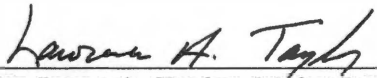
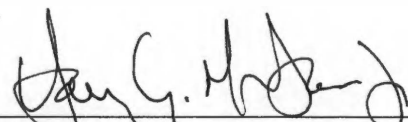


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I am submitting herewith a thesis written by Joshua Timothy Cahill entitled "Petrogenesis of Lunar Highlands Meteorites: Dhofar 025, Dhofar 081, Dar al Gani 262, and Dar al Gani 400." I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

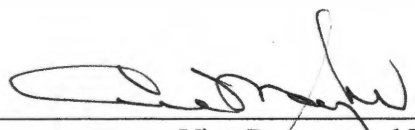

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Acceptance for the Council:


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THESIS

Submitted in partial fulfillment of the requirements for the degree of
Master of Science
in the Department of
Political Science
at the University of
Illinois at Chicago
Chicago, Illinois
1999

**PETROGENESIS OF LUNAR HIGHLANDS METEORITES: DHOFAR 025,
DHOFAR 081, DAR AL GANI 262, AND DAR AL GANI 400**

**A Thesis
Presented for the
Masters of Science
Degree
The University of Tennessee, Knoxville**

**Joshua Timothy Cahill
May 2003**

DEDICATION

This thesis is dedicated to my parents, Tim Cahill and Judy Cahill, who taught me to never give up, always finish what I start, and to *always* reach for the stars. To my younger brother, Adam Cahill, who taught me how to be a champion when he sat up in the hospital bed to talk to a caring young fan and pupil, without showing the child the pain he was in. Shortly thereafter, Adam also taught me the meaning of passion when he arose from the hospital bed, despite numerous injuries and opposition from those who doubted his determination, to fulfill his life-long dream by attending classes at the University of Notre Dame. To my younger sister, Alison Cahill, from whom I expect great things no matter what path she decides to take in life. And finally, to all other family members who have been relentless in their generous support of my dreams and goals. My families' cumulative passions, work ethics, and competitiveness have made me what I am today, and will continue to mold me in the future.

ACKNOWLEDGEMENTS

I would like to thank all those who have supported my studies at the University of Tennessee. I would like to express my appreciation to my advisor, Dr. Larry Taylor, for the many opportunities he has given me, and to his amazing wife, Dawn Taylor. I would like to thank Dr. Christine Floss of Washington University, St. Louis, for her exceptional knowledge of the ion-microprobe and unwavering patience when answering my many questions. Thanks to Misha Nazarov, for his candid reviews and touches of humor. Thanks to Dr. Harry McSween, Jr. and Dr. Dan Britt for accepting positions on my committee. Thanks to both Dr. Mahesh Anand and Dr. Barbara Cohen for their patience, advice, and direction on numerous occasions.

I would like to express my appreciation to Allan Patchen, for his help with the electron-microprobe analyses. My sincere thanks to Dr. Robert Clayton and Dr. Tosh Mayeda for sharing oxygen isotope data. I am also grateful to the Vernadsky Institute, the Max-Planck-Institute for Chemistry, Mainz, and the Institute for Planetology, Münster, for their willingness to supply the samples necessary for this study. A special thanks to the Joint United States/ Russia Research in Space Sciences (JURRISS) Program (NAG 5-8726 to L.A.T.) sponsored by NASA. Portions of this research have also been supported by NASA grants to L.A.T. (NAG5-11158) and C.F. (NAG5-9801; PI: R. Walker), and a Russian Academy of Science Award to M.A.N. (02-05-64981 to R.F.B.R.).

And finally, thank you to all the students of the University of Tennessee Geology Department. Most especially to Keith Milam, Karen Stockstill, Kathy Stone, Pin Promprated, Renee Wiesli, Cara Thompson, and Mike DeAngelis. Without their enthusiasm for geology and life this effort would not have been possible. I hope we work together again in the future.

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1. OVERVIEW OF MASTER'S DEGREE

During my time at the University of Tennessee, I have been involved in several planetary geoscience projects within Dr. Larry Taylor's research group. These projects involved research on lunar soils, and lunar and martian meteorites.

Lunar Soils: My work on lunar soil research have involved bulk chemical and modal characterization of different size splits of the $\leq 45 \mu\text{m}$ fraction of lunar highlands soils, and the evaluation of the qualitative *FeatureScan*® program. The findings of this research have direct use in the calibration of lunar remote-sensing data. The following abstracts were produced and presented at international conferences in poster format by the primary authors:

ANDERSON E. D., PATCHEN A., CAHILL J. T. and TAYLOR L. A. (2001) Mineral Modes in

Fine Fractions of Lunar Highland Soils: Experimentation with Subjective

Parameter of "Feturescan" (Abstract). *Meteorit. Planet. Sci* **36** (Suppl.), A11.

TAYLOR L. A., CAHILL J. T., PATCHEN A., PIETERS C. M., MORRIS R. V., KELLER L. P. and

McKAY D. S. (2001) Mineralogical and Chemical Characterization of Lunar

Highland Regolith: Lessons Learned from Mare Soils (Abstract). *Lunar Planet.*

Sci. Conf. **XXXII**, #2196.

My specific contributions towards these abstracts involved: (1) creating glasses from lunar soil fractions for bulk-chemical analysis, (2) determination of mineral modes

of lunar soils using the *FeatureScan*® software, (3) evaluating the *FeatureScan*® software, and (4) contributions towards creation of two posters for the Meteoritical Society and Lunar and Planetary Science conferences.

Meteorites: Russian expeditions to the desert region of Dhofar, Oman during 1999-2002 have recovered large numbers of meteorites for the scientific community. The Joint United States/ Russia Research in Space Sciences (JURRISS) Program has allowed us to obtain samples of these meteorites. As a result, our research group has performed various research activities in order to better understand extra-terrestrial materials and their parent bodies. I have been involved with research evaluating both lunar and martian achondrites.

My work on martian meteorites has involved the petrological and geochemical study of basaltic shergottite Dhofar 019 (Dh-019). The following abstract and publication were the result of this work:

CAHILL J. T., TAYLOR L. A., PATCHEN A. D., NAZAROV M. A., STOCKSTILL K. R. and ANAND

M. (2002) Basaltic Shergottite Dhofar 019: A “Normal” Olivine Cumulate

Product (Abstract). *Lunar Planet. Sci. Conf. XXXIII*, #1722.

TAYLOR L. A., ET AL. (2002) Martian Meteorite Dhofar 019: A New Shergottite.

Meteorit. Planet. Sci **37**, 1107-1128.

My contributions toward this research were: (1) creating transmitted and reflected light maps, (2) creating two thin sections for geochemical analysis, (3) creating

a back-scattered electron map of one thin section, (4) electron microprobe analyses and photography of melt inclusions and olivines (cumulates and megacrysts), (5) crystallization modeling using software such as MELTS (MAGPOX and MAGFOX were also used but not included in the abstract or paper), (6) compilation of the research group's effort into an abstract, (7) writing of the abstract, on which I am first author, (8) oral presentation of this work at the Lunar and Planetary Science Conference, and (9) an attempt to homogenize olivine-hosted melt inclusions in Dh-019 at Virginia Tech University (this work was abandoned due to difficulties in sample preparation, mainly because of the altered nature of the meteorite).

The majority of my research on lunar achondrites has involved the four meteorites Dhofar 025 (Dh-025), Dhofar 081 (Dh-081), Dar al Gani 262 (DaG 262), and Dar al Gani 400 (DaG 400). My task was to evaluate the lunar meteorite Dh-025 for the first time, as well as to complement the existing database on previously studied lunar meteorites Dh-081, DaG 262, and DaG 400. The following abstracts and manuscript were produced:

ANAND M., TAYLOR L. A., PATCHEN A., CAHILL J. T. and NAZAROV M. A. (2002) New Minerals from a New Meteorite Dhofar 280 (Abstract). *Lunar Planet. Sci. Conf. XXXIII*, #1653.

CAHILL J. T., COHEN B. A., TAYLOR L. A. and NAZAROV M. A. (2001a) Mineralogy and Petrology of "New" Lunar Meteorite Dhofar 025 (Abstract). *Lunar Planet. Sci. Conf. XXXII*, # 4185.

CAHILL J. T., FLOSS C., TAYLOR L. A., NAZAROV M. A., ANAND M. and COHEN B. A. (2002a)

Petrogenesis of Lunar Highland Meteorites: Dhofar 025, Dhofar 081, Dar Al Gani 262, and Dar Al Gani 400. *Meteorit. Planet. Sci.* (submitted).

CAHILL J. T., TAYLOR L. A., ANAND M., PATHCHEN A. D. and NAZAROV M. A. (2002b)

Mineralogy, Petrography, and Geochemistry of Lunar Meteorite Dhofar 081: New Developments (Abstract). *Lunar Planet. Sci. Conf. XXXII*, #1351.

CAHILL J. T., TAYLOR L. A., COHEN B. A., FAYEK M., RICIPUTI L. R. and NAZAROV M. A.

(2001b) Lunar Meteorite Dhofar 025: Plagioclase REEs Confirm Non-Pristine Nature for Highland Clasts (Abstract). *Meteorit. Planet. Sci.* **36** (Suppl.), A36.

Of all the work presented, I took control of the research involving lunar meteorites Dh-025, Dh-081, DaG 262, and DaG 400. Chapter two of this thesis is a slightly modified version of a paper submitted to *Meteoritics and Planetary Sciences* in 2002, on which I am the first author. My use of “we” in the following chapter refers to my co-authors and myself. These researchers involved in this study are Dr. Christine Floss, Dr. Larry Taylor, Dr. Mahesh Anand, Dr. Misha Nazarov, Dr. Barbara Cohen, and myself.

My contributions to this paper include: (1) creating transmitted and reflected light maps for Dh-025 and Dh-081, (2) electron microprobe analyses of Dh-025 and Dh-081, (3) trace-element analyses of Dh-025 at Oak Ridge National Laboratory using a CAMECA IMS 3f secondary ion mass spectrometer (it was later found that this data was flawed and Oak Ridge was not properly set-up for trace-element analyses of single

minerals at that time), (4) creating reflected light and back-scattered electron images of Dh-025 and Dh-081 for ion microprobe analysis by Dr. Christine Floss at Washington University, St. Louis, (5) selection of spot sites for ion microprobe analysis of Dh-025 and Dh-081, (6) updating a database of lunar meteorite oxygen isotope values, (7) creating a database of lunar meteorite whole-rock compositions, and re-interpretation of these whole-rock compositions, (8) creating a database of all ion microprobe analyses of lunar minerals to date, (9) interpretation of Dh-025, Dh-081, DaG 262, and DaG 400 ion microprobe data, (10) writing and submission of abstracts, (11) creation of three posters on Dh-025 and Dh-081 and presentation at the Meteoritical Society and Lunar and Planetary Science Conferences, (12) and compilation of research on these lunar meteorites into one paper, and (13) writing of the manuscript.

2. ABSTRACT

The petrogenesis of four lunar highlands meteorites, Dhofar 025 (Dh-025), Dhofar 081 (Dh-081), Dar al Gani 262 (DaG 262), and Dar al Gani 400 (DaG 400) have been studied. For Dh-025, measured oxygen isotopic values ($\delta^{18}\text{O} = +5.47\text{‰}$ and $\delta^{17}\text{O} = +2.81\text{‰}$) and Fe-Mn ratios for mafic minerals (Px-49.7; Ol-86) provide corroboratory evidence that it originated on the Moon. Similarly, Fe-Mn ratios in the mafic minerals (Px-52.3; Ol-87.8) of Dh-081 also indicate its lunar origin. Whole-rock Sc and Al_2O_3 concentrations of Dh-025 (10.2 ppm and 26.1 wt%, resp.), Dh-081 (5.4 ppm and 30.5 wt%, resp.), DaG 262 (7.85 ppm and 27.5 wt%), and DaG 400 (5.40 ppm and 26.2 wt%, resp.; Bischoff *et al.*, 1998) are also indicative of anorthositic lunar highlands material.

Each of the four lunar samples is a breccia, with texturally pristine and non-pristine lithologies. Lithologies in Dh-025 and Dh-081 include igneous rocklets, partially recrystallized impact melt rocklets, granulites, and mineral fragments. Some of these lithologies have plagioclase AN and coexisting mafic mineral Mg# that plot within the “gap” separating ferroan anorthosite suite (FAN) and high-magnesium suite (HMS) rocks. These atypical compositions are more common in recent collections of lunar highlands meteorites, and may indicate the FAN field should be expanded. This is consistent with whole-rock Ti-Sm ratios for Dh-025 (1.5 ppm), Dh-081 (0.63 ppm), and DaG 262 (1.15), which are also intermediate compared to FAN and HMS lithologies.

Compared to other lunar highlands meteorites, whole-rock compositions also show that Dh-025 is enriched in Sc and Mg# (70), whereas Dh-081 has the highest Al_2O_3

content measured to date. Systematic depletions (by a factor of 10) in whole-rock Sm concentrations are apparent in Dh-025 (1.5 ppm), Dh-081 (0.63 ppm), and DaG 262 (1.15 ppm), as compared to Apollo 14 and 16 highland regolith breccias. This may indicate that these samples have been derived from an entirely different terrain of highlands regolith, perhaps on the lunar far-side.

Ion-microprobe analyses were also performed to evaluate trace-element (including rare earth elements—REE) variations in Dh-025, Dh-081, DaG 262, and DaG 400 clasts and minerals. These analyses show far stronger FAN affinities for these meteorites than whole-rock data suggest, although most clasts indicate admixture of a $\leq 12\%$ HMS component. Ratios of Sc-Sm in all clasts are typical of low-incompatible trace-element abundances in FAN lithologies (>12).

Several analyses of Dh-025 plagioclases indicate redistribution of HREEs due to shock metamorphism. However, the majority of mineral analyses in all these meteorites are typical of FAN lithologies. Coexisting plagioclase-pyroxene REE concentration ratios in several clasts were compared to experimentally determined plagioclase-pyroxene REE distribution coefficient ratios. Two Dh-025 clasts have concordant plagioclase-pyroxene profiles indicating that the equilibrium between these minerals has not been modified by shock metamorphism. These clasts plot within the FAN-HMS gap and possibly represent new pristine highland compositions. Since these compositions have not been sampled on the lunar near-side, it is possible they represent far-side rocks and suggest that the FAN or HMS fields should be expanded.

2.1 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-side are substantially different in terms of inferred chemistry and lithologies (Spudis *et al.*, 2000; Spudis *et al.*, 2002). Thus, it is likely that our vision of lunar geologic processes and history is incomplete. However, newly discovered lunar meteorites could potentially supply samples necessary to characterize numerous unsampled terrains of the Moon. Recent meteorite finds from the Dhofar region of Oman (which represent nearly half of the thirty known lunar meteorites) may represent such samples.

In this study, we examine the mineralogy and petrology of the four lunar-meteorite breccias Dhofar 025 (Dh-025), Dhofar 081 (Dh-081), Dar al Gani 262 (DaG 262), and Dar al Gani (DaG 400). We used geochemical (major-, minor-, and trace-element) analyses to: (1) provide evidence for lunar origin of these rocks, (2) distinguish between mare and highland clasts, (3) identify clasts least affected by shock metamorphism, and (4) infer near- or far-side origin for these rocks.

2.2 ANALYTICAL TECHNIQUES

Thin sections of each meteorite were examined with an optical microscope using transmitted and reflected light. Major- and minor-element mineral chemistry of

plagioclase, olivine, and pyroxene in Dh-025 and Dh-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 analysis, 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. Counting times were 20 seconds for all elements analyzed in plagioclase, and 30 seconds for elements in all other minerals. Standard on-line matrix corrections (PAP) were applied to all analyses.

The oxygen isotopic composition of Dh-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 Dh-025 was determined at the Vernadsky Institute, Moscow, Russia. A 1-g sample was powdered in an agate mill to obtain homogeneous material for whole-rock analyses. Si, Ti, Al, Cr, Fe, Mn, Mg, and Ca were determined by XRF and ICP. Na and K were measured by atomic absorption. Trace elements were analyzed by instrumental neutron activation analysis (INAA).

Major-, minor-, and trace-element (including REE) concentrations were determined for selected Dh-025, Dh-081, DaG 262, and DaG 400 mineral grains and clasts using the modified CAMECA IMS 3f ion-microprobe at Washington University, St. Louis, according to methods outlined by Zinner and Crozaz (1986b). 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 (100V 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), Hsu (1995), and Zinner and Crozaz (1986a) for the REE and by Hsu (1995) for other elements. All mineral analyses were normalized using Si as a reference element. SiO₂ concentrations were determined by electron microprobe as mentioned previously. Polymineralic clast analyses were normalized using an arbitrary concentration of SiO₂ concentration of 50 wt%.

2.3 PETROGRAPHY AND MINERAL CHEMISTRY

Dh-025, an anorthositic regolith breccia, was found in Dhofar, Oman in January of 2000, weighing 751g (Grossman, 2000). Dh-081, a shocked, feldspathic-fragmental-highlands breccia, was discovered a year earlier. The cosmogenic exposure age for Dh-025 ranges from 13-20 Myr (Nishiizumi *et al.*, 2001b). However, for Dh-081, the transition time between the Moon and Earth was too short for detectable amounts of long-lived nuclides to be produced (Nishiizumi *et al.*, 2001a). The lithologies present in these meteorites include: (1) igneous rocklets, (2) impact-melt rocklets, (3) granulites, and (4) mineral fragments. A summary of clast types and their mineral compositions is listed in TABLE A1.

Impact-melt rocklets are the dominant lithology in Dh-025 (FIG. 1a-b). These clasts are partially recrystallized monomict and polymict rocks that consist mainly of plagioclase (AN 94-98), with minor amounts of mafic minerals (Mg# 64-83). Mafic minerals in these clasts have subhedral shape due to interaction with an impact-melt.

FIG. 1. Backscattered electron images of lunar meteorite Dh-025. (a-b) Texturally non-pristine impact-melt rocklets, with embayed mafic minerals resulting from interaction with impact-melt. These clasts are surrounded by a fine-grained and glassy meteorite-matrix. (c-d) Troctolitic clasts classified as igneous rocklets because of monomict textural appearances and spherical olivine crystals. (e) Granulite clast with granoblastic texture and plagioclase and olivine mineralogy. (f) Bimineralic pyroxene fragment consisting of augite and orthopyroxene.

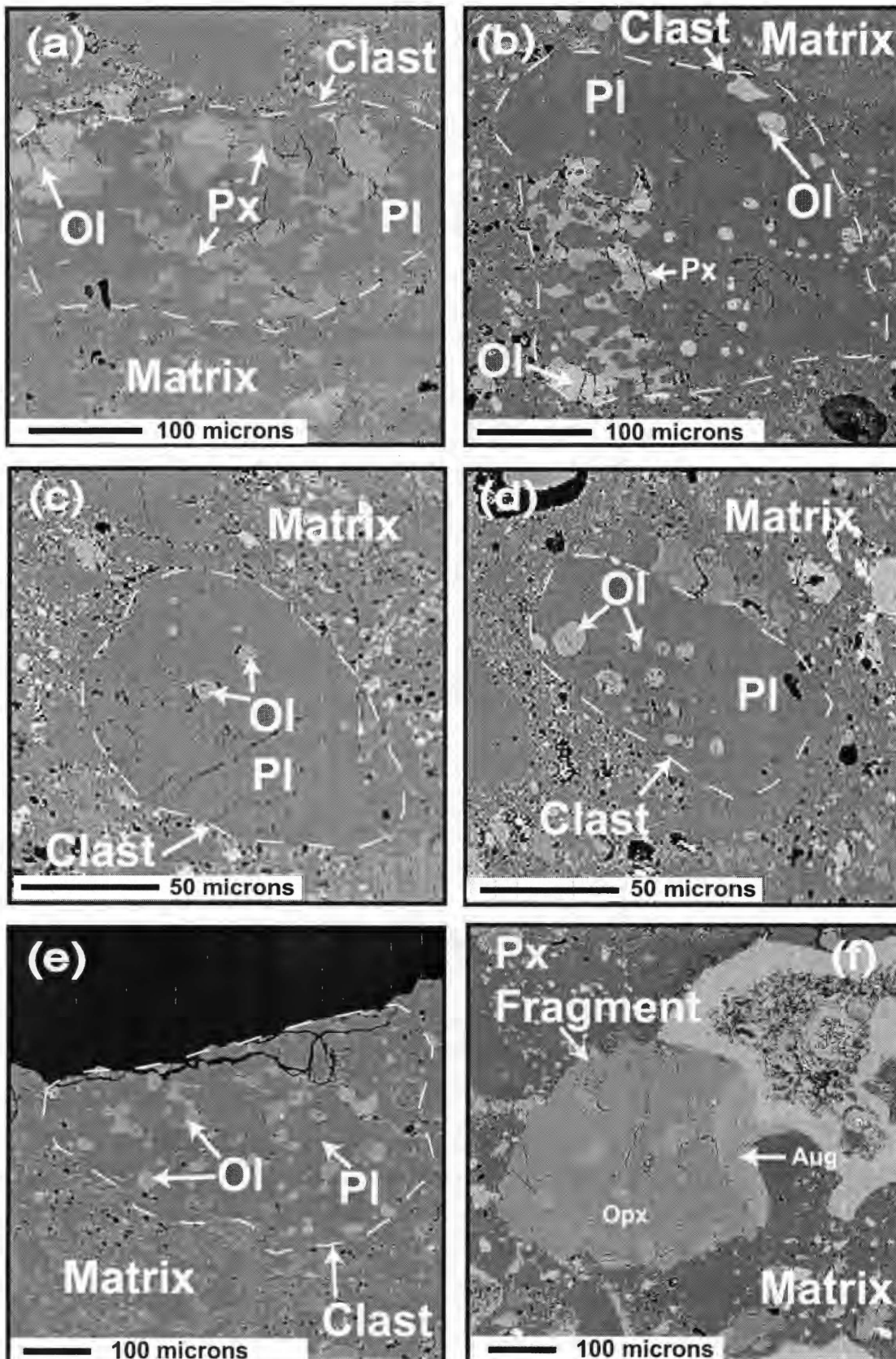


Figure 1:

Igneous rocklets in Dh-025 occur as troctolites that are about 100-200 μm in size, and consist predominantly of plagioclase (AN 96-98) (FIG. 1c-d). Olivines form minor constituents, sub-rounded in shape, and relatively homogenous in composition (Fo 69-80) (FIG. 2a). Only one granulitic-troctolite clast was observed in Dh-025. 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). Two inverted pigeonites were also found. Accessory minerals include spinel, ilmenite, FeNi metal, troilite, and silica. Akaganéite ($\beta\text{-FeOOH}$) occurs as rims on FeNi metal grains, and are most likely of terrestrial origin. Other terrestrial alteration products (calcite, celestite, and gypsum) are also present in the meteorite, mainly filling cracks.

Compared to Dh-025, Dh-081 is poor in mafic-mineral constituents. Impact-melt clasts in this breccia consist dominantly of plagioclase (AN 94-97), with embayed and/or zoned mafic minerals (FIG. 3a-c). Olivine is the most abundant mafic mineral (Fo 56-83), whereas pyroxenes (Mg# 58-78) are minor constituents in these clasts (FIG. 2b). Granulite lithologies, in Dh-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 Dh-081 clasts are individual mineral fragments. Plagioclase fragments (AN 94-98) are most abundant, whereas mafic mineral fragments are mainly olivine, often with pyroxene rims. Olivine fragments often exhibit reverse zoning (e.g., core - Fo ~ 71 vs. rim - Fo ~ 80).

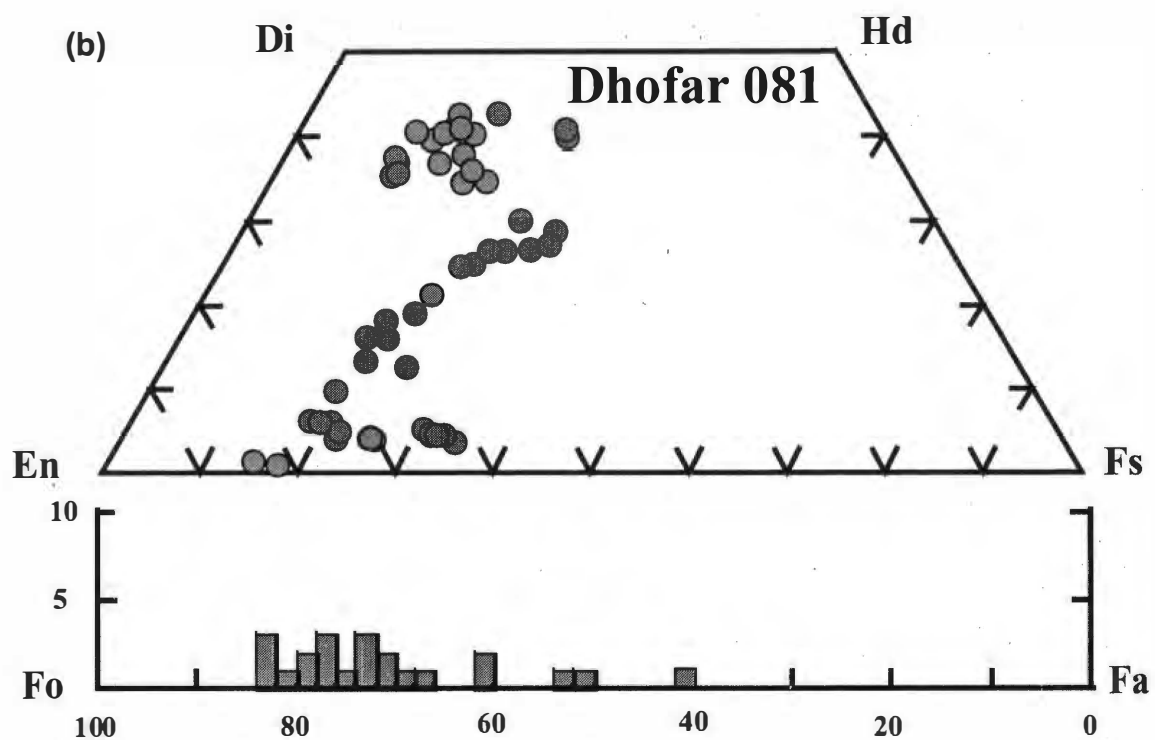
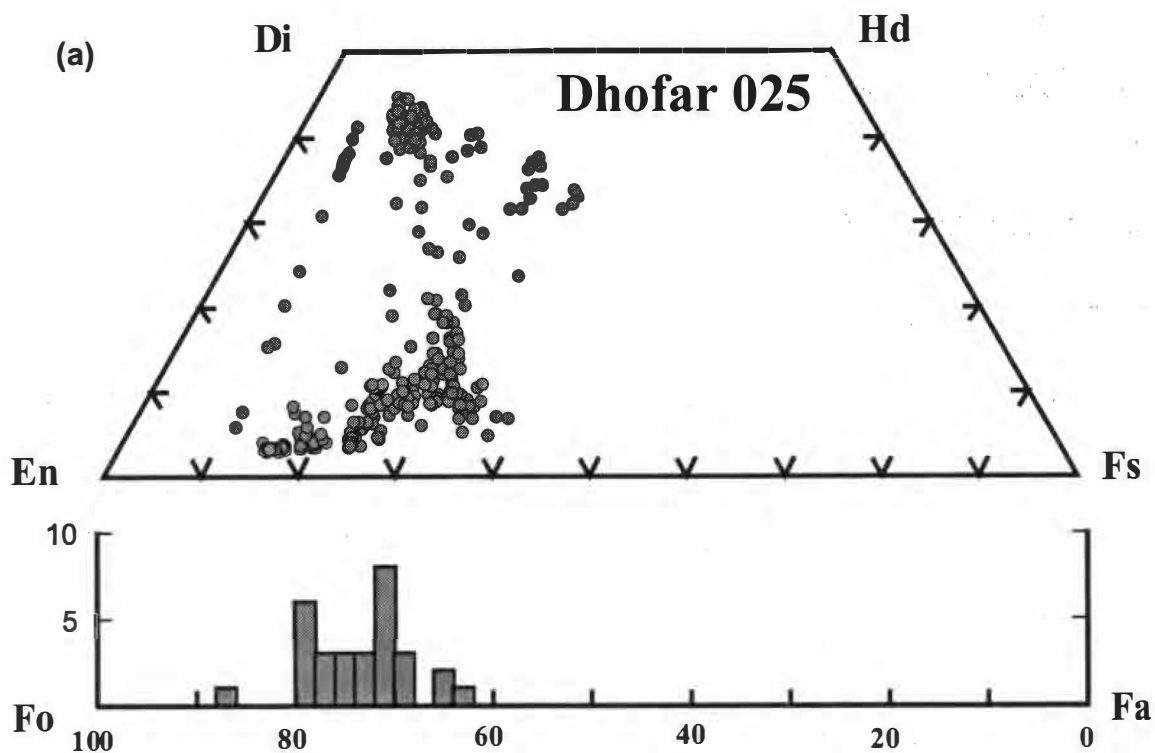
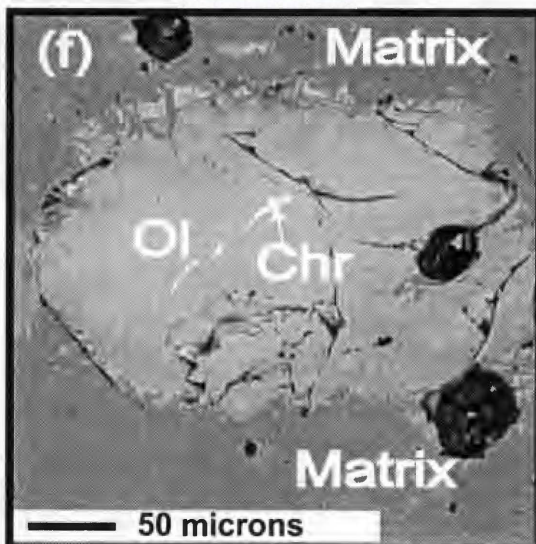
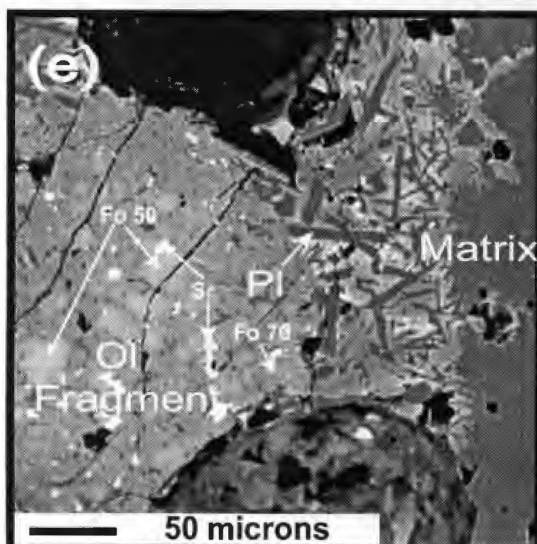
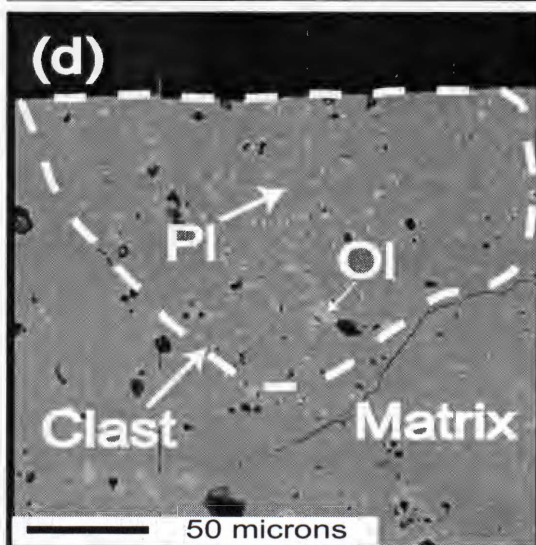
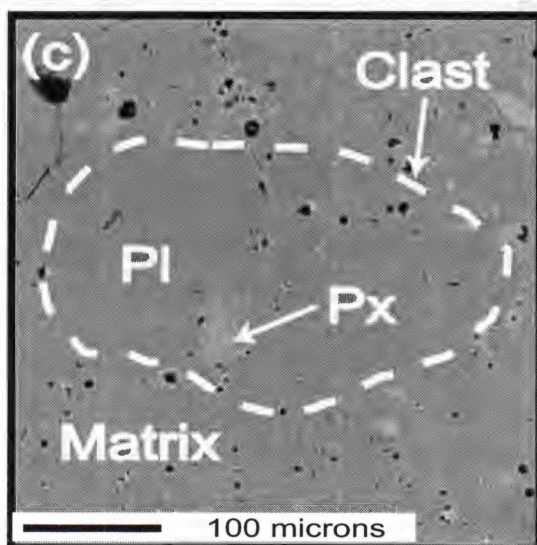
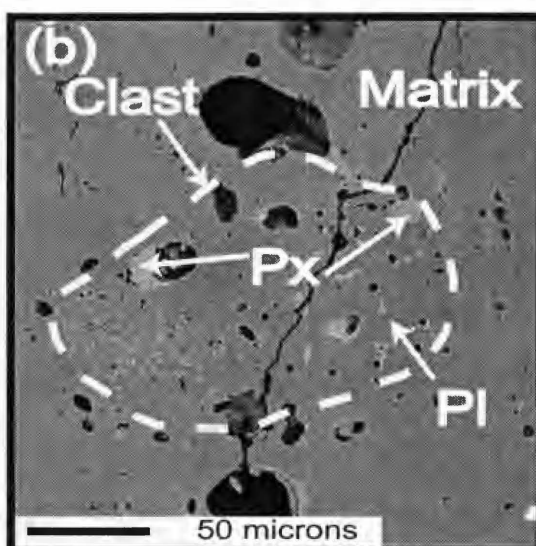
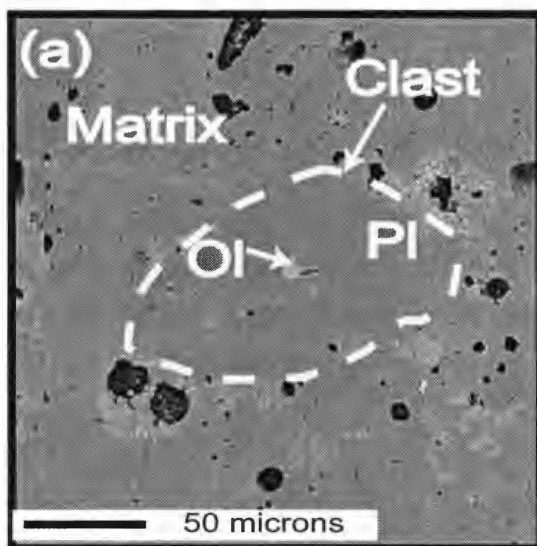


FIG. 2. Pyroxene and olivine major-element compositions for lunar meteorites (a) Dh-025 and (b) Dh-081.

FIG. 3. Backscattered electron images of lunar meteorite Dh-081. (a-c) Mafic-poor impact-melt rocklets. (d) Granoblastic granulite with fine-grained olivine mineralogy. (e) Back-scattered electron (BSE) image of a heavily melted and embayed relic olivine mineral fragment with several vesicles in and around its edges. This olivine fragment has reverse zonation (core: Fo ~53; rims: Fo ~ 73) probably due to re-equilibration with the impact-melt matrix. (f) Olivine mineral fragment with chromite vein.



One olivine grain ($\sim 350\ \mu\text{m}$; FIG. 3e) in particular, is characterized by a compositional variance of Fo ~ 20 from core to rim (i.e., Fo ~ 53 to Fo ~ 73). Reverse zoning is likely due to interaction with 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). Although we have made trace-element measurements in a number of DaG 262 and DaG 400 clasts, we have not carried out a detailed characterization of the types of clasts present and their mineral chemistries. However, Bischoff *et al.* (1998) note that DaG 262 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 ($\text{AN} \geq 95$) 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 Dh-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, the samples Dh-025 and Dh-081 have lithologies with strong FAN affinities; some of them plot within the FAN-HMS gap (FIG. 4 and 5). Traditionally, Apollo and Luna rocks, as well as other lunar meteorites have plotted within the FAN and HMS envelopes. However, recent characterizations of minerals in lunar meteorites have revealed clast compositions falling within this gap. Three of the four lunar meteorites in this study (DaG 400, Dh-025, and Dh-081), as well as several other Dhofar meteorites (Dh-280, Dh-301, Dh-302, and Dh-303) (Anand *et al.*, 2002b; Nazarov *et al.*, 2002; Semenova *et al.*, 2000), display such gap compositions. Either these lunar meteorite clasts are new lithologies not previously seen in Apollo and Luna sampled rocks, or they are mixtures of FAN and HMS components created by impact melting. Both possibilities were investigated further using whole rock, clast, and mineral compositional data.

2.4 EVIDENCE FOR LUNAR ORIGIN

2.4.1 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).

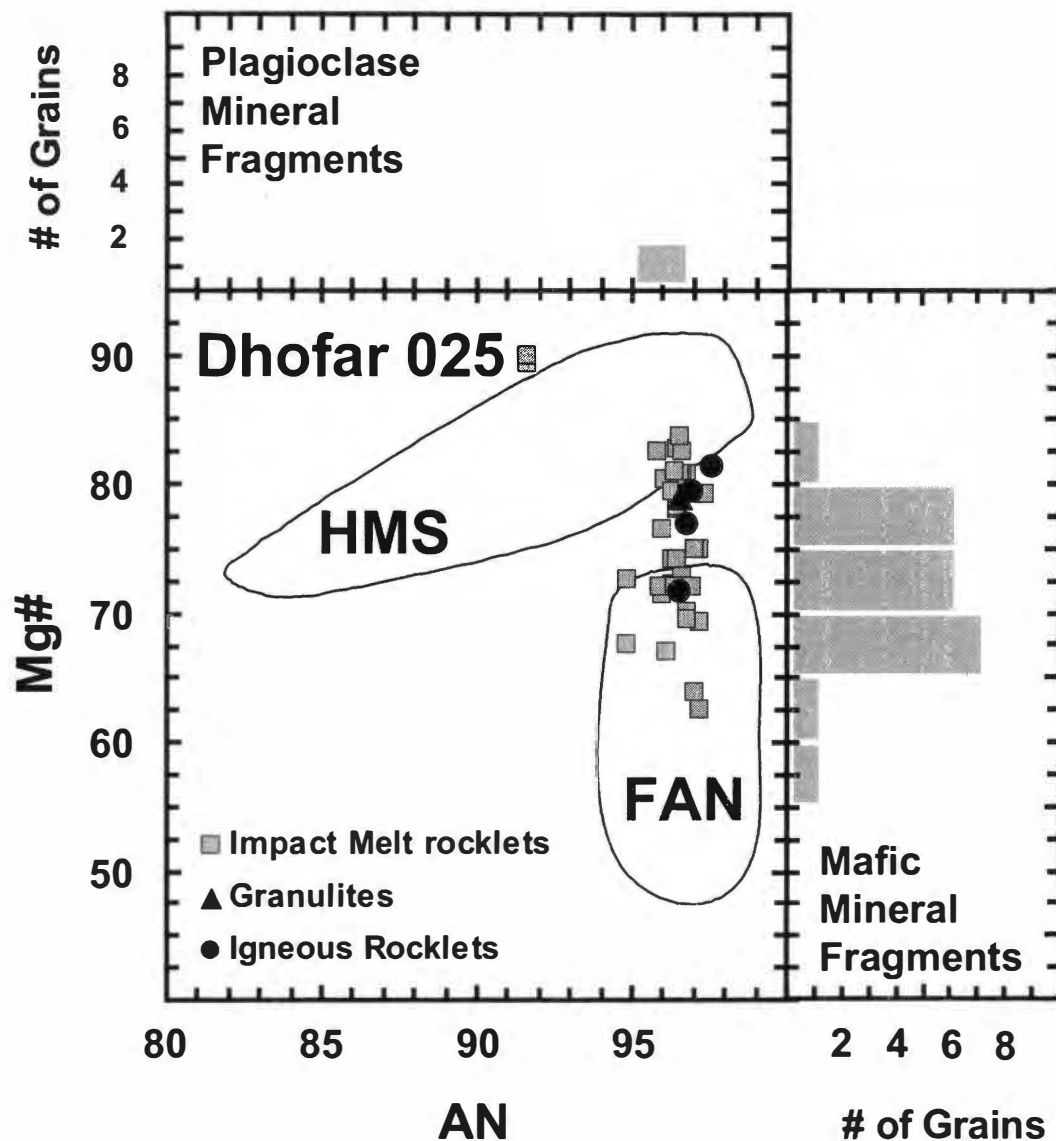


FIG. 4. Mafic phase (olivine and pyroxenes) Mg# vs. AN in plagioclase for Dh-025 lunar meteorite clasts. FAN and HMS rock suites are shown for comparison (Warren, 1985). Mafic mineral fragment Mg# values that lack corresponding plagioclase chemistries are shown on the right portion of the diagram. Plagioclase mineral fragment AN values that lack coexisting mafic mineral chemistries are shown on the top portion of the diagram.

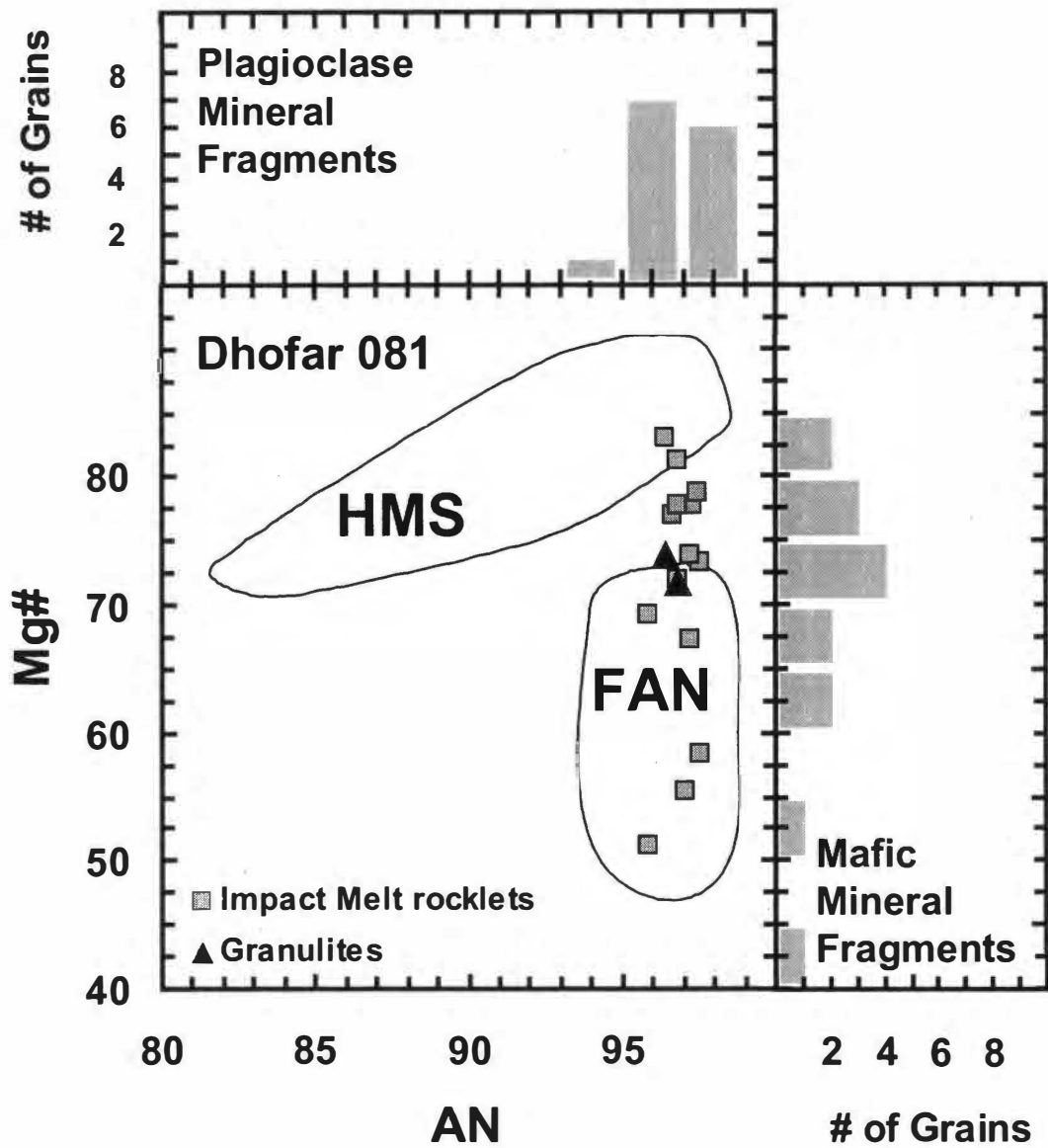


FIG. 5. Dh-081 lunar meteorite clasts mafic phase (olivine and pyroxenes) Mg# vs. AN in plagioclase. FAN and HMS compositional envelopes are as in previous figure.

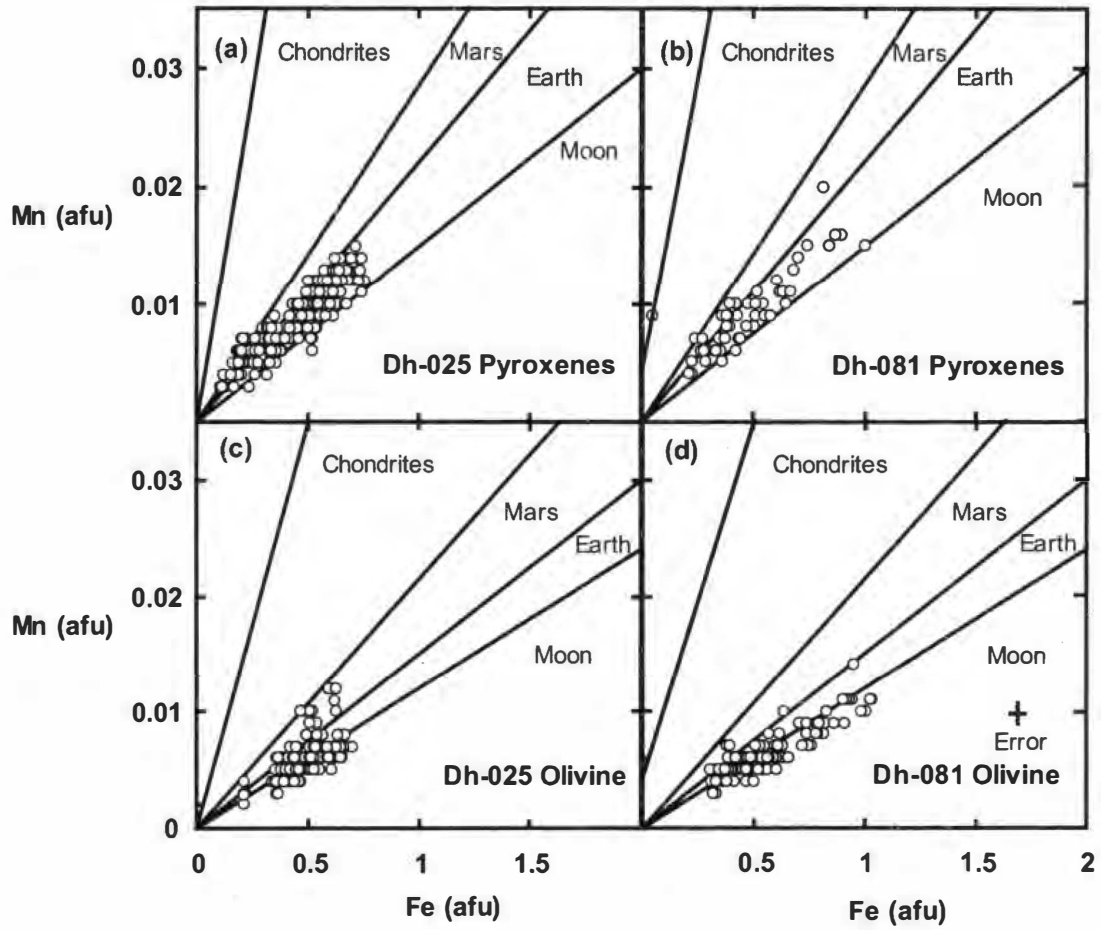


FIG. 6. Fe-Mn ratios (Papike, 1998) for Dh-025 and Dh-081 (a-b) pyroxene and (c-d) olivine. Fe-Mn ratios in olivines are typical of lunar rocks. However, Mn concentrations in pyroxenes for both Dh-025 and Dh-081 are slightly enriched.

In FIG. 6, the Fe-Mn ratios of olivines and pyroxenes from Dh-025 and Dh-081 are shown. Although olivine data from both meteorites plot along the lunar trend, pyroxene data from each meteorite appear to have elevated Mn, with average pyroxene Fe-Mn ratios in Dh-025 and Dh-081 of 49.7 and 52.3, respectively. These analyses may indicate that fractionation of Fe and Mn in olivine compared to pyroxenes differs slightly. However, this is difficult to determine considering the low concentrations of both Fe and Mn in these minerals. Despite both of these hypotheses, olivine Fe-Mn ratios in Dh-025 and Dh-081 (86.0 and 87.9, respectively) are consistent with Apollo and Luna rocks (FIG. 6). Furthermore, whole-rock Fe-Mn ratios for Dh-025 are 65.7, similar to the lunar meteorite average of 70 (Palme *et al.*, 1991).

2.4.2 Oxygen Isotopes: The Dh-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 (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.

2.5 WHOLE-ROCK COMPOSITIONS

The whole-rock composition of Dh-025 was compared to those of Dh-081, DaG 262, DaG 400, other lunar highlands and mare meteorites, as well Apollo samples (TABLE 1). Most of the known lunar meteorites (~80%) are breccias or impact melts with highlands characteristics (e.g., Dh-026, MAC88104/5, Y86032, Y82192, ALHA81005,

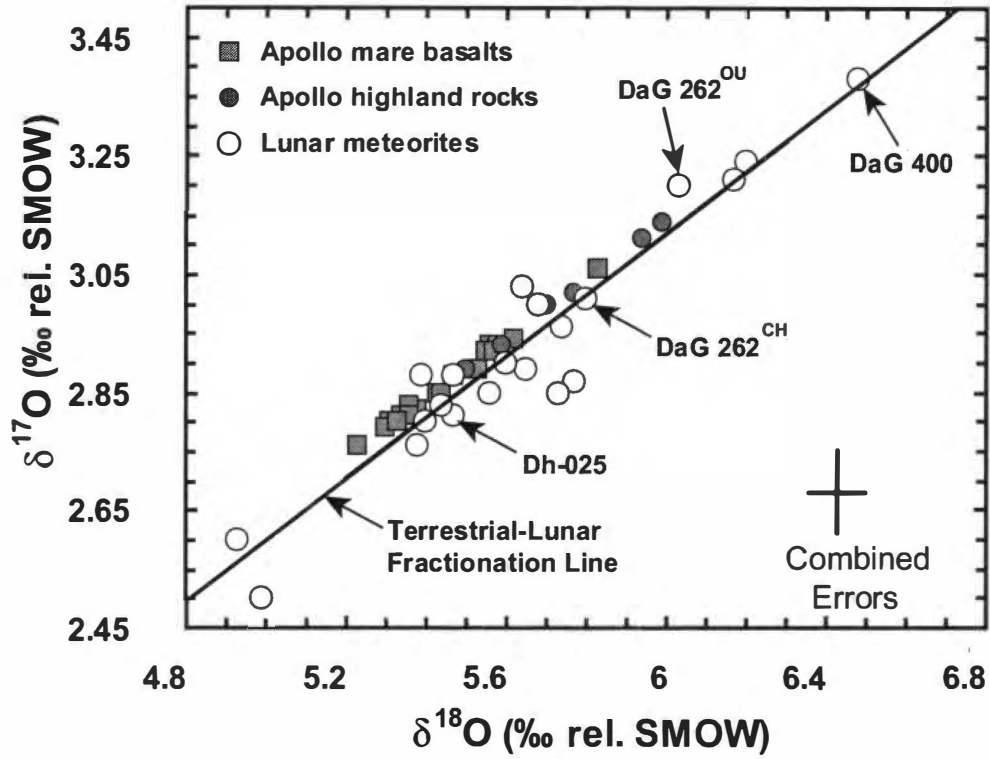


FIG. 7. The oxygen isotopic composition of Dh-025 compared to other lunar meteorites, Apollo mare basalts, and Apollo highland rocks (Arai and Warren, 1999; Clayton and Mayeda, 1983, 1996; Fagan *et al.*, 2000; Fagan *et al.*, 2001a; Kaiden and Kojima, 2002; Kojima and Imae, 2001; Wiechert *et al.*,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

TABLE 1: Bulk composition of Dh-025, Dh-081, DaG 262, DaG 400, and other lunar-highland meteorites.

	Dh-025	Dh-081	DaG 262	DaG 400	DaG 400
	(1)	(2)	(3)	(4)	(5)
SiO ₂ (wt%)	43.9	44.9	n.d.	43.4	n.d.
TiO ₂	0.30	0.15	0.22	0.23	0.18
Al ₂ O ₃	26.1	30.5	27.5	28.6	29.2
FeO	4.98	2.93	4.40	3.52	3.78
MnO	0.08	n.d.	n.d.	0.06	0.05
MgO	6.53	2.82	5.21	3.80	5.14
CaO	16.1	16.8	16.5	18.7	17.4
Na ₂ O	0.282	0.31	0.35	0.33	0.32
K ₂ O	0.07	0.02	0.05	0.10	0.07
P ₂ O ₅	0.08	n.d.	0.06	n.d.	0.11
H ₂ O	0.03	n.d.	n.d.	n.d.	n.d.
Sc (ppm)	10.2	5.40	7.85	n.d.	5.40
Cr	674	410	639	n.d.	550
Co	16.5	9.80	22.0	n.d.	14.0
Ni	200	85.0	270	n.d.	113
Ga	3.10*	2.40	4.25	n.d.	n.d.
Sr	2010	240	245	n.d.	190
Ba	130*	19.0	240	n.d.	140
Zr	62.0	n.d.	34.0	n.d.	n.d.
Cs	0.550	n.d.	0.120	n.d.	n.d.
La	3.60	1.43	2.44	n.d.	n.d.
Ce	8.60	3.40	7.25	n.d.	n.d.
Nd	5.20	1.90	3.25	n.d.	n.d.
Sm	1.50	0.630	1.15	n.d.	n.d.
Eu	1.30	0.700	0.730	n.d.	n.d.
Tb	0.35	0.150	0.240	n.d.	n.d.
Ho	0.44*	0.180	0.300	n.d.	n.d.
Yb	1.20	0.510	0.910	n.d.	n.d.
Lu	0.210	0.0730	0.130	n.d.	n.d.
Hf	1.30	0.440	0.850	n.d.	n.d.
Ta	<0.3*	<0.1	0.110	n.d.	n.d.
Th	0.80	<10	0.430	n.d.	n.d.
U	0.27	<300	0.210	n.d.	n.d.
Re (ppb)	<20*	5.00	n.d.	n.d.	n.d.
Os	<300*	5.20	n.d.	n.d.	n.d.
Ir	7.20	0.200	12.0	n.d.	4.0
Au	3.00	0.0700	4.30	n.d.	n.d.

(1) This study; * Elemental abundances taken from Warren *et al.*, (2001); (2) Warren *et al.*, (2001); (3) Bischoff *et al.*, (1998); (4) Semenova *et al.*, (2000); (5) Zipfel *et al.*, (1998); n.d. - not determined.

TABLE 1: Continued

	Average Highland Meteorites	Average Mare/Mixed Meteorites	Average A-16 Highland Regolith	Average FANs	Average HMS
	(6)	(7)	(8)	(9)	(10)
SiO ₂ (wt%)	n.d.	n.d.	n.d.	44.7	45.8
TiO ₂	0.27	0.57	0.38	0.09	0.30
Al ₂ O ₃	26.3	24.8	28.4	32.9	19.0
FeO	5.24	6.60	4.18	1.7	6.5
MnO	0.07	n.d.	n.d.	0.03	0.1
MgO	6.10	6.80	4.53	1.6	16.6
CaO	15.4	15.8	16.4	18.6	10.7
Na ₂ O	0.33	0.45	0.45	0.33	0.34
K ₂ O	0.02	0.07	0.12	0.03	0.08
P ₂ O ₅	0.02	n.d.	n.d.	0.02	0.25
H ₂ O	0.30	n.d.	n.d.	n.d.	n.d.
Sc (ppm)	9.06	52.0	7.46	3.77	3.30
Cr	699	1927	561	207	729
Co	17.0	39.7	17.8	4.16	24.8
Ni	177	87.8	212	9.56	115
Ga	3.43	6.75	n.d.	n.d.	n.d.
Sr	251	159	181	159	102
Ba	65.5	101.5	81.9	9.59	194
Zr	35.4	97.6	168	31	84
Cs	0.142	0.0750	0.126	0.0190	0.29
La	2.58	7.36	6.64	0.334	7.66
Ce	6.60	19.1	30.9	0.838	19.9
Nd	3.80	13.9	18.4	0.691	12.5
Sm	1.17	4.00	3.10	0.131	3.10
Eu	0.810	1.00	1.04	0.769	1.19
Tb	0.243	0.880	1.12	0.0364	0.663
Ho	0.282	n.d.	n.d.	n.d.	n.d.
Yb	0.966	3.31	2.28	0.16	2.05
Lu	0.142	0.482	0.321	0.014	0.284
Hf	0.874	2.78	n.d.	0.126	0.804
Ta	0.130	0.380	n.d.	n.d.	n.d.
Th	0.411	0.923	1.095	0.0364	1.26
U	0.132	0.248	0.526	n.d.	0.239
Re (ppb)	22.5	n.d.	n.d.	n.d.	n.d.
Os	283	n.d.	n.d.	n.d.	n.d.
Ir	38.9	6.40	12.2	0.351	0.0719
Au	3.27	3.10	9.94	0.441	0.0745

(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); Semanova 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 et al., (1993), Snyder et al., (1999), Fagan et al., (2002); (8) Korotev, (1996); (9-10) Papike (1988); n.d. - not determined.

Y791197, and QUE93069). However, some lunar meteorites (e.g., Dh-287, QUE94281, Y793272, Y981031, EET87521, EET96008, A881757, and NWA032) contain substantial portions of mare basalt components. Highlands rocks and mare basalts can have similar trends on Mg# vs. AN plots, but they can be distinguished by their Fe-Sc ratios (Palme *et al.*, 1991). It can be seen in FIG. 8 that Dh-025, Dh-081, DaG 262, and DaG 400 have similar Fe-Sc ratios, close to the typical highland average of ~4000.

In FIG. 9, Dh-025, Dh-081, DaG 262, DaG 400, and other lunar highland meteorites are compared to highlands regoliths 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. Dh-025, Dh-081, DaG 262, and DaG 400 have similar concentrations of Sc and Al_2O_3 to Apollo 16 regolith (FIG. 9a). In contrast, all lunar-highlands meteorites have systematically depleted Sm concentrations (by a factor of 10) compared to Apollo 14 and 16 lunar highlands regolith (FIG. 9b). Thus, these data suggest that although these meteorites are composed of highlands material, they are compositionally different from Apollo and Luna highlands regolith samples of the lunar near-side. The large compositional separation between Apollo regoliths and lunar meteorites, in FIG. 9b, suggests that these meteorites represent a distinct compositional envelope. Considering their highly anorthositic nature and the apparent lack of near-side components (i.e., KREEP), these meteorites may represent a far-side lunar highlands regolith.

Dh-025 has a lower Al_2O_3 concentration (26.1 wt%) compared to most other lunar highlands meteorites. In contrast, Dh-081 and DaG 400 have the highest concentrations

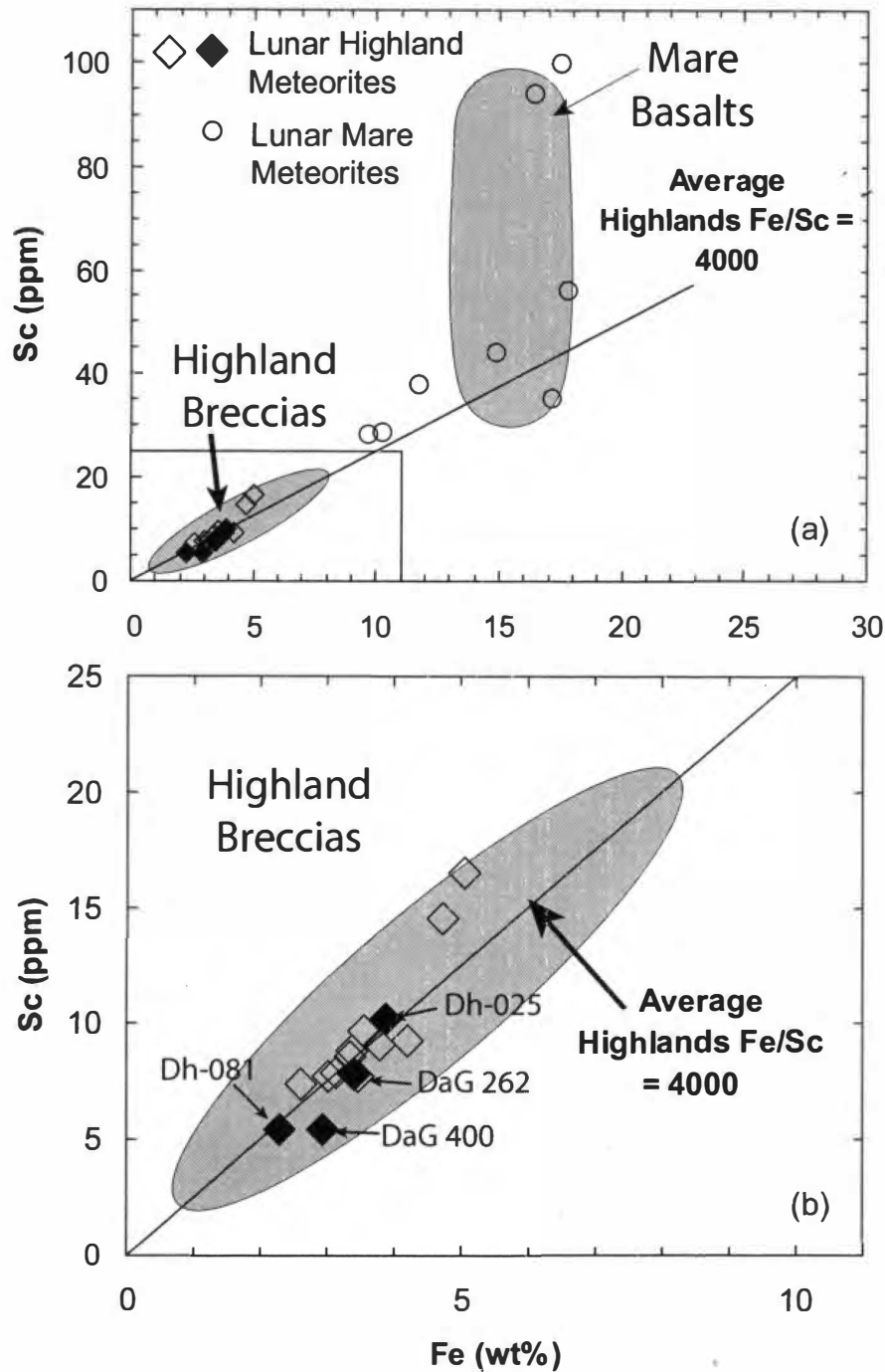


FIG. 8. Diagram of whole-rock Sc vs. Fe easily distinguishes mare and highland lithologies. (a) Mare and mixed lithologies (Dh-287, QUE94281, Y793272, Y981031, EET87521, EET96008, A881757, and NWA032) are shown as open circles (Anand *et al.*, 2002a; Demidova *et al.*, 2002; Fagan *et al.*, 2001b; Jolliff *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. Filled diamonds are lunar highland meteorites Dh-025, Dh-081, DaG 262, and DaG 400 (Bischoff *et al.*, 1998; Warren *et al.*, 2001; Zipfel *et al.*, 1998). Open diamonds represent lunar highland meteorites from other studies (Dh-026, MAC88104/5, Y86032, Y82192, ALHA81005, Y791197, and QUE93069) (Cohen *et al.*, 2002; Koeberl *et al.*, 1991a; Korotev *et al.*, 1996; Neal *et al.*, 1991; Palme *et al.*, 1991; Semenova *et al.*, 2000; Spettel *et al.*, 1995).

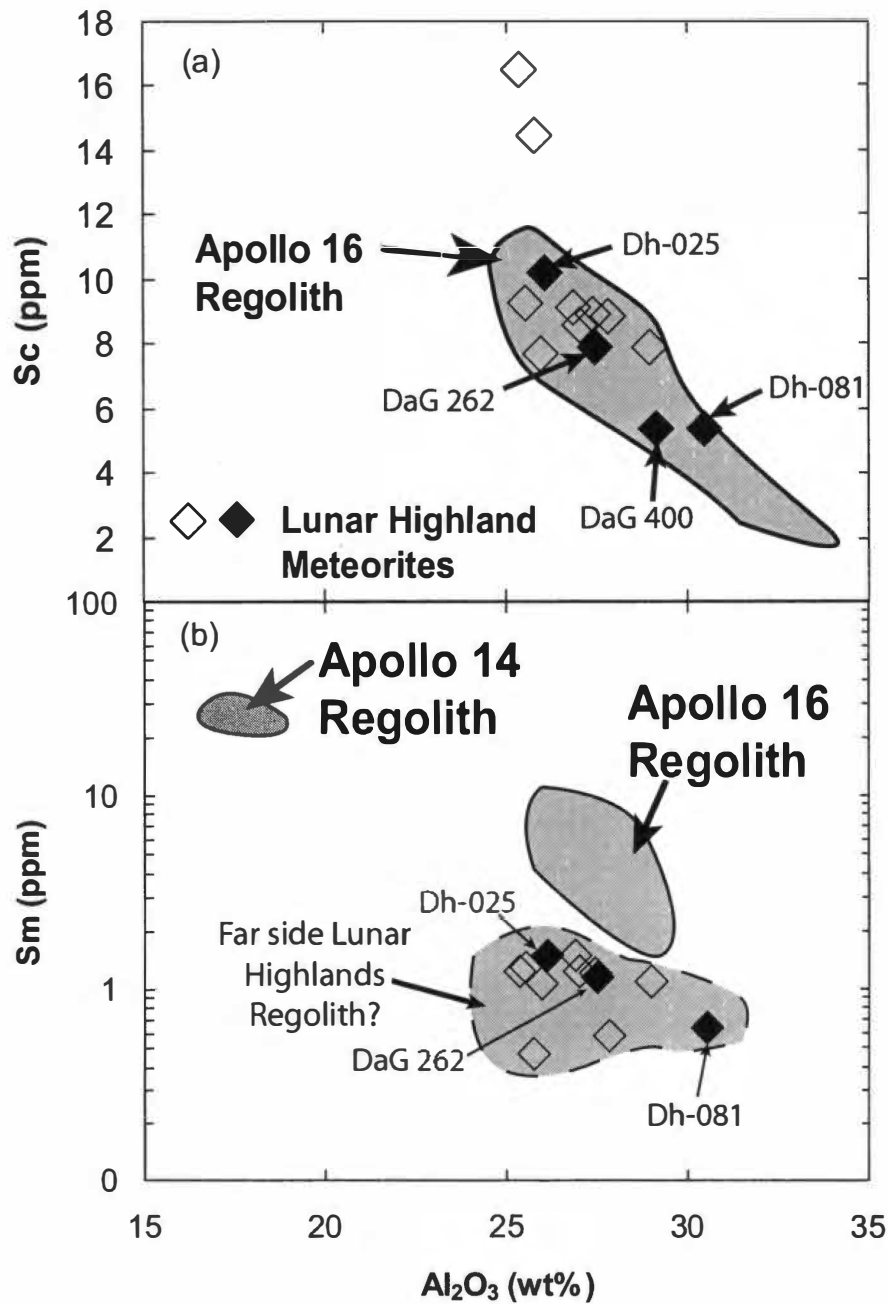


FIG. 9. Whole-rock Sc and Sm vs. Al_2O_3 in lunar meteorites. (a) Apollo 16 regolith compositional envelope (Korotev, 1997) is shown for comparison. (b) Compositional envelopes for Apollo 14 and Apollo 16 regoliths (Warren and Wasson, 1980) are shown for comparison. Lunar highlands meteorites Dh-025, Dh-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.*, 2002; Koeberl *et al.*, 1991a; Korotev *et al.*, 1996; Neal *et al.*, 1991; Palme *et al.*, 1991; Semanova *et al.*, 2000; Spettel *et al.*, 1995).

of Al_2O_3 (30.5 and 29.2 wt%, resp.), and, thus, the largest modal percentage of plagioclase relative to other lunar meteorites. These meteorites represent the most anorthositic compositions relative to all other lunar highlands meteorites reported to date (Fig. 9a).

Compared to other FAN, HMS, and KREEP rocks (Taylor, 1982), Dh-025, Dh-081, and DaG 262 have intermediate Ti-Sm ratios (Fig. 10). All highlands meteorites (with the exception of Y82192 and QUE93069) have similar Ti-Sm ratios and Mg# compositions. These compositions may have resulted by mixing between HMS and FAN-rich constituents. However, a second possible interpretation is that these meteorites are, in fact, FAN rocks, and that the FAN field needs to be expanded to encompass these meteorites. 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.

It has been noted previously that desert weathering tends to alter the LREE chemistry of hot-desert meteorites, particularly in olivine and pyroxenes (Croaz and Wadhwa, 2001; Floss and Croaz, 2001). However, petrogenetic information can still be extracted due to the heterogeneous nature of terrestrial weathering processes (Croaz and Wadhwa, 2001). Dh-081, DaG 262, and DaG 400 have relatively young terrestrial exposure ages (< 100 kyr) (Nishiizumi *et al.*, 2002), whereas Dh-025 has the oldest terrestrial exposure age of 500-600 kyr (Nishiizumi *et al.*, 2002) compared to all other hot-desert meteorites. Dh-025 shows a pronounced enrichment of Sr (2010 ppm), most

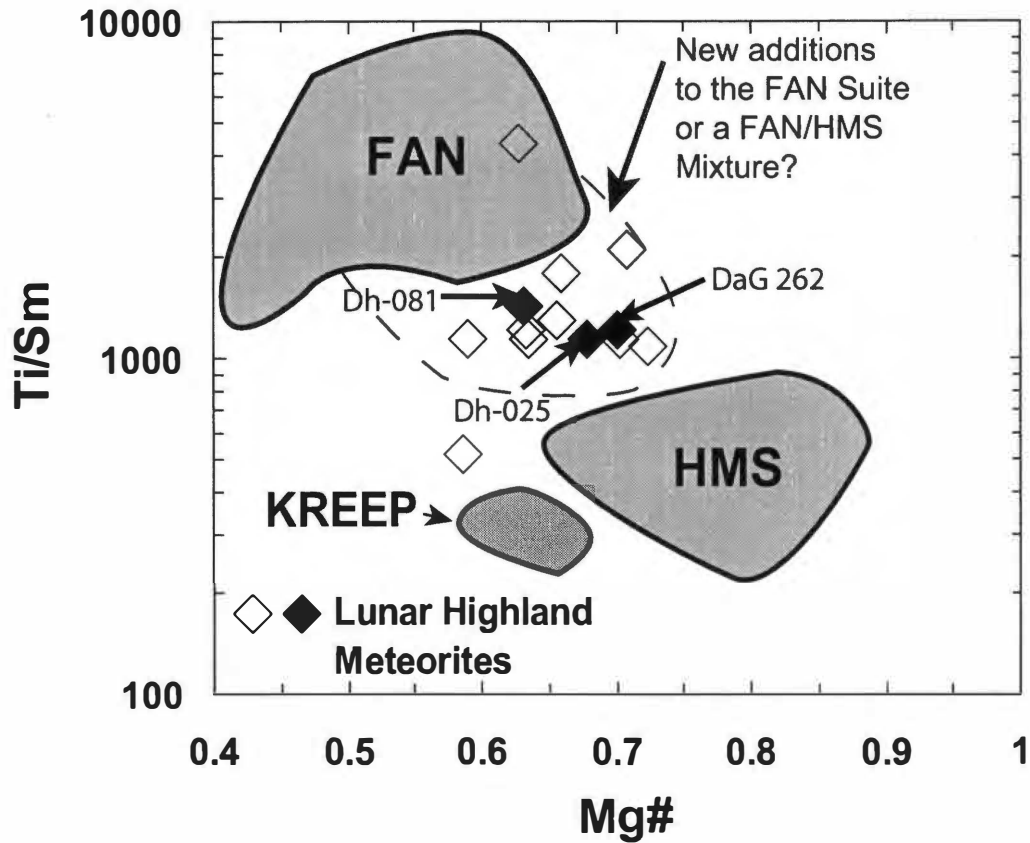


FIG. 10. Whole-rock Ti/Sm vs. Mg/(Mg+Fe) (Longhi and Boudreau, 1979) for various lunar highlands meteorites. FAN, HMS, and KREEP compositional envelopes are shown for comparison (Taylor, 1982). Dh-025, Dh-081, and DaG 262 are shown by filled diamonds (Bischoff *et al.*, 1998; Warren *et al.*, 2001; Zipfel *et al.*, 1998), and lunar highlands meteorites from other studies are shown as open diamonds (Cohen *et al.*, 2002; Koeberl *et al.*, 1991a; Korotev *et al.*, 1996; Neal *et al.*, 1991; Palme *et al.*, 1991; Semanova *et al.*, 2000; Spettel *et al.*, 1995).

likely due to terrestrial weathering, compared to the other lunar meteorites and lunar highlands meteorite average (TABLE 1). Other elements that may have been affected by terrestrial weathering include Ca, Ba, and K. Dh-025, DaG 262, and DaG 400 are all elevated in Ca, Ba, and K compared to the lunar highland meteorite average, whereas Dh-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 Dh-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 exposure to the terrestrial environment (Barrat *et al.*, 1999; Bland *et al.*, 1996; Crozaz and Wadhwa, 2001). This is due to the rapid infilling of pores and fractures within the meteorite. As space within a meteorite is filled with alteration material, the rate of weathering begins to decrease. Thus, the high degree of terrestrial alteration observed in Dh-025 may be due to a larger volume of pore and fracture space in this meteorite. Indeed, a comparison of thin-sections of Dh-025 and Dh-081 shows that Dh-025 has many more fractures and pore spaces than Dh-081.

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

2.6 TRACE-ELEMENT DISTRIBUTIONS IN INDIVIDUAL CLASTS AND MINERALS

We measured major-, minor-, and trace-element (including REE) compositions in minerals, within individual clasts, in Dh-025, Dh-081, DaG 262, and DaG 400. Analyses were done on plagioclase, pyroxene, and olivine—the modally dominant minerals in these meteorites. 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 chemistries. Trace-element concentrations typical of FAN, HMS, and high-alkali suite (HAS) minerals were compiled from the literature (Floss *et al.*, 1998; Papike, 1996; Papike *et al.*, 1994, 1996, 1997; Shervais and McGee, 1998a, b, 1999; Shervais *et al.*, 1997; Snyder *et al.*, 2003) 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 Dh-025, DaG 262, and DaG 400 were presented by Cahill *et al.* (2001) and Floss and Crozaz (2001).

Earlier, we noted that these meteorites have affinities to FANs (FIG. 4 and 5). However, some of these clasts plot within the FAN-HMS gap. Furthermore, whole-rock data appear to 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. We expected that analysis of fine-grained and microcrystalline clasts would eliminate the influence of matrix chemistries, the chemical mixing of several clasts that whole-rock data show, and provide us a representative clast whole-rock chemistry that will allow us to trace its origin.

2.6.1 “Bulk” Clast Inventory: The clasts we analyzed from Dhofar and DaG lunar highland meteorites are compared to Apollo 16, sample 67513 (2-4 mm rock fragments) (Jolliff and Haskin, 1995) on a Sc vs. Sm diagram (FIG. 11). Sm tracks the relative incompatible-trace-element (ITE) enrichment, whereas Sc (which is compatible in pyroxene) is an indicator of how mafic the sample assemblage is. 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), whereas the other ITE-rich trend is compositionally similar to impact-melt breccias (Korotev, 1994; Lindstrom *et al.*, 1990). FIG. 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 Apollo sample 67513 anorthositic rock fragments (FIG. 11b). The DaG clasts are slightly depleted in Sm compared to sample 67513, indicating their more ferroan nature. However, both Dh-025 and DaG 400 have single clasts with more mafic mineral-rich chemistries (Sm >2.5 ppm and Sc >30 ppm).

Whole-rock compositions of several other lunar highlands meteorites (MAC88104/5, ALHA81005, Y791197, Y88032, and Y82192) tend to have elevated Sm

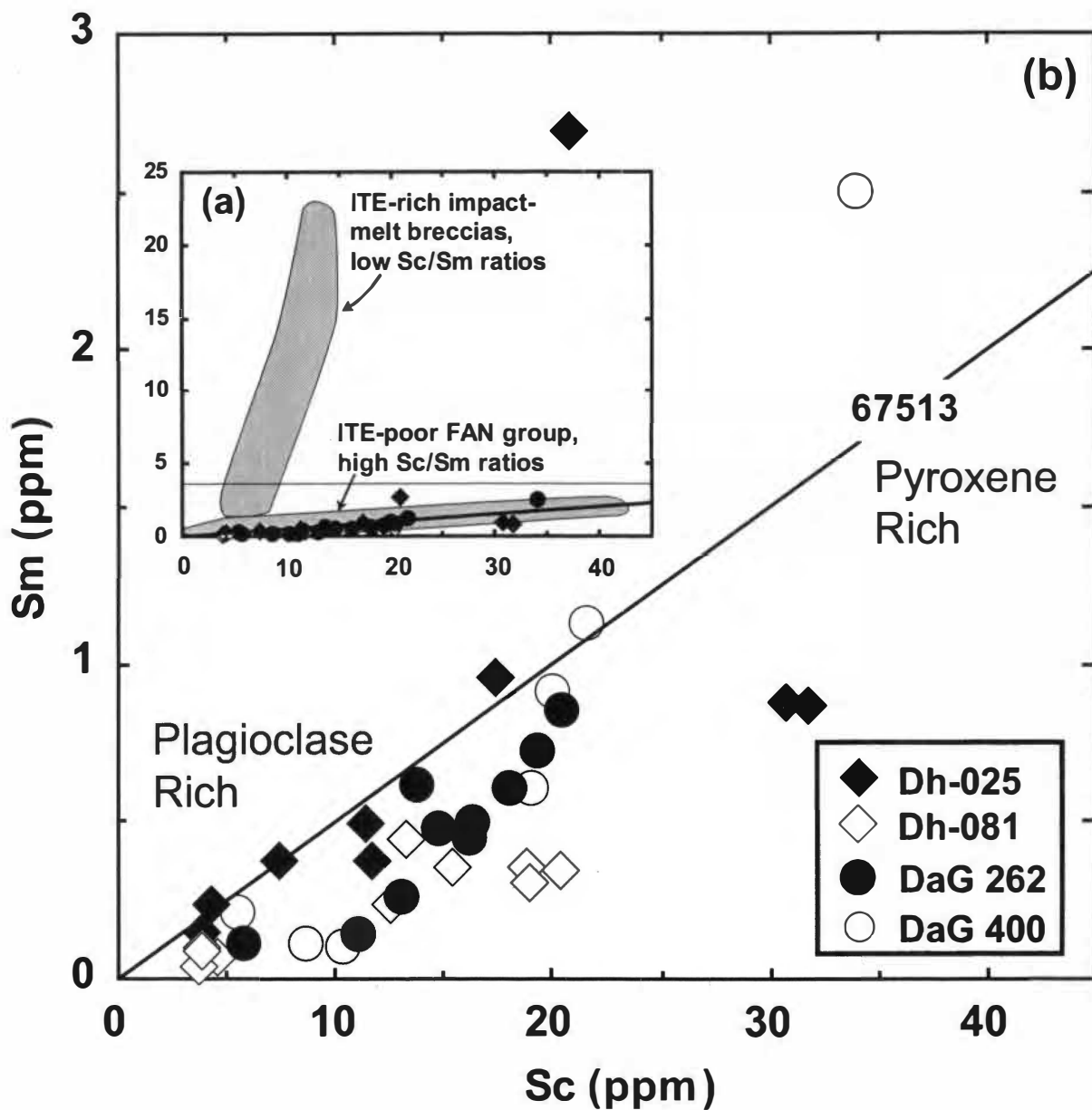


FIG. 11. Lunar lithologies from Apollo 16 show two compositional trends, illustrated in (a). Impact-melt breccias are incompatible trace element (ITE)-rich, whereas ferroan anorthosites (FAN) are ITE-poor (Jolliff and Haskin, 1995; Korotev, 1994). (b) Enlargement of ITE-poor portion of diagram (a). Dh-025,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

compared to Apollo 16 sample 67513 (Jolliff and Haskin, 1995; Jolliff *et al.*, 1991; Koeberl *et al.*, 1991a; Warren and Kallymelyn, 1991). This is because the analyses in these studies were of whole-rock samples (matrix + multiple clast chemistries), and not from single clasts as in this study and in 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; Semanova *et al.*, 2000; Zipfel *et al.*, 1998).

2.6.2 Compositional Mixing Model: A closer examination of REE concentrations in comparison to FAN and HMS rocks also presents the possibility that Dhofar and DaG chemistries were subjected to a degree of mixing (TABLE 2). In this model, increasing increments of an average HMS component (Papike, 1998) were added to an average FAN composition (Papike, 1998) to determine if any HMS influence was present in these lunar meteorite clasts. Comparison of these analyses to the model indicates that all four meteorites contain a noticeable HMS component. However, this influence is small in Dhofar and DaG clasts that show $\leq 10\%$ and $\leq 12\%$ HMS component present in most clasts, respectively. One DaG 400 clast shows a 62% HMS influence, whereas one Dh-025 clast shows a 71% HMS influence on its REE chemistry.

2.6.3 Plagioclase Inventory: The REE patterns for individual plagioclase grains from Dh-025, Dh-081, DaG 262, and DaG 400 are illustrated in FIG. 12. All plagioclase analyses have REE abundances similar to those in FAN rocks. However, some Dh-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 Dh-025 plagioclase tend to be enriched relative to plagioclases from Dh-081,

TABLE 2: Continued.

Dh-025									
	Clast 1	Clast 2	Clast 3	Clast 4	Clast 5	Clast 6	Clast 7	Clast 8	Clast 10
	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS
La	4	8	10	18	11	2	69	26	14
Ce	5	9	10	13	14	1	81	28	16
Nd	2	6	8	10	17	0	71	21	17
Sm	3	8	8	11	24	1	82	27	24
Eu	0	0	0	0	0	0	0	0	0
Tb	0	6	6	8	32	1	81	24	26
Yb	0	6	11	0	40	0	86	28	42
Lu	0	12	21	0	46	0	100	36	56
Average	2	7	9	8	23	1	71	24	24
Average % HMS Influence =									18.7

Dh-081										
	Clast 1	Clast 2	Clast 3	Clast 4	Clast 5	Clast 6	Clast 7	Clast 8	Clast 9	Clast 10
	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS
La	0	4	8	4	0	0	4	0	8	2
Ce	0	6	7	5	0	0	5	0	9	2
Nd	0	4	5	3	0	0	3	0	7	1
Sm	0	7	7	7	0	0	7	0	10	3
Eu	0	0	0	0	0	0	0	0	0	0
Tb	0	7	5	6	0	0	7	15	8	3
Yb	0	11	13	9	0	0	9	0	16	4
Lu	0	17	0	18	0	0	13	0	23	6
Average	0	7	6	7	0	0	6	2	10	3
Average % HMS Influence =										4.0

TABLE 2: Percentage influence of an average HMS REE composition on Dhofar and DaG FAN clasts.

DaG 262										
	Clast 1	Clast 2	Clast 3	Clast 4	Clast 5	Clast 6	Clast 7	Clast 8	Clast 10	Clast 11
	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS
La	10	21	14	1	16	21	1	17	8	16
Ce	10	21	13	1	12	25	0	11	6	11
Nd	7	17	9	0	11	21	0	10	4	14
Sm	11	16	12	1	20	23	0	11	5	16
Eu	0	0	0	0	0	0	0	0	0	0
Tb	0	0	0	0	0	0	0	9	5	0
Yb	16	24	20	4	21	35	0	10	18	13
Lu	17	34	17	7	34	35	1	15	20	13
Average	9	17	11	2	14	20	0	10	8	10
Average % HMS Influence =										10.1

DaG 400							
	Clast 1	Clast 2	Clast 3	Clast 4	Clast 5	Clast 6	Clast 7
	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS	% HMS
La	11	12	0	19	0	78	4
Ce	17	13	0	21	0	73	5
Nd	16	14	0	16	0	70	1
Sm	32	16	0	25	0	77	3
Eu	0	0	0	0	0	0	0
Tb	0	0	0	0	0	0	3
Yb	47	21	0	34	7	100	0
Lu	45	31	0	20	8	100	2
Average	21	13	0	17	2	62	2
Average % HMS Influence =							16.8

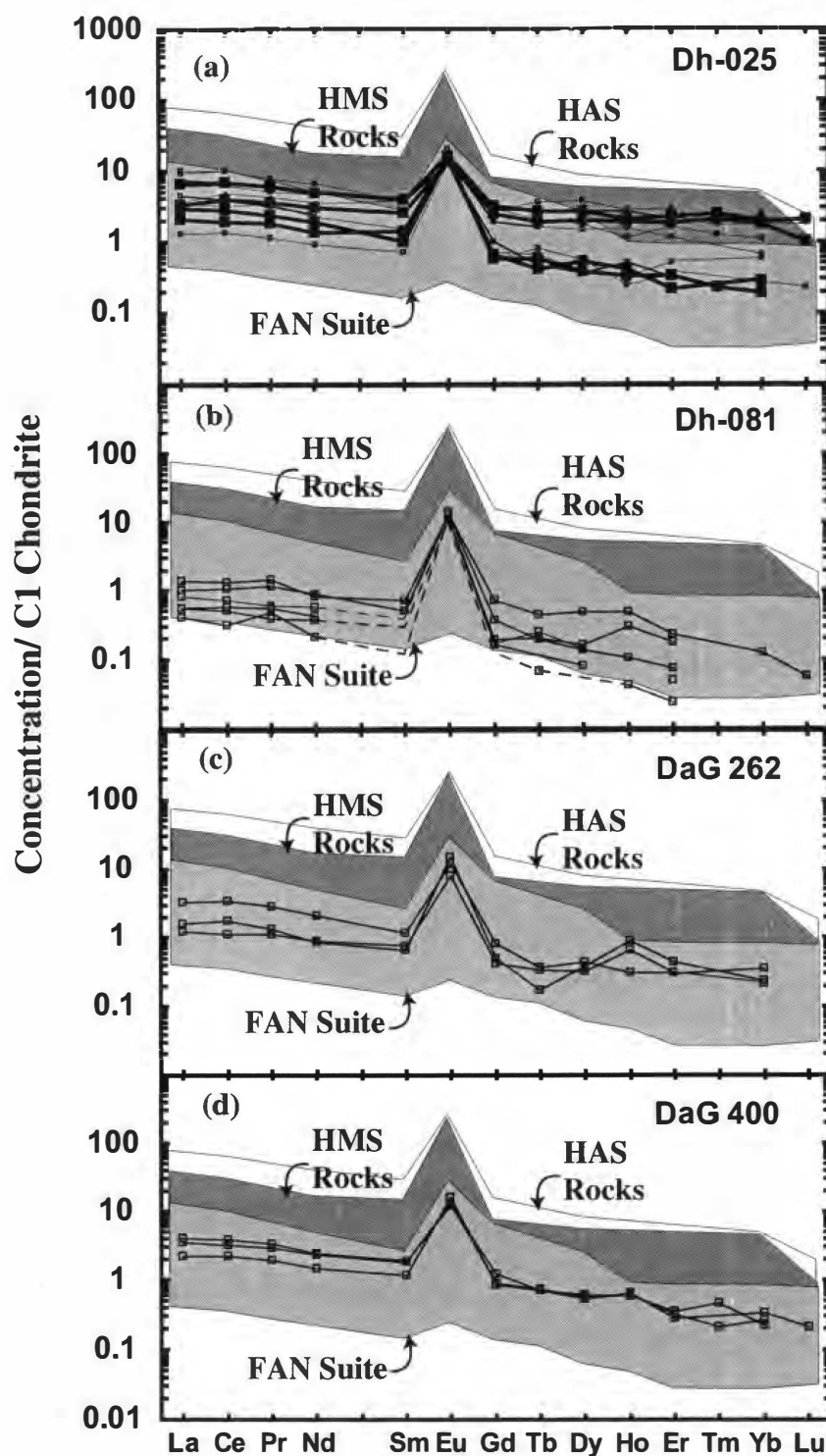


FIG. 12. C1-chondrite normalized (Anders and Grevesse, 1989) REE patterns for plagioclase from lunar meteorites Dh-025 (a), Dh-081 (b), DaG 262 (c), and DaG 400 (d). These patterns are compared to pristine plagioclase grains from FAN, HMS, and (high-alkali suite) HAS rocks (Floss *et al.*, 1998; Papike *et al.*, 1996, 1997; Shervais and McGee, 1998a, b, 1999; Shervais *et al.*, 1997; Snyder *et al.*, 2003). Dh-025 patterns with bold lines and symbols represent clasts that were designated as texturally “pristine” in this study.

DaG 262, and DaG 400. Despite the HREE enrichments in many Dh-025 clasts, five clasts show plagioclase REE trends typical of pristine FAN lithologies (FIG. 12a). These include two texturally pristine rocklets (clasts AA and AI), as well as three clasts with non-pristine textural characteristics (clasts 108b, BA, and BB). All Dh-081 plagioclases have lower REE abundances than those in the other meteorites analyzed, with patterns that fall towards the lower range observed for FANs (FIG. 12b). DaG 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 also similar to those of other FAN suite rocks (FIG. 13). However, Fe and Mg abundances are elevated, whereas Sr is depleted, although still similar to FAN plagioclase. This suggests that the terrestrial Sr influx in Dh-025, interpreted from whole-rock data, is dominated by surficial additions of terrestrial Sr-bearing minerals, and that exchange with Dh-025 plagioclase was limited. Furthermore, Sr and Ba concentrations show some indication of positive trends with increasing La abundance (FIG. 14). Positive trends between La and Ba have also been shown to exist in other lunar highlands rocks (Floss *et al.*, 1998; Snyder *et al.*, 2003). This suggests that Sr may behave incompatibly in lunar plagioclases despite the fact that its partition coefficient ($K_{D_{Sr}}$) is 1.61 (FIG. 14) (Phinney and Morrison, 1990). This trend is typical of HMS rocks, but questionable in FAN rocks, both here and in other studies (Floss *et al.*, 1998).

2.6.4 Pyroxene Inventory: REEs in low-Ca pyroxenes from Dh-025, Dh-081, and DaG 262 have concentrations similar to those from typical FAN and HMS rocks (FIG. 15a and b). Dh-025 and Dh-081 low-Ca pyroxenes have Ce and Zr abundances similar to

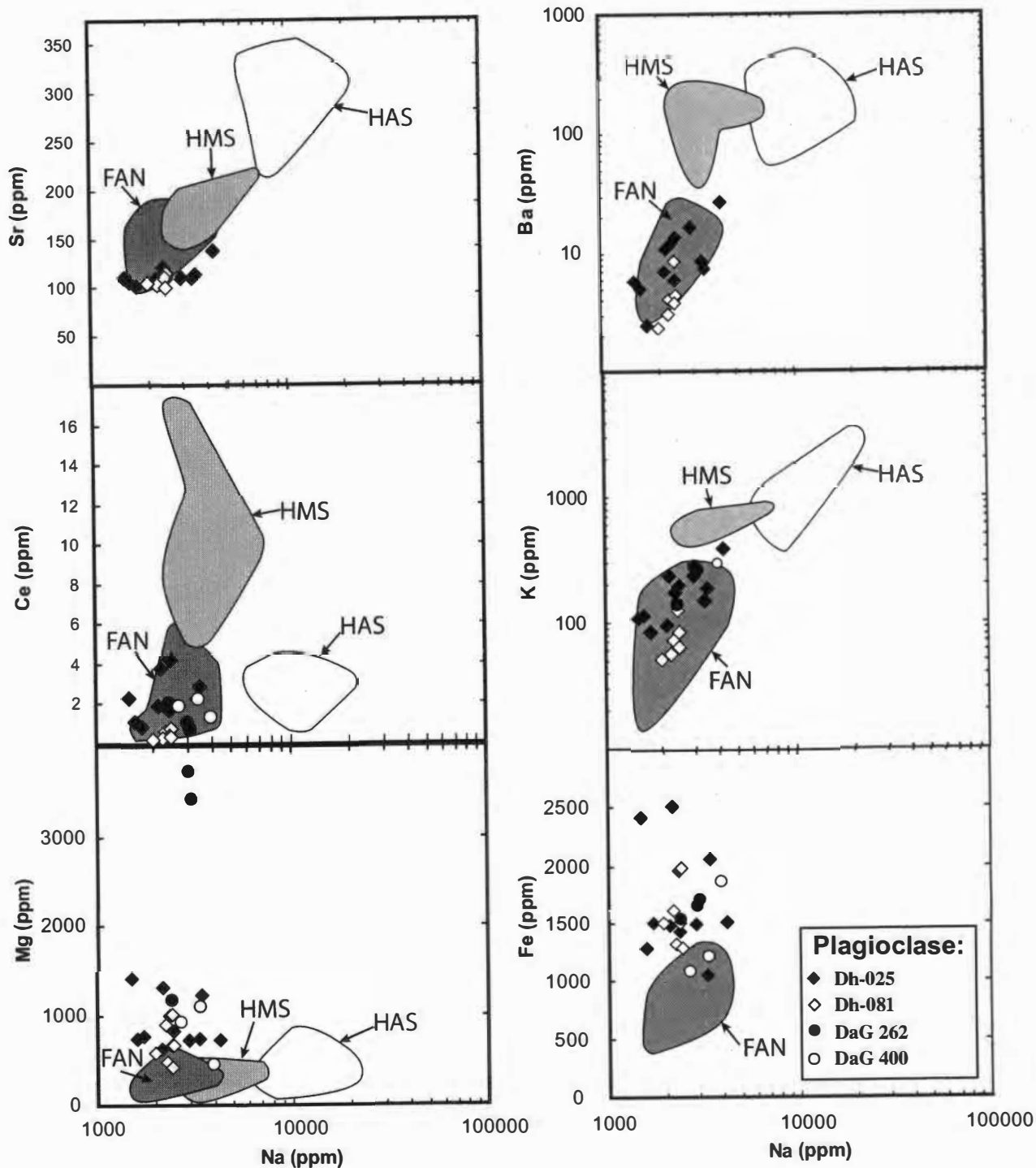


FIG. 13. Major-, minor-, and trace-element data for plagioclase from lunar highlands meteorites Dh-025, Dh-081, DaG 262, and DaG 400. The data are compared to that of pristine FAN, HMS, and (high-alkali suite) HAS plagioclase (Floss *et al.*, 1998; Snyder *et al.*, 2003).

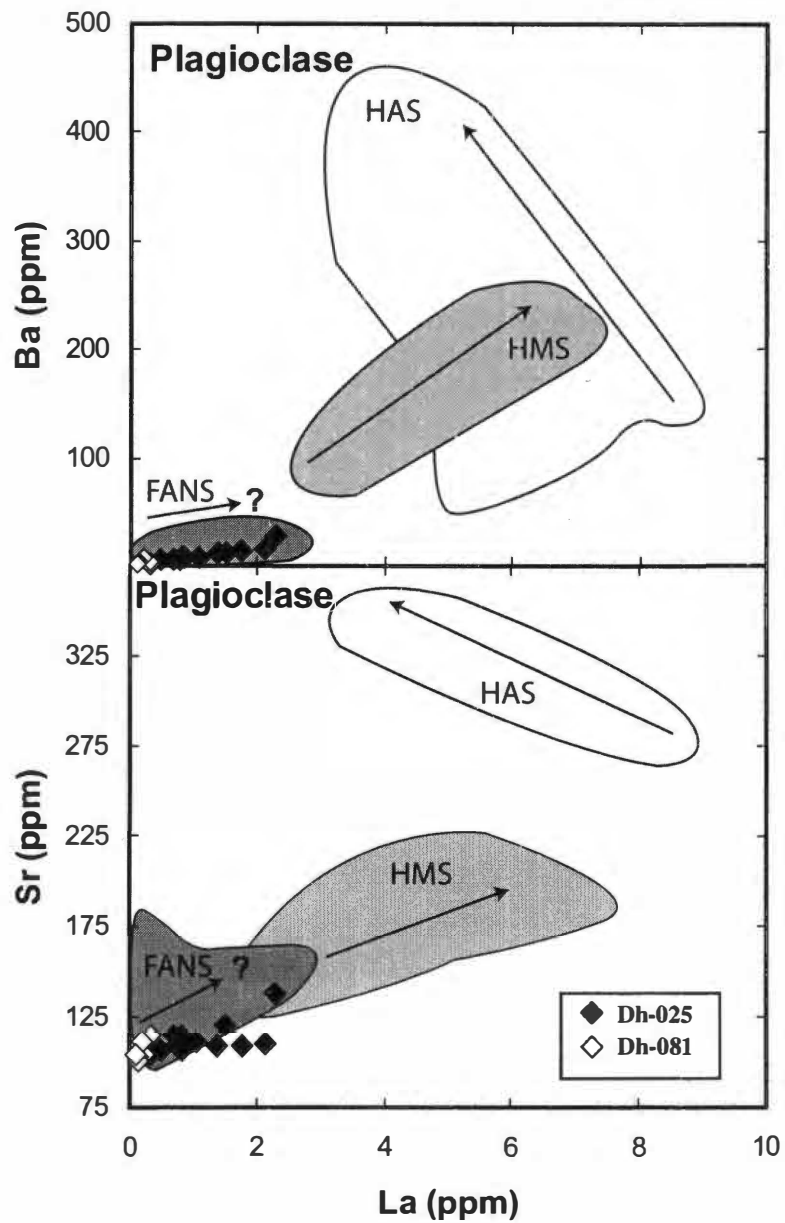


FIG. 14. Plagioclase Ba, Sr, and La systematics for lunar meteorites Dh-025 and Dh-081 compared to FAN, HMS, and high-alkali suite (HAS) data (Floss *et al.*, 1998; Papike *et al.*, 1997; Snyder *et al.*, 2003).

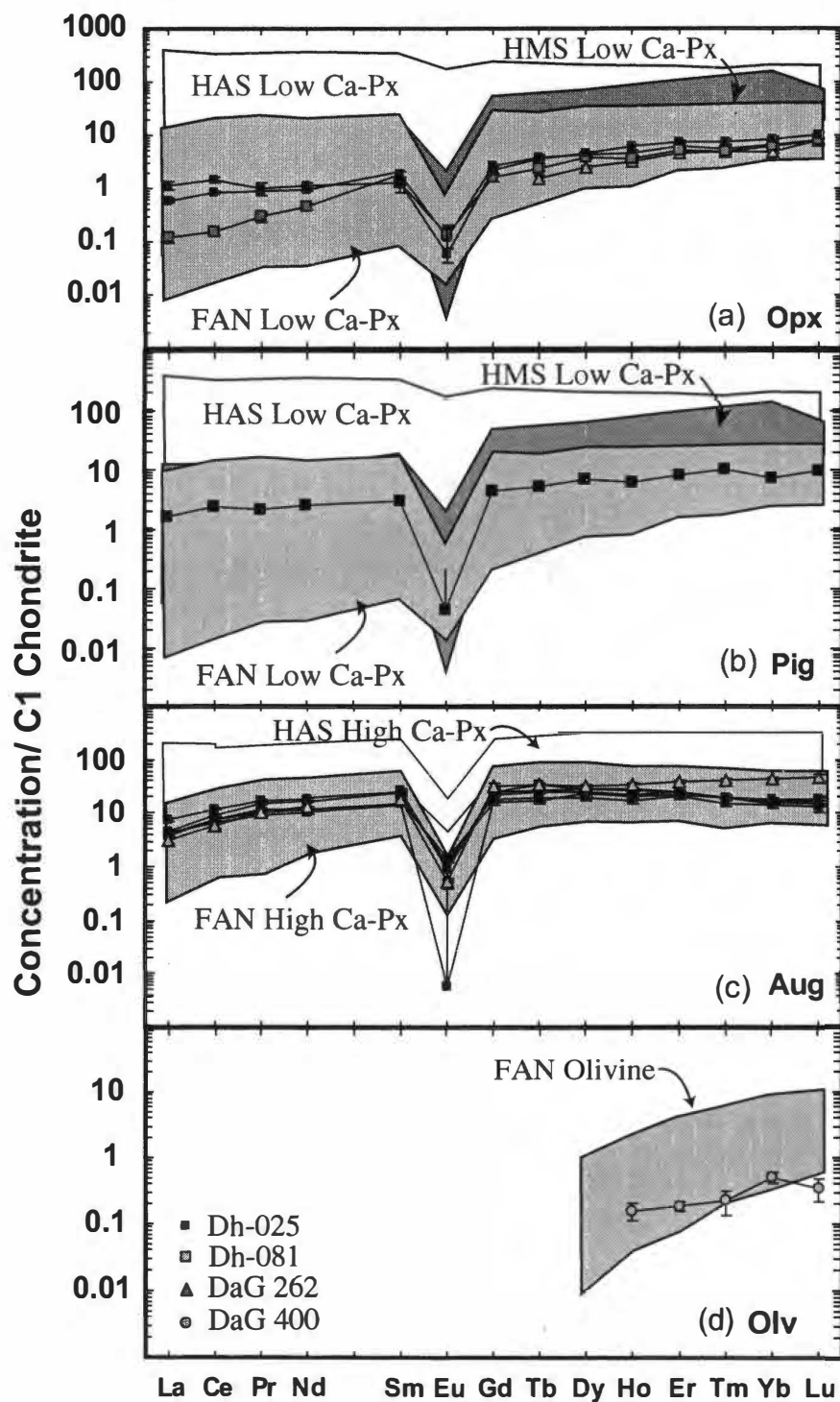


FIG. 15. C1-chondrite normalized (Anders and Grevesse, 1989) REE patterns for pyroxenes and olivine grains. Orthopyroxene (a) and pigeonite (b) REEs are compared to pristine low-Ca pyroxene analyses of FAN, HMS, and high-alkali suite (HAS) rocks (Floss *et al.*, 1998; Papike, 1996; Papike *et al.*, 1994, 1996; Shervais and McGee, 1998a, b, 1999; Shervais *et al.*, 1997; Snyder *et al.*, 2003). High-Ca pyroxene (c) and olivine (d) are compared to pristine analyses from FAN rocks (Floss *et al.*, 1998).

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, whereas HMS and HAS rocks define steeper slopes (FIG. 16).

High-Ca pyroxenes in Dh-025 and DaG 262 have REE abundances similar to those of FAN high-Ca pyroxenes (FIG. 15c). However, one Dh-025 analysis has a much-deeper negative Eu anomaly ($0.01 \times \text{CI}$) than the rest. This Eu anomaly, however, falls within FAN compositions, when considering a 1σ error. Ce and Zr are positively correlated, similar to the trend seen in FANs (FIG. 16). Y concentrations are also similar to those in the FANs, but Sc is low in Dh-025 compared to DaG 262 and other FANs.

2.6.5 Olivine Inventory: A few SIMS trace-element analyses have been previously reported for olivine 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 these meteorites did not allow us to study several troctolitic clasts. However, one olivine grain was successfully analyzed in DaG 400 (FIG. 15d). This grain has low HREE abundances ($\leq 0.5 \times \text{CI}$) and falls at the low end of the range observed for FAN olivines.

2.6.6 Plagioclase-Pyroxene REE ratios: One can evaluate whether a rock or clast represents an equilibrium assemblage by comparing 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., $K_{\text{D REE}}^{\text{Pl}}/K_{\text{D REE}}^{\text{Px}}$). In our survey, we were only able to analyze polymineralic clasts with non-relict textures. All

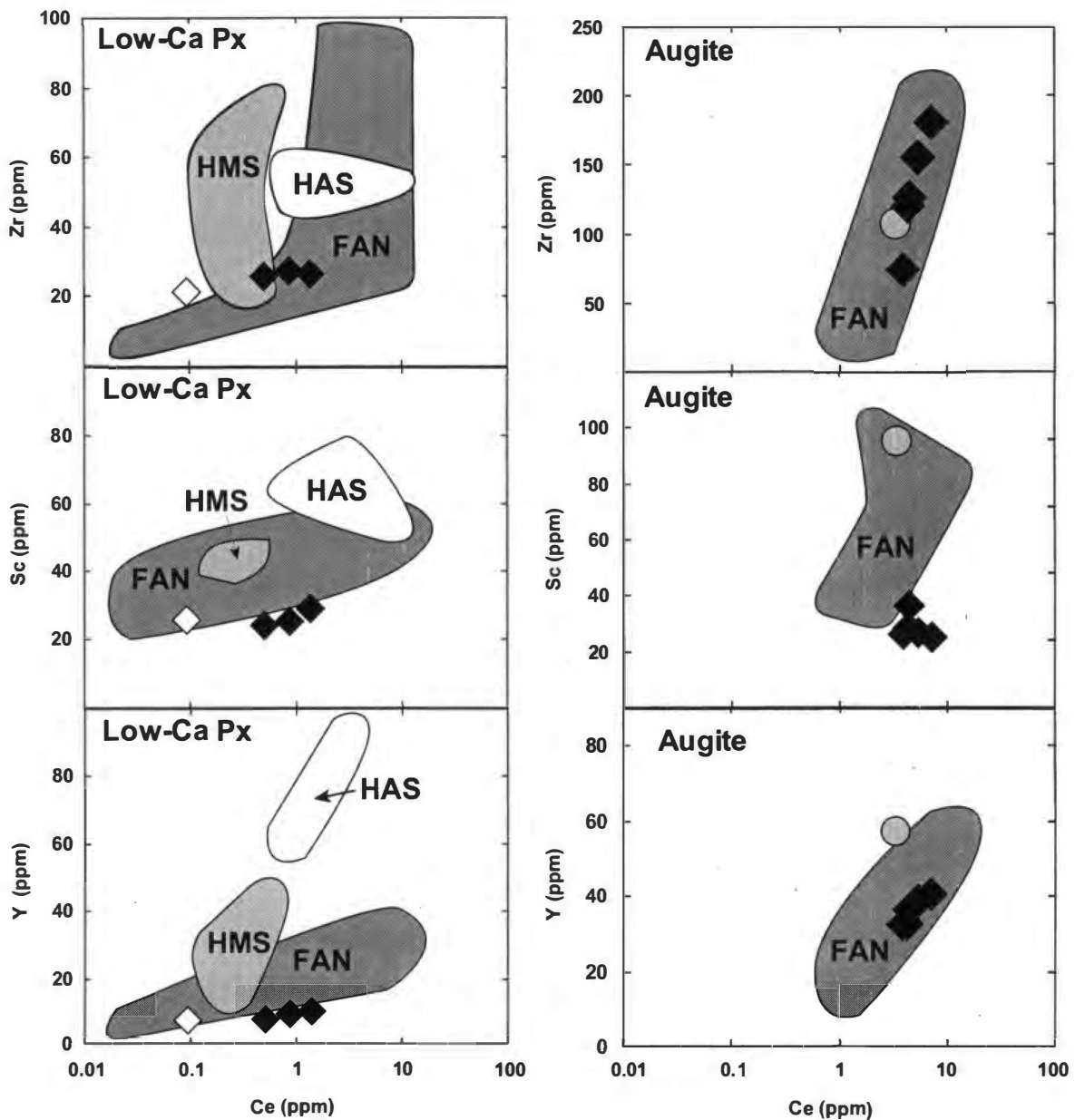


FIG. 16. Trace-element concentrations of low- and high-Ca pyroxenes in the lunar meteorites Dh-025, Dh-081, and DaG 262. These values are compared to data for typical FANs, HMS, and high-alkali suite (HAS) rocks (Floss *et al.*, 1998; Papike, 1996; Papike *et al.*, 1994, 1996; Snyder *et al.*, 2003).

clasts with pristine textures were troctolitic and, as previously mentioned, olivine REE abundances are often not easily measured with SIMS.

In FIG. 17, the concentration ratios of several impact-melt clasts are compared with the ratios expected from experimentally determined distribution coefficients (listed in TABLE 3). If a rock, or clast, preserves the integrity it inherited from the original melt, then these ratios should be identical. Inherent here is the assumption that the K_D values chosen are valid.

Distribution coefficients were selected from studies by (McKay *et al.*, 1991; McKay *et al.*, 1986; 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) (TABLE 3). 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 is considered to have a concordant ratio, when considering the large error associated with its Eu analysis. All other clasts have discordant plagioclase-pyroxene ratios indicating that the coexisting minerals are out of equilibrium.

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

Plagioclase/Pyroxene

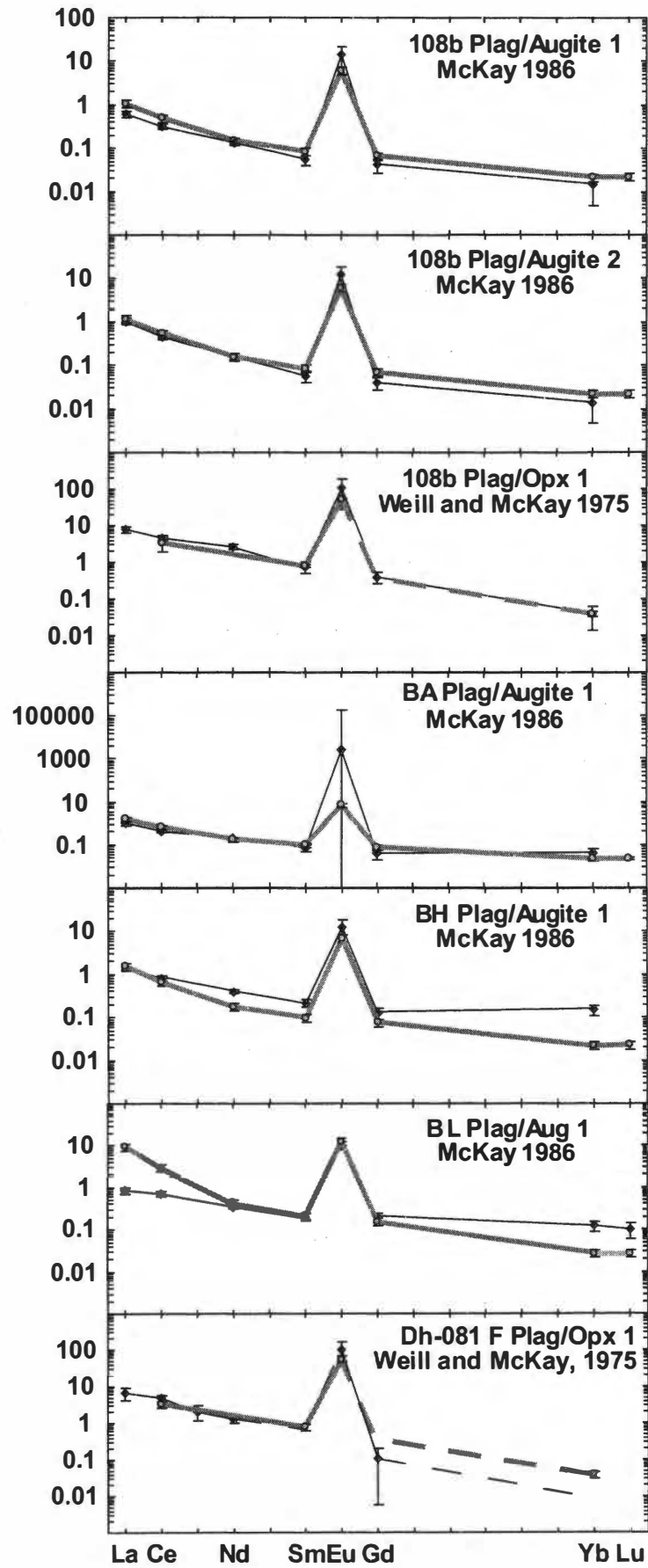


TABLE 3: REE mineral/melt distribution coefficients.

	Plag	Pyroxene						
		Dh-025						Dh-081
		108b	108b	108b	BA	BH	BL	F
		Aug 1 Wo ₃₈	Aug 2 Wo ₃₇	Opx 1 Wo ₄	Aug 1 Wo ₃₄	Aug 1 Wo ₃₄	Aug 1 Wo ₁₅	Opx 1 Wo ₄
La	0.0420	0.0392	0.0363		0.0278	0.0271	0.0045	
Ce	0.0300	0.0611	0.0573	0.0090	0.0460	0.0450	0.0103	0.0090
Pr	0.0250							
Nd	0.0200	0.1364	0.1312		0.1148	0.1133	0.0462	
Sm	0.0175	0.2116	0.2047	0.0220	0.1826	0.1806	0.0840	0.0220
Eu	1.2000	0.1994	0.1941	0.0220	0.1768	0.1752	0.0939	0.0220
Gd	0.0160	0.2418	0.2348		0.2121	0.2100	0.1064	
Tb	0.0095							
Dy	0.0085							
Ho	0.0080							
Er	0.0075							
Tm	0.0070							
Yb	0.0065	0.3039	0.3017	0.1700	0.2941	0.2934	0.2473	0.1700
Lu	0.0068	0.3121	0.3098		0.3018	0.3010	0.2526	
	(1)	(3)	(3)	(2)	(3)	(3)	(3)	(2)

(1) Phinney and Morrison, 1990

(2) Weill and McKay, 1975

(3) McKay et al., 1986

(4) McKay et al., 1991

2.7 DISCUSSION

In this study, we analyzed several clasts with and without relict textures in an attempt to find lunar samples contain equilibrium mineral assemblages. We approached this task by evaluating plagioclase-pyroxene REE ratios, as described earlier. Clasts with concordant REE ratios patterns are likely samples that contain unmodified chemical information from a pre-existing melt, and may be *considered* pristine lithologies. Of the clasts analyzed, the mineral REE ratios show that the minerals in two Dh-025 clasts (108b and BA) have retained equilibrium with a parent melt (FIG. 17). In addition, clasts BL and BH also show certain REEs that appear to still be in equilibrium between coexisting minerals. However, most of the clasts evaluated 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, (1) incorrect distribution coefficients, (2) subsolidus re-equilibration, and (3) impact processes, all of which are evaluated below.

2.7.1 *Distribution coefficients:* Of foremost concern when determining REE ratios is the appropriate experimental determination and selection of 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). In addition, plagioclase REE values determined by experiment 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 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 determined to be evident in this study.

2.7.2 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 it can also occur between coexisting minerals. Homogenization of zoned minerals will cause higher average REE concentrations than those of the original mineral cores (Floss *et al.*, 1998). With internal

mineral redistribution, plagioclase-pyroxene REE ratios will be affected with 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 coexisting pyroxene and plagioclase in a manner dependent upon their crystal chemistries (Papike, 1996; Papike *et al.*, 1996). During coexisting 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 pigeonite and subsequent subsolidus re-equilibration takes place, REEs move from orthopyroxene into augite, with HREEs migrating with a greater mobility than LREEs (James *et al.*, 2002). As this occurs, orthopyroxene-augite REE ratios develop lower and steeper positive trends. Furthermore, if a larger amount of LREEs migrate from orthopyroxene to augite, plagioclase-augite REE ratio patterns will develop steeper negative trends.

Although REE enrichments are apparent in some mineral analyses, not all minerals appear to have the anomalous REE patterns. Most lunar meteorite plagioclase, pyroxene, and olivine grains have the expected REE patterns for FAN. However, when comparing coexisting plagioclase and pyroxene REE ratio and K_D ratio patterns, some clasts show non-concordant REE ratio patterns. These patterns tend to be flatter or lower

than the expected K_D ratio patterns. This may indicate that these minerals were previously zoned and have homogenized, although homogenization usually entails lower overall patterns in addition to flatter slopes. Because these patterns are not lower and flatter, subsolidus re-equilibration is not the sole influence on their REE ratio patterns.

2.7.3 Impact processes: Possible evidence for impact-induced mixing, as presented in 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. 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 meteorite plagioclase compared to ion-probed FAN, HMS, and HAS rock 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.

In contrast, impact modification is readily apparent in REE concentrations of Dh-025 plagioclases (FIG. 12a). In fact, the HREE are disproportionately enriched compared to the LREEs. The likely source of these REE enrichments could be exchange with a surrounding impact melt or a coexisting pyroxene. During normal igneous processes,

pyroxene has a lower melting point than olivine and anorthite. However, the dynamics of impact-induced melting remain poorly understood. Nonetheless, discrimination between these two possible sources is problematic since both have large Fe, Mg, and HREE reservoirs.

2.7.4 Lunar Provenance: Remote-sensing studies of the Moon indicate that the lunar surface is heterogeneous (Davis and Spudis, 1985). A map of orbital data for Th-Ti ratio vs. Fe originally made it possible to recognize three major lunar rock types 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 also show that the bulk of the highlands are anorthositic, although petrologically heterogeneous (Spudis *et al.*, 2000; Spudis *et al.*, 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 (86 km) than the near-side (64 km) (Taylor, 1982), have given a detailed view of the Moon's crustal geology.

The lunar meteorites in this study are highly anorthositic breccias, although a small HMS component is inferred from clast analyses. Furthermore, KREEPy chemical signatures are not evident in any of the meteorite whole-rock compositions. Therefore, these rocks must have originated from a largely FAN-rich terrain, removed from appreciable HMS and KREEP influences. The near-side of the Moon, though characterized by some FAN highlands terrains, has far too much HMS and KREEP-

signed lithologies to have been the source regions for these rocks. Therefore, these meteorites likely originated on the far-side. This inference supports the studies of Greshake *et al.* (1998), Bischoff *et al.* (1998), and Semenova *et al.* (2000).

As a result, these meteorites allow a database to be created which include both near- and far-side rocks. In this study, multiple clasts have been identified that show REE ratio profiles consistent with experimentally determined mineral-melt REE profiles. Thus, these clasts are approximated to be pristine lunar lithologies having retained chemical characteristics inherited from the melt from which they crystallized. These clasts also show distinctly atypical highlands chemistries by plotting within the FAN-HMS gap. Therefore, this new “whole-Moon” database is characterized with rock chemistries suggesting either an expansion of the FAN-field to higher Mg# compositions, or an expansion of the HMS-field to lower Mg# compositions.

2.8 SUMMARY

The lunar meteorites Dh-025, Dh-081, DaG 262, and DaG 400 are feldspathic highlands breccias. All four meteorites consist dominantly of FAN clasts based on major-, minor-, and trace-element data; although some Dh-025, Dh-081, and DaG 400 clast compositions plot within the FAN-HMS “gap” on a plagioclase AN vs. mafic-mineral Mg# diagram (Semenova *et al.*, 2000). These gap compositions are atypical of rocks collected by the Apollo and Luna missions from the lunar near-side. Whole-rock Ti-Sm ratios of Dhofar and DaG meteorites also plot between the FAN and HMS suites suggesting that these rocks represent a mixture of these two lithologies. However, SIMS

analyses of single clasts from DaG and Dhofar meteorites show stronger FAN affinities than seen in whole-rock data, although still indicating small ($\leq 12\%$ average) HMS components. Furthermore, these meteorites lack mare lithologies and KREEP-signatured rocks typical of the lunar near-side. Therefore, these meteorites may represent lunar highlands regolith breccias from FAN-rich locales on the far-side of the Moon.

This new “whole Moon” database is also characterized with clasts having the propensity to plot within the FAN-HMS gap. In addition to Dh-025, Dh-081, and DaG 400, several other Dhofar lunar meteorites also have gap compositions (e.g., 280, 301, 302, and 303; (Anand *et al.*, 2002; Nazarov *et al.*, 2002). This evidence, coupled with the identification of two potentially pristine Dh-025 clasts (108b and BA) that also fall within this gap, suggests that either the FAN-field should be expanded to more Mg#-rich compositions, or the HMS-field should be expanded to less Mg#-rich compositions.

3. FUTURE WORK

One goal of this study was to identify the chemical information inherited by a rock from its igneous parent-melt. In this study, two methods were employed to distinguish igneous chemistry from modified chemical signatures. First, we examined the petrographic textures of single clasts. Then we compared the REE ratios of co-existing minerals with experimentally determined mineral-melt ratios. Our results indicate that it is *possible* a clast can retain chemical equilibrium with its parent-melt despite having partially modified characteristics.

Potential methods to produce corroborative information to support this possibility include analysis of these texturally modified clasts by isotope-dating techniques. A clast that retains its inherited igneous chemistry would likely have older ages than a clast modified by impact processes. No age-dating techniques have been successfully implemented for Dh-025 and Dh-081 clasts. One possible technique is to identify a clast, micro-core it from a thick-section, and then age-date it using Ar-Ar methods. An additional method would be to evaluate the siderophile element contents of these micro-cored meteorite clasts; low siderophile element concentrations are also a good indicator of pristinity (Warren 1993). However, siderophile elements can only be analyzed by INAA, which is destructive and would therefore be a final step in evaluating the chemical information contained in a clast.

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APPENDICES

APPENDIX 1

TABLE A1-1: Summary of petrographic classifications and mineral compositions of Dh-025 and Dh-081 clasts.

Sample	Rock	Plagioclase	Olivine	Pyroxene			
<i>Dh-025</i>	Textural Type	An	Fo	Wo	En	Fs	Mg#
AA	PIR	96.6 - 97.3	75.1 - 77.8				
AB	PIR	96.9 - 98.0	80.2 - 82.0				
AF	PIR	95.9 - 96.9	69.2 - 73.2				
AI	PIR	96.1 - 97.5	78.9 - 80.3				
A	IMR	96.7	72				
B	IMR	96.6	72				
K	IMR	97.2	75				
T	IMR	97	75				
V	IMR	95.9	72				
Y	IMR	97	64				
AC	IMR	96.0 - 96.8		5.66 - 8.91	67.0 - 70.5	23.2 - 25.8	
AD	IMR	95.6 - 96.4	66.7 - 69.7				
AE	IMR	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	IMR	95.1 - 96.9		33.0 - 38.2	47.0 - 50.4	14.1 - 16.0	75.9 - 77.1
AH	IMR	96.4 - 97.1	80.8 - 81.5				
BA	IMR	95.6 - 96.9		3.30 - 4.41	75.2 - 76.5	19.6 - 20.4	79
				39.3 - 44.4	46.7 - 50.0	8.9 - 10.7	81.5 - 83.4
BB	IMR	96.9 - 97.6	74.1 - 82.1				
BC	IMR	95.1 - 98.0		8.04 - 15.3	56.4 - 66.0	22.1 - 31.1	65.5 - 75.2
BD	IMR	96.6 - 97.5		4.9 - 9.6	54.9 - 60.4	28.2 - 37.1	58.9 - 68.8
				38.3 - 40.3	41.3 - 43.3	18.0 - 19.6	70
BF	IMR	94.7 - 97.9		8.30 - 14.6	58.6 - 67.3	22.8 - 31.0	65.7 - 74.5
BH	IMR	96.4 - 97.0		3.66 - 7.08	73.6 - 77.8	17.4 - 19.3	81
				37.4 - 41.8	46.6 - 48.2	10.0 - 12.3	81
BL	IMR	95.7 - 96.7	69.9 - 73.2	38.2 - 44.3	45.6 - 49.9	9.3 - 15.3	79
BM	IMR	96.0 - 97.1	77.5 - 82.7	2.91 - 6.40	78.5 - 81.7	15.2 - 16.8	83
BO	IMR	96.1 - 97.0	71.4 - 73.0				
BP	IMR	95.6 - 96.3	70.6 - 72.5				
25.8	IMR	90.6 - 92.9	89	5.90 - 7.74	81.7 - 83.4	10.5 - 10.7	88

Abbreviations: IMR – Polymict impact-melt rocklet; PIR – Primary igneous rocklet by petrographic appearance; MF – Mineral fragment; GR – Granulite rocklet. Clasts with two pyroxenes are organized so low-Ca pyroxene is listed first, followed by high-Ca pyroxene.

TABLE A1-1: Continued.

Sample	Rock	Plagioclase	Olivine	Pyroxene			
<i>Dh-025</i>	Textural Type	An	Fo	Wo	En	Fs	Mg#
78	IMR	94.2 - 96.9	68.0 - 73.3	6.31 - 10.8 34.9 - 39.5	66.0 - 69.2 47.0 - 50.4	23.1 - 24.5 13.9 - 14.7	73.8 - 74.5 77.4 - 77.8
93	IMR	95.2 - 97.5	76.4 - 80.7	2.73 - 8.38	70.3 - 80.6	15.5 - 17.2	82.5
108b	IMR	95.6 - 95.9		3.26 - 3.77 39.5 - 44.5	79.3 - 79.9 46.6 - 50.1	16.6 - 17.1 8.77 - 11.2	82 82
Troc1	IMR	96.4	81				
Troc3	IMR	96.7	72				
Troc4	IMR	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 40.4 - 43.4	72.1 - 73.1 45.3 - 47.1	23.3 - 23.6 11.1 - 13.4	75 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				
126.3	MF		79.7 - 82.				
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				

TABLE A1-1: Continued.

Sample	Rock	Plagioclase	Olivine	Pyroxene			
<i>Dh-081</i>	Textural Type	An	Fo	Wo	En	Fs	Mg#
C	IMR	96.8 - 97.5	56.7 - 75.4				
F	IMR	97.8 - 97.0		3.8 - 4.1	70.0 - 70.5	25.4 - 26.0	72.9 - 73.5
H	IMR	96.4 - 98.1		5.93 - 9.63	71.2 - 75.6	18.3 - 21.9	76.9 - 80.5
I	IMR	96.7 - 97.6	76.0 - 78.5				
I2	IMR	96.1 - 97.4	74.3 - 79.4				
L	IMR	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	IMR	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	IMR	97.3 - 97.5		26.5 - 28.8	39.2 - 45.5	28.0 - 32.1	55.0 - 61.9
AE	IMR	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					

TABLE A1-2a: Dh-025 plagioclase analyses by clast.

Clast:	AA	AB	AF	AI	A	B	K	T	V
# *	5	7	7	10	6	7	4	5	4
SiO ₂	43.3 (3)	43.2 (2)	43.5 (2)	43.5 (5)	44.2 (1)	44.1 (8)	43.3 (2)	43.9 (3)	44.4 (1)
Al ₂ O ₃	34.9 (3)	35.1 (2)	35.0 (3)	34.4 (15)	32.8 (15)	33.2 (15)	34.2 (12)	34.6 (7)	33.4 (13)
MgO	0.18 (4)	0.18 (2)	0.15 (2)	0.45 (8)	n.d. **	n.d.	n.d.	n.d.	n.d.
CaO	19.6 (1)	19.8 (1)	19.6 (2)	19.7 (3)	19.0 (4)	18.7 (6)	19.0 (6)	19.6 (2)	19.0 (3)
FeO	0.26 (5)	0.32 (7)	0.32 (10)	0.50 (7)	1.68 (21)	1.56 (9)	0.66 (7)	0.50 (27)	0.90 (5)
Na ₂ O	0.34 (2)	0.27 (3)	0.37 (3)	0.33 (4)	0.35 (4)	0.35 (8)	0.29 (7)	0.32 (2)	0.41 (2)
K ₂ O	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.05 (1)
total	98.6 (3)	98.9 (3)	98.9 (2)	98.9 (5)	98.5 (8)	99.9 (7)	99.4 (2)	98.9 (5)	98.1 (12)
Cation Basis per 8 Oxygens									
Si	2.035	2.026	2.038	2.043	2.100	2.091	2.061	2.059	2.097
Al	1.935	1.943	1.934	1.905	1.834	1.858	1.915	1.909	1.858
Mg	0.012	0.012	0.010	0.032	n.d.	n.d.	n.d.	n.d.	n.d.
Ca	0.989	0.997	0.983	0.990	0.966	0.952	0.966	0.983	0.964
Fe	0.011	0.012	0.012	0.020	0.067	0.062	0.027	0.019	0.036
Na	0.031	0.024	0.034	0.030	0.033	0.032	0.027	0.029	0.038
K	b.d.***	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.004
total	5.014	5.015	5.013	5.020	5.000	4.997	4.996	5.001	4.995
AN	96.9 (3)	97.6 (3)	96.5 (3)	96.9 (4)	97.3 (5)	97.3 (7)	97.2 (1)	97.0 (2)	95.9 (1)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2a: Continued.

Clast: # *	Y 8	AC 6	AD 4	AE 8	AG 13	AH 9	BA 7	BB 6	BC 9
SiO ₂	43.7 (2)	43.8 (5)	43.8 (8)	43.9 (3)	43.6 (2)	43.3 (3)	43.9 (2)	43.6 (3)	43.7 (6)
Al ₂ O ₃	35.3 (2)	34.3 (9)	34.5 (2)	34.4 (4)	34.8 (3)	35.1 (3)	34.7 (5)	34.6 (5)	34.7 (8)
MgO	n.d. **	0.43 (47)	0.19 (2)	0.23 (12)	0.16 (7)	0.15 (4)	0.23 (12)	0.51 (32)	0.24 (4)
CaO	19.7 (1)	19.4 (3)	19.6 (2)	19.1 (3)	19.4 (2)	19.5 (1)	19.3 (2)	19.4 (3)	19.4 (4)
FeO	0.24 (7)	0.73 (44)	0.47 (6)	0.48 (13)	0.38 (14)	0.33 (4)	0.35 (12)	0.54 (37)	0.43 (20)
Na ₂ O	0.33 (5)	0.39 (4)	0.41 (3)	0.54 (8)	0.42 (6)	0.35 (4)	0.41 (5)	0.28 (4)	0.40 (13)
K ₂ O	<0.03	<0.03	0.05 (2)	0.05 (1)	0.04 (1)	<0.03	<0.03	<0.03	0.05 (1)
total	99.3 (2)	99.1 (2)	99.1 (2)	98.8 (3)	98.8 (2)	98.7 (3)	98.9 (5)	98.9 (4)	98.9 (4)
Cation Basis per 8 Oxygens									
Si	2.041	2.054	2.053	2.061	2.048	2.032	2.055	2.046	2.049
Al	1.941	1.895	1.906	1.905	1.922	1.944	1.914	1.910	1.917
Mg	n.d.	0.030	0.013	0.016	0.011	0.010	0.016	0.036	0.017
Ca	0.983	0.973	0.985	0.961	0.976	0.980	0.970	0.974	0.974
Fe	0.010	0.029	0.019	0.019	0.015	0.013	0.014	0.021	0.017
Na	0.030	0.036	0.037	0.049	0.039	0.032	0.037	0.026	0.037
K	b.d.***	b.d.	0.003	0.003	0.002	b.d.	b.d.	b.d.	0.003
total	5.004	5.017	5.014	5.013	5.012	5.012	5.006	5.013	5.012
AN	97.0 (5)	96.3 (4)	96.1 (4)	94.8 (8)	96.0 (5)	96.8 (3)	96.3 (4)	97.3 (3)	96.2 (12)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2a: Continued.

Clast: # *	BD 10	BF 11	BH 5	BL 13	BO 10	BP 13	25.8 8	78 5	93 10
SiO ₂	43.5 (3)	43.7 (5)	44.0 (14)	43.8 (3)	43.7 (2)	44.0 (1)	45.3 (5)	43.5 (3)	43.5 (4)
Al ₂ O ₃	34.9 (4)	34.6 (7)	34.6 (2)	34.6 (4)	34.7 (5)	34.3 (7)	33.6 (3)	35.1 (2)	35.2 (3)
MgO	0.17 (9)	0.27 (22)	0.27 (5)	0.46 (28)	0.28 (20)	0.41 (53)	0.39 (4)	0.15 (3)	0.15 (5)
CaO	19.5 (1)	19.3 (3)	19.4 (1)	19.3 (3)	19.4 (2)	19.2 (5)	18.3 (3)	19.6 (2)	19.6 (2)
FeO	0.41 (11)	0.46 (21)	0.52 (9)	0.42 (14)	0.41 (16)	0.59 (39)	0.33 (5)	0.23 (7)	0.21 (10)
Na ₂ O	0.30 (3)	0.34 (10)	0.34 (2)	0.37 (3)	0.36 (3)	0.42 (3)	0.91 (9)	0.38 (5)	0.30 (2)
K ₂ O	<0.03	<0.03	0.05 (1)	<0.03	<0.03	0.03 (1)	<0.03	<0.03	<0.03
total	98.7 (2)	98.8 (3)	99.1 (2)	99.0 (4)	98.9 (3)	99.0 (3)	98.8 (2)	99.0 (2)	99.0 (5)
Cation Basis per 8 Oxygens									
Si	2.041	2.052	2.057	2.050	2.048	2.061	2.115	2.036	2.037
Al	1.931	1.912	1.906	1.910	1.918	1.895	1.848	1.939	1.939
Mg	0.012	0.019	0.019	0.032	0.020	0.029	0.027	0.010	0.010
Ca	0.979	0.973	0.972	0.969	0.976	0.963	0.917	0.982	0.984
Fe	0.016	0.018	0.020	0.016	0.016	0.023	0.013	0.009	0.008
Na	0.028	0.031	0.031	0.034	0.032	0.038	0.082	0.035	0.028
K	b.d.***	b.d.	0.003	b.d.	b.d.	0.002	b.d.	b.d.	b.d.
total	5.007	5.007	5.008	5.012	5.011	5.011	5.003	5.012	5.008
AN	97.2 (3)	96.8 (10)	96.6 (2)	96.5 (4)	96.6 (3)	96.0 (3)	91.6 (8)	96.5 (5)	97.1 (3)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2a: Continued.

Clast: # *	108b 7	Troc1 4	Troc3 4	Troc4 4	Gran1 4	BI 15	74 8
SiO ₂	43.6 (2)	44.2 (6)	43.6 (1)	43.6 (6)	44.0 (3)	43.8 (2)	43.8 (4)
Al ₂ O ₃	34.5 (3)	34.7 (3)	34.9 (4)	34.2 (9)	34.2 (114)	35.0 (2)	34.4 (10)
MgO	0.31 (33)	n.d.	n.d.	n.d.	n.d.	0.07 (2)	0.38 (43)
CaO	19.5 (4)	19.3 (3)	19.6 (1)	19.3 (6)	19.3 (2)	19.4 (1)	19.3 (4)
FeO	0.29 (9)	0.41 (21)	0.44 (15)	0.64 (4)	0.49 (27)	0.16 (3)	0.58 (45)
Na ₂ O	0.46 (1)	0.39 (4)	0.32 (3)	0.39 (8)	0.37 (3)	0.49 (3)	0.37 (5)
K ₂ O	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
total	98.6 (3)	98.9 (4)	99.0 (4)	98.2 (7)	98.6 (8)	98.9 (4)	98.9 (5)
Cation Basis per 8 Oxygens							
Si	2.049	2.066	2.045	2.062	2.073	2.048	2.055
Al	1.910	1.912	1.927	1.903	1.896	1.932	1.902
Mg	0.022	n.d.	n.d.	n.d.	n.d.	0.005	0.026
Ca	0.982	0.966	0.986	0.978	0.975	0.973	0.971
Fe	0.011	0.016	0.017	0.026	0.019	0.006	0.023
Na	0.042	0.036	0.029	0.035	0.034	0.045	0.034
K	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
total	5.018	4.996	5.006	5.005	4.998	5.009	5.012
AN	95.8 (1)	96.4 (5)	97.0 (2)	96.4 (8)	96.5 (2)	95.5 (2)	96.4 (5)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2b: Dh-025 orthopyroxene analyses by clast.

Clast:	BA	BM	93	108b	BK
# *	9	10	9	5	10
SiO2	54.0 (2)	54.8 (2)	54.7 (3)	54.4 (2)	53.7 (2)
TiO2	0.57 (2)	0.76 (7)	0.49 (3)	0.71 (4)	0.78 (4)
Al2O3	1.19 (13)	1.36 (3)	1.08 (2)	1.05 (2)	1.05 (10)
Cr2O3	0.59 (3)	0.51 (3)	0.70 (3)	0.45 (1)	0.44 (3)
MgO	27.9 (3)	30.2 (4)	29.5 (5)	29.9 (3)	26.6 (2)
CaO	1.97 (2)	1.66 (7)	1.94 (73)	1.85 (9)	1.95 (17)
MnO	0.24 (3)	0.20 (3)	0.21 (2)	0.21 (4)	0.28 (3)
FeO	13.0 (2)	10.5 (3)	11.1 (3)	11.2 (2)	15.3 (1)
Na2O	<0.03	<0.03	<0.03	<0.03	<0.03
total	99.4 (3)	99.9 (5)	99.7 (5)	99.8 (3)	100.1 (3)
Cation Basis per 6 Oxygens					
Si	1.947	1.940	1.948	1.938	1.945
Ti	0.016	0.020	0.013	0.019	0.021
Al	0.051	0.057	0.045	0.044	0.045
Cr	0.017	0.014	0.020	0.013	0.013
Mg	1.500	1.592	1.568	1.589	1.434
Ca	0.076	0.063	0.074	0.071	0.076
Mn	0.007	0.006	0.006	0.006	0.009
Fe	0.391	0.311	0.330	0.334	0.463
Na	b.d.	b.d.	b.d.	b.d.	b.d.
total	4.005	4.004	4.006	4.015	4.006
Wo	3.87 (30)	3.20 (14)	3.76 (144)	3.55 (19)	3.83 (34)
En	76.3 (4)	81.0 (6)	79.5 (12)	79.7 (2)	72.7 (3)
Fs	19.9 (3)	15.8 (5)	16.7 (4)	16.8 (2)	23.5 (1)
Mg#	79.3 (3)	83.7 (5)	82.6 (3)	82.6 (2)	75.6 (1)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2c: Dh-025 pigeonite analyses by clast.

Clast:	AC	AE	BC	BD	BF	BH	78	BE
# *	6	6	18	8	16	7	10	20
SiO ₂	52.8 (9)	52.8 (8)	52.4 (6)	51.7 (3)	51.9 (8)	54.6 (2)	52.9 (4)	51.7 (4)
TiO ₂	0.83 (52)	0.75 (9)	0.62 (18)	0.46 (7)	0.66 (28)	0.55 (3)	0.82 (11)	0.39 (8)
Al ₂ O ₃	1.18 (31)	1.01 (12)	1.56 (68)	0.81 (16)	1.34 (56)	1.16 (9)	1.23 (52)	1.65 (43)
Cr ₂ O ₃	0.41 (3)	0.41 (3)	0.53 (10)	0.28 (4)	0.52 (4)	0.59 (1)	0.39 (3)	0.80 (6)
MgO	24.7 (7)	25.1 (2)	22.2 (12)	20.4 (7)	21.7 (15)	28.2 (7)	24.3 (9)	19.4 (8)
CaO	3.71 (60)	2.38 (16)	5.14 (110)	3.27 (57)	5.48 (88)	2.82 (62)	3.42 (80)	8.09 (119)
MnO	0.27 (1)	0.25 (3)	0.30 (3)	0.41 (2)	0.31 (4)	0.24 (22)	0.29 (2)	0.35 (3)
FeO	15.3 (8)	16.8 (1)	16.8 (15)	21.8 (13)	16.9 (15)	12.0 (4)	15.6 (4)	17.0 (9)
Na ₂ O	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
total	99.1 (12)	99.6 (3)	99.6 0.45	99.2 (3)	98.9 (4)	100.1 (3)	98.9 (7)	99.3 (4)
Cation Basis per 6 Oxygens								
Si	1.942	1.940	1.941	1.960	1.942	1.949	1.949	1.939
Ti	0.023	0.021	0.017	0.013	0.019	0.015	0.023	0.011
Al	0.051	0.044	0.068	0.036	0.059	0.049	0.054	0.073
Cr	0.012	0.012	0.016	0.008	0.015	0.017	0.011	0.024
Mg	1.352	1.377	1.224	1.151	1.207	1.501	1.336	1.084
Ca	0.146	0.094	0.204	0.132	0.220	0.108	0.135	0.326
Mn	0.008	0.008	0.009	0.013	0.010	0.007	0.009	0.011
Fe	0.469	0.517	0.519	0.691	0.530	0.357	0.480	0.533
Na	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
total	4.005	4.013	4.001	4.006	4.004	4.004	3.997	4.002
Wo	7.44 (126)	4.71 (32)	10.5 (23)	6.71 (115)	11.2 (19)	5.48 (125)	6.94 (161)	16.8 (26)
En	68.7 (128)	69.3 (3)	62.8 (28)	58.3 (19)	61.7 (35)	76.3 (14)	68.4 (14)	55.8 (18)
Fs	23.8 (101)	26.0 (10)	26.7 (25)	35.0 (21)	27.1 (25)	18.2 (7)	24.6 (9)	27.4 (13)
Mg#	74.2 (101)	72.7 (1)	70.2 (26)	62.5 (21)	69.4 (31)	80.8 (8)	73.5 (8)	67.0 (10)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2c: Continued.

Clast:	71a	71b	74	121.1	126.1	130.2
# *	7	8	8	11	6	10
SiO ₂	51.8 (7)	51.6 (7)	53.9 (5)	51.5 (4)	52.3 (41)	52.5 (4)
TiO ₂	0.43 (13)	0.51 (13)	0.23 (4)	0.56 (7)	0.22 (7)	0.49 (7)
Al ₂ O ₃	0.86 (25)	1.00 (43)	1.04 (12)	1.95 (45)	1.36 (48)	1.25 (21)
Cr ₂ O ₃	0.28 (7)	0.20 (5)	0.52 (6)	0.69 (3)	0.42 (6)	0.52 (5)
MgO	21.6 (9)	20.9 (14)	25.8 (9)	20.4 (8)	20.8 (11)	21.6 (11)
CaO	3.61 (84)	2.79 (52)	2.99 (100)	4.88 (41)	3.92 (50)	4.92 (43)
MnO	0.37 (2)	0.38 (5)	0.29 (2)	0.35 (5)	0.33 (3)	0.33 (4)
FeO	20.2 (17)	21.1 (18)	15.2 (4)	19.0 (13)	20.0 (13)	17.7 (13)
Na ₂ O	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
total	99.2 (4)	98.6 (19)	99.9 (7)	99.4 (3)	99.4 (3)	99.4 (3)
Cation Basis per 6 Oxygens						
Si	1.951	1.957	1.958	1.931	1.960	1.955
Ti	0.012	0.014	0.006	0.016	0.006	0.014
Al	0.038	0.045	0.045	0.086	0.060	0.055
Cr	0.008	0.006	0.015	0.021	0.013	0.015
Mg	1.211	1.183	1.396	1.142	1.160	1.200
Ca	0.146	0.113	0.116	0.196	0.158	0.196
Mn	0.012	0.012	0.009	0.011	0.010	0.010
Fe	0.636	0.670	0.461	0.597	0.628	0.550
Na	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
total	4.014	4.003	4.007	4.001	3.997	3.997
Wo	7.3 (17)	5.8 (11)	5.9 (21)	10.1 (9)	8.1 (11)	10.1 (9)
En	60.8 (21)	60.1 (25)	70.7 (19)	59.0 (20)	59.6 (28)	61.7 (27)
Fs	31.9 (28)	34.1 (29)	23.4 (6)	30.9 (21)	32.3 (21)	28.3 (22)
Mg#	65.6 (27)	63.8 (28)	75.1 (7)	65.7 (22)	70.4 (67)	68.6 (26)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2d: Dh-025 augite analyses by clast.

Clast:	AG	BA	BD	BH	25.8	78	108b	BE
# *	6	14	4	18	6	3	11	10
SiO ₂	50.9 (5)	51.6 (2)	50.9 (2)	51.5 (2)	52.1 (3)	50.9 (6)	50.9 (6)	52.0 (4)
TiO ₂	1.46 (16)	1.01 (6)	0.75 (3)	1.14 (6)	1.11 (17)	1.60 (31)	1.44 (27)	0.47 (8)
Al ₂ O ₃	2.17 (33)	2.23 (62)	1.50 (16)	2.40 (17)	3.31 (26)	2.44 (35)	2.38 (51)	1.61 (19)
Cr ₂ O ₃	0.70 (9)	0.84 (3)	0.46 (3)	0.94 (5)	0.70 (10)	0.76 (5)	0.65 (7)	0.63 (6)
MgO	17.0 (7)	17.0 (4)	14.5 (3)	16.7 (5)	19.8 (7)	16.8 (7)	17.1 (5)	17.5 (14)
CaO	17.6 (12)	19.9 (70)	18.9 (5)	20.3 (8)	18.4 (8)	18.3 (8)	20.4 (6)	14.6 (27)
MnO	0.20 (3)	0.17 (1)	0.23 (4)	0.16 (3)	0.10 (1)	0.19 (1)	0.14 (2)	0.25 (4)
FeO	9.27 (61)	6.36 (46)	11.5 (43)	6.32 (71)	3.93 (23)	8.31 (46)	6.01 (50)	12.2 (18)
Na ₂ O	0.07 (1)	0.05 (1)	<0.03	0.04 (1)	0.09 (1)	0.07 (1)	0.06 (2)	0.05 (1)
total	99.4 (2)	99.2 (5)	98.7 (4)	99.5 (2)	99.5 (5)	99.4 (3)	99.1 (3)	99.4 (4)

Cation Basis per 6 Oxygens

Si	1.898	1.913	1.935	1.905	1.892	1.895	1.891	1.945
Ti	0.041	0.028	0.022	0.032	0.030	0.045	0.040	0.013
Al	0.095	0.097	0.067	0.105	0.142	0.107	0.104	0.071
Cr	0.021	0.025	0.014	0.027	0.020	0.022	0.019	0.019
Mg	0.945	0.941	0.823	0.922	1.070	0.932	0.947	0.975
Ca	0.705	0.790	0.771	0.804	0.716	0.729	0.813	0.583
Mn	0.006	0.005	0.007	0.005	0.003	0.006	0.005	0.008
Fe	0.289	0.197	0.364	0.195	0.120	0.258	0.187	0.383
Na	0.005	0.004	b.d.	0.003	0.007	0.005	0.004	0.004
total	4.005	4.000	4.005	3.999	4.000	3.998	4.010	4.000
Wo	36.4 (26)	41.0 (16)	39.4 (9)	41.8 (15)	37.6 (19)	38.0 (20)	41.8 (13)	30.0 (55)
En	48.7 (17)	48.8 (9)	42.0 (9)	48.0 (14)	56.1 (16)	48.5 (16)	48.6 (10)	50.2 (34)
Fs	14.9 (9)	10.2 (7)	18.6 (7)	10.2 (12)	6.28 (31)	13.5 (6)	9.61 (86)	19.7 (31)
Mg#	76.6 (5)	82.7 (8)	69.3 (9)	82.5 (18)	89.9 (2)	78.3 (4)	83.5 (13)	71.9 (28)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2d: Continued.

Clast:	BK	123.1	108
# *	16	9	10
SiO ₂	50.9 (3)	51.9 (4)	50.5 (6)
TiO ₂	1.69 (30)	0.77 (3)	0.83 (13)
Al ₂ O ₃	2.34 (33)	2.10 (7)	1.64 (48)
Cr ₂ O ₃	0.73 (4)	0.67 (4)	0.71 (6)
MgO	16.0 (3)	15.8 (4)	13.0 (13)
CaO	20.3 (6)	19.6 (10)	15.4 (15)
MnO	0.17 (2)	0.18 (2)	0.31 (4)
FeO	7.41 (45)	8.62 (32)	16.9 (16)
Na ₂ O	0.07 (2)	0.09 (3)	0.09 (2)
total	99.6 (3)	99.7 (6)	99.4 (4)

Cation Basis per 6 Oxygens

Si	1.894	1.929	1.938
Ti	0.047	0.021	0.024
Al	0.103	0.092	0.074
Cr	0.022	0.020	0.022
Mg	0.885	0.876	0.744
Ca	0.808	0.779	0.632
Mn	0.006	0.006	0.010
Fe	0.231	0.268	0.544
Na	0.005	0.006	0.006
total	4.000	3.997	3.993
Wo	42.0 (10)	40.5 (17)	32.9 (34)
En	46.0 (5)	45.6 (11)	38.8 (35)
Fs	12.0 (8)	13.9 (6)	28.3 (27)
Mg#	79.3 (11)	76.6 (5)	57.8 (37)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2e: Dh-025 olivine analyses by clast.

Clast: # *	AA 6	AB 10	AF 8	AI 8	A 9	B 8	K 6	T 5
SiO ₂	37.9 (3)	39.1 (2)	37.7 (5)	38.7 (2)	37.7 (3)	37.6 (12)	38.8 (2)	38.6 (13)
Cr ₂ O ₃	0.10 (10)	0.08 (4)	0.15 (9)	0.04 (1)	0.15 (3)	0.16 (9)	0.05 (5)	0.07 (9)
MgO	39.4 (18)	43.0 (7)	36.0 (9)	41.7 (2)	36.0 (1)	36.0 (37)	42.7 (3)	41.3 (27)
CaO	0.27 (15)	0.23 (22)	0.53 (33)	0.30 (2)	0.53 (26)	0.51 (21)	0.25 (9)	0.41 (4)
MnO	0.26 (3)	0.22 (4)	0.26 (3)	0.23 (5)	0.26 (6)	0.29 (7)	0.22 (2)	0.22 (4)
FeO	21.0 (3)	17.5 (4)	25.3 (13)	19.2 (6)	25.3 (3)	25.0 (41)	18.3 (1)	18.6 (48)
NiO	<0.03	0.04 (3)	<0.03	<0.03	<0.03	n.d.	n.d.	n.d.
total	98.8 (8)	100.2 (3)	100.0 (8)	100.1 (4)	100.0 (6)	99.6 (7)	100.4 (2)	99.2 (4)
Cation Basis per 4 Oxygens								
Si	0.993	0.992	0.997	0.991	0.997	0.997	0.988	0.995
Cr	0.002	0.002	0.003	0.001	0.003	0.004	0.001	0.002
Mg	1.538	1.629	1.419	1.592	1.419	1.422	1.622	1.590
Ca	0.008	0.006	0.015	0.008	0.015	0.015	0.007	0.011
Mn	0.006	0.005	0.006	0.005	0.006	0.007	0.004	0.005
Fe	0.461	0.372	0.561	0.411	0.561	0.558	0.390	0.400
Ni	b.d.	0.001	b.d.	b.d.	b.d.	n.d.	n.d.	n.d.
total	3.007	3.007	3.002	3.009	3.002	3.001	3.012	3.003
Fo	76.9 (10)	81.4 (6)	71.7 (14)	79.5 (6)	71.5 (5)	71.8 (53)	80.6 (2)	75.0 (30)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2e: Continued.

Clast:	V	AC	AD	AE	AH	BB	BM	BO
# *	5	3	6	9	13	14	29	9
SiO ₂	37.4 (3)	33.6 (37)	36.6 (5)	36.6 (3)	38.6 (7)	38.8 (4)	39.1 (36)	37.8 (4)
Cr ₂ O ₃	0.08 (3)	0.11 (6)	0.20 (5)	0.12 (3)	0.10 (4)	0.10 (3)	0.09 (6)	0.21 (4)
MgO	36.4 (5)	32.2 (19)	33.2 (16)	33.6 (7)	42.7 (6)	41.0 (21)	42.4 (15)	36.4 (7)
CaO	0.43 (34)	0.53 (27)	0.40 (12)	0.32 (12)	0.22 (7)	0.28 (15)	0.26 (16)	0.46 (14)
MnO	0.28 (2)	0.27 (4)	0.31 (4)	0.29 (2)	0.20 (2)	0.24 (4)	0.22 (3)	0.27 (21)
FeO	25.2 (4)	23.9 (9)	29.0 (14)	28.9 (8)	18.1 (10)	19.3 (23)	18.0 (14)	24.6 (5)
NiO	<0.03	0.04 (2)	<0.03	0.04 (5)	<0.03	<0.03	<0.03	<0.03
total	99.9 (3)	90.6	99.8	99.9	100.0	99.8	100.2	99.7
Cation Basis per 4 Oxygens								
Si	0.991	0.985	0.990	0.988	0.986	0.998	0.996	0.999
Cr	0.002	0.003	0.004	0.003	0.002	0.002	0.002	0.004
Mg	1.438	1.414	1.339	1.353	1.627	1.572	1.610	1.432
Ca	0.012	0.016	0.012	0.009	0.006	0.008	0.007	0.013
Mn	0.006	0.007	0.007	0.007	0.004	0.005	0.005	0.006
Fe	0.559	0.588	0.656	0.651	0.387	0.415	0.384	0.542
Ni	b.d.	0.001	b.d.	0.001	b.d.	b.d.	b.d.	b.d.
total	3.009	3.013	3.008	3.011	3.013	3.001	3.003	2.998
Fo	72.1 (2)	70.6 (5)	67.1 (21)	67.5 (10)	80.8 (10)	79.2 (27)	80.8 (17)	72.8 (7)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2e: Continued.

Clast:	BP	25.8	78	93	Troc1	Troc3	Troc4
# *	19	11	12	20	5	5	5
SiO ₂	37.4 (2)	40.4 (1)	37.4 (3)	38.5 (6)	38.8 (4)	37.9 (5)	37.4 (3)
Cr ₂ O ₃	0.15 (4)	0.16 (2)	0.08 (3)	0.07 (3)	0.10 (4)	0.15 (1)	0.08 (3)
MgO	35.5 (6)	48.4 (3)	36.4 (5)	41.5 (12)	41.7 (18)	36.2 (1)	36.4 (5)
CaO	0.43 (16)	0.23 (3)	0.43 (34)	0.29 (38)	0.34 (23)	0.46 (5)	0.43 (34)
MnO	0.29 (3)	0.13 (3)	0.28 (2)	0.22 (2)	0.20 (3)	0.23 (7)	0.28 (2)
FeO	25.5 (5)	10.5 (1)	25.2 (4)	19.0 (9)	18.2 (16)	24.6 (2)	25.2 (4)
NiO	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
total	99.2 (7)	99.9 (2)	99.9 (8)	99.6 (9)	99.3 (4)	99.5 (3)	99.9 (2)
Cation Basis per 4 Oxygens							
Si	0.999	0.996	0.991	0.991	0.998	1.003	0.991
Cr	0.003	0.003	0.002	0.002	0.002	0.003	0.002
Mg	1.411	1.779	1.438	1.592	1.596	1.427	1.438
Ca	0.012	0.006	0.012	0.008	0.010	0.013	0.012
Mn	0.007	0.003	0.006	0.005	0.005	0.005	0.006
Fe	0.568	0.216	0.559	0.410	0.392	0.545	0.559
Ni	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
total	3.000	3.003	3.009	3.008	3.002	2.995	3.009
Fo	71.5 (6)	89.3 (2)	72.2 (6)	79.7 (12)	80.6 (5)	72.4 (3)	72.0 (2)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-2e: Continued.

Clast: # *	Gran1 10	71c 8	121.2 8	123.2 10	126.2 10	130.2 6
SiO ₂	39.3 (4)	38.6 (4)	38.0 (10)	38.1 (5)	38.8 (4)	37.8 (3)
Cr ₂ O ₃	0.10 (3)	0.07 (5)	0.11 (4)	0.14 (3)	0.10 (4)	0.22 (2)
MgO	40.8 (4)	41.7 (20)	38.6 (41)	38.0 (18)	41.7 (19)	37.4 (6)
CaO	0.42 (3)	0.32 (17)	0.30 (11)	0.44 (16)	0.34 (24)	0.42 (9)
MnO	0.22 (1)	0.21 (3)	0.24 (6)	0.24 (4)	0.20 (2)	0.27 (2)
FeO	18.9 (4)	18.3 (18)	22.4 (48)	22.6 (22)	18.2 (16)	23.5 (3)
NiO	n.d.	<0.03	<0.03	<0.03	<0.03	<0.03
total	99.8 (4)	99.2 (5)	99.6 (3)	99.6 (4)	99.3 (5)	99.6 (3)
Cation Basis per 4 Oxygens						
Si	1.009	0.994	0.994	0.998	0.998	0.996
Cr	0.002	0.002	0.002	0.003	0.002	0.005
Mg	1.559	1.601	1.502	1.485	1.596	1.466
Ca	0.012	0.009	0.008	0.013	0.010	0.012
Mn	0.005	0.005	0.005	0.005	0.005	0.006
Fe	0.406	0.395	0.494	0.496	0.392	0.517
Ni	n.d.	b.d.	b.d.	b.d.	b.d.	b.d.
total	2.991	3.005	3.005	3.000	3.002	3.002
Fo	79.4 (5)	80.4 (22)	75.4 (59)	75.2 (27)	80.5 (19)	74.1 (4)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-3a: Dh-081 plagioclase analyses by clast.

Clast:	C	F	H	I	I2	L	R	V
# *	10	10	8	10	12	10	21	9
SiO2	43.4 (2)	44.3 (21)	43.6 (3)	43.4 (2)	43.6 (3)	43.6 (2)	43.4 (2)	43.3 (16)
Al2O3	35.2 (3)	33.7 (40)	35.3 (4)	35.3 (4)	34.9 (3)	35.3 (2)	35.5 (1)	35.3 (3)
MgO	0.16 (7)	0.40 (6)	0.18 (1)	0.17 (12)	0.26 (18)	0.20 (6)	0.13 (3)	0.13 (8)
CaO	19.6 (3)	18.8 (22)	19.6 (2)	19.6 (2)	19.4 (2)	19.5 (2)	19.6 (1)	19.8 (1)
FeO	0.21 (11)	1.15 (24)	0.24 (15)	0.24 (23)	0.35 (19)	0.26 (5)	0.19 (6)	0.12 (13)
Na2O	0.30 (3)	0.31 (7)	0.28 (5)	0.29 (3)	0.38 (5)	0.35 (9)	0.32 (4)	0.28 (2)
K2O	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
total	98.9 (7)	98.7 (12)	99.2 (1)	99.1 (2)	98.8 (37)	99.2 (2)	99.2 (2)	98.9 (11)

Cation Basis per 8 Oxygens

Si	2.035	2.083	2.035	2.030	2.045	2.035	2.029	2.027
Al	1.943	1.865	1.941	1.947	1.926	1.944	1.954	1.951
Mg	0.011	0.029	0.013	0.012	0.018	0.014	0.009	0.009
Ca	0.983	0.947	0.983	0.984	0.972	0.973	0.981	0.993
Fe	0.008	0.046	0.009	0.010	0.013	0.010	0.007	0.005
Na	0.027	0.028	0.025	0.027	0.034	0.032	0.029	0.025
K	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.001
total	5.008	4.999	5.007	5.010	5.009	5.009	5.010	5.010

AN	97.2 (2)	96.9 (12)	97.4 (5)	97.3 (3)	96.6 (5)	96.8 (6)	97.0 (4)	97.5 (2)
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* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-3a: Continued.

Clast: # *	AE 10	G 8	AF 10	B 10	D 10	E 8	K 13	M 10
SiO ₂	43.5 (3)	43.6 (3)	43.8 (1)	43.6 (3)	43.4 (2)	43.5 (3)	43.5 (2)	43.6 (1)
Al ₂ O ₃	35.4 (2)	35.4 (3)	35.0 (4)	34.8 (17)	35.4 (2)	35.4 (2)	35.5 (2)	35.3 (1)
MgO	0.12 (6)	0.11 (7)	0.23 (19)	0.38 (108)	0.09 (3)	0.07 (1)	0.08 (1)	0.07 (1)
CaO	19.6 (2)	19.4 (2)	19.3 (2)	19.3 (7)	19.7 (2)	19.6 (1)	19.6 (2)	19.6 (1)
FeO	0.19 (6)	0.21 (9)	0.33 (23)	0.49 (103)	0.19 (5)	0.20 (3)	0.10 (9)	0.18 (4)
Na ₂ O	0.38 (10)	0.34 (5)	0.39 (4)	0.37 (2)	0.30 (4)	0.31 (2)	0.34 (9)	0.36 (3)
K ₂ O	0.04 (8)	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
total	99.2 (4)	99.2 (2)	99.1 (2)	99.0 (2)	99.0 (3)	99.0 (4)	99.1 (2)	99.1 (2)
Cation Basis per 8 Oxygens								
Si	2.031	2.036	2.047	2.043	2.029	2.034	2.032	2.037
Al	1.948	1.949	1.930	1.921	1.951	1.949	1.953	1.945
Mg	0.008	0.008	0.016	0.027	0.006	0.004	0.006	0.005
Ca	0.983	0.972	0.966	0.969	0.989	0.983	0.981	0.980
Fe	0.007	0.008	0.013	0.019	0.007	0.008	0.004	0.007
Na	0.034	0.031	0.036	0.034	0.027	0.028	0.030	0.032
K	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
total	5.013	5.006	5.007	5.014	5.009	5.006	5.007	5.007
AN	96.4 (13)	96.8 (6)	96.4 (4)	96.6 (3)	97.2 (3)	97.2 (2)	96.9 (9)	96.8 (2)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-3a: Continued.

Clast: # *	O 10	P 10	Q 10	W 10	X 10	Y 10	Z 10	AC 10	AI 10
SiO ₂	43.6 (2)	43.6 (2)	44.0 (9)	43.5 (2)	43.6 (1)	43.6 (2)	43.5 (9)	43.6 (7)	43.5 (6)
Al ₂ O ₃	35.4 (4)	35.2 (5)	34.4 (33)	35.5 (3)	35.4 (1)	35.6 (5)	35.2 (9)	34.9 (4)	35.3 (9)
MgO	0.18 (12)	0.15 (14)	0.47 (119)	0.12 (7)	0.11 (5)	0.15 (19)	0.30 (3)	0.19 (9)	0.14 (12)
CaO	19.6 (1)	19.6 (1)	19.2 (9)	19.6 (2)	19.6 (1)	19.6 (2)	19.3 (5)	19.5 (4)	19.7 (5)
FeO	0.26 (16)	0.31 (19)	0.80 (207)	0.22 (8)	0.16 (5)	0.17 (17)	0.39 (31)	0.20 (14)	0.31 (6)
Na ₂ O	0.28 (3)	0.33 (2)	0.42 (4)	0.29 (2)	0.33 (3)	0.29 (2)	0.34 (5)	0.38 (2)	0.28 (5)
K ₂ O	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
total	99.3 (1)	99.2 (2)	99.2 (2)	99.3 (3)	99.2 (2)	99.4 (1)	99.1 (7)	98.8 (14)	99.2 (6)
Cation Basis per 8 Oxygens									
Si	2.032	2.038	2.058	2.031	2.036	2.031	2.033	2.045	2.032
Al	1.947	1.937	1.894	1.951	1.948	1.953	1.943	1.929	1.945
Mg	0.013	0.010	0.034	0.008	0.008	0.010	0.021	0.013	0.010
Ca	0.980	0.980	0.960	0.981	0.978	0.978	0.968	0.978	0.984
Fe	0.010	0.012	0.032	0.009	0.006	0.007	0.015	0.008	0.012
Na	0.026	0.030	0.039	0.026	0.030	0.026	0.031	0.035	0.026
K	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
total	5.008	5.008	5.015	5.006	5.006	5.006	5.013	5.009	5.009
AN	97.4 (3)	97.0 (2)	96.1 (5)	97.4 (2)	97.0 (3)	97.4 (1)	96.7 (5)	96.5 (2)	97.4 (5)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-3b: Dh-081 pyroxene analyses.

Clast:	F	H	V1	W1	R	V	H1	J	V2
# *	7	5	5	5	4	5	11	6	7
	opx	pig	pig	pig	aug	aug	aug	aug	aug
SiO ₂	52.8 (7)	54.3 (3)	50.0 (12)	50.9 (3)	46.8 (3)	48.3 (13)	50.5 (8)	47.5 (8)	48.8 (27)
TiO ₂	0.70 (10)	0.25 (4)	0.58 (8)	0.32 (7)	0.93 (7)	0.56 (19)	0.40 (11)	0.78 (26)	0.98 (6)
Al ₂ O ₃	1.38 (56)	1.89 (7)	7.29 (35)	0.61 (19)	5.63 (40)	6.24 (43)	4.83 (98)	3.31 (48)	6.24 (49)
Cr ₂ O ₃	0.27 (2)	0.44 (2)	0.87 (14)	0.54 (6)	0.80 (16)	0.21 (10)	1.33 (32)	0.17 (8)	0.75 (19)
MgO	25.4 (3)	26.2 (12)	21.1 (7)	23.0 (5)	10.3 (12)	13.0 (6)	17.4 (9)	10.1 (11)	13.9 (10)
CaO	2.00 (5)	3.21 (81)	7.30 (95)	2.24 (30)	17.8 (8)	11.7 (11)	17.6 (7)	10.0 (9)	18.6 (5)
MnO	0.25 (3)	0.27 (5)	0.25 (4)	0.36 (4)	0.30 (5)	0.28 (3)	0.16 (3)	0.46 (1)	0.19 (3)
FeO	15.9 (11)	12.6 (9)	12.4 (13)	20.7 (9)	15.6 (3)	16.6 (20)	7.3 (3)	26.4 (18)	9.55 (112)
Na ₂ O	<0.03	<0.03	0.05 (1)	<0.03	0.03 (2)	0.15 (18)	<0.03	<0.03	0.03 (1)
total	98.7 (11)	99.2 (4)	99.9 (3)	98.7 (1)	98.6 (2)	99.6 (7)	99.5 (1)	98.8 (6)	99.1 (4)
Cation Basis per 6 Oxygens									
Si	1.945	1.960	1.822	1.929	1.827	1.817	1.862	1.894	1.832
Ti	0.019	0.006	0.016	0.009	0.027	0.016	0.011	0.023	0.028
Al	0.060	0.081	0.313	0.027	0.259	0.392	0.210	0.155	0.276
Cr	0.008	0.013	0.025	0.016	0.025	0.006	0.039	0.006	0.022
Mg	1.393	1.411	1.146	1.300	0.599	0.729	0.954	0.601	0.780
Ca	0.079	0.124	0.285	0.091	0.747	0.471	0.695	0.429	0.747
Mn	0.008	0.008	0.008	0.011	0.010	0.008	0.005	0.016	0.006
Fe	0.491	0.381	0.377	0.657	0.511	0.522	0.225	0.880	0.300
Na	b.d.	b.d.	0.004	b.d.	0.002	0.011	b.d.	b.d.	0.002
total	4.003	3.997	3.996	4.001	4.005	3.993	4.003	4.003	3.993
Wo	4.01 (9)	6.51 (181)	15.8 (19)	4.44 (57)	40.2 (5)	27.3 (13)	37.1 (19)	22.4 (19)	40.9 (12)
En	71.0 (15)	73.6 (17)	63.4 (14)	63.5 (10)	32.2 (1)	42.5 (32)	50.9 (19)	31.5 (29)	42.7 (28)
Fs	25.0 (15)	19.9 (14)	20.9 (25)	32.1 (15)	27.5 (3)	30.2 (20)	12.0 (4)	46.1 (36)	16.4 (19)
Mg#	74.0 (15)	78.7 (13)	75.3 (24)	66.4 (14)	53.9 (2)	58.4 (34)	80.9 (8)	40.6 (39)	72.2 (36)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-3c: Dh-081 olivine analyses.

Clast: # *	C 7	I 10	I2 16	L 7	L 5	L 8	R-rims 4	R-cores 5
SiO2	36.8 (10)	38.0 (4)	37.8 (8)	37.7 (31)	38.6 (65)	38.2 (9)	37.3 (2)	34.7 (5)
Cr2O3	0.10 (10)	0.05 (3)	0.06 (4)	0.06 (3)	0.15 (10)	0.19 (3)	0.06 (1)	0.03 (4)
MgO	32.1 (49)	39.3 (14)	39.6 (34)	36.4 (7)	40.2 (23)	41.9 (22)	34.4 (12)	23.7 (14)
CaO	0.99 (88)	0.78 (39)	0.43 (39)	0.26 (12)	0.39 (15)	0.40 (6)	0.55 (7)	0.52 (22)
MnO	0.31 (6)	0.22 (2)	0.25 (4)	0.27 (1)	0.24 (4)	0.22 (2)	0.26 (1)	0.45 (1)
FeO	28.4 (56)	20.7 (6)	21.3 (43)	25.2 (11)	20.5 (32)	18.5 (24)	27.7 (4)	40.6 (25)
NiO	<0.03	n.d.	n.d.	<0.03	<0.03	<0.03	n.d.	n.d.
total	98.7 (12)	99.4 (6)	99.6 (3)	99.9 (3)	100.0 (2)	99.6 (6)	100.3 (2)	100.0 (4)
Cation Basis per 4 Oxygens								
Si	1.003	0.991	0.984	0.995	0.995	0.983	0.996	0.993
Cr	0.002	0.001	0.001	0.001	0.003	0.004	0.001	0.001
Mg	1.301	1.525	1.539	1.435	1.546	1.607	1.368	1.013
Ca	0.029	0.022	0.012	0.007	0.011	0.011	0.016	0.016
Mn	0.007	0.005	0.006	0.006	0.005	0.005	0.006	0.011
Fe	0.650	0.451	0.465	0.558	0.443	0.401	0.617	0.973
Ni	b.d.	n.d.	n.d.	b.d.	b.d.	b.d.	n.d.	n.d.
total	2.993	3.004	3.012	3.004	3.003	3.014	3.003	3.007
Fo	67.3 (73)	77.8 (7)	77.0 (54)	72.0 (12)	77.8 (37)	80.3 (30)	69.3 (18)	51.2 (32)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

TABLE A1-3c: Continued.

Clast: # *	AE 5	G 7	AF 14	J 4	J 6	J 5	K1 10	T 30	W1 5
SiO ₂	39.2 (5)	37.7 (8)	38.1 (14)	37.7 (1)	36.2 (7)	34.7 (7)	38.0 (19)	35.1 (43)	39.2 (3)
Cr ₂ O ₃	0.20 (3)	0.06 (3)	0.06 (7)	0.13 (3)	0.10 (3)	0.07 (1)	0.28 (1)	0.69 (1)	0.21 (3)
MgO	44.0 (8)	34.6 (19)	37.1 (47)	36.9 (7)	30.3 (27)	25.3 (17)	41.2 (18)	28.9 (19)	44.5 (18)
CaO	0.40 (5)	1.01 (66)	0.60 (19)	0.47 (2)	0.46 (12)	0.43 (10)	0.46 (4)	0.41 (63)	0.37 (2)
MnO	0.18 (3)	0.26 (4)	0.27 (3)	0.26 (2)	0.37 (3)	0.43 (1)	0.25 (3)	0.36 (4)	0.23 (1)
FeO	16.0 (9)	25.3 (24)	23.3 (27)	24.5 (9)	32.8 (34)	39.5 (24)	19.7 (30)	33.8 (29)	14.6 (27)
NiO	<0.03	0.04	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
total	99.9 (7)	99.0 (5)	99.5 (6)	99.9 (4)	100.2 (2)	100.5 (2)	99.9 (4)	99.3 (4)	99.0 (5)
Cation Basis per 4 Oxygens									
Si	0.990	1.009	1.003	0.994	0.993	0.983	0.981	0.981	0.994
Cr	0.004	0.002	0.001	0.003	0.002	0.002	0.006	0.015	0.005
Mg	1.657	1.379	1.455	1.450	1.237	1.070	1.584	1.203	1.682
Ca	0.011	0.029	0.017	0.013	0.014	0.013	0.013	0.012	0.011
Mn	0.004	0.006	0.006	0.006	0.009	0.010	0.005	0.009	0.005
Fe	0.338	0.566	0.514	0.540	0.753	0.938	0.428	0.789	0.309
Ni	b.d.	0.001	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
total	3.004	2.991	2.996	3.005	3.007	3.016	3.016	3.010	3.006
Fo	83.0 (11)	71.8 (30)	73.9 (33)	73.2 (11)	62.3 (46)	53.4 (32)	78.8 (32)	60.5 (40)	84.5 (30)

* # - number of analyses

** n.d. - not determined.

*** b.d. - below detection limit

APPENDIX 2

TABLE A2-1a: Bulk major-, minor-, trace-, and REE concentrations (ppm) for lunar meteorite clasts.

TABLE 12. La: Dark major, minor, trace, and REE concentrations (ppm) for lunar meteorite clasts.

	Dh-025									
	Clast 1	Clast 2	Clast 3	Clast 4	Clast 5	Clast 6	Clast 7	Clast 8	Clast 10	
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.	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)	

b.d. - below detection

* Errors are 1σ due to counting statistics.

** It should be noted that concentrations in bold/italics have larger than normal errors.

TABLE A2-1b: Continued.

	Dh-081									
	Clast 1	Clast 2	Clast 3	Clast 4	Clast 5	Clast 6	Clast 7	Clast 8	Clast 9	Clast 10
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)**	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)**	0.081 (6)	0.037 (8)

b.d. - below detection

* Errors are 1σ due to counting statistics.

** It should be noted that concentrations in bold/italics have larger than normal errors.

TABLE A2-1c: Continued.

	DaG 262									
	Clast 1	Clast 2	Clast 3	Clast 4	Clast 5	Clast 6	Clast 7	Clast 8	Clast 10	Clast 11
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)
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)

b.d. - below detection

* Errors are 1σ due to counting statistics.

** It should be noted that concentrations in bold/italics have larger than normal errors.

TABLE A2-1d: Continued.

	DaG 400						
	Clast 1	Clast 2	Clast 3	Clast 4	Clast 5	Clast 6	Clast 7
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)**	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)

b.d. - below detection

* Errors are 1σ due to counting statistics.

** It should be noted that concentrations in bold/italics have larger than normal errors.

TABLE A2-1e: Continued.

		Dh-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
Mg		1493	44738	69322	80415	59934	1556	56090	28209	62840
Si		233500	233500	233500	233500	233500	233500	233500	233500	233500
K		213	198	406	506	426	203	1045	493	504
Ca		120876	114124	102425	104938	103090	124184	106375	117260	100072
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
Fe		2193	15758	58428	95748	82535	1316	52832	40199	82900
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

		Dh-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
Mg		537	22828	41195	31604	482	597	43982	363	24407	18867
Si		233500	233500	233500	233500	233500	233500	233500	233500	233500	233500
K		97.7	158	162	113	80.7	62.6	176	92.3	197	194
Ca		125580	119971	115054	122959	123861	125633	112336	124133	114257	117768
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
Fe		3005	36583	102271	40574	2146	1976	47082	1783	27447	27721
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

Errors are 1σ due to counting statistics.

TABLE A2-1f: Continued.

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
Mg	41339	34455	34848	291359	36614	39076	10955	35276	26535	7380
Si	233500	233500	233500	233500	233500	233500	233500	233500	233500	233500
K	602	694	531	204	432	558	394	664	459	707
Ca	115611	117781	115849	36364	112048	112864	121198	120995	115110	133695
Sc	15	18	16	11	19	21	5.9	16	13	14
Ti	792	1043	879	420	1207	1400	48	1650	748	1523
Fe	37904	35041	29772	209957	35625	39214	4423	34756	20899	5685
Sr	n.r.	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.

DaG 400							
	Clast 1	Clast 2	Clast 3	Clast 4	Clast 5	Clast 6	Clast 7
Na	2232	3285	1753	2517	643	3701	2745
Mg	71560	31280	192413	39755	129804	49607	5852
Si	233500	233500	233500	233500	233500	233500	233500
K	926	895	824	497	368	1669	1166
Ca	98805	113202	65228	112695	37778	78259	113257
Sc	22	19	8.7	20	10	34	5.6
Ti	1293	1273	303	1342	941	4659	924
Fe	62297	37333	78239	41179	35263	83965	21127
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.

n.r. - values not reported due to probable terrestrial contamination. See Floss and Crozaz, 2001.

Errors are 1σ due to counting statistics.

TABLE A2-2a: Major-, minor-, trace-, and REE concentrations (ppm) of Dh-025 lunar highlands plagioclase.

	Dh-025											
	AA	AB	AF	AI	108b	AE	AG	BA	BB	BD	BH	BL
La	0.68 (8)*	0.77 (6)	1.52 (7)	0.49 (4)	1.06 (8)	2.31 (16)	2.14 (12)	0.82 (8)	0.31 (4)	1.76 (8)	1.39 (9)	0.84 (6)
Ce	1.69 (18)	2.32 (13)	4.13 (15)	1.15 (7)	2.35 (18)	5.96 (35)	5.97 (30)	1.91 (11)	0.82 (8)	4.18 (20)	3.75 (24)	2.89 (15)
Pr	0.21 (3)	0.32 (2)	0.54 (2)	0.16 (2)	0.29 (3)	0.68 (4)	0.70 (5)	0.31 (3)	0.10 (2)	0.56 (4)	0.45 (4)	0.37 (2)
Nd	0.85 (7)	1.38 (5)	2.18 (6)	0.62 (4)	1.11 (7)	2.33 (13)	2.97 (11)	1.00 (6)	0.42 (4)	2.25 (8)	2.11 (11)	1.60 (7)
Sm	0.15 (4)	0.38 (6)	0.57 (5)	0.20 (3)	0.20 (4)	0.53 (7)	0.52 (6)	0.17 (4)	0.10 (4)	0.52 (5)	0.63 (9)	0.50 (5)
Eu	0.84 (5)	0.77 (4)	0.89 (4)	0.85 (4)	0.72 (5)	1.09 (7)	0.87 (5)	0.74 (5)	0.70 (4)	0.74 (4)	0.77 (5)	0.85 (3)
Gd	0.11 (5)	0.49 (5)	0.61 (7)	0.13 (3)	0.20 (5)	0.58 (10)	0.37 (8)	0.14 (5)	0.11 (4)	0.55 (7)	0.54 (10)	0.63 (6)
Tb	0.021 (9)	0.070 (11)	0.10 (1)	0.015 (6)	0.017 (9)	0.076 (19)	0.057 (13)	0.024 (1)	0.029 (10)	0.10 (1)	0.13 (2)	0.10 (1)
Dy	0.092 (20)	0.49 (3)	0.66 (3)	0.13 (2)	0.087 (20)	0.43 (4)	0.36 (3)	0.095 (21)	0.13 (3)	0.66 (4)	0.90 (7)	0.69 (4)
Ho	0.019 (9)	0.11 (1)	0.11 (1)	0.023 (6)	0.028 (9)	0.063 (13)	0.086 (11)	0.018 (7)	0.013 (7)	0.15 (2)	0.16 (2)	0.14 (1)
Er	0.052 (18)	0.29 (3)	0.36 (2)	0.035 (13)	0.051 (18)	0.25 (4)	0.18 (2)	0.081 (20)	0.056 (20)	0.33 (3)	0.46 (5)	0.36 (3)
Tm	0.0055 (58)**	0.050 (11)	0.059 (9)	b.d.	b.d.	0.030 (15)	b.d.	b.d.	b.d.	0.063 (11)	0.042 (17)	0.04 (1)
Yb	0.031 (24)	0.29 (4)	0.31 (3)	0.046 (19)	0.040 (24)	0.17 (4)	0.11 (3)	0.092 (30)	b.d.	0.34 (3)	0.39 (7)	0.30 (4)
Lu	b.d.	0.024 (9)	0.051 (8)	b.d.	b.d.	b.d.	b.d.	b.d.	0.0055 (80)**	0.05 (1)	b.d.	0.042 (11)

b.d - below detection

* Errors are 1 σ due to counting statistics.

** It should be noted that concentrations in bold/italics have larger than normal errors.

TABLE A2-2b: Continued.

	Dh-081					
	AE	C	F	H	L	V
La	0.23 (3)*	0.32 (3)	0.19 (2)	0.13 (1)	0.13 (2)	0.094 (15)
Ce	0.63 (7)	0.81 (6)	0.44 (4)	0.30 (3)	0.35 (4)	0.19 (3)
Pr	0.10 (1)	0.13 (1)	0.054 (12)	0.034 (7)	0.05 (1)	0.043 (9)
Nd	0.41 (4)	0.38 (3)	0.26 (3)	0.17 (2)	0.19 (3)	0.094 (18)
Sm	0.076 (31)	0.10 (3)	b.d.	b.d.	b.d.	b.d.
Eu	0.71 (5)	0.72 (3)	0.79 (5)	0.60 (3)	0.61 (4)	0.60 (4)
Gd	0.074 (27)	0.14 (3)	0.034 (26)	0.038 (16)	0.032 (19)	b.d.
Tb	0.007 (6)	0.016 (7)	0.0092 (75)	0.0073 (43)	b.d.	0.0025 (37)**
Dy	0.034 (14)	0.12 (2)	0.035 (18)	0.039 (11)	0.020 (10)	b.d.
Ho	0.0059 (50)**	0.027 (8)	b.d.	0.016 (5)	b.d.	0.0023 (34)**
Er	0.012 (13)**	0.037 (14)	0.0082 (142)**	0.028 (11)	b.d.	0.0039 (77)**
Tm	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Yb	b.d.	0.021 (17)**	b.d.	b.d.	b.d.	b.d.
Lu	b.d.	0.0014 (55)**	b.d.	b.d.	b.d.	b.d.

b.d. - below detection

* Errors are 1σ due to counting statistics.

** It should be noted that concentrations in bold/italics have larger than normal errors.

TABLE A2-2c: Continued.

	DaG 262			DaG 400		
	1	2	3	1	2	3
La	0.76 (4)	0.38 (3)	0.29 (3)	0.80 (5)	0.51 (4)	0.95 (5)
Ce	2.04 (9)	1.04 (7)	0.67 (5)	1.88 (11)	1.33 (7)	2.26 (11)
Pr	0.25 (2)	0.12 (1)	0.10 (1)	0.26 (2)	0.17 (1)	0.30 (2)
Nd	0.93 (5)	0.39 (3)	0.39 (3)	1.02 (5)	0.66 (3)	1.07 (4)
Sm	0.17 (3)	0.097 (24)	0.11 (3)	0.27 (4)	0.17 (2)	0.27 (3)
Eu	0.67 (3)	0.81 (8)	0.44 (6)	0.68 (4)	0.88 (4)	0.75 (3)
Gd	0.16 (3)	0.098 (23)	0.081 (23)	0.23 (4)	0.16 (3)	0.17 (3)
Tb	0.013 (6)	0.0062 (44)	0.012 (5)	0.025 (8)	0.025 (6)	0.026 (6)
Dy	0.11 (2)	0.093 (15)	0.077 (13)	0.14 (2)	0.13 (1)	0.13 (1)
Ho	0.017 (5)	0.051 (8)	0.036 (7)	0.033 (7)	0.035 (6)	0.033 (5)
Er	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.	0.011 (8)	b.d.	0.0051 (57)**
Yb	0.056 (19)	0.035 (21)	0.038 (19)	0.036 (19)	0.055 (19)	0.043 (15)
Lu	b.d.	b.d.	b.d.	b.d.	0.0051 (39)	b.d.

b.d. - below detection

* Errors are 1 σ due to counting statistics.

** It should be noted that concentrations in bold/italics have larger than normal errors.

TABLE A2-2d: Continued.

	Dh-025											
	AA	AB	AF	AI	108b	AE	AG	BA	BB	BD	BH	BL
Na	2420	1504	2363	1612	3361	4246	2961	2141	1746	2461	2193	3471
Mg	666	1410	986	732	727	721	714	619	769	816	1311	1226
Si	201744	201744	203145	203145	204079	204079	204079	205013	204079	203145	205480	205480
K	68	111	179	117	152	397	242	98	85	204	242	194
Ca	126789	129617	126143	125922	124663	121047	122414	126255	127081	130594	128096	125814
Sc	3.5	4.4	4.4	3.5	3.4	3.1	4.4	3.4	3.8	4.1	4.2	3.9
Ti	87	226	235	56	125	204	193	94	57	434	265	218
Fe	1437	2428	1978	1291	1054	1526	1501	1492	1512	1997	2528	2072
Sr	114	110	120	107	111	138	110	107	103	109	109	114
Y	0.5	3.6	3.6	0.7	0.6	2.2	1.8	0.8	0.7	3.7	4.3	3.7
Zr	0.3	6.7	7.3	0.3	0.2	3.0	10.9	0.6	1.0	14.8	11.1	8.5
Ba	6.0	5.8	12.5	5.0	8.7	27.0	16.6	7.0	2.5	13.7	10.9	7.4

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	Dh-081						DaG 262			DaG 400		
	AE	C	F	H	L	V	1	2	3	1	2	3
Na	2293	2471	2428	2240	2446	1996	2438	2998	3098	2713	3969	3418
Mg	472	667	418	886	1006	573	1162	3725	3425	925	446	1098
Si	203612	202678	206881	203612	203612	204546	205480	205480	205480	205480	205480	205480
K	74	66	128	58	86	53	143	288	263	515	301	494
Ca	123739	125963	123937	128879	124359	124199	125124	126984	107470	127627	131551	129481
Sc	3.9	3.6	2.9	3.5	3.2	4.2	3.4	4.4	3.2	3.0	3.4	4.0
Ti	36	82	28	32	56	21	80	68	90	118	62	171
Fe	1328	1294	1511	1615	1995	1511	1539	1667	1712	1092	1878	1224
Sr	104	115	111	103	100	104	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Y	0.4	0.7	0.4	0.2	0.3	0.2	0.6	0.5	0.5	0.9	0.8	0.7
Zr	0.2	0.3	0.2	0.7	0.2	0.1	1.0	2.1	2.9	0.4	0.2	0.3
Ba	4.1	4.4	8.5	3.1	3.8	2.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.r. - values not reported due to probable terrestrial contamination. See Floss and Crozaz, 2001.

Errors are 1 σ due to counting statistics.

TABLE A2-3a: Major-, minor-, trace-, and REE concentrations (ppm) of Dh-025, Dh-081, DaG 262, and DaG 400 pyroxene and olivine.

	Dh-025					
	108b	BM	ACB	108b	108b	BA
	opx	opx	pig	aug	aug	aug
La	0.14 (1)*	0.27 (4)	0.37 (5)	1.73 (13)	1.05 (9)	0.86 (9)
Ce	0.51 (4)	0.86 (11)	1.39 (14)	7.19 (40)	5.43 (32)	4.37 (35)
Pr	0.077 (12)	0.089 (21)	0.19 (2)	1.47 (12)	1.32 (10)	0.90 (8)
Nd	0.42 (3)	0.51 (6)	1.12 (8)	8.14 (36)	7.52 (35)	5.16 (31)
Sm	0.27 (4)	0.19 (6)	0.43 (6)	3.74 (23)	3.65 (33)	2.25 (25)
Eu	0.0068 (45)	0.0032 (69)**	0.0024 (89)**	0.049 (21)	0.056 (24)	0.0003 (215)**
Gd	0.51 (5)	0.44 (9)	0.83 (11)	4.69 (47)	4.98 (44)	3.60 (47)
Tb	0.14 (1)	0.13 (2)	0.19 (2)	0.97 (8)	1.21 (11)	0.70 (12)
Dy	1.04 (5)	1.10 (9)	1.61 (10)	6.57 (31)	6.66 (32)	4.57 (35)
Ho	0.25 (2)	0.33 (4)	0.33 (3)	1.52 (12)	1.44 (9)	0.96 (12)
Er	0.97 (5)	1.19 (8)	1.24 (7)	4.03 (22)	3.83 (20)	3.18 (24)
Tm	0.13 (1)	0.18 (2)	0.24 (3)	0.47 (5)	0.46 (5)	0.37 (5)
Yb	1.05 (6)	1.38 (14)	1.16 (11)	2.71 (25)	2.98 (23)	2.23 (27)
Lu	0.19 (2)	0.25 (3)	0.23 (3)	0.41 (6)	0.44 (7)	0.32 (8)

b.d. - below detection

* Errors are 1 σ due to counting statistics.

** It should be noted that concentrations in bold/italics have larger than normal errors.

TABLE A2-3b: Continued.

	Dh-025		Dh-081	DaG 262		DaG 400
	BH aug	BL aug	F opx	1 aug	2 opx	1 ol
La	0.92 (9)	0.98 (9)	0.028 (6)	0.71 (9)	b.d.	b.d.
Ce	4.55 (29)	3.99 (29)	0.093 (14)	3.47 (33)	b.d.	b.d.
Pr	1.00 (8)	0.83 (7)	0.026 (6)	0.89 (9)	b.d.	b.d.
Nd	5.34 (23)	4.67 (23)	0.21 (2)	5.79 (31)	b.d.	b.d.
Sm	2.90 (25)	2.42 (16)	0.19 (3)	2.64 (29)	b.d.	b.d.
Eu	0.063 (30)	0.082 (15)	0.008 (4)	0.030 (58)**	b.d.	b.d.
Gd	4.34 (35)	3.21 (38)	0.32 (6)	6.26 (58)	b.d.	b.d.
Tb	0.91 (7)	0.61 (7)	0.086 (12)	1.21 (12)	0.056 (7)	b.d.
Dy	6.05 (25)	5.45 (28)	0.93 (5)	7.59 (44)	0.60 (3)	b.d.
Ho	1.17 (9)	1.15 (11)	0.20 (2)	1.84 (16)	0.18 (2)	0.0086 (24)
Er	3.80 (16)	3.53 (19)	0.82 (5)	5.96 (34)	0.72 (3)	0.029 (5)
Tm	0.45 (4)	0.47 (4)	0.12 (2)	0.96 (10)	0.12 (1)	0.0053 (21)
Yb	2.63 (22)	2.49 (25)	1.01 (9)	7.06 (64)	0.80 (7)	0.082 (14)
Lu	0.37 (5)	0.41 (6)	0.19 (3)	1.10 (16)	0.19 (2)	0.0082 (30)

b.d. - below detection

* Errors are 1 σ due to counting statistics.

** It should be noted that concentrations in bold/italics have larger than normal errors.

TABLE A2-3c: Continued.

	Dh-025			Dh-025			Dh-081		DaG 262		DaG 400	
	108b opx	BM opx	ACB pig	108b aug	108b aug	BA aug	BH aug	BL aug	F opx	1 aug	2 opx	1 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
Si	253581	256383	248444	231165	239571	239571	240972	239571	248911	233500	242840	163450
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.	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.

n.r. - values not reported due to probable terrestrial contamination. See Floss and Crozaz, 2001.

Errors are 1 σ due to counting statistics.

VITA

Joshua Timothy Cahill was born on September 16, 1978, in Tampa, Florida. At the age of one, Josh's family moved around the mid-west before finally settling in Richmond, Kentucky. It was here that Josh's competitiveness and work ethic were instilled through this ultra-competitive brother and various athletic teams. Through all this, swimming was the one constant family activity and tradition. From age 4 to 18, his father was his one and only enduring coach. Many life lessons began and ended at the dinner table discussing the sport of swimming. And because of his father's parent-like coaching philosophy, many teammates became part of the Cahill family.

The lessons and skills learned in these pursuits eventually overflowed into academics during high school at Model Laboratory High. At Model, Josh was diligent in his studies while also contributing his efforts to his father's high school swimming team. During his senior year, these efforts came to a climax with contributions towards Model's crowning as Combined State High School Champion and Josh being admitted to the University of Notre Dame.

At Notre Dame, Josh majored in Science-Business. Here he also became involved with environmental geoscience based research projects led by both Dr. Clive Neal and Dr. Jeremy Fein. And because of Dr. Neal, Josh was exposed to the realm of lunar geology, and subsequently enrolled at the University of Tennessee in Knoxville for a master's of science degree. There, under the direction of Dr. Larry Taylor, his research focused on the petrology and geochemistry of lunar and martian meteorites, and the

chemical characterization of lunar soils for remote sensing calibration. Josh is currently pursuing a doctorate in geology at the University of Tennessee.

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