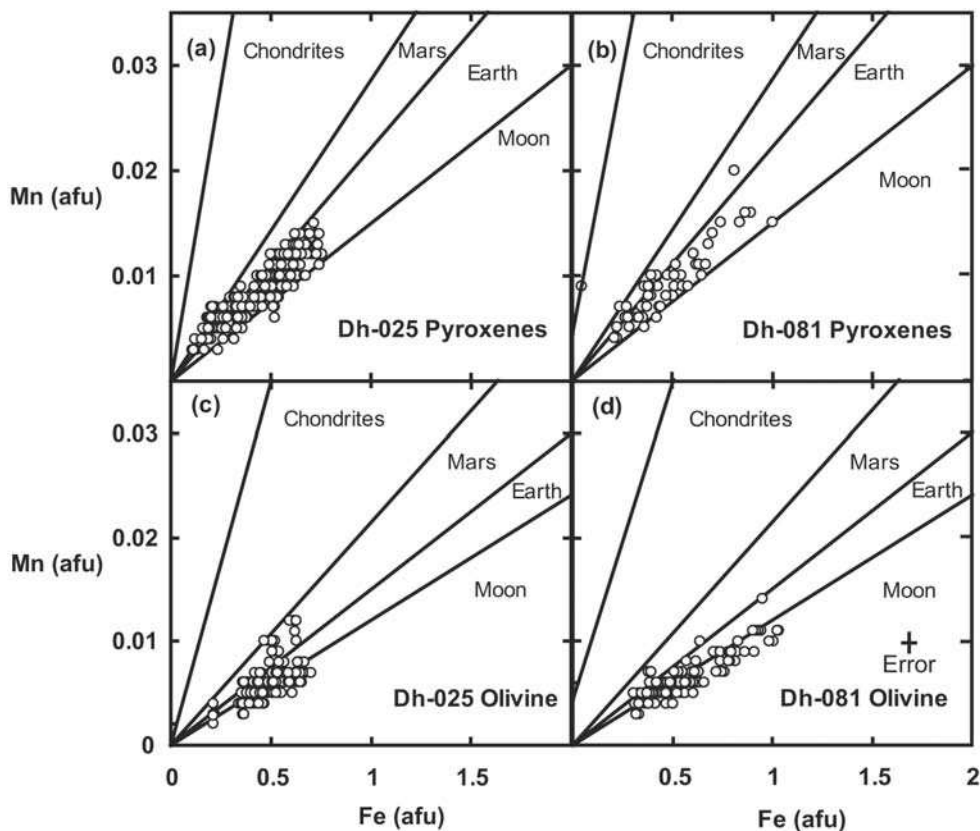


Fig. 6. Fe-Mn ratios for Dho 025 and Dho 081: a and b) pyroxene; c and d) olivine. The Fe-Mn ratios in olivines are typical of lunar rocks. However, the Mn concentrations in pyroxenes for both Dho 025 and Dho 081 are slightly elevated. The Fe-Mn trends for various planetary bodies are from Papike (1988) and Papike et al. (2003).

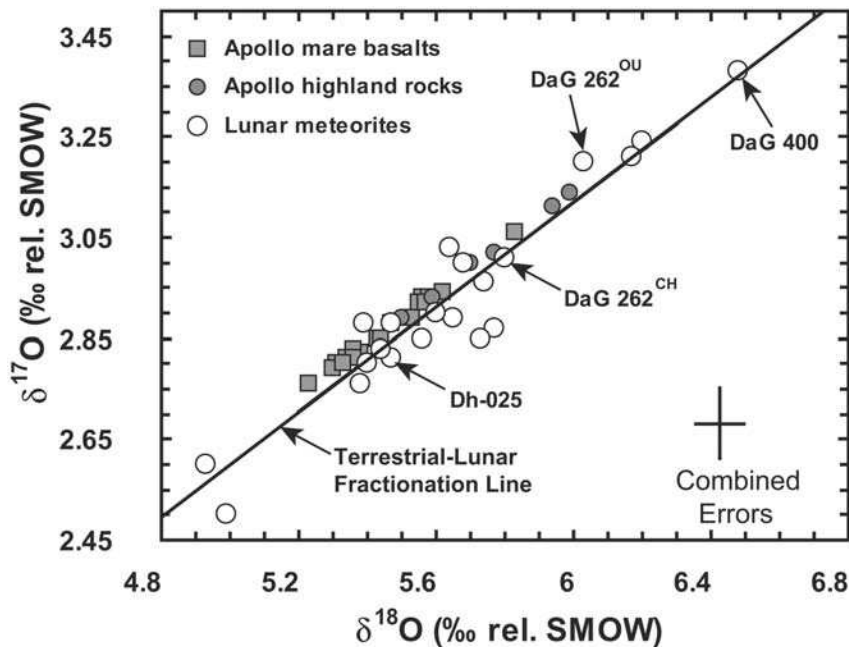


Fig. 7. The oxygen isotopic composition of Dho 025 compared to other lunar meteorites, Apollo mare basalts, and Apollo highland rocks (Arai and Warren 1999; Clayton and Mayeda 1983, 1996; Fagan et al. 2000, 2001a; Kaiden and Kojima 2002; Kojima and Imae 2001; Wiechert et al. 2001). Data for DaG 262 and 400 were reported by Bischoff et al. (1998) and Zipfel et al. (1998), respectively. One analyses of DaG 262 was made at Chicago University (CH) and one at Open University (OU).

WHOLE ROCK COMPOSITIONS

The whole rock composition of Dho 025 was compared to those of Dho 081, DaG 262, DaG 400, other lunar highlands and mare meteorites, as well as Apollo samples (Table 1). Most of the known lunar meteorites (~80%) are breccias or impact melts with highlands characteristics (e.g., Dho 026, MAC 88104/5, Y-86032, Y-82192, ALH A81005, Y-791197, and QUE 93069). However, some lunar meteorites (e.g., Dho 287, QUE 94281, Y-793272, Y-981031, EET 87521, EET 96008, A-881757, and NWA 032) contain substantial mare basalt components. Highlands rocks and mare basalts can have similar trends on Mg# versus AN# plots, but they can be distinguished by their Fe-Sc ratios (Palme et al. 1991). Figure 8 shows that Dho 025, Dho 081, DaG 262, and DaG 400 have similar Fe-Sc ratios, close to the typical highland average of ~4000.

Figure 9 compares Dho 025, Dho 081, DaG 262, DaG 400, and other lunar highland meteorites with highlands regolith samples from the Apollo 14 and 16 sites (Korotev 1997; Warren and Wasson 1980). Using these diagrams, the relative proportions of modal pyroxene (Sc, Sm) and plagioclase (Al_2O_3) can be inferred. Dho 025, Dho 081, DaG 262, and DaG 400 have similar concentrations of Sc and Al_2O_3 to Apollo 16 regolith breccias (Fig. 9a). In contrast, all lunar highlands meteorites have systematically depleted Sm concentrations (by a factor of 10) compared to Apollo 14 and 16 highlands regolith (Fig. 9b). Thus, these data suggest that although these meteorites are composed of highlands material,

they are compositionally different from the Apollo and Luna highlands regolith samples collected to date. The large compositional separation between Apollo regolith breccias and lunar meteorites, in Fig. 9b, suggests that these meteorites represent a distinct compositional suite. Considering their highly anorthositic nature and the apparent lack of KREEP, these meteorites may represent a type of crustal terrain that differs significantly from the KREEPy impact melt breccias that are prevalent in the Apollo collection. Because of these readily apparent differences, the highland regions of the lunar far side appear to be likely candidates for the source areas of these rocks. However, it is also possible that a previously unsampled KREEP-poor highland terrain on the lunar near side is the source region for these meteorites. In either case, these lunar meteorites represent new lithological variants in the lunar database and may provide additional clues about the genetic history of the Moon.

Dho 025 has a lower Al_2O_3 concentration (26.1 wt%) compared to most other lunar highlands meteorites. In contrast, Dho 081 and DaG 400 have the highest concentrations of Al_2O_3 (30.5 and 29.2 wt%, respectively) and, thus, are consistent with having the largest modal percentage of plagioclase relative to other lunar meteorites. These two meteorites represent the most anorthositic compositions of all lunar highlands meteorites reported to date (Fig. 9a).

Dho 025, Dho 081, DaG 262, and DaG 400 have low concentrations of Na, Th, Ti, and other incompatible elements compared to typical Apollo 14 and 16 highlands regolith

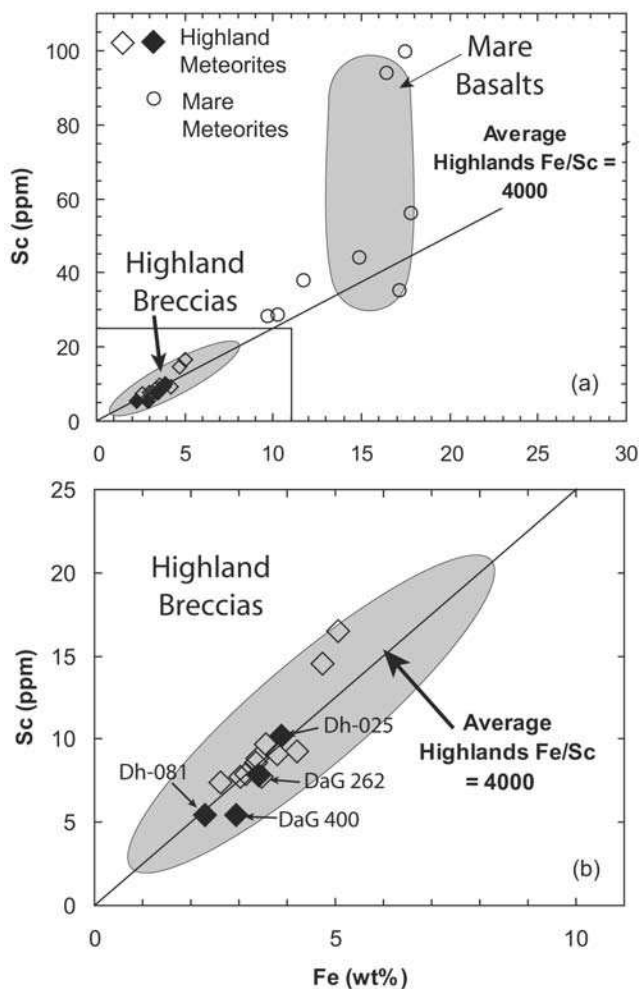


Fig. 8. Whole rock Fe versus Sc easily distinguishes mare and highland lithologies: a) mare and mixed lithologies (Dho 287, QUE 94281, Y-793272, Y-981031, EET 87521, EET 96008, A-881757, and NWA 032) are shown as open circles (Anand et al. 2003; Demidova et al. 2002; Fagan et al. 2001b; Jolliff et al. 1998; Koeberl et al. 1991b; Lindstrom et al. 1991; Snyder et al. 1999; Warren and Kallemeyn 1989, 1993); b) enlarged view of the highland breccia suite. The filled diamonds are lunar highland meteorites Dho 025, Dho 081, DaG 262, and DaG 400 (Bischoff et al. 1998; Warren et al. 2001; Zipfel et al. 1998). The open diamonds represent highland meteorites from other studies (Dho 026, MAC 88104/5, Y-86032, Y-82192, ALH A81005, Y-791197, and QUE 93069) (Cohen et al. 2003; Koeberl et al. 1991a; Korotev et al. 1996; Neal et al. 1991; Palme et al. 1991; Semanova et al. 2000; Spettel et al. 1995).

breccias but have concentrations similar to those of other lunar meteorites (Table 1). Siderophile element (Re, Os, Ir, and Au) abundances in Dho 025 are similar to other highlands meteorites, but Dho 081 is depleted (Bischoff et al. 1998; Palme et al. 1991).

Compared to other FAN, HMS, and KREEP rocks (Taylor 1982), Dho 025, Dho 081, and DaG 262 have intermediate Ti-Sm ratios (Fig. 10). All highlands meteorites (with the exception of Y-82192 and QUE 93069) have similar Ti-Sm ratios and Mg#. These compositions may have resulted

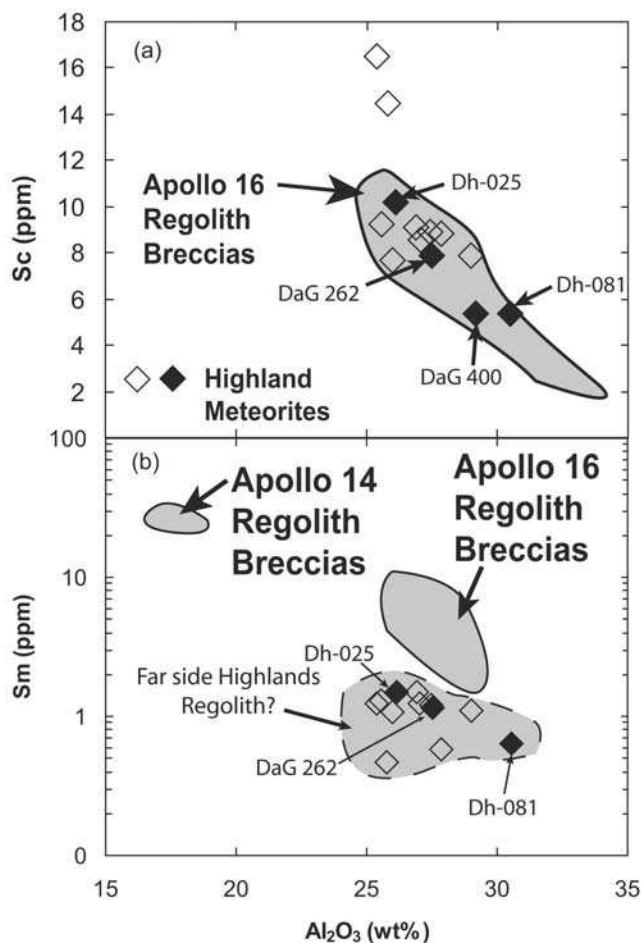


Fig. 9. Whole rock Sc and Sm versus Al_2O_3 in lunar meteorites: a) Apollo 16 regolith compositional envelope (Korotev 1997) is shown for comparison; b) compositional envelopes for Apollo 14 and Apollo 16 regoliths (Warren and Wasson 1980) are shown for comparison. Lunar highlands meteorites Dho 025, Dho 081, and DaG 262 are shown as filled diamonds (Bischoff et al. 1998; Warren et al. 2001; Zipfel et al. 1998). Other lunar highland meteorites are shown as open diamonds (Cohen et al. 2003; Koeberl et al. 1991a; Korotev et al. 1996; Neal et al. 1991; Palme et al. 1991; Semanova et al. 2000; Spettel et al. 1995).

from mixing between HMS and FAN-rich constituents. However, another possible interpretation is that these meteorites are, in fact, FAN rocks, and the FAN and HMS rocks are more closely related than previously thought. We have attempted to further constrain these two possibilities by analyzing trace elements in single, fine-grained to microcrystalline clasts with SIMS. A major premise of these analyses is that they represent whole rock compositions of individual clasts without the influence of the meteorite matrix.

Terrestrial Weathering

It has been noted previously that desert weathering tends to alter the LREE chemistry of hot-desert meteorites,

Table 1. Bulk composition of Dho 025, Dho 081, DaG 262, DaG 400, and other lunar highland meteorites.^a

| | Dho 025 | Dho 081 | DaG 262 | DaG 400 | DaG 400 | Average highland meteorites | Average mare/mixed meteorites | Average A-16 highland regolith | Average FANs | Average HMS |
|--------------------------------|-------------------|---------|-------------------|---------|---------|-----------------------------|-------------------------------|--------------------------------|--------------|-------------|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| SiO ₂ (wt%) | 43.9 | 44.9 | n.d. ^b | 43.4 | n.d. | n.d. | n.d. | n.d. | 44.7 | 45.8 |
| TiO ₂ | 0.30 | 0.15 | 0.22 | 0.23 | 0.18 | 0.27 | 0.57 | 0.38 | 0.09 | 0.30 |
| Al ₂ O ₃ | 26.1 | 30.5 | 27.5 | 28.6 | 29.2 | 26.3 | 24.8 | 28.4 | 32.9 | 19.0 |
| FeO | 4.98 | 2.93 | 4.40 | 3.52 | 3.78 | 5.24 | 6.60 | 4.18 | 1.71 | 6.45 |
| MnO | 0.08 | n.d. | n.d. | 0.06 | 0.05 | 0.07 | n.d. | n.d. | 0.03 | 0.09 |
| MgO | 6.53 | 2.82 | 5.21 | 3.80 | 5.14 | 6.10 | 6.80 | 4.53 | 1.62 | 16.6 |
| CaO | 16.1 | 16.8 | 16.5 | 18.7 | 17.4 | 15.4 | 15.8 | 16.4 | 18.6 | 10.7 |
| Na ₂ O | 0.282 | 0.31 | 0.35 | 0.33 | 0.32 | 0.33 | 0.45 | 0.45 | 0.33 | 0.34 |
| K ₂ O | 0.07 | 0.02 | 0.05 | 0.10 | 0.07 | 0.02 | 0.07 | 0.12 | 0.03 | 0.08 |
| P ₂ O ₅ | 0.08 | n.d. | 0.06 | n.d. | 0.11 | 0.02 | n.d. | n.d. | 0.02 | 0.25 |
| H ₂ O | 0.03 | n.d. | n.d. | n.d. | n.d. | 0.30 | n.d. | n.d. | n.d. | n.d. |
| Sc (ppm) | 10.2 | 5.40 | 7.85 | n.d. | 5.40 | 9.06 | 52.0 | 7.46 | 3.77 | 3.30 |
| Cr | 674 | 410 | 639 | n.d. | 550 | 699 | 1927 | 561 | 207 | 729 |
| Co | 16.5 | 9.80 | 22.0 | n.d. | 14.0 | 17.0 | 39.7 | 17.8 | 4.16 | 24.8 |
| Ni | 200 | 85.0 | 270 | n.d. | 113 | 177 | 87.8 | 212 | 9.56 | 115 |
| Ga | 3.10 ^c | 2.40 | 4.25 | n.d. | n.d. | 3.43 | 6.75 | n.d. | n.d. | n.d. |
| Sr | 2010 | 240 | 245 | n.d. | 190 | 251 | 159 | 181 | 159 | 102 |
| Ba | 130 ^c | 19.0 | 240 | n.d. | 140 | 65.5 | 101.5 | 81.9 | 9.59 | 194 |
| Zr | 62.0 | n.d. | 34.0 | n.d. | n.d. | 35.4 | 97.6 | 168 | 31 | 84 |
| Cs | 0.550 | n.d. | 0.120 | n.d. | n.d. | 0.142 | 0.075 | 0.126 | 0.019 | 0.29 |
| La | 3.60 | 1.43 | 2.44 | n.d. | n.d. | 2.58 | 7.36 | 6.64 | 0.334 | 7.66 |
| Ce | 8.60 | 3.40 | 7.25 | n.d. | n.d. | 6.60 | 19.1 | 30.9 | 0.838 | 19.9 |
| Nd | 5.20 | 1.90 | 3.25 | n.d. | n.d. | 3.80 | 13.9 | 18.4 | 0.691 | 12.5 |
| Sm | 1.50 | 0.630 | 1.15 | n.d. | n.d. | 1.17 | 4.00 | 3.10 | 0.131 | 3.10 |
| Eu | 1.30 | 0.700 | 0.730 | n.d. | n.d. | 0.810 | 1.00 | 1.04 | 0.769 | 1.19 |
| Tb | 0.35 | 0.150 | 0.240 | n.d. | n.d. | 0.243 | 0.880 | 1.12 | 0.036 | 0.663 |
| Ho | 0.44 ^c | 0.180 | 0.300 | n.d. | n.d. | 0.282 | n.d. | n.d. | n.d. | n.d. |
| Yb | 1.20 | 0.510 | 0.910 | n.d. | n.d. | 0.966 | 3.31 | 2.28 | 0.16 | 2.05 |
| Lu | 0.210 | 0.073 | 0.130 | n.d. | n.d. | 0.142 | 0.482 | 0.321 | 0.014 | 0.284 |
| Hf | 1.30 | 0.440 | 0.850 | n.d. | n.d. | 0.874 | 2.78 | n.d. | 0.126 | 0.804 |
| Ta | <0.3 ^c | <0.1 | 0.110 | n.d. | n.d. | 0.130 | 0.380 | n.d. | n.d. | n.d. |
| Th | 0.80 | <10 | 0.430 | n.d. | n.d. | 0.411 | 0.923 | 1.095 | 0.0364 | 1.26 |
| U | 0.27 | <300 | 0.210 | n.d. | n.d. | 0.132 | 0.248 | 0.526 | n.d. | 0.239 |
| Re (ppb) | <20 ^c | 5.00 | n.d. | n.d. | n.d. | 22.5 | n.d. | n.d. | n.d. | n.d. |
| Os | <300 ^c | 5.20 | n.d. | n.d. | n.d. | 283 | n.d. | n.d. | n.d. | n.d. |
| Ir | 7.20 | 0.200 | 12.0 | n.d. | 4.0 | 38.9 | 6.40 | 12.2 | 0.351 | 0.072 |
| Au | 3.00 | 0.070 | 4.30 | n.d. | n.d. | 3.27 | 3.10m | 9.94 | 0.441 | 0.075t |

^a(1) This study; (2) Warren et al. (2001); (3) Bischoff et al. (1998); (4) Semenova et al. (2000); (5) Zipfel et al. (1998); (6) Cohen et al. (2002), Palme et al. (1991), Koeberl et al. (1991), Neal et al. (1991), Spettel et al. (1995), Korotev et al. (1996), Warren et al. (2001), Bischoff et al. (1998), Semenova et al. (2000), Zipfel et al. (1998); (7) Anand et al. (2002), Jolliff et al. (1998), Lindstrom et al. (1991), Warren and Kallemeyn (1989, 1991, 1993), Koeberl (1993), Snyder et al. (1999), Fagan et al. (2002); (8) Korotev (1996); (9) and (10) Papike et al. (1988).

^bn.d. = not determined.

^cElemental abundances taken from Warren et al. (2001).

particularly through alteration of olivine and pyroxenes (Croaz and Wadhwa 2001; Croaz et al. 2003; Floss and Croaz 2001). However, petrogenetic information can still be extracted due to the heterogeneous nature of terrestrial weathering processes (Croaz and Wadhwa 2001). Dho 081, DaG 262, and DaG 400 have relatively young terrestrial exposure ages (<100 kyr) (Nishiizumi et al. 2002), while Dho 025 has the oldest terrestrial exposure age of 500–600 kyr (Nishiizumi et al. 2002) of all hot-desert meteorites. Dho 025 shows a pronounced enrichment of Sr (2010 ppm), most likely due to terrestrial weathering (Table 1). Other elements that may have been affected by terrestrial weathering include Ca, Ba, and K. Dho 025, DaG 262, and

DaG 400 are all elevated in Ca, Ba, and K compared to the lunar highland meteorite average, while Dho 081 is only elevated in Ca. Mineral phases that formed due to terrestrial alteration in these meteorites include barite, celestite, calcite, gypsum, and opal. Only celestite is seen frequently within Dho 025 cracks.

Although it seems logical that a longer exposure time in the desert would result in a greater amount of terrestrial alteration, studies have shown that weathering occurs most rapidly in the early part of the exposure to the terrestrial environment (Barrat et al. 1999; Bland et al. 1996; Croaz and Wadhwa 2001). This is due to the rapid infilling of pores and fractures within the meteorite. As space within a meteorite is

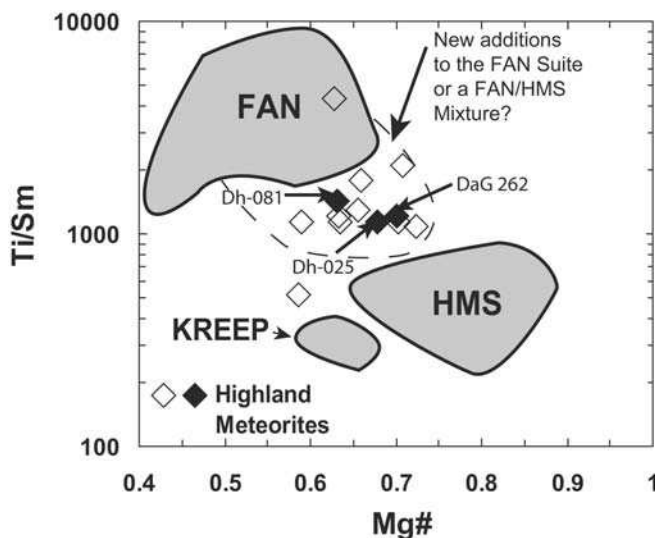


Fig. 10. Whole rock Ti/Sm versus Mg/(Mg + Fe) (Longhi and Boudreau 1979) for various lunar highlands meteorites. FAN, HMS, and KREEP compositional envelopes are shown for comparison (Taylor 1982). Dho 025, Dho 081, and DaG 262 are shown by filled diamonds (Bischoff et al. 1998; Warren et al. 2001; Zipfel et al. 1998), and lunar highlands meteorites from other studies are shown as open diamonds (Cohen et al. 2003; Koeberl et al. 1991a; Korotev et al. 1996; Neal et al. 1991; Palme et al. 1991; Semenova et al. 2000; Spettel et al. 1995).

filled with alteration material, the rate of weathering decreases with time. Thus, the high degree of terrestrial alteration observed in Dho 025 may be due to a larger volume of pore and fracture spaces in this meteorite. Indeed, a comparison of thin sections of Dho 025 and Dho 081 shows that Dho 025 has many more fractures and pore spaces than Dho 081.

TRACE ELEMENT DISTRIBUTIONS IN INDIVIDUAL CLASTS AND MINERALS

We measured minor and trace element (including REE) compositions in individual minerals (plagioclase, pyroxene and olivine) and in bulk clasts from Dho 025, Dho 081, DaG 262, and DaG 400 (Tables 2–4). With these data, we attempt to: 1) determine if any lunar meteorite clasts are pristine (retain inherited igneous chemistry) using mineral-mineral REE concentration ratios; 2) compare the mineral and clast chemistries with those of Apollo lunar samples to constrain their origins; and 3) evaluate how impact processes affected mineral compositions. A more complete account of these data can be found in Cahill (2003). Trace element concentrations typical of FAN, HMS, and high-alkali suite (HAS) minerals were compiled from the literature (Floss et al. 1998; Papike et al. 1994, 1996, 1997; Papike 1996; Shervais et al. 1997; Shervais and McGee 1998a, b, 1999; Snyder et al. Forthcoming) for comparison with Dhofar and DaG individual mineral grains. All lunar samples in these publications are

considered pristine with a high level of confidence (pristinity levels of 6–8) (Warren 1993). Preliminary trace element data on Dho 025, DaG 262, and DaG 400 were presented by Cahill (2001) and Floss and Crozaz (2001).

Earlier, we noted that these meteorites have affinities to FANs (Figs. 4 and 5). However, some of the clasts plot within the FAN-HMS gap. Furthermore, whole rock data also indicate possible mixing of FAN and HMS lithologies (Fig. 10). Therefore, to evaluate this further, we analyzed single clasts, in addition to the single minerals mentioned earlier, with the ion microprobe (Table 2). We expected that analysis of fine-grained and microcrystalline clasts would eliminate the influence of matrix chemistry, the chemical mixing of several clasts, that whole rock data show and provide us with a representative clast whole rock chemistry that will allow us to trace its origin.

“Bulk” Clast Inventory

The clasts we analyzed from Dhofar and DaG highland meteorites are compared to Apollo 16, sample 67513 (2–4 mm rock fragments) (Jolliff and Haskin 1995) on a Sc versus Sm diagram (Fig. 11). Sm tracks the relative incompatible trace element (ITE) enrichment, while Sc (which is compatible in pyroxene) is an indicator of the proportion of mafic assemblage in the sample. One of two trends emerges in this type of elemental comparison (Fig. 11a). One is a ITE-depleted (Sc/Sm values >12) trend that is typical of the FAN suite (Norman and Ryder 1980), while the other ITE-rich trend is compositionally similar to impact melt breccias (Korotev 1994; Lindstrom et al. 1990). Figure 11b focuses on the ITE-depleted trend of this diagram. Low Sm and Sc abundances are indicative of plagioclase-rich mineralogies, while higher Sm and Sc concentrations are indicative of pyroxene-rich mineralogies. In general, Dhofar and DaG clasts fall along the ITE-poor trend and have characteristics similar to 67513 anorthositic rock fragments (Fig. 11b). All four meteorites are slightly depleted in Sm at a given Sc value, compared to sample 67513. This may indicate their transitional nature between FAN and HMS suites, as suggested by earlier observations. However, we cannot rule out analytical artifacts in the SIMS analyses, since ion yields are not as well-known for these bulk clast compositions as they are for single mineral analyses. Both Dho 025 and DaG 400 also have single clasts with slightly ITE and mafic mineral-rich chemistries (Sm >2.5 ppm and Sc >30 ppm).

Whole rock compositions of several other lunar highlands meteorites (MAC 88104/5, ALH A81005, Y-791197, Y-88032, and Y-82192) have elevated Sm compared to Apollo 16 sample 67513 (Jolliff et al. 1991; Jolliff and Haskin 1995; Koeberl et al. 1991a; Warren and Kallymeyn 1991). This may be because these studies used whole rock analyses (matrix + multiple clast chemistries) instead of the single clast analyses

Table 2. Bulk minor, trace, and REE concentrations (ppm) for lunar meteorite clasts.^a

| Dho 025 | Clast 1 | Clast 2 | Clast 3 | Clast 4 | Clast 5 | Clast 6 | Clast 7 | Clast 8 | Clast 10 | |
|---------|-------------------|-----------|------------|-------------------|-----------|-------------|-----------|--------------------------|-----------|-----------|
| Na | 2416 | 2023 | 2630 | 2302 | 2779 | 2038 | 3195 | 3026 | 2577 | |
| K | 213 | 198 | 406 | 506 | 426 | 203 | 1045 | 493 | 504 | |
| Sc | 4.26 | 7.47 | 11.7 | 11.4 | 30.8 | 3.89 | 20.8 | 17.4 | 31.7 | |
| Ti | 195 | 322 | 752 | 690 | 2132 | 63 | 3565 | 1407 | 2253 | |
| Sr | 164 | 141 | 133 | 1765 | 111 | 157 | 126 | 145 | 113 | |
| Y | 1.16 | 3.51 | 3.74 | 4.95 | 12.4 | 1.45 | 25.8 | 9.12 | 11.4 | |
| Zr | 3.62 | 15.2 | 13.1 | 15.2 | 22.2 | 1.28 | 154 | 32.9 | 26.7 | |
| Ba | 16.0 | 12.7 | 14.3 | 1472 | 12.9 | 6.85 | 53.2 | 23.7 | 14.6 | |
| La | 0.69 (2) | 0.92 (5) | 1.10 (7) | 1.74 (8) | 1.17 (4) | 0.44 (4) | 5.62 (19) | 2.34 (9) | 1.42 (7) | |
| Ce | 1.79 (5) | 2.52 (10) | 2.71 (14) | 3.42 (13) | 3.60 (12) | 1.05 (7) | 17.0 (4) | 6.35 (23) | 4.19 (15) | |
| Pr | 0.24 (1) | 0.30 (2) | 0.35 (2) | 0.52 (3) | 0.56 (3) | 0.15 (1) | 2.14 (10) | 0.88 (5) | 0.57 (4) | |
| Nd | 0.94 (2) | 1.44 (5) | 1.64 (7) | 1.98 (9) | 2.79 (9) | 0.56 (2) | 10.0 (3) | 3.73 (12) | 2.79 (10) | |
| Sm | 0.23 (2) | 0.37 (3) | 0.37 (4) | 0.49 (3) | 0.88 (4) | 0.15 (1) | 2.70 (15) | 0.96 (7) | 0.87 (6) | |
| Eu | 0.60 (2) | 0.55 (2) | 0.50 (3) | 0.44 (9) | 0.47 (2) | 0.48 (3) | 0.61 (4) | 0.59 (3) | 0.45 (3) | |
| Gd | 0.22 (2) | 0.49 (4) | 0.46 (6) | 0.49 (6) | 1.20 (7) | 0.17 (2) | 3.28 (23) | 1.11 (9) | 1.25 (9) | |
| Tb | 0.030 (4) | 0.074 (7) | 0.075 (7) | 0.088 (9) | 0.26 (2) | 0.045 (4) | 0.58 (5) | 0.19 (2) | 0.21 (2) | |
| Dy | 0.18 (1) | 0.52 (3) | 0.47 (3) | b.d. ^b | 1.75(5) | 0.20 (1) | 3.63 (14) | 1.35 (6) | 1.54 (6) | |
| Ho | 0.036 (3) | 0.11 (1) | 0.12 (1) | b.d. | 0.39 (2) | 0.047 (6) | 0.77 (4) | 0.28 (2) | 0.38 (3) | |
| Er | 0.13 (1) | 0.34 (2) | 0.34 (2) | b.d. | 1.08(4) | 0.14 (1) | 2.29 (9) | 0.85 (4) | 1.11 (5) | |
| Tm | 0.013 (3) | 0.040 (5) | 0.065 (8) | b.d. | 0.15(1) | 0.012 (4) | 0.32 (3) | 0.11 (1) | 0.15 (1) | |
| Yb | 0.078 (9) | 0.28 (2) | 0.36 (3) | b.d. | 0.98(5) | 0.12 (1) | 1.92 (10) | 0.74 (6) | 1.02 (6) | |
| Lu | 0.014 (9) | 0.048 (5) | 0.074 (10) | b.d. | 0.15 (1) | 0.015 (3) | 0.36 (4) | 0.12 (1) | 0.18 (2)a | |
| Dho 081 | Clast 1 | Clast 2 | Clast 3 | Clast 4 | Clast 5 | Clast 6 | Clast 7 | Clast 8 | Clast 9 | Clast 10 |
| Na | 2527 | 2243 | 2039 | 1300 | 2819 | 2199 | 2558 | 1932 | 2550 | 2660 |
| K | 97.7 | 158 | 162 | 113 | 80.7 | 62.6 | 176 | 92.3 | 197 | 194 |
| Sc | 4.55 | 18.8 | 20.3 | 18.9 | 3.78 | 3.68 | 15.4 | 3.84 | 13.2 | 12.5 |
| Ti | 74.2 | 1045 | 1035 | 883 | 80.0 | 64.1 | 1021 | 113 | 781 | 770 |
| Sr | 147 | 126 | 902 | 131 | 151 | 140 | 125 | 149 | 133 | 136 |
| Y | 0.488 | 4.58 | 4.10 | 3.96 | 0.611 | 0.241 | 3.98 | 0.391 | 4.83 | 3.20 |
| Zr | 0.29 | 14.6 | 14.2 | 13.4 | 0.31 | 0.16 | 12.9 | 0.51 | 17.5 | 9.70 |
| Ba | 5.45 | 8.96 | 19.9 | 7.26 | 6.15 | 3.60 | 9.13 | 5.84 | 11.9 | 7.23 |
| La | 0.14 (1) | 0.66 (3) | 0.95 (5) | 0.60 (4) | 0.23 (1) | 0.10 (1) | 0.63 (3) | 0.23 (2) | 0.91 (4) | 0.47 (3) |
| Ce | 0.37 (2) | 1.92 (7) | 2.23 (9) | 1.71 (9) | 0.58 (3) | 0.25 (1) | 1.70 (7) | 0.50 (4) | 2.52 (8) | 1.29 (7) |
| Pr | 0.048 (3) | 0.23 (2) | 0.29 (2) | 0.27 (2) | 0.073 (5) | 0.031 (3) | 0.23 (1) | 0.057 (7) | 0.36 (1) | 0.17 (1) |
| Nd | 0.20 (1) | 1.22 (4) | 1.36 (5) | 1.07 (4) | 0.31 (1) | 0.13 (1) | 1.06 (3) | 0.27 (1) | 1.55 (4) | 0.82 (3) |
| Sm | 0.069 (6) | 0.36 (3) | 0.35 (3) | 0.31 (3) | 0.010 (9) | 0.042 (6) | 0.35 (2) | 0.086 (13) | 0.45 (2) | 0.24 (2) |
| Eu | 0.53 (2) | 0.46 (2) | 0.39 (2) | 0.47 (3) | 0.54 (2) | 0.46 (2) | 0.46 (2) | 0.53 (2) | 0.50 (2) | 0.51 (2) |
| Gd | 0.063 (6) | 0.43 (3) | 0.41 (4) | 0.36 (4) | 0.090 (9) | 0.042 (6) | 0.43 (3) | 0.080 (12) | 0.47 (4) | 0.32 (3) |
| Tb | 0.0094 (13) | 0.080 (8) | 0.071 (7) | 0.077 (8) | 0.015 (2) | 0.006 (1) | 0.085 (8) | 0.014 (4) | 0.089 (9) | 0.056 (8) |
| Dy | 0.060 (4) | 0.61 (2) | 0.56 (3) | 0.55 (3) | 0.089 (5) | 0.037 (4) | 0.56 (2) | 0.060 (7) | 0.71 (3) | 0.44 (2) |
| Ho | 0.012 (1) | 0.14 (1) | 0.12 (1) | 0.13 (1) | 0.018 (2) | 0.0085 (14) | 0.13 (1) | 0.013 (3) | 0.15 (1) | 0.099 (9) |
| Er | 0.036 (3) | 0.42 (2) | 0.39 (2) | 0.33 (2) | 0.044 (5) | 0.016 (3) | 0.40 (2) | 0.032 (6) | 0.45 (2) | 0.26 (2) |
| Tm | 0.0045 (26) | 0.063 (6) | 0.054 (6) | 0.047 (6) | b.d. | b.d. | 0.047 (5) | 0.0028 (40) ^c | 0.063 (7) | 0.043 (6) |
| Yb | b.d. | 0.38(2) | 0.42 (3) | 0.34 (2) | 0.042 (5) | b.d. | 0.35(2) | 0.018 (7) | 0.48 (2) | 0.25 (2) |
| Lu | b.d. | 0.063 (5) | b.d. | 0.064 (8) | b.d. | b.d. | 0.052 (5) | 0.0026 (20) ^c | 0.081 (6) | 0.037 (8) |
| DaG 262 | Clast 1 | Clast 2 | Clast 3 | Clast 4 | Clast 5 | Clast 6 | Clast 7 | Clast 8 | Clast 10 | Clast 11 |
| Na | 2962 | 3226 | 3082 | 988 | 2896 | 4527 | 2386 | 3272 | 3810 | 3138 |
| K | 602 | 694 | 531 | 204 | 432 | 558 | 394 | 664 | 459 | 707 |
| Sc | 15 | 18 | 16 | 11 | 19 | 21 | 5.9 | 16 | 13 | 14 |
| Ti | 792 | 1043 | 879 | 420 | 1207 | 1400 | 48 | 1650 | 748 | 1523 |
| Sr | n.r. ^d | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. |
| Y | 5.2 | 7.6 | 6.3 | 1.4 | 7.3 | 9.9 | 1.3 | 4.7 | 4.5 | 6.2 |
| Zr | 31 | 35 | 30 | 6.8 | 35 | 42 | 3.5 | 87 | 27 | 52 |
| Ba | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. |
| La | 1.08 (8) | 1.96 (12) | 1.37 (14) | 0.40 (5) | 1.51 (14) | 1.84 (11) | 0.33 (3) | 1.62 (15) | 0.96 (7) | 1.50 (7) |
| Ce | 2.82 (15) | 4.88 (23) | 3.46 (30) | 1.06 (9) | 3.23 (29) | 5.74 (30) | 0.64 (4) | 3.02 (26) | 1.96 (12) | 3.91 (16) |
| Pr | 0.46 (3) | 0.66 (5) | 0.32 (4) | 0.085 (16) | 0.48 (5) | 0.73 (5) | 0.10 (1) | 0.45 (4) | 0.29 (3) | 0.59 (4) |

Table 2. Bulk minor, trace, and REE concentrations (ppm) for lunar meteorite clasts.^a *Continued.*

| DaG 262 | Clast 1 | Clast 2 | Clast 3 | Clast 4 | Clast 5 | Clast 6 | Clast 7 | Clast 8 | Clast 10 | Clast 11 |
|---------|------------|------------|------------|------------|-------------------------|-----------|------------|------------|------------|------------|
| Nd | 1.50 (6) | 2.70 (11) | 1.78 (13) | 0.51 (4) | 1.98 (13) | 3.35 (13) | 0.36 (2) | 1.87 (13) | 1.11 (7) | 2.32 (9) |
| Sm | 0.47 (5) | 0.60 (6) | 0.49 (7) | 0.14 (4) | 0.72 (8) | 0.85 (8) | 0.10 (2) | 0.44 (8) | 0.26 (5) | 0.62 (6) |
| Eu | 0.45 (6) | 0.62 (9) | 0.49 (11) | 0.13 (5) | 0.40 (14) | 0.39 (7) | 0.35 (7) | 0.20 (19) | 0.37 (6) | 0.66 (7) |
| Gd | 0.47 (6) | 0.92 (11) | 0.60 (11) | 0.20 (4) | 0.57 (13) | 1.11 (13) | 0.12 (2) | 0.47 (11) | 0.35 (6) | 0.58 (8) |
| Tb | 0.11 (1) | 0.14 (1) | 0.11 (3) | 0.03 (8) | 0.13 (3) | 0.19 (3) | 0.024 (5) | 0.091 (20) | 0.068 (12) | 0.10 (2) |
| Dy | 0.66 (4) | 1.11 (5) | 0.77 (8) | 0.16 (2) | 0.93 (9) | 1.41 (7) | 0.18 (2) | 0.67 (6) | 0.58 (5) | 0.79 (5) |
| Ho | 0.15 (2) | 0.28 (2) | 0.24 (4) | 0.042 (10) | 0.24 (3) | 0.27 (2) | 0.068 (8) | 0.14 (2) | 0.13 (1) | 0.18 (2) |
| Er | 0.40 (3) | 0.77 (5) | 0.57 (6) | 0.11 (2) | 0.75 (6) | 0.89 (6) | 0.12 (2) | 0.50 (5) | 0.46 (4) | 0.50 (3) |
| Tm | 0.078 (10) | 0.080 (16) | 0.071 (20) | 0.035 (10) | 0.10 (2) | 0.14 (1) | 0.011 (6) | 0.058 (20) | 0.067 (14) | 0.046 (9) |
| Yb | 0.45 (6) | 0.64 (6) | 0.53 (10) | 0.22 (4) | 0.56 (9) | 0.86 (8) | 0.11 (2) | 0.35 (9) | 0.50 (8) | 0.41 (5) |
| Lu | 0.060 (12) | 0.11 (1) | 0.061 (17) | 0.034 (12) | 0.11 (2) | 0.13 (2) | 0.017 (6) | 0.055 (18) | 0.095 (17) | 0.050 (11) |
| DaG 400 | Clast 1 | Clast 2 | Clast 3 | Clast 4 | Clast 5 | Clast 6 | Clast 7 | | | |
| Na | 2232 | 3285 | 1753 | 2517 | 643 | 3701 | 2745 | | | |
| K | 926 | 895 | 824 | 497 | 368 | 1669 | 1166 | | | |
| Sc | 22 | 19 | 8.7 | 20 | 10 | 34 | 5.6 | | | |
| Ti | 1293 | 1273 | 303 | 1342 | 941 | 4659 | 924 | | | |
| Sr | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. | | | |
| Y | 16 | 7.8 | 0.95 | 9.0 | 2.6 | 33 | 2.8 | | | |
| Zr | 46 | 28 | 2.84 | 41.7 | 9.5 | 146 | 4.2 | | | |
| Ba | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. | n.r. | | | |
| La | 1.18 (1) | 1.24 (13) | 0.25 (5) | 1.75 (12) | 0.29 (3) | 6.30 (39) | 0.63 (6) | | | |
| Ce | 4.00 (27) | 3.35 (26) | 0.62 (5) | 4.97 (31) | 0.49 (4) | 15.4 (69) | 1.74 (15) | | | |
| Pr | 0.70 (7) | 0.48 (5) | 0.09 (1) | 0.72 (6) | 0.069 (9) | 2.08 (14) | 0.16 (2) | | | |
| Nd | 2.55 (16) | 2.31 (13) | 0.41 (3) | 2.54 (13) | 0.31 (2) | 9.45 (38) | 0.74 (5) | | | |
| Sm | 1.12 (14) | 0.61 (10) | 0.11 (2) | 0.91 (11) | 0.10 (2) | 2.50 (2) | 0.21 (4) | | | |
| Eu | 0.35 (5) | 0.53 (6) | 0.34 (3) | 0.41 (4) | 0.046 (67) ^c | 0.41 (8) | 0.48 (4) | | | |
| Gd | 1.39 (17) | 0.65 (12) | 0.077 (23) | 0.95 (13) | 0.12 (2) | 2.50 (38) | 0.24 (5) | | | |
| Tb | 0.36 (5) | 0.13 (2) | 0.017 (5) | 0.22 (3) | 0.036 (6) | 0.62 (7) | 0.056 (10) | | | |
| Dy | 2.23 (15) | 0.98 (7) | 0.11 (2) | 1.28 (8) | 0.29 (2) | 4.12 (23) | 0.43 (4) | | | |
| Ho | 0.44 (5) | 0.21 (2) | 0.035 (6) | 0.22 (3) | 0.075 (9) | 0.83 (11) | 0.076 (14) | | | |
| Er | 1.46 (10) | 0.78 (7) | 0.092 (13) | 0.74 (5) | 0.29 (2) | 2.74 (13) | 0.20 (3) | | | |
| Tm | 0.22 (3) | 0.066 (12) | b.d. | 0.089 (2) | 0.038 (6) | 0.32 (4) | 0.023 (9) | | | |
| Yb | 1.16 (16) | 0.55 (7) | b.d. | 0.85 (8) | 0.28 (3) | 2.30 (34) | b.d. | | | |
| Lu | 0.14 (3) | 0.10 (2) | 0.011 (5) | 0.12 (2) | 0.036 (7) | 0.48 (8) | 0.020 (8) | | | |

^aErrors are 1 σ due to counting statistics.

^bb.d. = below detection.

^cNote the larger than normal errors.

^dn.r. = values not reported due to probable terrestrial contamination. See Floss and Crozaz (2001).

of this study and that of Jolliff and Haskin (1995). Dhofar and DaG clast analyses clearly show stronger affinities to FAN than previously seen in whole rock analyses (Bischoff et al. 1998; Semenova et al. 2000; Zipfel et al. 1998).

Compositional Mixing Model

A closer examination of the REE concentrations of Dhofar and DaG clasts compared to FAN and HMS rocks suggests the possibility that Dhofar and DaG chemistries were subjected to a degree of mixing. Mixing of average HMS components and average FAN composition (Papike 1998) and comparison with the clast data show that clasts from all four meteorites contain an appreciable HMS component. Most Dhofar and DaG clasts show $\leq 12\%$ HMS component, but one DaG 400 clast contains 62% of an HMS component and one Dho 025 clast contains 71% of an HMS component.

Plagioclase Inventory

The REE patterns for individual plagioclase grains from Dho 025, Dho 081, DaG 262, and DaG 400 are shown in Fig. 12. All plagioclase analyses have REE abundances similar to those seen in FAN rocks. However, some Dho 025 clasts have plagioclases that are enriched in heavy rare earth elements (HREE) compared to typical pristine FAN plagioclase (Fig. 12a). In addition, light rare earth elements (LREE) in Dho 025 plagioclase tend to be enriched relative to plagioclase from Dho 081, DaG 262, and DaG 400. Despite the HREE enrichments in many Dho 025 plagioclase grains, five grains show REE trends typical of pristine FAN lithologies (clasts AA, AI, 108b, BA, and BB; Fig. 12a). All Dho 081 plagioclases have lower REE abundances than those in the other meteorites analyzed, with patterns that fall toward the lower end of the range observed for FANs (Fig. 12b). DaG

Table 3. Major, minor, trace, and REE concentrations (ppm) of Dho 025 lunar highlands plagioclase.^a *Continued.*

| | Dho 081 | | | | | | DaG 262 | | | DaG 400 | | |
|----|--------------------------|--------------------------|---------------------------|-------------|------------|--------------------------|------------|-------------|------------|------------|-------------|--------------------------|
| | AE | C | F | H | L | V | 1 | 2 | 3 | 1 | 2 | 3 |
| La | 0.23 (3) | 0.32 (3) | 0.19 (2) | 0.13 (1) | 0.13 (2) | 0.094 (15) | 0.76 (4) | 0.38 (3) | 0.29 (3) | 0.80 (5) | 0.51 (4) | 0.95 (5) |
| Ce | 0.63 (7) | 0.81 (6) | 0.44 (4) | 0.30 (3) | 0.35 (4) | 0.19 (3) | 2.04 (9) | 1.04 (7) | 0.67 (5) | 1.88 (11) | 1.33 (7) | 2.26 (11) |
| Pr | 0.10 (1) | 0.13 (1) | 0.054 (12) | 0.034 (7) | 0.05 (1) | 0.043 (9) | 0.25 (2) | 0.12 (1) | 0.10 (1) | 0.26 (2) | 0.17 (1) | 0.30 (2) |
| Nd | 0.41 (4) | 0.38 (3) | 0.26 (3) | 0.17 (2) | 0.19 (3) | 0.094 (18) | 0.93 (5) | 0.39 (3) | 0.39 (3) | 1.02 (5) | 0.66 (3) | 1.07 (4) |
| Sm | 0.076 (31) | 0.10 (3) | b.d. | b.d. | b.d. | b.d. | 0.17 (3) | 0.097 (24) | 0.11 (3) | 0.27 (4) | 0.17 (2) | 0.27 (3) |
| Eu | 0.71 (5) | 0.72 (3) | 0.79 (5) | 0.60 (3) | 0.61 (4) | 0.60 (4) | 0.67 (3) | 0.81 (8) | 0.44 (6) | 0.68 (4) | 0.88 (4) | 0.75 (3) |
| Gd | 0.074 (27) | 0.14 (3) | 0.034 (26) | 0.038 (16) | 0.032 (19) | b.d. | 0.16 (3) | 0.098 (23) | 0.081 (23) | 0.23 (4) | 0.16 (3) | 0.17 (3) |
| Tb | 0.007 (6) | 0.016 (7) | 0.0092 (75) | 0.0073 (43) | b.d. | 0.0025 (37) ^b | 0.013 (6) | 0.0062 (44) | 0.012 (5) | 0.025 (8) | 0.025 (6) | 0.026 (6) |
| Dy | 0.034 (14) | 0.12 (2) | 0.035 (18) | 0.039 (11) | 0.020 (10) | b.d. | 0.11 (2) | 0.093 (15) | 0.077 (13) | 0.14 (2) | 0.13 (1) | 0.13 (1) |
| Ho | 0.0059 (50) ^b | 0.027 (8) | b.d. | 0.016 (5) | b.d. | 0.0023 (34) ^b | 0.017 (5) | 0.051 (8) | 0.036 (7) | 0.033 (7) | 0.035 (6) | 0.033 (5) |
| Er | 0.012 (13) ^b | 0.037 (14) | 0.0082 (142) ^b | 0.028 (11) | b.d. | 0.0039 (77) ^b | 0.050 (12) | 0.068 (14) | 0.049 (12) | 0.055 (15) | 0.043 (10) | 0.051 (11) |
| Tm | b.d. | b.d. | b.d. | b.d. | b.d. | b.d. | b.d. | b.d. | b.d. | 0.011 (8) | b.d. | 0.0051 (57) ^c |
| Y | b.d. | 0.021 (17) ^b | b.d. | b.d. | b.d. | b.d. | 0.056 (19) | 0.035 (21) | 0.038 (19) | 0.036 (19) | 0.055 (19) | 0.043 (15) |
| Lu | b.d. | 0.0014 (55) ^b | b.d. | b.d. | b.d. | b.d. | b.d. | b.d. | b.d. | b.d. | 0.0051 (39) | b.d. |

^aErrors are 1 σ due to counting statistics.^bNote the larger than normal errors.^cb.d. = below detection.^dn.r. = values not reported due to probable terrestrial contamination. See Floss and Crozaz (2001).Table 4. Major, minor, trace, and REE concentrations (ppm) of Dho 025, Dho 081, DaG 262, and DaG 400 pyroxene and olivine.^a

| | Dho 025 | | | | Dho 081 | | | | DaG 262 | | DaG 400 | |
|----|-------------|------------|------------|-------------|-------------|-----------|-----------|-----------|------------|-------------------|-------------------|---------|
| | 108b opx | BM opx | ACB pig | 108b aug | 108b aug | BA aug | BH aug | BL aug | F opx | l aug | 2 opx | l ol |
| Na | 144 | 120 | 339 | 692 | 558 | 487 | 518 | 583 | 116 | 291 | 183 | 104 |
| Mg | 158268 | 165688 | 144925 | 98878 | 104638 | 103798 | 109237 | 162851 | 154448 | 70780 | 112336 | 223297 |
| K | 132 | 78 | 206 | 103 | 103 | 79 | 123 | 365 | 53 | 163 | 185 | 75 |
| Ca | 12201 | 9392 | 24729 | 114243 | 117264 | 107434 | 107773 | 69010 | 12010 | 88824 | 13338 | 1089 |
| Sc | 24 | 25 | 29 | 52 | 56 | 60 | 75 | 55 | 26 | 95 | 30 | 8 |
| Ti | 3247 | 3439 | 2691 | 6229 | 6474 | 4632 | 5477 | 5164 | 3478 | 3001 | 2687 | 159 |
| Fe | 57316 | 54422 | 81324 | 35572 | 38760 | 50516 | 42399 | 163533 | 93678 | 305743 | 192382 | 220049 |
| Sr | 4.4 | 6.4 | 8.6 | 8.2 | 9.6 | 8.9 | 37 | 58 | 1.2 | n.r. ^b | n.r. | n.r. |
| Y | 7.5 | 9.2 | 10 | 41 | 39 | 33 | 36 | 32 | 7.5 | 57 | 5.2 | 0.19 |
| Zr | 26 | 27 | 27 | 180 | 155 | 120 | 126 | 74 | 21 | 107 | 6.0 | 0.25 |
| Ba | 0.63 | 0.35 | 2.2 | 3.1 | 1.2 | 1.7 | 33 | 1.7 | 0.14 | n.r. | n.r. | n.r. |
| La | 0.14 (1)* | 0.27 (4) | 0.37 (5) | 1.73 (13) | 1.05 (9) | 0.86 (9) | 0.92 (9) | 0.98 (9) | 0.028 (6) | 0.71 (9) | b.d. ^c | b.d. |
| Ce | 0.51 (4) | 0.86 (11) | 1.39 (14) | 7.19 (40) | 5.43 (32) | 4.37 (35) | 4.55 (29) | 3.99 (29) | 0.093 (14) | 3.47 (33) | b.d. | b.d. |
| Pr | 0.077 (12) | 0.089 (21) | 0.19 (2) | 1.47 (12) | 1.32 (10) | 0.90 (8) | 1.00 (8) | 0.83 (7) | 0.026 (6) | 0.89 (9) | b.d. | b.d. |

Table 4. Major, minor, trace, and REE concentrations (ppm) of Dho 025, Dho 081, DaG 262, and DaG 400 pyroxene and olivine. ^aContinued.

| Dho 025 | | 108b | | 108b | | 108b | | BA | | BH | | BL | | F | | 1 | | 2 | | 1 | |
|---------|-------------|--------------------------|--------------------------|------------|------------|---------------------------|------------|---------------------------|------------|------------|------------|------------|-------------------------|------------|------------|-------------------------|-------------------------|-----------|-----------|-------------|-------------|
| 108b | opx | BM | ACB | 108b | aug | 108b | aug | BA | aug | BH | agu | BL | aug | opx | opx | aug | aug | opx | opx | ol | ol |
| Nd | 0.42 (3) | 0.51 (6) | 1.12 (8) | 8.14 (36) | 7.52 (35) | 5.16 (31) | 5.34 (23) | 5.16 (31) | 5.34 (23) | 5.34 (23) | 5.34 (23) | 4.67 (23) | 5.79 (31) | 0.21 (2) | 0.21 (2) | 5.79 (31) | 5.79 (31) | b.d. | b.d. | b.d. | b.d. |
| Sm | 0.27 (4) | 0.19 (6) | 0.43 (6) | 3.74 (23) | 3.65 (33) | 2.25 (25) | 2.90 (25) | 2.25 (25) | 2.90 (25) | 2.90 (25) | 2.90 (25) | 2.42 (16) | 2.64 (29) | 0.19 (3) | 0.19 (3) | 2.64 (29) | 2.64 (29) | b.d. | b.d. | b.d. | b.d. |
| Eu | 0.0068 (45) | 0.0032 (69) ^d | 0.0024 (89) ^d | 0.049 (21) | 0.056 (24) | 0.0003 (215) ^d | 0.063 (30) | 0.0003 (215) ^d | 0.063 (30) | 0.063 (30) | 0.063 (30) | 0.082 (15) | 0.030 (58) ^d | 0.008 (4) | 0.008 (4) | 0.030 (58) ^d | 0.030 (58) ^d | b.d. | b.d. | b.d. | b.d. |
| Gd | 0.51 (5) | 0.44 (9) | 0.83 (11) | 4.69 (47) | 4.98 (44) | 3.60 (47) | 3.34 (35) | 3.60 (47) | 3.34 (35) | 3.34 (35) | 3.34 (35) | 3.21 (38) | 6.26 (58) | 0.32 (6) | 0.32 (6) | 6.26 (58) | 6.26 (58) | b.d. | b.d. | b.d. | b.d. |
| Tb | 0.14 (1) | 0.13 (2) | 0.19 (2) | 0.97 (8) | 1.21 (11) | 0.70 (12) | 0.91 (7) | 0.70 (12) | 0.91 (7) | 0.91 (7) | 0.91 (7) | 0.61 (7) | 1.21 (12) | 0.086 (12) | 0.086 (12) | 1.21 (12) | 1.21 (12) | 0.056 (7) | 0.056 (7) | b.d. | b.d. |
| Dy | 1.04 (5) | 1.10 (9) | 1.61 (10) | 6.57 (31) | 6.66 (32) | 4.57 (35) | 0.05 (25) | 4.57 (35) | 0.05 (25) | 0.05 (25) | 0.05 (25) | 5.45 (28) | 7.59 (44) | 0.93 (5) | 0.93 (5) | 7.59 (44) | 7.59 (44) | 0.60 (3) | 0.60 (3) | b.d. | b.d. |
| Ho | 0.25 (2) | 0.33 (4) | 0.33 (3) | 1.52 (12) | 1.44 (9) | 0.96 (12) | 1.17 (9) | 0.96 (12) | 1.17 (9) | 1.17 (9) | 1.17 (9) | 1.15 (11) | 1.84 (16) | 0.20 (2) | 0.20 (2) | 1.84 (16) | 1.84 (16) | 0.18 (2) | 0.18 (2) | 0.0086 (24) | 0.0086 (24) |
| Er | 0.97 (5) | 1.19 (8) | 1.24 (7) | 4.03 (22) | 3.83 (20) | 3.18 (24) | 3.80 (16) | 3.18 (24) | 3.80 (16) | 3.80 (16) | 3.80 (16) | 3.53 (19) | 5.96 (34) | 0.82 (5) | 0.82 (5) | 5.96 (34) | 5.96 (34) | 0.72 (3) | 0.72 (3) | 0.029 (5) | 0.029 (5) |
| Tm | 0.13 (1) | 0.18 (2) | 0.24 (3) | 0.47 (5) | 0.46 (5) | 0.37 (5) | 0.45 (4) | 0.37 (5) | 0.45 (4) | 0.45 (4) | 0.45 (4) | 0.47 (4) | 0.96 (10) | 0.12 (2) | 0.12 (2) | 0.96 (10) | 0.96 (10) | 0.12 (1) | 0.12 (1) | 0.0053 (21) | 0.0053 (21) |
| Yb | 1.05 (6) | 1.38 (14) | 1.16 (11) | 2.71 (25) | 2.98 (23) | 2.23 (27) | 2.63 (22) | 2.23 (27) | 2.63 (22) | 2.63 (22) | 2.63 (22) | 2.49 (25) | 7.06 (64) | 1.01 (9) | 1.01 (9) | 7.06 (64) | 7.06 (64) | 0.80 (7) | 0.80 (7) | 0.082 (14) | 0.082 (14) |
| Lu | 0.19 (2) | 0.25 (3) | 0.23 (3) | 0.41 (6) | 0.44 (7) | 0.32 (8) | 0.37 (5) | 0.32 (8) | 0.37 (5) | 0.37 (5) | 0.37 (5) | 0.41 (6) | 1.10 (16) | 0.19 (3) | 0.19 (3) | 1.10 (16) | 1.10 (16) | 0.19 (2) | 0.19 (2) | 0.0082 (30) | 0.0082 (30) |

^aErrors are 1σ due to counting statistics.^bn.r. = values not reported due to probable terrestrial contamination. See Floss and Crozaz (2001).^cb.d. = below detection.^dNote the larger than normal errors.

262 and DaG 400 also have plagioclase REE concentrations falling within the typical FAN suite.

Concentrations of Ce, K, and Ba in plagioclase grains are similar to those of other FAN suite rocks (Fig. 13). However, Fe and Mg abundances are elevated, while Sr is depleted, although still similar to FAN plagioclases. This suggests that the terrestrial Sr influx in Dho 025, interpreted from whole rock data, is dominated by surficial additions of terrestrial Sr-bearing minerals and that exchange with Dho 025 plagioclase was limited. Furthermore, Sr and Ba concentrations show slight positive trends with increasing La abundance (Fig. 14), similar to trends seen in other highlands rocks (Floss et al. 1998; Snyder et al. 2003, personal communication). This suggests that Sr may behave incompatibly in lunar plagioclases despite the fact that its partition coefficient ($K_{D Sr}$) is 1.61 (Phinney and Morrison 1990).

Pyroxene Inventory

REEs in low-Ca pyroxenes from Dho 025, Dho 081, and DaG 262 have concentrations similar to those from typical FAN and HMS rocks (Figs. 15a and 15b). Dho 025 and Dho 081 low-Ca pyroxenes have Ce and Zr abundances similar to those observed in FAN rocks but appear to be slightly depleted in both Sc and Y (Fig. 16). However, Sc and Y concentrations fall along the trends observed for FANs, while HMS and HAS rocks define steeper slopes, particularly for Y (Fig. 16).

High-Ca pyroxenes in Dho 025 and DaG 262 have REE abundances similar to those of FAN high-Ca pyroxenes (Fig. 15c). One Dho 025 analysis has a much deeper negative Eu anomaly ($0.01 \times CI$) than the rest, although it also falls within the FAN compositional range, within 1σ errors. Cerium and Zr are positively correlated, similar to the trend seen in FANs (Fig. 16). Yttrium concentrations are also similar to those in the FANs, but Sc is low in Dho 025 compared to DaG 262 and other FAN pyroxenes.

Olivine Inventory

A few SIMS trace element analyses have been reported for olivines from FAN lithologies (Floss et al. 1998). Generally, the low abundances of LREE in olivine do not allow their quantitative determination with this technique. Furthermore, the small size of olivine grains in the meteorites that we studied did not allow SIMS measurements in any troctolitic-anorthosite clasts. However, one olivine grain was successfully analyzed in DaG 400 (Fig. 15d). This grain has low HREE abundances ($\leq 0.5 \times CI$) and falls at the low end of the range observed for FAN olivines.

Plagioclase-Pyroxene REE Ratios

It is possible to evaluate whether a rock or clast represents an equilibrium assemblage by comparing

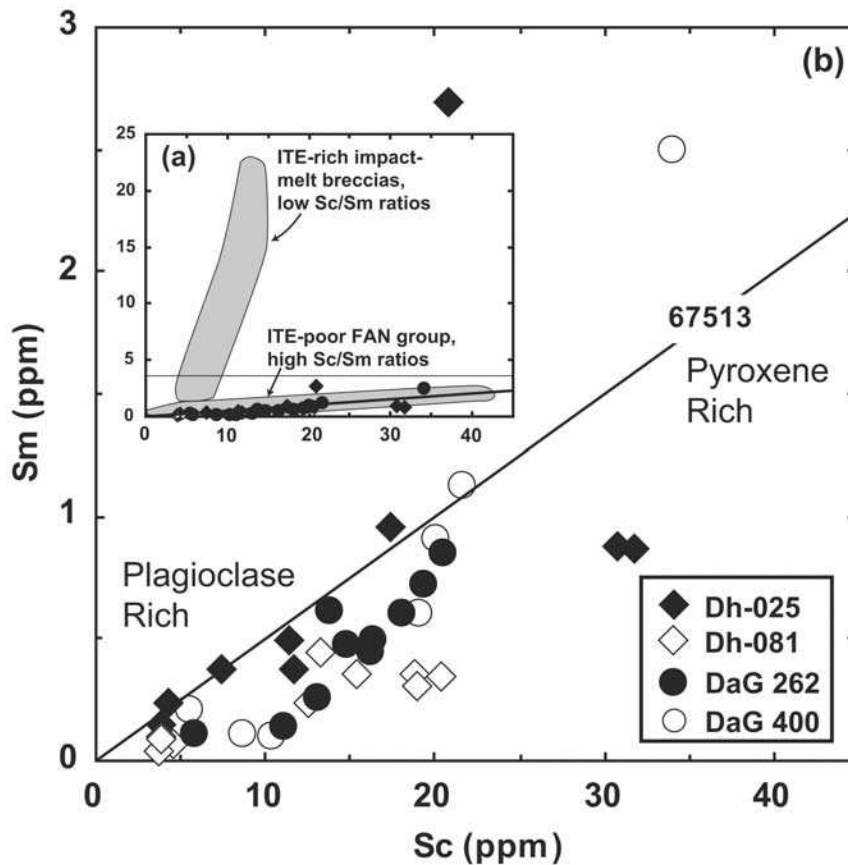


Fig. 11. Apollo 16 samples show two compositional trends in terms of Sc and Sm as illustrated in (a). Impact melt breccias are incompatible trace element (ITE)-rich, while ferroan anorthosites (FAN) are ITE-poor (Jolliff and Haskin 1995; Korotev 1994); b) enlargement of ITE-poor portion of diagram (a). Dho 025, Dho 081, DaG 262, and DaG 400 have Sm and Sc concentrations similar to ITE-poor and plagioclase-rich lithologies.

plagioclase-pyroxene REE concentration ratios (i.e., $C_{\text{REE}}^{\text{Pl}}/C_{\text{REE}}^{\text{Px}}$) with experimentally determined mineral-melt partition coefficient ratios for plagioclase and pyroxene (i.e., $K_{\text{D}}^{\text{Pl}}/K_{\text{D}}^{\text{Px}}$). It should be noted that all the polyminerally clasts we analyzed have non-relict textures.

In Fig. 17, the concentration ratios of several impact-melt clasts are compared with the ratios expected from experimentally determined distribution coefficients. If a rock, or clast, preserves the chemical signature inherited from its parental melt, then these ratios should be identical. The assumption that the chosen K_{D} values are valid is inherent here.

Distribution coefficients were selected from studies by McKay et al. (1986, 1991) and Weill and McKay (1975). Mineral-melt ratio errors are 1σ , based on a partition coefficient uncertainty of 20% (McKay 1989). Since pyroxene distribution coefficients are sensitive to their Ca contents, each clast's pyroxene K_{D} value was calculated individually (McKay et al. 1986). We used caution with orthopyroxene, since K_{D} values were determined at a time when the difficulties in measuring low concentrations of the REE with electron microprobe were not fully appreciated (McKay 1989; Weill and McKay 1975). Out of the five clasts

evaluated, only two (108b and BA) show plagioclase-pyroxene ratios concordant with those of experimentally determined plagioclase-pyroxene ratios (Fig. 17). Clast 108b ratios were corroborated using three sets of coexisting minerals within this clast. Clast BA also has a concordant plagioclase-pyroxene ratio, although the error associated with Eu is large. All other clasts have discordant plagioclase-pyroxene ratios indicating that the coexisting minerals do not represent magmatic equilibrium conditions.

DISCUSSION

In this study, we analyzed several clasts for their trace element concentrations in an attempt to find if these lunar samples contain equilibrium mineral assemblages. We approached this task by evaluating plagioclase-pyroxene REE ratios, as described in the previous section. Clasts with concordant REE ratio patterns are likely samples that contain unmodified chemical information from a parental melt and may be considered pristine lithologies. Of the clasts analyzed, the mineral REE ratios show that the minerals in two Dho 025 clasts (108b and BA) have retained equilibrium with a parent

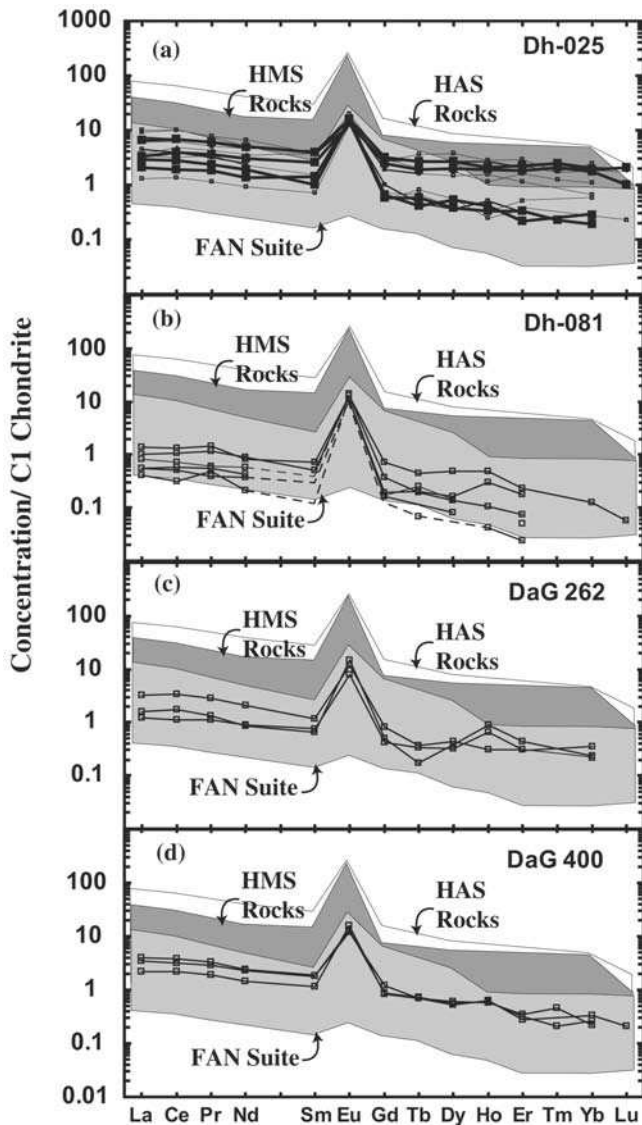


Fig. 12. C1-chondrite normalized REE patterns for plagioclase grains from lunar meteorites Dho 025 (a), Dho 081 (b), DaG 262 (c), and DaG 400 (d). The normalization values are from Anders and Grevesse (1989). These patterns are compared to pristine plagioclase grains from FAN, HMS, and (high-alkali suite) HAS rocks (Floss et al. 1998; Papike et al. 1996, 1997; Shervais et al. 1997; Shervais and McGee 1998a, b, 1999; Snyder et al. 2004). The Dho 025 patterns with bold lines and symbols represent clasts that were designated as texturally "pristine" in this study.

melt (Fig. 17). However, the other three clasts show discordant REE ratio profiles when compared to experimentally determined REE ratios. Despite not representing equilibrium assemblages, clasts with discordant REE ratio profiles can still provide insight about the processes that modified them. Discordant REE ratio profiles can result from several processes, including: 1) use of incorrect distribution coefficients; 2) subsolidus re-equilibration; and 3) impact processes, all of which are evaluated below.

Distribution Coefficients

Of foremost concern when determining REE ratios is the use of appropriate experimental distribution coefficients. Plagioclase melt partition coefficients for the REEs have been studied specifically for lunar conditions (McKay 1982; Phinney and Morrison 1990; Weill and McKay 1975), and values determined experimentally and by direct measurement are in good agreement (Phinney and Morrison 1990). Thus, distribution coefficients for plagioclase REEs are unlikely to be a large source of error here.

In contrast, the behavior of REEs in pyroxene has not been rigorously evaluated for lunar conditions. Pyroxene distribution coefficients have been determined, but they were determined for a shergottite composition and oxidation state (McKay et al. 1986). Despite this, preliminary work on clinopyroxene partitioning under lunar conditions does not indicate substantial differences in distribution coefficients compared to the more oxidizing conditions appropriate for shergottite crystallization (McKay et al. 1991). Thus, oxygen fugacity does not appear to have a large effect on the K_D values for trivalent REEs in pyroxene (James et al. 2002). Partition coefficient values used for orthopyroxene have also been noted to be a topic of concern, as mentioned earlier (Floss et al. 1998; McKay 1989); however, no inherent problems with these distribution coefficients were evident in this study.

Subsolidus Re-Equilibration

Subsolidus re-equilibration can also cause discordant mineral REE ratios (Floss et al. 1998; James et al. 2002; Papike 1996; Treiman 1996). This process generally involves material that has undergone extensive recrystallization and prolonged thermal metamorphism (Floss et al. 1998). Re-equilibration can occur within zoned minerals or between coexisting minerals. Homogenization of zoned minerals will cause higher average REE concentrations than those of the original mineral cores (Floss et al. 1998). Plagioclase-pyroxene REE ratios will have lower and less steep patterns than experimental REE ratio patterns (Hsu and Crozaz 1996, 1997).

Recent ion microprobe studies have also demonstrated that both the HREEs and LREEs may be redistributed between co-existing pyroxene and plagioclase in a manner dependent upon their crystal chemistries (Papike 1996; Papike et al. 1996). During co-existing mineral re-equilibration, plagioclase is depleted in HREE, and pyroxene is depleted in LREE. The resulting REE ratio pattern would have a steeper negative trend than would a pattern reflecting experimentally determined distribution coefficients.

Problems are also prevalent when considering augite and orthopyroxene formed by inversion of pigeonite (James et al. 2002). Upon inversion, extensive internal redistribution of major, minor, and trace elements are required for the necessary structural changes to occur. As inversion of

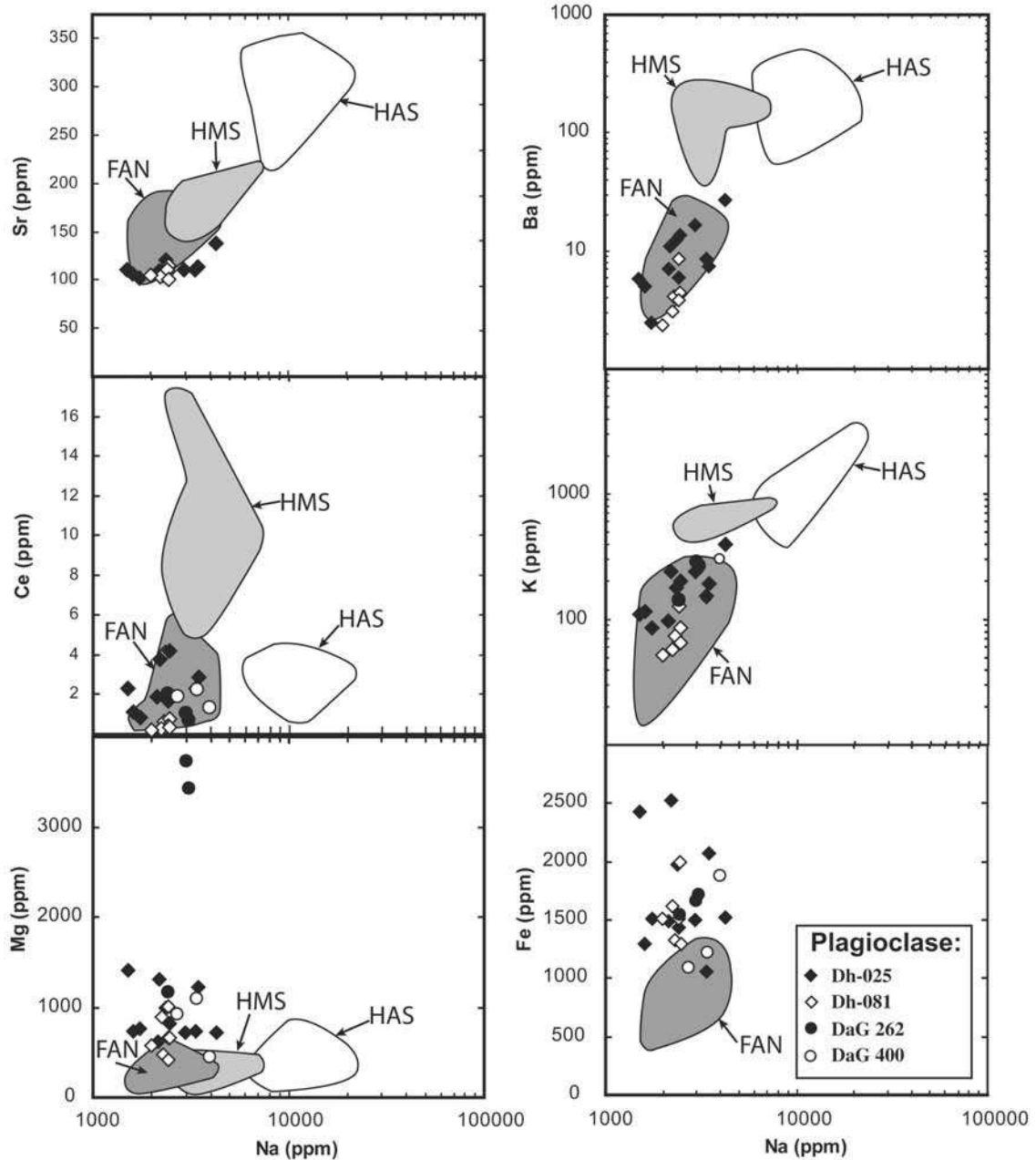


Fig. 13. Minor and trace element data for plagioclase grains from lunar highlands meteorites Dho 025, Dho 081, DaG 262, and DaG 400 compared to that of pristine FAN, HMS, and (high-alkali suite) HAS plagioclase (Floss et al. 1998; Snyder et al. 2004).

pigeonite and subsequent subsolidus re-equilibration take place, REEs move from orthopyroxene into augite, with HREEs migrating with a greater mobility than LREEs (James et al. 2002). Orthopyroxene-augite REE ratios develop lower and steeper positive trends. Furthermore, migration of LREEs from orthopyroxene to augite will result in plagioclase-augite REE ratio patterns with steeper negative trends.

The REE ratio patterns for discordant clasts tend to be flatter than the expected K_D ratio patterns (Fig. 17). This may indicate that these minerals were previously zoned and have homogenized, although homogenization usually entails lower

overall patterns in addition to flatter slopes. Thus, subsolidus re-equilibration may have been one, but not the only, influence on their REE ratio patterns.

Impact Processes

Impact-induced mixing, as discussed for the whole rock and clast analyses of these meteorites, may have influenced some of the mineral analyses. When impact processes occur, some amount of material may be vaporized, and a larger amount of material will be melted and/or partially melted.

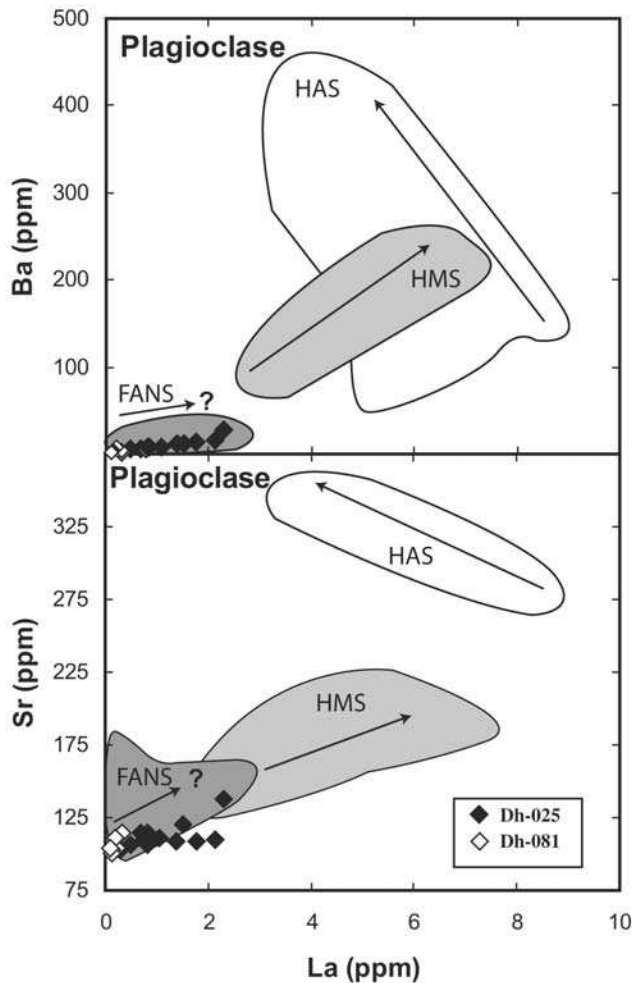


Fig. 14. Plagioclase Ba, Sr, and La systematics for lunar meteorites Dh-025 and Dh-081 compared to FAN, HMS, and high-alkali suite (HAS) data (Floss et al. 1998; Papike et al. 1997; Snyder et al. 2004).

Certain volatile minor elements, such as Na and K, are likely to be affected. However, it is also important to consider how the REEs would react to such an event.

As shown in Fig. 13, Fe and Mg concentrations are elevated in the lunar meteorite plagioclase grains compared to FAN, HMS, and HAS plagioclase. This suggests that impact metamorphism has affected these clasts. However, Fe concentrations do not surpass the upper limit for FeO in primary igneous plagioclases from Apollo 14 highlands rocks (1 wt% FeO) (Stöffler and Knöll 1977). Furthermore, Na and K concentrations in clast plagioclases are similar to FAN lithologies (Fig. 13) and do not suggest volatilization. In addition, optical analyses of feldspar crystals do not exhibit isotropic characteristics typical of maskelynite.

However, impact modification does appear to have affected the REE concentrations of some Dh-025 plagioclase grains (Fig. 12a) in which the HREE are disproportionately enriched. The source of these REE enrichments could be exchange with a surrounding impact melt or a coexisting

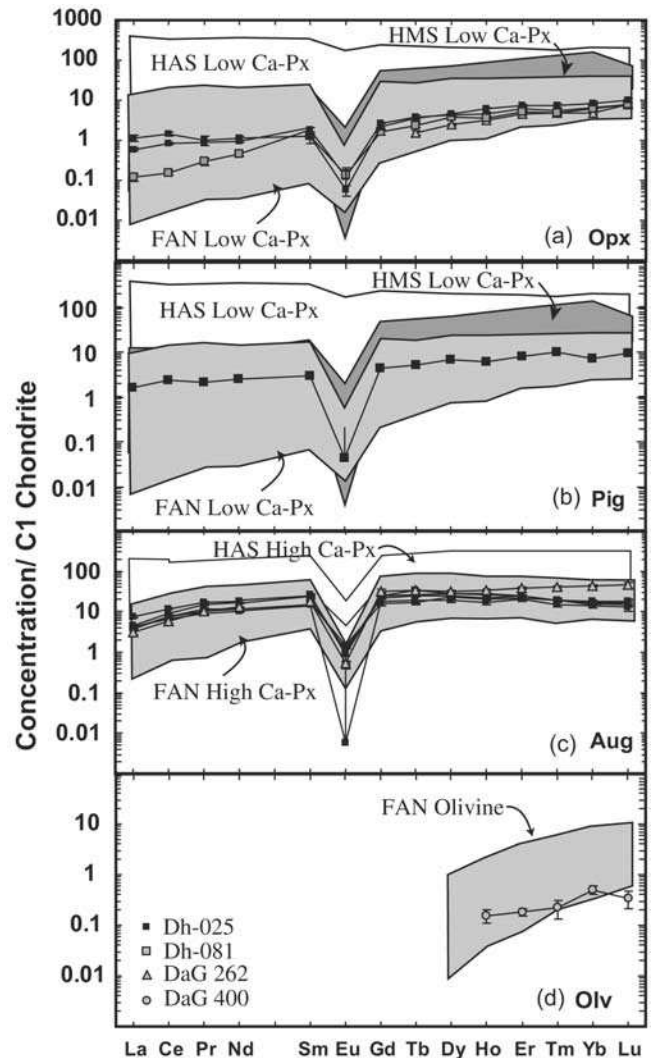


Fig. 15. C1-chondrite normalized REE patterns for pyroxenes and olivine grains. Normalization values are from Anders and Grevesse (1989). Orthopyroxene (a) and pigeonite (b) REEs are compared to pristine low-Ca pyroxene data of FAN, HMS, and high-alkali suite (HAS) rocks (Floss et al. 1998; Papike et al. 1994, 1996; Papike 1996; Shervais et al. 1997; Shervais and McGee 1998a, b, 1999; Snyder et al. 2004). High-Ca pyroxene (c) and olivine (d) analyses are compared to pristine analyses from FAN rocks (Floss et al. 1998).

pyroxene. During normal igneous processes, pyroxene has a lower melting point than olivine and anorthite, while the dynamics of impact-induced melting are poorly understood. Discrimination between these two possible sources is problematic, however, since both have large Fe, Mg, and HREE reservoirs.

Lunar Provenance and Implications

Remote sensing studies of the Moon indicate that the lunar surface is heterogeneous (Davis and Spudis 1985). A map of orbital data for the Th-Ti ratio versus Fe originally made it possible to recognize three major lunar rock types

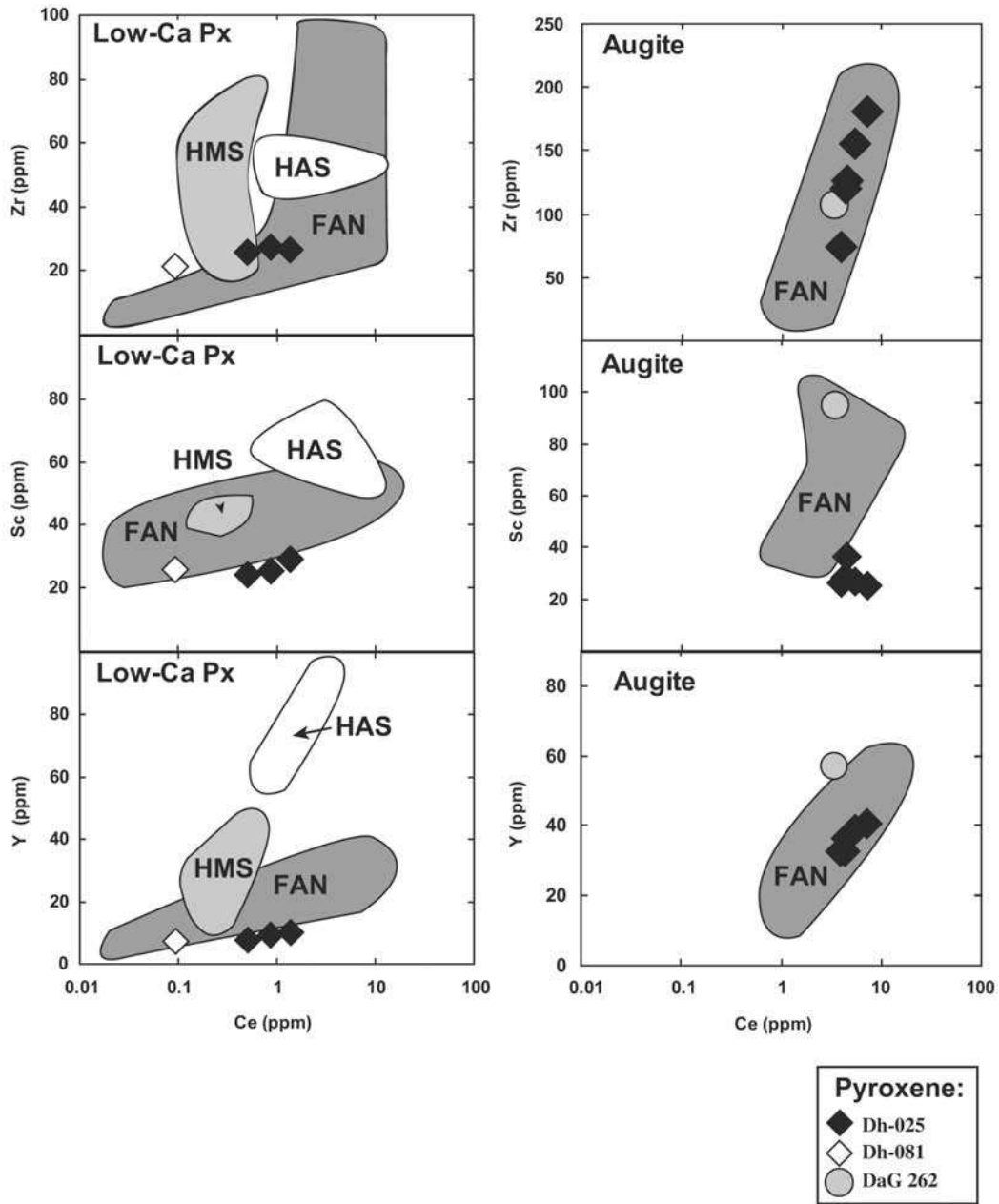


Fig. 16. Trace element concentrations of low- and high-Ca pyroxenes in the lunar meteorites Dho 025, Dho 081, and DaG 262 compared to data for typical FANs, HMS, and high-alkali suite (HAS) rocks (Floss et al. 1998; Papike et al. 1994, 1996; Papike 1996; Snyder et al. 2004).

across a large fraction of the lunar surface. These rock types are ferroan anorthosites, mare basalts, and KREEP/HMS norites. Nearly all mare basalts occur on the near side of the Moon, although a few mare terrains are seen on the far side. More recent maps generated from Clementine and Lunar Prospector data show that the bulk of the highlands are anorthositic, although petrologically heterogeneous (Spudis et al. 2000, 2002). Mare terrains also show heterogeneous characteristics with no impact basin being filled with a single type of basalt. These observations, along with the knowledge that the far side has a substantially thicker crust than the near

side (86 versus 64 km) (Taylor 1982), provide a detailed view of the Moon's crustal geology.

The lunar meteorites in this study are highly anorthositic breccias with a small HMS contribution and lack KREEPy signatures. Many clasts within these breccias show a mixture of FAN and HMS chemistries but do not exhibit textures typical of lunar granulites. These characteristics represent a type of highland terrain that differs significantly from the KREEPy impact breccias that dominate the lunar collection. These rocks must have originated from a largely FAN-rich terrain, removed from appreciable HMS and KREEP influences.

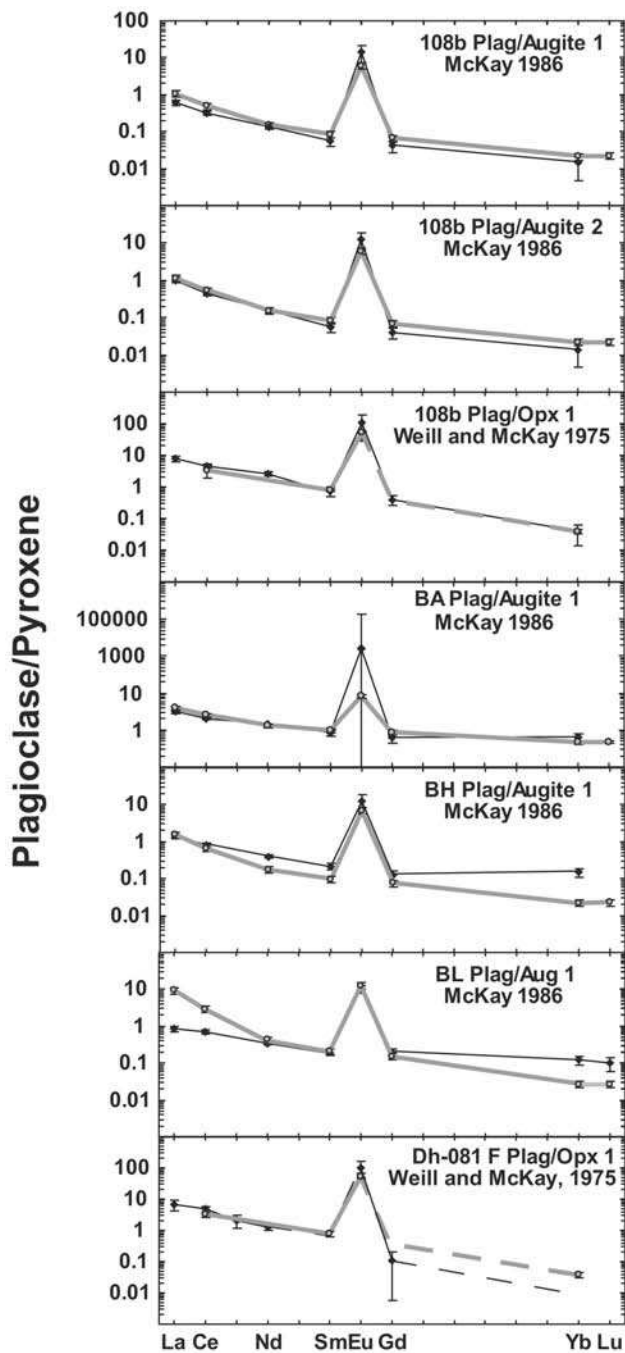


Fig. 17. Comparison of plagioclase-pyroxene REE concentration ratios and their mineral-melt distribution coefficient ratios (McKay et al. 1986, 1991; Phinney and Morrison 1990; Weill and McKay 1975). The filled diamonds and solid lines show the REE concentration ratios. The open circles and gray lines show experimentally determined distribution coefficient ratios.

On average, the highland regions on the near side of the Moon are dominated by HMS and KREEP-signatured lithologies, making an origin of these Dhofar and DaG meteorites from a terrain on the near side less likely. Nevertheless, the near side is not monolithic, and an origin on

this side of the Moon cannot be completely ruled out. Norman (1981) made a detailed study of a similar set of rocks collected from the rim of North Ray crater in the Descartes Mountains. Like the lunar meteorites studied here, 67016 is also characterized by a small regolith component, low concentrations of KREEP, and similar abundances of magnesian and ferroan clast types. Thus, a near side origin for these meteorites is possible.

However, based on remote sensing data, the lunar far side is shown to be comprised almost exclusively of highland terrains with little HMS and KREEPy components. Thus, the Dhofar and DaG meteorites could also have come from the far side. Studies by Greshake et al. (1998), Bischoff et al. (1998), and Semenova et al. (2000) have reached similar conclusions.

If these meteorites are indeed from the far side, this has implications for our current view of the Moon. It suggests that FAN and HMS magmatism may be global events. One clast, with arguably pristine chemistry, occupies the FAN and HMS gap, implying that FAN and HMS magmatism may be more closely related than previously thought. Based on low concentrations of ITE, the role of KREEP in far side HMS magmatism may be less significant than on the near side. This observation is consistent with recent claims that KREEP is restricted to the western limb of the near side. And, finally, impact gardening of the lunar crust appears to have produced a widespread and ubiquitous group of mixed impactite rocks that are similar in composition to lunar granulites.

SUMMARY

The lunar meteorites Dho 025, Dho 081, DaG 262, and DaG 400 are feldspathic highlands breccias. All four meteorites consist dominantly of FAN clasts, although some Dho 025, Dho 081, and DaG 400 clast compositions plot within the FAN-HMS “gap” on a plagioclase AN versus mafic-mineral Mg# diagram (Semenova et al. 2000). All four meteorites also plot between the FAN and HMS suites in terms of whole rock Ti-Sm ratios. These “gap” fillers are dominantly mixed rocks, but REE ratios suggest that pristine lithologies may exist with FAN + HMS chemistries. SIMS analyses of single clasts from DaG and Dhofar meteorites show stronger FAN affinities than seen in whole rock data but also indicate admixture of a small ($\leq 12\%$ average) HMS component. Furthermore, these meteorites lack mare lithologies and the KREEPy signatures that dominate the impact breccias of previously characterized highland terrains from the lunar near side and probably represent a type of highlands terrain not previously documented in the lunar collection.

Based on a comparison of their chemistries with the remote sensing data from Clementine and Lunar Prospector, it is inferred that these rocks probably originated on the far side of the Moon; albeit, a near side origin cannot be conclusively dismissed as an option. A far side origin for these rocks has several implications for our understanding of the Moon:

- A new type of highlands terrain has been characterized that differs significantly from the KREEPy impact breccias that dominate the lunar database.
- Impact gardening of the lunar crust produces mixed rocks similar in composition to lunar granulites, and these rocks are geographically widespread.
- FAN and HMS magmatism are global events.
- The relationship between FAN and HMS magmatism may be closer than previously recognized.
- The role of KREEP assimilation in the petrogenesis of HMS rocks on the far side may be less significant than on the near side.

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APPENDIX

Table A1. Summary of petrographic classifications and mineral compositions of Dho 025 and Dho 081 clasts.^a

| Sample | Rock | Plagioclase | Olivine | Pyroxene | | | |
|---------|---------------|-------------|-----------|-----------|-----------|-----------|-----------|
| Dho 025 | Textural type | An | Fo | Wo | En | Fs | Mg# |
| AA | LC | 96.6–97.3 | 75.1–77.8 | | | | |
| AB | LC | 96.9–98.0 | 80.2–82.0 | | | | |
| AF | LC | 95.9–96.9 | 69.2–73.2 | | | | |
| AI | LC | 96.1–97.5 | 78.9–80.3 | | | | |
| A | LC | 96.7 | 72 | | | | |
| B | LC | 96.6 | 72 | | | | |
| K | LC | 97.2 | 75 | | | | |
| T | LC | 97 | 75 | | | | |
| V | LC | 95.9 | 72 | | | | |
| Y | LC | 97 | 64 | | | | |
| AC | LC | 96.0–96.8 | | 5.66–8.91 | 67.0–70.5 | 23.2–25.8 | 72.2–74.9 |
| AD | LC | 95.6–96.4 | 66.7–69.7 | | | | |
| AE | LC | 94.2–96.1 | 65.1–68.7 | 4.53–5.36 | 68.8–69.5 | 25.9–26.1 | 72.6–72.9 |
| AG | LC | 95.1–96.9 | | 33.0–38.2 | 47.0–50.4 | 14.1–16.0 | 75.9–77.1 |
| AH | LC | 96.4–97.1 | 80.8–81.5 | | | | |
| BA | LC | 95.6–96.9 | | 3.30–4.41 | 75.2–76.5 | 19.6–20.4 | 79 |
| | LC | | | 39.3–44.4 | 46.7–50.0 | 8.9–10.7 | 81.5–83.4 |
| BB | LC | 96.9–97.6 | 74.1–82.1 | | | | |
| BC | LC | 95.1–98.0 | | 8.04–15.3 | 56.4–66.0 | 22.1–31.1 | 65.5–75.2 |
| BD | LC | 96.6–97.5 | | 4.9–9.6 | 54.9–60.4 | 28.2–37.1 | 58.9–68.8 |
| | LC | | | 38.3–40.3 | 41.3–43.3 | 18.0–19.6 | 70 |
| BF | LC | 94.7–97.9 | | 8.30–14.6 | 58.6–67.3 | 22.8–31.0 | 65.7–74.5 |
| BH | LC | 96.4–97.0 | | 3.66–7.08 | 73.6–77.8 | 17.4–19.3 | 81 |
| | LC | | | 37.4–41.8 | 46.6–48.2 | 10.0–12.3 | 81 |
| BL | LC | 95.7–96.7 | 69.9–73.2 | 38.2–44.3 | 45.6–49.9 | 9.3–15.3 | 79 |
| BM | LC | 96.0–97.1 | 77.5–82.7 | 2.91–6.40 | 78.5–81.7 | 15.2–16.8 | 83 |
| BO | LC | 96.1–97.0 | 71.4–73.0 | | | | |
| BP | LC | 95.6–96.3 | 70.6–72.5 | | | | |
| 25.8 | LC | 90.6–92.9 | 89 | 5.90–7.74 | 81.7–83.4 | 10.5–10.7 | 88 |
| 78 | LC | 94.2–96.9 | 68.0–73.3 | 6.31–10.8 | 66.0–69.2 | 23.1–24.5 | 73.8–74.5 |
| | | | | 34.9–39.5 | 47.0–50.4 | 13.9–14.7 | 77.4–77.8 |
| 93 | LC | 95.2–97.5 | 76.4–80.7 | 2.73–8.38 | 70.3–80.6 | 15.5–17.2 | 82.5 |
| 108b | LC | 95.6–95.9 | | 3.26–3.77 | 79.3–79.9 | 16.6–17.1 | 82 |
| | | | | 39.5–44.5 | 46.6–50.1 | 8.77–11.2 | 82 |
| Troc1 | LC | 96.4 | 81 | | | | |
| Troc3 | LC | 96.7 | 72 | | | | |
| Troc4 | LC | 96.4 | 72 | | | | |
| Gran1 | GR | 96.5 | 79 | | | | |
| BE | MF | | | 20.8–37.8 | 45.1–55.4 | 15.2–23.9 | 67.5–75.8 |
| BG | MF | | | 12.7–21.4 | 52.3–58.7 | 25.8–30.4 | 65.2–69.2 |
| BI | MF | 95.3–96.1 | | | | | |
| BK | MF | | | 3.4–4.6 | 72.1–73.1 | 23.3–23.6 | 75 |
| | | | | 40.4–43.4 | 45.3–47.1 | 11.1–13.4 | 76.5–80.7 |
| 71a | MF | | | 5.51–9.94 | 54.8–61.9 | 29.0–37.5 | 60.8–68.1 |
| 71b | MF | | | 4.46–9.28 | 58.9–64.1 | 28.0–36.5 | 61.8–69.6 |
| 71c | MF | | 75.2–81.5 | | | | |
| 74 | MF | | | 4.43–10.3 | 66.5–72.5 | 22.7–24.6 | 74.2–76.5 |
| 108 | MF | | | 28.7–37.5 | 34.5–46.7 | 24.8–32.5 | 51.5–65.2 |
| 121.1 | MF | | | 9.03–12.2 | 56.3–61.8 | 27.4–33.6 | 62.4–68.4 |
| 121.2 | MF | | 70.7–81.6 | | | | |
| 123.1 | MF | | | 37.4–42.8 | 44.0–47.8 | 13.2–15.0 | 75.7–77.1 |
| 123.2 | MF | | 72.5–77.7 | | | | |
| 126.1 | MF | | | 6.05–8.97 | 56.7–64.3 | 29.8–34.3 | 57.7–68.4 |
| 126.2 | MF | | 77.9–83.2 | | | | |

Table A1. Summary of petrographic classifications and mineral compositions of Dho 025 and Dho 081 clasts.^a

| Sample | Rock | Plagioclase | | Olivine | Pyroxene | | | | |
|--------|------|-------------|---------------|-----------|-----------|-----------|-----------|-----------|-----|
| | | Dho 025 | Textural type | An | Fo | Wo | En | Fs | Mg# |
| 126.3 | MF | | | 79.7–82.0 | | | | | |
| 130.1 | MF | | | | 9.20–13.1 | 58.5–66.0 | 25.4–31.4 | 65.1–71.5 | |
| 130.2 | MF | | | 73.1–74.4 | | | | | |
| C | LC | | 96.8–97.5 | 56.7–75.4 | | | | | |
| F | LC | | 97.8–97.0 | | 3.8–4.1 | 70.0–70.5 | 25.4–26.0 | 72.9–73.5 | |
| H | LC | | 96.4–98.1 | | 5.93–9.63 | 71.2–75.6 | 18.3–21.9 | 76.9–80.5 | |
| I | LC | | 96.7–97.6 | 76.0–78.5 | | | | | |
| I2 | LC | | 96.1–97.4 | 74.3–79.4 | | | | | |
| L | LC | | 95.4–97.4 | 71.0–74.4 | | | | | |
| | | | 95.4–97.4 | 72.4–81.0 | | | | | |
| | | | 95.4–97.4 | 69.8–82.0 | | | | | |
| R | LC | | 95.1–97.4 | | 39.9–40.6 | 32.1–32.4 | 27.2–27.8 | 53.8–54.1 | |
| | | | | | 27.2–30.3 | 40.5 | 29.2–32.3 | 55.7–58.0 | |
| V | LC | | 97.3–97.5 | | 26.5–28.8 | 39.2–45.5 | 28.0–32.1 | 55.0–61.9 | |
| AE | LC | | 92.8–97.3 | 81.2–83.9 | | | | | |
| G | GR | | 96.0–97.0 | 67.7–74.1 | | | | | |
| AF | GR | | 95.8–96.1 | 64.1–76.1 | | | | | |
| B | MF | | 96.0–96.9 | | | | | | |
| D | MF | | 97.0–96.8 | | | | | | |
| E | MF | | 96.4–97.4 | | | | | | |
| H1 | MF | | | | 30.1–40.4 | 42.0–51.9 | 11.4–27.9 | 60.1–81.8 | |
| J | MF | | | 50.2–74.1 | 19.6–25.3 | 25.8–32.1 | 42.6–52.9 | 32.7–43.0 | |
| K | MF | | 95.3–97.7 | | | | | | |
| K1 | MF | | | 71.2–81.6 | | | | | |
| M | MF | | 96.4–97.3 | | | | | | |
| O | MF | | 96.7–97.7 | | | | | | |
| P | MF | | 96.7–97.2 | | | | | | |
| Q | MF | | 94.8–96.5 | | | | | | |
| T | MF | | | 59.0–70.5 | | | | | |
| V1 | MF | | | | 12.6–24.9 | 49.4–62.8 | 21.3–25.7 | 65.8–74.7 | |
| V2 | MF | | | 81.2–84.9 | 39.4–42.4 | 38.1–46.3 | 14.3–19.4 | 66.2–76.4 | |
| W | MF | | 97.1–97.7 | | | | | | |
| W1 | MF | | | 80.7–82.6 | 3.62–5.21 | 62.1–64.4 | 30.4–34.3 | 64.4–67.9 | |
| X | MF | | 96.4–97.0 | | | | | | |
| Y | MF | | 97.2–97.7 | | | | | | |
| Z | MF | | 96.0–97.4 | | | | | | |
| AC | MF | | 96.0–96.8 | | | | | | |
| AI | MF | | 97.1–97.7 | | | | | | |

^aAbbreviations: LC = Lithic clast; MF = Mineral fragment; GR = Granulite rocklet. Clasts with two pyroxenes are organized so that low-Ca pyroxene is listed first, followed by high-Ca pyroxene.