

Petrography, mineralogy, and geochemistry of lunar meteorite Sayh al Uhaymir 300

Weibiao HSU^{1*}, Aicheng ZHANG¹, Rainer BARTOSCHEWITZ², Yunbin GUAN³, Takayuki USHIKUBO³,
Urs KRÄHENBÜHL⁴, Rainer NIEDERGESAEISS⁵, Rudolf PEPELNIK⁵, Ulrich REUS⁵,
Thomas KURTZ⁶, and Paul KURTZ⁶

¹Laboratory for Astrochemistry and Planetary Sciences, Lunar and Planetary Science Center, Purple Mountain Observatory,
2 West Beijing Road, Nanjing, 210008, China

²Bartoschewitz Meteorite Lab, Lehmweg 53, D-38518 Gifhorn, Germany

³Department of Geological Sciences, Arizona State University, Tempe, Arizona 85287, USA

⁴Abteilung für Chemie und Biochemie, Universität Bern, Freiestr. 3, CH-3012 Bern, Switzerland

⁵GKSS Forschungszentrum GmbH, Institut für Küstenforschung, Max-Planck-Strasse, D-21502 Geesthacht, Germany

⁶Henckellweg 25, D-30459 Hannover, Germany

*Corresponding author. E-mail: wbxu@pmo.ac.cn

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Abstract—We report here the petrography, mineralogy, and geochemistry of lunar meteorite Sayh al Uhaymir 300 (SaU 300). SaU 300 is dominated by a fine-grained crystalline matrix surrounding mineral fragments (plagioclase, pyroxene, olivine, and ilmenite) and lithic clasts (mainly feldspathic to noritic). Mare basalt and KREEPy rocks are absent. Glass melt veins and impact melts are present, indicating that the rock has been subjected to a second impact event. FeNi metal and troilite grains were observed in the matrix. Major element concentrations of SaU 300 (Al₂O₃ 21.6 wt% and FeO 8.16 wt%) are very similar to those of two basalt-bearing feldspathic regolith breccias: Calalong Creek and Yamato (Y-) 983885. However, the rare earth element (REE) abundances and pattern of SaU 300 resemble the patterns of feldspathic highlands meteorites (e.g., Queen Alexandra Range (QUE) 93069 and Dar al Gani (DaG) 400), and the average lunar highlands crust. It has a relatively LREE-enriched (7 to 10 × CI) pattern with a positive Eu anomaly (~11 × CI). Values of Fe/Mn ratios of olivine, pyroxene, and the bulk sample are essentially consistent with a lunar origin. SaU 300 also contains high siderophile abundances with a chondritic Ni/Ir ratio. SaU 300 has experienced moderate terrestrial weathering as its bulk Sr concentration is elevated compared to other lunar meteorites and Apollo and Luna samples. Mineral chemistry and trace element abundances of SaU 300 fall within the ranges of lunar feldspathic meteorites and FAN rocks. SaU 300 is a feldspathic impact-melt breccia predominantly composed of feldspathic highlands rocks with a small amount of mafic component. With a bulk Mg# of 0.67, it is the most mafic of the feldspathic meteorites and represents a lunar surface composition distinct from any other known lunar meteorites. On the basis of its low Th concentration (0.46 ppm) and its lack of KREEPy and mare basaltic components, the source region of SaU 300 could have been within a highland terrain, a great distance from the Imbrium impact basin, probably on the far side of the Moon.

INTRODUCTION

Since the discovery of the first three lunar meteorites in Antarctica in 1979, more than 50 unpaired lunar meteorites (total mass ~50 kg) have been recovered from hot and cold deserts (Korotev 2005; Korotev et al. 2008). Lunar meteorites are rocks ejected from the Moon by meteoroid impacts. The source craters of lunar meteorites are likely distributed randomly across the lunar surface. In comparison, Apollo and Luna samples were collected from a restricted area (covering only 5–8% of the lunar surface) on the near side of the Moon,

within and around the geochemically anomalous Procellarum KREEP Terrane (PKT) (Warren and Kallemeyn 1991; Jolliff et al. 2000). Therefore, lunar meteorites provide an important complementary source of data in understanding of the nature of the lunar crust and its evolution history. Lunar meteorites can be grouped into three types: 1) feldspathic breccias with high Al₂O₃ (25–30 wt%), low FeO (3–6 wt%), and low incompatible trace element concentrations (e.g., Th <1 ppm); 2) mare basalts with high FeO (18–22 wt%), moderately low Al₂O₃ (8–10 wt%) and incompatible trace element concentrations (Th 0.4–2.1 ppm); 3) “mingled” breccias

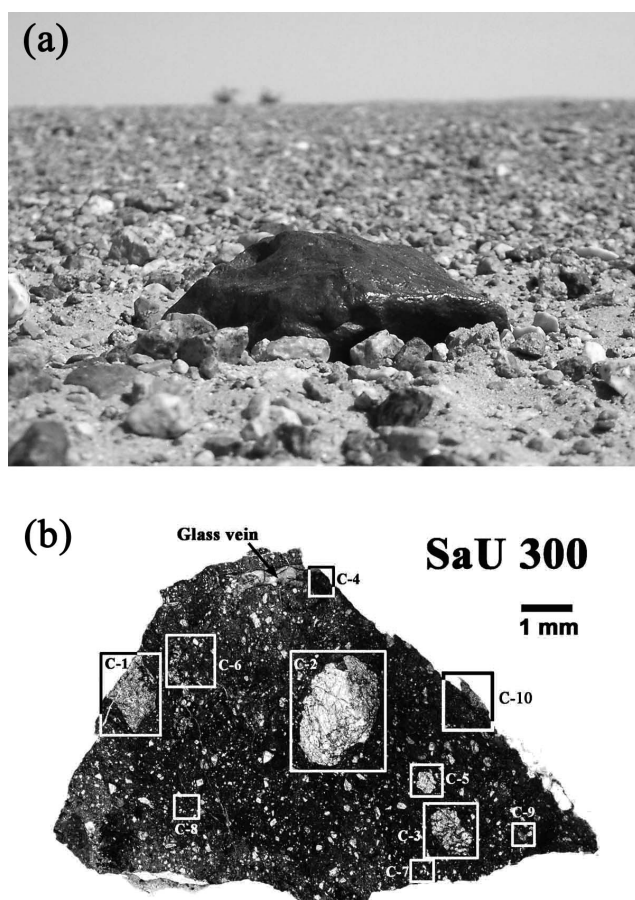


Fig. 1. a) Overview of SaU 300 in the desert. b) Microscopic view of SaU 300 in transmitted light. Various clasts and mineral fragments are embedded in the dark glassy matrix.

containing both feldspathic and basaltic clasts with compositions intermediate to the feldspathic and basaltic meteorites (Korotev 2005). Only a few lunar meteorites (e.g., Sayh al Uhaymir 169) contain elevated concentrations of K, REE, P, and other incompatible elements (typically referred to as KREEP). In contrast, Apollo and Luna samples commonly contain various amounts of KREEP-related rocks.

Sayh al Uhaymir (SaU) 300 was recovered from Oman in 2004. It is a single 152.6 g stone that has a rounded, flat shape and a light green color (Fig. 1a). The lunar origin of SaU 300 is indicated by its mineralogy and petrology (Hsu et al. 2007; Hudgins et al. 2007), and trace element geochemistry (Hsu et al. 2006, 2007; Korotev et al. 2007). It comprises a crystalline igneous matrix, dominated by feldspathic clasts and mineral fragments (plagioclase, olivine, and pyroxene). In this paper, we present a detailed mineralogical, petrological, and geochemical study of lunar meteorite SaU 300.

EXPERIMENTAL METHODS

We characterized the mineralogy, textures, and petrography of SaU 300 using optical and reflected light microscopy (Nikon E400POL) and scanning electron

microscopy (JEOL-845 and Hitachi S-3400N) on a polished thin section. Mineral chemistry was analyzed with electron microprobes (JEOL JXA-8800M at Nanjing University and JEOL 8100 at China University of Geosciences). Accelerating voltage was 15 keV with a focused beam current of 20 nA for silicate and oxide minerals, and 20 keV and 20 nA were used for metal and sulfide. Both synthetic (NBS) and natural mineral standards were used, and matrix corrections were based on ZAF procedures (Armstrong 1982). The rare earth element (REE) and trace element concentrations were measured in situ on individual grains of olivine, pyroxenes, plagioclase, apatite, and impact-melt glass with the Cameca-6f ion microprobe at Arizona State University, using procedures described in Hsu et al. (2004). An O^- primary ion beam of 1–4 nA was accelerated to -12.5 KeV. Secondary ions, offset from a nominal $+10$ KeV accelerating voltage by -100 eV, were collected in peak-jumping mode with an electron multiplier. Total counting time varied from ~ 30 min to ~ 2 h depending on the phase analyzed. Silicon and calcium were used as the reference elements for silicates and phosphates, respectively. NBS-610, NBS-612, synthetic titanium-pyroxene glass, and Durango apatite standards were measured periodically to account for any variation of ionization efficiencies caused by minor changes of operating conditions.

For instrumental neutron activation analysis (INAA), two samples were irradiated in the FRG-1 reactor of GKSS in Geesthacht and analyzed several times with HPGe-coaxial-detector. The obtained spectra were evaluated using the peak-fitting routine of Greim et al. (1976). One 0.030 g sample was irradiated for 2 min with a flux of 2×10^{13} n/cm²s and was counted 15, 150, and 600 min after irradiation for periods of 7, 40, and 180 min respectively, determining the elements Na, Mg, Al, Cl, K, Ti, V, Mn, Ga, Sr, Sm, Eu, and Dy. The second sample of 0.0305 g was irradiated for 3 days with a flux of 6.4×10^{13} n/cm²s and was counted 6, 12, and 26 days after irradiation with counting periods of 4, 6 and, 8 h, respectively, determining the elements Na, K, Ca, Sc, Cr, Fe, Co, Ni, Zn, As, Se, Br, Sr, Zr, Ru, Sb, Ba, La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Hf, Ta, Ir, Au, Th, and U.

A sample of 0.0301 g was digested for ICP-MS and TXRF at GKSS in Geesthacht by a mixture of concentrated high purity HNO₃ and HF (2:1) at 150 °C. The clear solution was evaporated to dryness, and the residue was dissolved in subboiled 6 M HCl. The resulting solution was measured by TXRF (Atomika 8030C) and a H₂O-diluted (1:10) solution by ICP-MS (Agilent 7500 c) for 15 and 48 elements, respectively.

An additional sample of 0.0563 g was run by ICP-OES and ICP-MS at the University of Bern. The digestion was performed using mixtures of concentrated high purity acids of HF, HNO₃ and HClO₄. For complete dissolution, the samples were heated by microwave excitation in Teflon pressure bombs. The resulting solutions were measured with ICP-OES and ICP-MS, respectively. Before the dissolution, the chunks of sample material were cleaned by their submerging into 4%

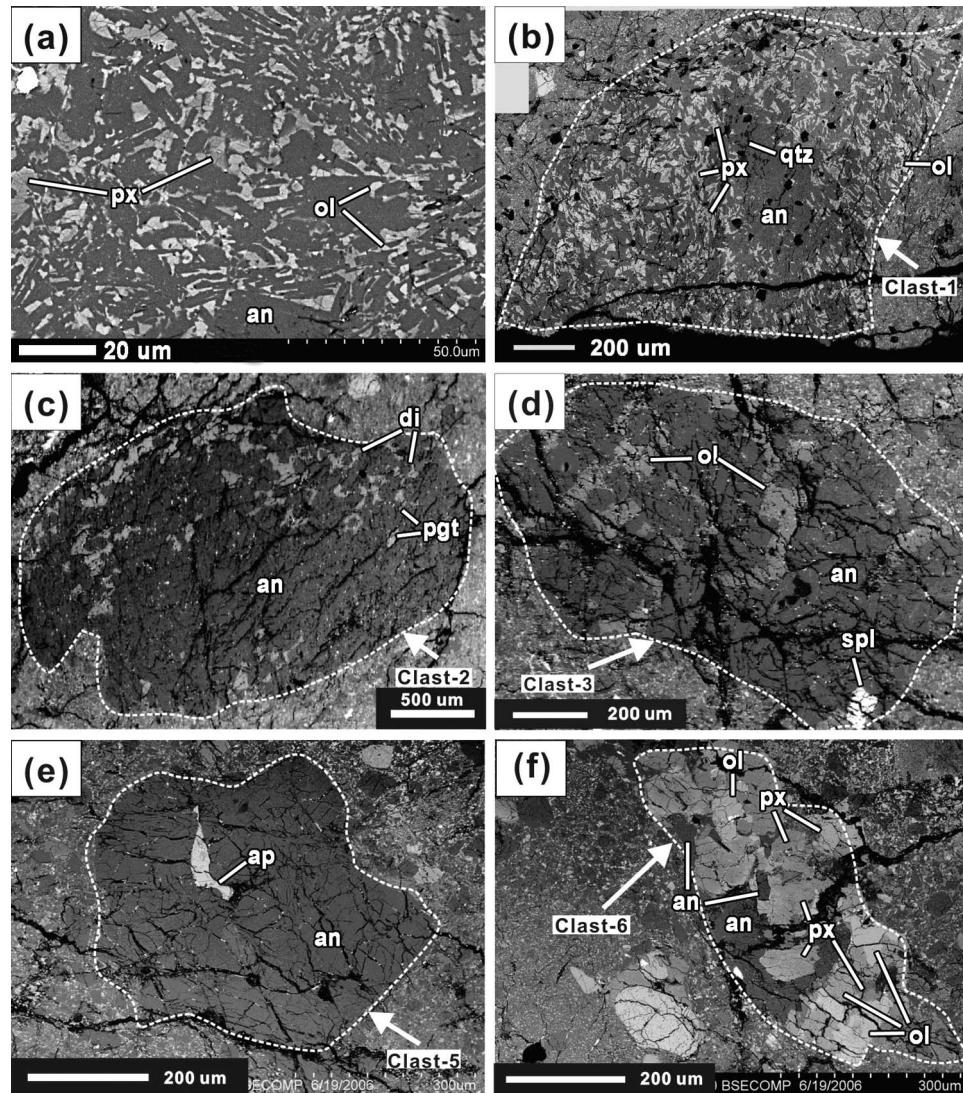


Fig. 2. Backscattered electron images of the matrix and representative lithic clasts in SaU 300. a) The matrix displays an igneous texture of euhedral anorthite intergrown with pyroxene and olivine. b) C-1 (Clast-1) exhibits a sub-ophitic texture. It contains euhedral anorthite (an) crystals and anhedral pyroxene (px) and olivine (ol) grains. Some silica (qtz) grains are present at the center of the clast. c) C-2 (Clast-2) shows a granoblastic texture. Pigeonite (pgt) and diopside (di) grains exhibit rounded grain boundaries. d) C-3 (Clast-3) also displays a granoblastic texture. Olivine grains are enclosed by anorthite grains. e) C-5 (Clast-5) consists mainly of anorthite grains with an apatite grain. f) C-6 (Clast-6) consists mainly of pyroxene grains with minor olivine and anorthite. Both pyroxene and olivine exhibit compositional heterogeneity.

HNO₃ for 2 min followed by washing with Milli-Q water and drying at 60 °C.

PETROGRAPHY AND MINERALOGY

SaU 300 is a polymict breccia predominantly composed of a fine-grained crystalline matrix surrounding abundant mineral fragments and a few lithic clasts (Fig. 1b). The matrix exhibits an igneous texture consisting of fine-grained (~20 μm) plagioclase, pyroxene, and olivine (Fig. 2a). Numerous mineral fragments (<100 μm) of plagioclase, pyroxenes, olivine, and ilmenite are set in the matrix. FeNi metal and troilite grains (a few μm to 400 μm) also occur in the matrix as individual grains. Both

feldspathic and mafic lithic clasts exhibit irregular or rounded shapes and range in size from several hundred microns to a few mm (Fig. 2). Modal abundances of some lithic clasts were determined on their backscattered electron images by image processing with a commercial software. They are listed in Table 1.

Feldspathic Clasts

Most lithic clasts (C-1, C-2, C-3, C-5, C-9, and C-10) are feldspathic, mainly consisting of plagioclase (75 to 99 vol%) with minor amounts of pyroxene (up to 23 vol%) and olivine (up to 13 vol%). Their compositions range from anorthositic to noritic anorthositic and anorthositic noritic.

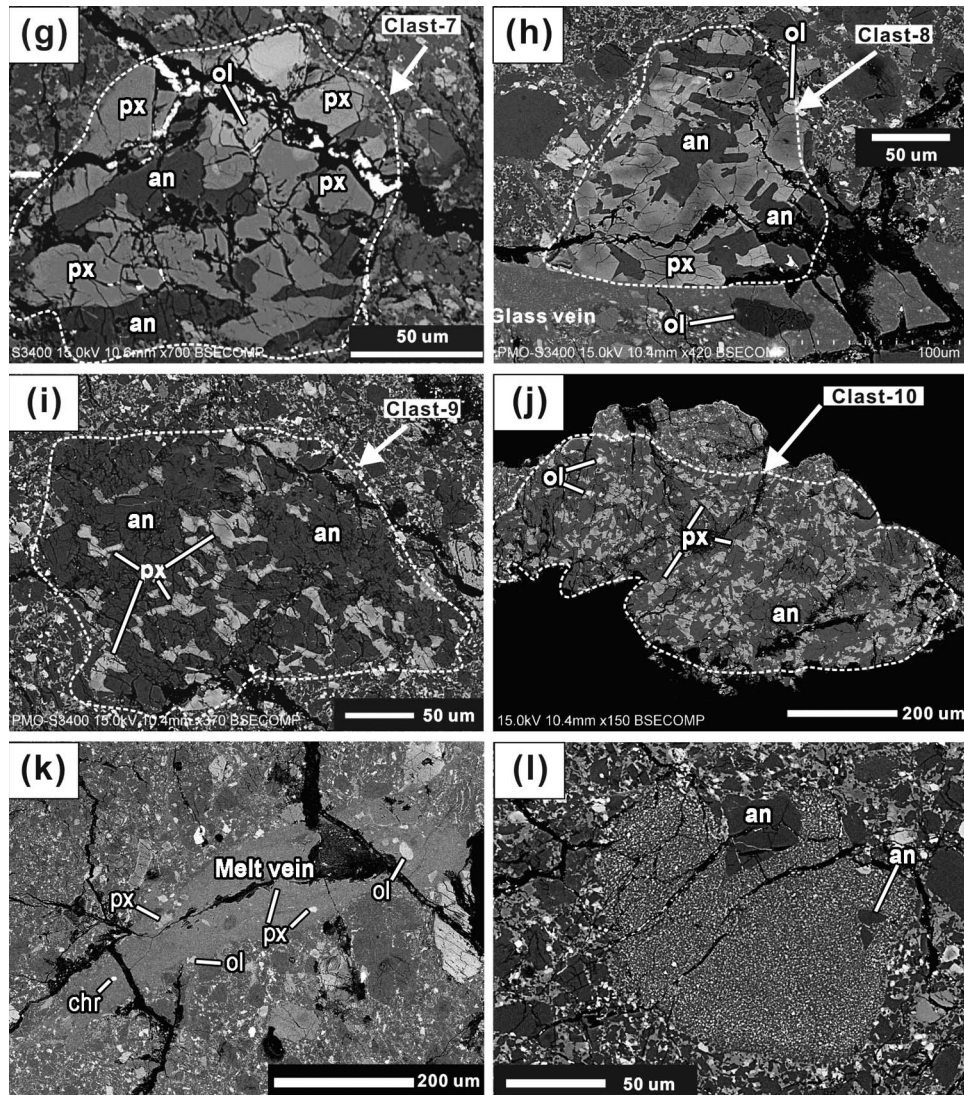


Fig. 2. *Continued.* Backscattered electron images of the matrix and representative lithic clasts in SaU 300. g) C-7 (Clast-7) shows an ophitic texture. The olivine grain is embraced by pyroxene grains. h) C-8 (Clast-8) displays an ophitic texture. It contains euhedral anorthite grains and anhedral pyroxene grains. i) C-9 (Clast-9) contains subhedral to euhedral anorthite grains and anhedral pyroxene grains. j) C-10 (Clast-10) displays a subophitic texture. Small olivine grains are commonly included by pyroxene grains. k) Relict mineral grains of olivine, pyroxenes, and chromite (chr) are visible in the melt vein. l) Glassy impact melts are commonly devitrified and contain finely crystalline grains of plagioclase and pyroxene.

These clasts exhibit either ophitic/sub-ophitic (Figs. 2b and 2j) or granulitic textures (Figs. 2c, 2d, and 2i). Plagioclase shows a small compositional range (An_{94-98}) among these clasts (Table 2). The variation is even smaller ($<1\%$) within the granulitic clasts C-3 and C-9 (Fig. 3). Olivine shows a small intergrain compositional variation (Fo_{61-66}) within C-1, but is essentially homogeneous (Fo_{81-82}) within C-3 (Table 3 and Fig. 4). Pyroxene has a relatively low Ca content and shows a considerable intergrain variation in composition (see Table 4 and Fig. 5). C-2 also contains some high-Ca pyroxene ($Wo_{31-40}En_{48-54}Fs_{12-15}$) (Fig. 5). The Mg# (molar $Mg/[Mg + Fe]$) of pyroxene ranges from 0.63 to 0.74.

C-5 is a rounded lithic clast about 0.4×0.6 mm in size (Fig. 2e). It is predominantly composed of plagioclase grains.

Plagioclase grains (An_{97}) are subhedral to euhedral and about 100 to 300 μm in size. There is an elongated apatite grain (30×150 μm) present in the clast. C-5 is distinctive from all other lithic clasts in this meteorite. Its plagioclase is highly anorthositic (An_{97}), similar to Apollo ferroan anorthosite (FAN) rocks, and it contains phosphate. FAN rocks generally do not contain phosphate, but Apollo alkali anorthosites do. Alkali anorthosites tend to be more sodic than FAN and were only found at the Apollo 12 and 14 landing sites within the PKT.

Mafic Clasts

Mafic clasts (C-6, C-7, and C-8) are also present in SaU 300. They are mainly composed of pyroxene (52–58 vol%)

Table 1. Modal abundance (vol%) of some clasts in SaU 300.

	Clast-1	Clast-2	Clast-3	Clast-5	Clast-6	Clast-7	Clast-8	Clast-9	Clast-10
Olivine	3		12.7		16	5.5	0.5		0.2
Plagioclase	79	91	86.5	98.5	30.5	36.5	44.5	85	76.5
Pyroxene	16.5	9			52.5	58	55	15	23.3
Silica	0.5								
Phosphate				1.5					
Opaque minerals	1		0.8		1				

Table 2. Representative electron microprobe analyses (wt%) of plagioclase in SaU 300.

	Clast-1		Clast-2	Clast-5	Clast-6	Clast-7	Clast-8	Clast-9		Clast-10		Fragment		
SiO ₂	43.38	43.83	43.74	43.56	44.66	46.23	44.81	44.12	44.98	44.58	43.60	44.72	45.19	45.12
TiO ₂	0.03	0.03	0.03	0.03	0.04	0.02	0.04	0.03	bd	0.33	0.02	0.07	0.02	0.06
Al ₂ O ₃	36.00	35.55	36.79	36.42	35.85	33.10	35.23	35.51	35.91	32.87	34.91	34.41	34.71	35.41
MgO	0.08	0.06	0.10	0.36	0.26	0.20	0.06	0.09	0.08	1.33	0.09	0.19	0.19	0.11
FeO	0.27	0.49	0.08	0.28	1.09	0.64	0.37	0.44	0.41	1.38	0.36	0.33	0.38	0.27
CaO	19.26	19.25	18.98	19.29	17.92	18.07	18.11	19.09	19.34	18.08	19.40	18.86	18.90	18.58
Na ₂ O	0.49	0.32	0.46	0.28	0.39	0.29	0.56	0.29	0.23	0.49	0.34	0.39	0.35	0.36
K ₂ O	0.03	0.02	0.02	0.02	bd	bd	0.10	0.05	0.04	0.06	0.04	bd	bd	0.05
Total	99.54	99.55	100.2	100.3	100.2	98.58	99.30	99.62	101.0	98.63	98.42	99.00	99.74	99.96
Ab	5	3	4	3	4	3	5	3	2	5	3	4	3	3
An	95	97	96	97	96	97	94	97	98	95	97	96	97	96
Or	<1	<1	<1	<1	bd	bd	1	<1	<1	<1	<1	bd	bd	<1

bd: below detection limit.

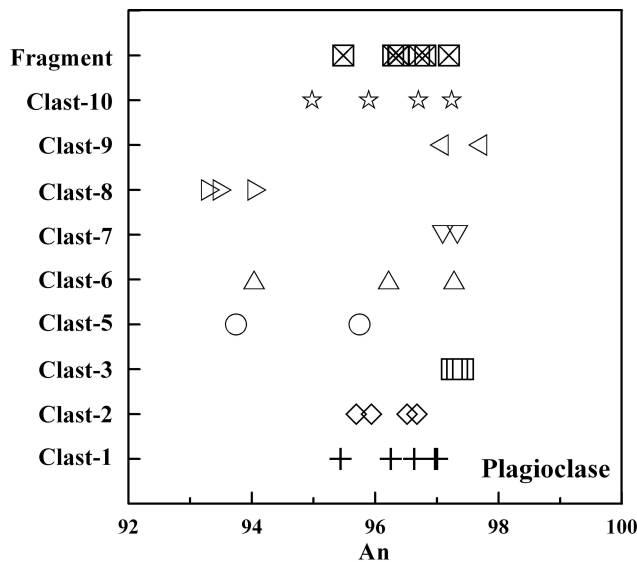


Fig. 3. Variation in An content for plagioclase in lithic clasts and fragments in SaU 300.

and plagioclase (30–45 vol%) with minor olivine (0.5–16 vol%) (Table 1). Their compositions range from noritic to olivine noritic. They exhibit ophitic or sub-ophitic textures (Fig. 2b and 2g). Pyroxene grains are anhedral to euhedral and vary in size from 10 to 100 μm . They are mostly low-Ca pyroxene (Table 4 and Fig. 5). The Mg# of pyroxene ranges from 0.52 to 0.77. Plagioclase grains are homogeneous in C-7 (An_{97}) and C-8 (An_{93-94}) but show a small compositional variation (An_{94-97}) in C-6 (Fig. 3). Olivine is relatively

homogeneous (Fo_{58-60}) within a given clast but shows a small compositional variation among different clasts (Fo from 58 to 73).

Mineral Fragments

Mineral fragments embedded in the matrix of SaU 300 include plagioclase, olivine, and pyroxene. Plagioclase fragments range in size from a few microns to several hundred microns and are anhedral to subhedral in shape. Plagioclase displays a small intergrain compositional variation (An_{95-97}) (Fig. 3). Olivine fragments vary in size from a few microns to several hundred microns and are anhedral in shape. Olivine exhibits a wide compositional range (Fo_{43-91}). Most grains are in the range of Fo_{60-75} (Fig. 4). The molar Fe/Mn ratio of olivine grains varies from 69 to 118, with an average of 90. One olivine fragment displays chemical zoning from Fo_{86} at the core to Fo_{73} at the rim. Pyroxene fragments vary in size from a few microns to several hundred microns and are anhedral to euhedral in shape. Both low-Ca and high-Ca pyroxene fragments were observed. Low-Ca pyroxene fragments have a compositional range of $\text{Wo}_{4-18}\text{En}_{43-76}\text{Fs}_{21-39}$, whereas high-Ca pyroxene fragments have a range of $\text{Wo}_{24-40}\text{En}_{33-46}\text{Fs}_{17-37}$. The Mg#s of low-Ca and high-Ca pyroxenes vary between 0.52 and 0.79 and between 0.47 and 0.71, respectively. The molar Fe/Mn ratio of pyroxene fragments varies from 41 to 70, with an average of 51. In one analyzed grain containing lamellae (μm -sized), the pyroxene host had a composition of $\text{Wo}_4\text{En}_{59}\text{Fs}_{37}$ and the lamellae were rich in Ca ($\text{Wo}_{34}\text{En}_{46}\text{Fs}_{20}$). Ilmenite fragments are commonly subhedral

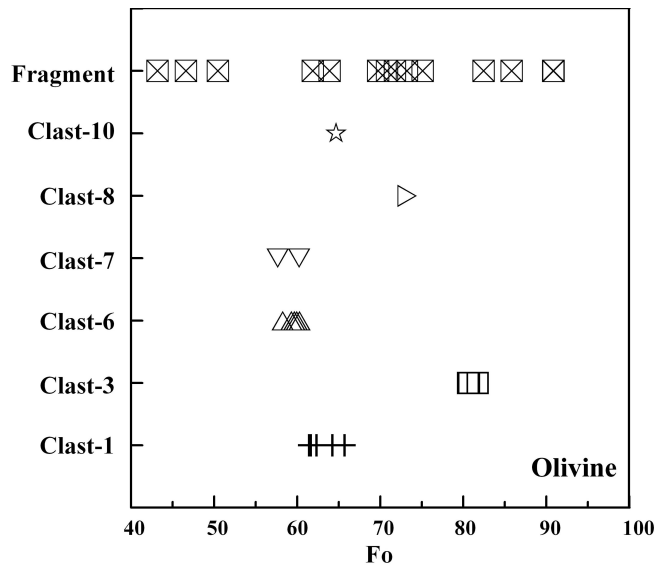


Fig. 4. Variation in Fo content for olivine in lithic clasts and fragments in SaU 300.

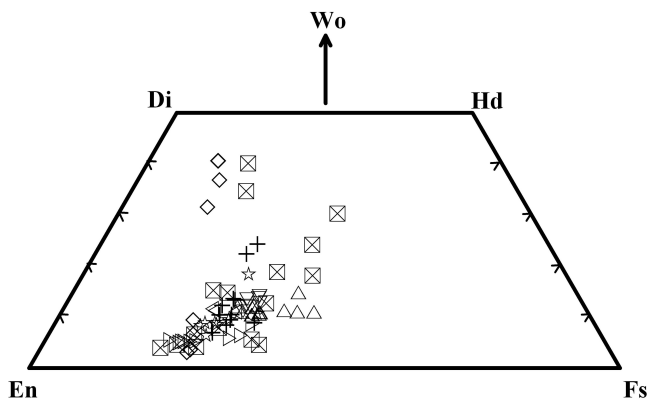


Fig. 5. Compositions of pyroxene in different lithic clasts and fragments of SaU 300. Symbols are the same as in Fig. 3 and Fig. 4.

to euhedral in shape and vary from 20 to 60 μm in size. They contain high MgO contents (6.99–7.27 wt%) (Table 5). Chromite fragments are more abundant than ilmenite fragments. Chromite grains are usually euhedral in shape and vary in size from 20 to 60 μm . Chemically, chromite fragments always contain various amounts of spinel (18 to 47 %) and ulvöspinel (3 to 25 %) (Table 5). A few metal grains with irregular shapes occur in the thin section. They range in size from several microns up to 400 μm . Electron microprobe analyses show that most metal grains are FeNi alloys (Ni 5.24–16.04 wt%) and a few grains are composed of only Fe (Table 6). One large FeNi alloy shows two sets of exsolution lamellae. The lighter lamellae contain a higher Ni content (16.04 wt%) than the host (6.24 wt%). Troilite grains are rare. They usually coexist with FeNi alloy. They vary in size from several microns to about 60 μm .

Mafic minerals in rocks from the Earth, Moon, Mars, and asteroids have distinct Fe to Mn ratios (Papike 1998). The Fe/

Mn ratio can be used to identify parent bodies for meteorites. Our mineral chemistry data support a lunar origin for SaU 300. Fig. 6 shows Fe/Mn ratios of olivines and pyroxenes in SaU 300. Olivine data generally plot along the lunar trend (Fig. 6a), but pyroxenes appear to have Mn slightly elevated above the lunar trend (Fig. 6b). Similar elevated Mn concentrations above the lunar trend (Fe/Mn ratios of 50 to 52) was also observed in pyroxene in lunar highlands meteorites Dhofar (Dho) 025 and Dho 081 (Cahill et al. 2004). Cahill et al. (2004) suggested that the observed variations in pyroxene are due to the difference in lithologies studied among various works (Papike 1998). It is also possible that the full suite of lunar rocks is more variable than the subset plotted by Papike (1998).

Melt Glass

Several glass veins cut across the section (Fig. 1b and Fig. 2k). Glassy impact melt is also present (Fig. 2l). Glassy impact melts are commonly devitrified and contain finely crystalline plagioclase and pyroxene grains. The largest glass vein is about 250 μm wide and 1 mm long. Veins commonly contain relict grains of plagioclase, olivine, pyroxene, chromite, and partially digested lithic fragments (Fig. 2k). A defocused electron beam ($\sim 20 \mu\text{m}$) was used to determine the chemical compositions of glass in inclusion-free areas. The results are listed in Table 7, together with their CIPW normative compositions. Compositions vary within a vein and between different veins (Al_2O_3 22.2–27.8 wt%, MgO 5.2–7.8 wt%, and FeO 5.3–8.1 wt%). Mg# of glasses ranges between 0.59 and 0.66. All glasses are Ca-rich but alkali-poor. CaO content ranges from 13.9 to 15.7 wt%. Na_2O content ranges from 0.16 to 0.40 wt% and K_2O content is very low (0.03 to 0.08 wt%), close to the detection limit. Molar $\text{Ca}/(\text{Ca} + \text{Na} + \text{K})$ ratios of glasses are ~ 0.96 . The bulk glass composition in terms of its molar $\text{Ca}/(\text{Ca} + \text{Na} + \text{K})$ and Mg# suggests an affinity to the noritic anorthosite. Based on CIPW norm calculations, glasses were determined to be plagioclase-rich, with 60 to 75% normative anorthite. Most analyses are also olivine normative. The average Fe/Mn ratio for glasses is 75, close to the bulk ratio of 71 (see bulk composition section).

Affinities to FAN and HMS Suite Rocks

On an Mg# versus An content plot, plagioclase and coexisting mafic minerals (in lithic clasts) generally fall within the distinct FAN and high magnesium suite (HMS) regions (Warren 1985). Clasts 1, 2, 3, 9, and 10 are highly feldspathic with more than 75 vol% of plagioclase. Clasts 1, 9, and 10 fall within the FAN region on the plot, whereas Clasts 2 and 3 plot close to the HMS area with higher Mg# (~ 0.80) than typical Apollo FAN rocks (Fig. 7). Rocks that plot within the FAN-HMS gap were classified as “lunar granulites” in previous investigations (e.g., Bickel and Warner 1978; Norman 1981; Lindstrom and Lindstrom

Table 3. Representative electron microprobe analyses (wt%) of olivine in SaU 300.

	Clast-1		Clast-3		Clast-6		Clast-7		Clast-8		Clast-10		Fragment	
SiO ₂	36.55	35.22	39.18	39.10	36.27	35.9	36.16	36.13	38.24	36.17	33.45	38.28	41.31	
TiO ₂	0.06	0.07	bd	0.03	0.05	bd	0.03	bd	0.04	0.09	0.05	0.06	0.03	
Al ₂ O ₃	0.04	0.07	0.05	0.06	bd	0.02	0.03	0.07	0.10	0.09	bd	0.04	bd	
Cr ₂ O ₃	0.12	0.16	0.02	0.04	0.10	0.10	0.14	0.14	0.11	0.18	0.10	0.05	0.07	
FeO	32.74	31.64	17.00	18.42	35.88	34.16	36.2	32.82	24.53	30.15	46.23	21.09	9.00	
MnO	0.40	0.33	0.13	0.20	0.40	0.40	0.46	0.40	0.28	0.33	0.46	0.22	0.08	
MgO	28.96	31.57	42.25	42.39	27.81	28.38	27.38	27.61	37.31	30.66	19.52	40.41	50.26	
CaO	0.28	0.33	0.08	0.07	0.17	0.25	0.28	0.25	0.24	0.3	0.45	0.13	0.15	
P ₂ O ₅	bd	0.12	0.02	bd	0.02	bd	bd	bd	0.10	0.13	0.02	bd	bd	
Total	99.15	99.51	98.73	100.3	100.7	99.21	100.7	97.42	100.9	98.06	100.3	100.3	100.9	
Fo	61	64	82	81	58	60	58	60	73	65	43	78	91	

bd: below detection limit.

Table 4. Representative electron microprobe analyses (wt%) of pyroxene in SaU 300.

	Clast-1		Clast-2		Clast-6		Clast-7		Clast-8		Clast-9		Clast-10		Fragment	
SiO ₂	51.85	51.44	53.19	49.89	49.86	51.92	52.55	53.53	53.62	52.49	52.94	51.7	52.11	51.18	51.19	50.25
TiO ₂	0.42	0.55	0.84	1.64	0.29	0.39	0.19	0.25	0.27	0.65	0.31	0.36	0.25	0.71	0.31	0.71
Al ₂ O ₃	2.39	1.74	0.81	1.98	0.98	1.58	1.50	2.15	1.38	1.26	1.54	1.95	2.64	2.01	0.94	2.28
Cr ₂ O ₃	0.82	0.80	0.28	0.71	0.45	0.53	0.83	0.73	0.80	0.37	0.84	0.84	0.80	0.57	0.46	0.89
FeO	18.65	16.33	15.64	7.37	26.04	19.58	19.05	18.39	15.10	20.24	16.11	18.41	16.73	16.83	23.12	11.99
MnO	0.34	0.33	0.36	0.17	0.52	0.42	0.34	0.37	0.26	0.44	0.33	0.28	0.24	0.28	0.43	0.24
MgO	22.00	18.28	24.29	16.38	15.60	20.68	19.54	17.21	25.53	20.85	22.35	20.63	23.00	17.81	20.51	15.57
CaO	3.93	10.75	3.05	19.21	4.99	5.22	5.65	5.90	2.40	2.87	5.53	5.13	2.85	8.31	2.02	16.17
Na ₂ O	0.01	0.05	0.02	0.04	0.07	bd	bd	0.04	0.02	0.03	bd	bd	0.03	0.09	bd	0.03
Total	100.3	100.3	98.49	97.39	98.80	100.4	99.65	98.57	99.38	99.20	99.95	99.30	98.62	97.70	98.98	98.13
En	63	52	69	48	46	59	57	54	72	61	63	60	54	41	59	46
Fs	29	26	25	12	43	31	31	32	24	33	25	30	39	39	37	20
Wo	8	22	6	40	11	11	12	13	5	6	11	11	7	19	4	34

bd: below detection limit.

Table 5. Representative electron microprobe analyses (wt%) of oxide minerals and apatite in SaU 300.

	Clast-3		Clast-6	Fragment				Clast-5
SiO ₂	bd	0.37	0.30		bd	bd		0.49
TiO ₂	1.35	1.97	2.88	9.6	1.1	56.66	54.37	0.02
Al ₂ O ₃	39.15	30.95	13.51	8.9	21.5	0.04	bd	0.08
Cr ₂ O ₃	27.14	32.81	45.43	41.6	33.0	0.29	0.23	
FeO	18.53	19.53	30.70	36.1	36.5	36.20	38.00	0.24
MnO	0.25	0.24	0.37			0.41	0.43	
MgO	12.26	10.63	3.93	3.9	7.9	6.99	7.27	0.28
CaO	0.07	0.15	0.08			0.10	0.09	56.20
Na ₂ O								0.04
P ₂ O ₅								41.22
Total	98.75	96.66	97.20	100 ¹	100 ¹	100.7	100.4	98.58
Chr	31	40	64	57	50			
Spl	66	55	28	18	47		Ilmenite	Apatite
Usp	3	5	8	25	3			

¹Energy dispersive spectroscopic data with an accuracy of ± 0.5 wt%.

1986). Lithic clasts that have this intermediate composition have previously been found in several lunar meteorites (e.g., Dhofar (Dho) 025, 081, 280, 301, 302, 303, 489, DaG 400) (Semenova et al. 2000; Anand et al. 2002; Nazarov et al. 2002; Cahill et al. 2004; Takeda et al. 2006). These rocks may simply be breccias containing a mixture of both FAN and HMS rocks or represent pristine crustal lithologies (Cahill et al. 2004). Clasts 6, 7, and 8 are mafic-rich, but still anorthositic relative to the typical mafic magnesian rocks from Apollo samples. Clasts 6 and 7 plot well below the HMS region, and fall within the FAN area. Clast 8 is also Fe-rich (Mg# 0.65–0.78) relative to HMS. Thus, Clasts 6–8 could represent unique lithologies distinct from Apollo mafic magnesian rocks.

The occurrence of mafic clasts in SaU 300 raises the question of whether these mafic clasts derive from mare basalts or HMS rocks. Pyroxenes from mare basalts usually have low Mg# and display distinctive chemical zoning with a Fe-rich (and Ca-rich) rim. In contrast, pyroxenes from HMS rocks are generally Mg-rich and have relatively homogeneous compositions. Petrographically, mare basalts exhibit a variety of textures (depending on cooling rates) from ophitic to subophitic. Some are coarse-grained and exhibit a gabbroic texture. In contrast, HMS rocks formed in a sub-surface environment and cooled relatively slowly. They usually have a poikilitic texture or granulitic texture due to sub-solidus annealing (Heiken et al. 1991).

Arai et al. (1996) found that Fe# [molar Fe/(Fe+Mg)] versus Ti# [molar Ti/(Ti+Cr)] of pyroxenes in lunar rocks displays three compositional trends. Pyroxenes from mare basalts show a strong correlation between Fe# and Ti#, reflecting local crystallization differentiation of interstitial melt. Other pyroxenes display a wide range of Ti# but have a relatively low and constant Fe#. These compositional trends may indicate a highlands origin or reflect thermal annealing histories. Arai et al. (1996) argued that diffusion rates of Ti and Cr in pyroxenes are slower than that of Fe and Mg. Therefore, Fe and Mg are more readily homogenized than Ti

and Cr. On the Ti#-Fe# plot (Fig. 8), most pyroxene grains from SaU 300 show a large variation in Ti# (0.2 to 0.75) with relatively low and limited Fe# (0.2 to 0.4). For the mafic clasts 6–8, pyroxene grains have restricted and low Fe# (<0.5), indicating a highlands origin or thermal annealing. Therefore, we suggest that the lithic clast population of SaU 300 consists mainly of a feldspathic highlands component with a minor amount of HMS rocks.

There are some alternative interpretations. The mafic components in SaU 300 could be mafic impact melt that might not necessarily have an origin as HMS; or they are perhaps a mafic component from a deeper level of the crust, including a more mafic FAN rock, e.g., norite or gabbro that is complementary to FAN. If the meteorite comes from the far side highlands, perhaps there is a mafic component that derives from the deposits of the South Pole-Aitken basin.

TRACE ELEMENT GEOCHEMISTRY

In situ ion microprobe measurements were carried out in olivine, plagioclase, pyroxene, and apatite grains of lithic clasts (C-1, C-2, C-3, C-4, C-5, and C-6), in mineral fragments, and in melt-glass veins (Table 8).

Because of their small grain size (<50 μ m), olivine analyses are often contaminated by a small amount of plagioclase. As a result, they usually show light rare earth element (LREE) enrichments and positive Eu anomalies, which were later excluded from the raw data. After correction, olivine exhibits a heavy rare earth element (HREE) enriched pattern with Lu at $2\text{--}10 \times \text{CI}$ and Gd at $0.1\text{--}1 \times \text{CI}$. REE concentrations vary between olivine grains, within the same clast, and among different clasts (Fig. 9a). Olivine grains in C-1 have the highest REE content (Gd $\sim 1 \times \text{CI}$, Lu $\sim 10 \times \text{CI}$) and the olivine grains in C-6 have the lowest REE content (Gd $\sim 0.1 \times \text{CI}$, Lu $\sim 2 \times \text{CI}$). The REE pattern and compositional range of olivine in SaU 300 are similar to those of olivine from FAN suite rocks (Floss et al. 1998).

Plagioclase displays a typical LREE-enriched pattern

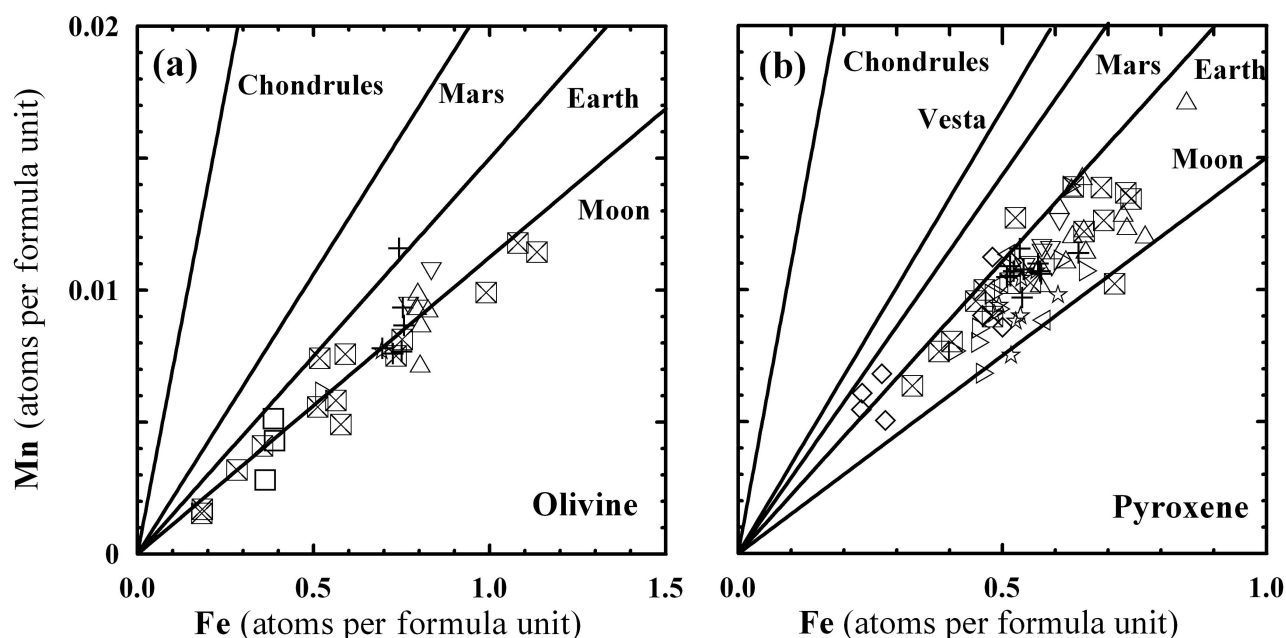


Fig. 6. Concentrations of Fe versus Mn in olivine and pyroxene of SaU 300. The atoms per formula unit are based on 4 oxygens for olivine and 6 oxygens for pyroxene. Symbols are the same as in Fig. 3 and Fig. 4.

with a positive Eu anomaly ($10\text{--}20 \times \text{CI}$). REE content of plagioclase varies within and among lithic clasts. Both LREE and HREE concentrations vary significantly, by a factor of more than 20 (Fig. 9b). The variation of Eu, however, is relatively small (factor of 2). La varies from 0.8 to $22 \times \text{CI}$ and Y, an analog of HREE, from 0.5 to $8 \times \text{CI}$. Plagioclase in C-1 has the highest REE content (La $\sim 22 \times \text{CI}$) while C-6 has the lowest REE content (La $\sim 0.8 \times \text{CI}$). Most plagioclase grains in SaU 300 have REE abundances and patterns that are in excellent agreement with those of plagioclase from FAN suite rocks (Papike et al. 1997; Floss et al. 1998). One grain in C-1 has a slightly higher REE content than average plagioclase from FAN suite rocks. It falls into the range of plagioclase from HMS rocks (Papike et al. 1996).

Both high-Ca and low-Ca pyroxenes were analyzed. All exhibit HREE-enriched patterns with negative Eu anomalies (Fig. 9c). High-Ca pyroxene has a higher REE content (La $1\text{--}25 \times \text{CI}$, Lu $50\text{--}60 \times \text{CI}$) than low-Ca pyroxene (Lu $10\text{--}30 \times \text{CI}$). The REE abundances and patterns of pyroxene grains in SaU 300 are similar to those of pyroxenes from FAN and HMS (Papike et al. 1997; Floss et al. 1998).

The apatite grain in C-5 has very high REE concentrations with a relatively LREE-enriched pattern (La $2800 \times \text{CI}$ and Lu $650 \times \text{CI}$) and a negative Eu anomaly (Eu $30 \times \text{CI}$) (Fig. 9d).

Two analyses of glass from two different veins yielded essentially identical REE abundances (Fig. 9d), which are also remarkably similar to the bulk REE contents of SaU 300. The glass displays a relatively LREE-enriched (La $11 \times \text{CI}$, Sm $7 \times \text{CI}$) pattern with a positive Eu anomaly (Eu $11 \times \text{CI}$) and relatively flat HREE pattern ($7 \times \text{CI}$). This pattern is

similar to that of the feldspathic lunar meteorites QUE 93069 and Dho 025 (Korotev et al. 1996, 2003).

Ba and Sr positively correlate with REEs in plagioclase of FAN rocks and lunar highlands meteorites (Papike et al. 1997; Floss et al. 1998; Cahill et al. 2004). The correlation between Ba and Ce is stronger than that of Sr and Ce (Fig. 10). Most plagioclase grains in SaU 300 fall within the fields of FAN and lunar highlands meteorites. A few plot close to the HMS suite of rocks (Fig. 10). Some plagioclase grains exhibit extremely high Sr concentrations (290 to 2720 ppm) (Fig. 10a).

BULK COMPOSITION

The bulk chemistry of SaU 300 was determined with INAA, ICP-OES/MS, and TXRF. The results are listed in Table 9. For major elements, individual rock chips of SaU 300 display a small compositional variation, indicating sample heterogeneity. For example, Mg concentration varies from 5.06 to 6.51 wt%; and Al from 9.43 to 12.73 wt%. For minor and trace elements, the results from different measurements are consistent within analytical uncertainties. For example, one 0.0301 g chip of SaU 300 was analyzed with ICP-MS and TXRF. Both techniques yield very similar results.

Al_2O_3 and FeO concentrations of SaU 300 fall along the trend defined by lunar meteorites and Apollo samples and are close to those of mingled lunar meteorites (Fig. 11a). FeO and MgO contents of SaU 300 are 8.16 wt% and 9.22 wt%, respectively, which are slightly higher than those of typical highland feldspathic meteorites (Table 9). SaU 300 has a relatively LREE-enriched (7 to $10 \times \text{CI}$) pattern with a

Table 6. Representative compositions (wt%) of metal and sulfide.

	Metal-1			Metal-2			Clast-6		Metal-3	Troilite
Fe	94.19	93.87	94.76	82.69	91.76	87.86	63.16	96.75	87.08	62.86
Ni	5.24	5.60	5.26	16.04	6.24	10.95	0.14	0.62	13.11	0.09
Co	0.55	0.55	0.54	0.35	0.65	0.60	0.04	0.11	0.22	0.03
S	bd	bd	bd	bd	bd	bd	36.65	0.04	0.03	35.37
Total	99.98	100.0	100.6	99.08	98.65	99.41	99.99	97.52	100.4	98.35

bd: below detection limit.

bd: below detection limit.

Table 7. Composition (wt%) of impact-melt glasses in SaU 300.

Element	Vein 1										Vein 2				Glass
	44.22	43.37	44.32	42.91	44.42	44.14	44.14	44.14	44.14	44.91	46.33	45.9	46.73	46.53	44.46
SiO ₂	44.22	43.37	44.32	42.91	44.42	44.14	44.14	44.14	44.14	44.91	46.33	45.9	46.73	46.53	44.46
TiO ₂	0.29	0.20	0.31	0.19	0.16	0.27	0.27	0.28	0.28	0.29	0.41	0.27	0.27	0.31	0.27
Al ₂ O ₃	24.06	25.88	24.13	24.52	23.94	26.73	24.19	24.19	24.19	22.66	22.22	23.5	27.81	24.50	25.01
Cr ₂ O ₃	0.15	0.15	0.15	0.13	0.19	0.22	0.20	0.20	0.20	0.18	0.20	0.19	0.11	0.15	0.14
FeO	6.76	6.23	6.66	6.79	7.87	6.48	8.12	8.12	8.12	7.47	6.94	7.01	5.32	6.78	8.74
MnO	0.08	0.06	0.10	0.08	0.08	0.10	0.13	0.13	0.13	0.17	0.12	0.05	0.1	0.11	0.12
MgO	6.72	6.62	6.74	6.40	6.98	6.37	7.77	7.77	7.77	7.72	6.98	7.46	5.15	6.25	6.98
CaO	14.51	15.10	14.81	15.08	14.35	14.70	14.05	14.05	14.05	14.34	14.25	14.04	15.65	15.05	13.90
Na ₂ O	0.34	0.39	0.36	0.37	0.31	0.40	0.30	0.30	0.30	0.35	0.34	0.29	0.34	0.32	0.35
K ₂ O	0.05	0.04	0.05	0.03	0.08	0.05	0.06	0.06	0.06	0.05	0.03	0.06	0.08	0.05	0.03
P ₂ O ₅	0.07	0.04	0.08	0.03	0.08	0.04	0.01	0.01	0.01	0.03	0.04	0.03	0.07	0.01	0.06
Total	97.25	98.08	97.71	96.53	98.46	99.50	99.25	99.25	99.25	98.17	97.86	98.80	101.6	100.1	100.1
CIPW values in wt%															
Ilm	0.55	0.38	0.59	0.36	0.30	0.51	0.53	0.53	0.53	0.55	0.78	0.51	0.51	0.59	0.51
Chrm	0.22	0.22	0.22	0.19	0.28	0.32	0.29	0.29	0.29	0.27	0.29	0.28	0.16	0.22	0.21
Apt	0.15	0.09	0.17	0.07	0.17	0.09	0.02	0.02	0.02	0.07	0.09	0.07	0.15	0.02	0.13
Or	0.30	0.24	0.30	0.18	0.47	0.30	0.35	0.35	0.35	0.30	0.18	0.35	0.47	0.30	0.18
Ab	2.87	3.30	3.04	3.13	2.62	3.38	2.54	2.54	2.54	2.96	2.87	2.45	2.87	2.70	2.96
An	63.90	68.67	64.00	65.08	63.62	70.91	64.41	64.41	64.41	60.04	58.95	62.57	74.03	65.19	66.51
Cpx	6.30	4.94	7.38	7.86	5.86	1.49	4.32	4.32	4.32	8.94	9.43	5.67	2.65	7.74	1.76
Ol	6.92	13.05	7.61	12.27	9.45	10.69	13.00	13.00	13.00	7.99	7.99	3.32	0.10	0.93	11.73
Opx	15.86	7.08	14.19	7.24	15.51	11.60	13.52	13.52	13.52	16.72	24.50	23.48	20.47	22.14	15.83
Mg#	0.64	0.66	0.65	0.63	0.61	0.64	0.63	0.63	0.63	0.65	0.64	0.66	0.64	0.62	0.59

Abbreviations: Ilm—ilmenite; Chrm—chromite; Apt—apatite; Or - ; Ab—albite; An—anorthite; Cpx—clinopyroxene; Ol—olivine; Opx—orthopyroxene.

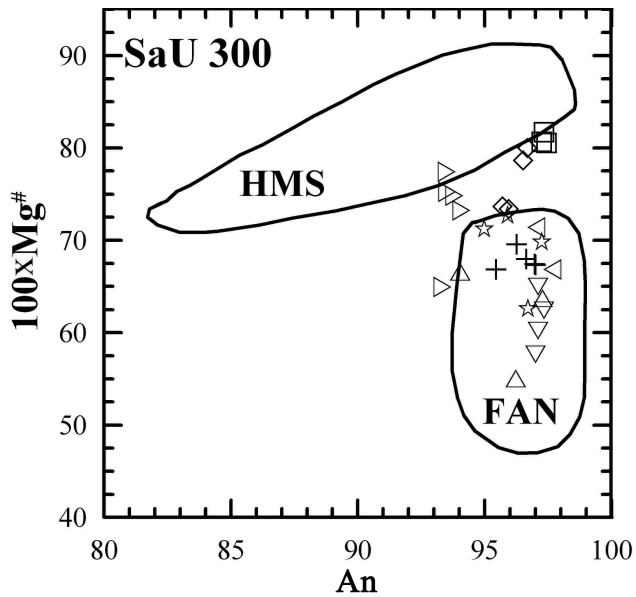


Fig. 7. Mg# of mafic phases (olivine and pyroxenes) versus An content of plagioclase in lithic clasts of SaU 300 and comparison with FAN and HMS suite rocks. HMS and FAN data are from Warren (1985). Symbols are the same as in Fig. 3 and Fig. 4.

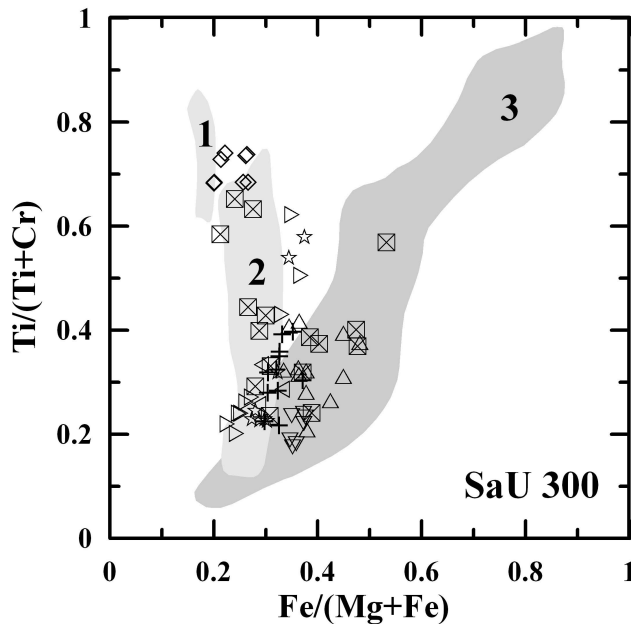


Fig. 8. Ti# [Ti/(Ti+Cr)] versus Fe# [Fe/(Fe+Mg)] for pyroxene grains of SaU 300. Shaded areas are adopted from Arai et al. (1996). Trends 1 and 2 represent rocks of highlands origin, and trend 3 represents rocks of basaltic origin (see Arai et al. 1996). Symbols are the same as in Fig. 3 and Fig. 4.

positive Eu anomaly ($\sim 11 \times \text{CI}$) (Fig. 11b). This REE pattern is typical of the feldspathic highlands meteorites and is dominated by the REE signature of lunar plagioclase. The bulk concentrations of Sc and Fe in SaU 300 fall within the range of typical highlands meteorites, and its Fe/Sc ratio varies from 3000 to 4000, which is close to the average of

highlands rocks (~ 4000 , Fig. 12). Th and Sm concentrations of SaU 300 fall along the trend defined by lunar meteorites but plot at the lower end (Fig. 13).

SaU 300, Dho 1180, Y-983885, and Calcalong Creek have very similar major element concentrations, close to that of Luna 20 soils (Boynton 2003; Warren 2003; Arai et al. 2005; Hill and Karouji et al. 2006; Zhang and Hsu 2006). They contain $\sim 22 \text{ wt\% Al}_2\text{O}_3$ and $\sim 9 \text{ wt\% FeO}$ and fall within the field of mingled lunar meteorites (Fig. 11a). Mingled lunar meteorites are mainly composed of feldspathic, mare basaltic, and KREEPy components (Korotev 2005). Dho 1180, Y-983885, Calcalong Creek mainly contain highlands components, including ferroan anorthosite, Mg-rich troctolite/norite, and granulite (Hill and Boynton 2003; Arai et al. 2005; Bunch et al. 2006; Hsu et al. 2006, 2007; Zhang and Hsu 2006). Y-983885 and Calcalong Creek have high REE abundances and display a pronounced negative Eu anomaly. Their REE patterns are similar to those of mare basalt (NWA 032) and KREEP rocks (Fig. 11b), indicating Y-983885 and Calcalong Creek contain a small amount of basaltic and/or KREEPy components. Indeed, petrographic studies have revealed that these two lunar meteorites contain minor amounts of low-Ti and very low-Ti basalts, high-Al basalt, and KREEP basalt (Hill and Boynton 2003; Arai et al. 2005). Dho 1180 also contains a few KREEPy clasts (Zhang and Hsu 2007).

SaU 300 is largely free of KREEP and mare basaltic components, but contains mainly feldspathic components with a small amount of mafic clasts. Feldspathic regolith breccias have relatively low REE abundances (1 to $10 \times \text{CI}$) with a characteristic positive Eu anomaly (Fig. 11b). The REE pattern and abundances of SaU 300 are remarkably similar to those of feldspathic lunar meteorites (Fig. 11b). Relative to lunar highlands feldspathic regolith breccias such as DaG 400 and QUE 93069, SaU 300 has low Al_2O_3 but high FeO contents (Fig. 11a). This suggests that SaU 300 is essentially composed of highlands feldspathic rocks but contains a higher amount of mafic rocks than other nominally feldspathic lunar meteorites. With $8.16 \text{ wt\% FeO}$, SaU 300 is the most mafic feldspathic lunar meteorite that has been studied to date. It is also noted that mafic clasts in SaU 300 are slightly more Fe-rich when compared to HMS rocks. SaU 300 is a unique lunar meteorite that has low trace element concentrations but a relatively high FeO content.

SaU 300 has very high abundances of the siderophile elements Co, Ni, Ir, and Au (by a factor of 2 to 3) compared to other highlands meteorites and the average highlands regolith (Fig. 14a). This enrichment in siderophile elements indicates that one or more components have a high concentration of meteoritic metal. It is also possible that the source of SaU 300 was close to the lunar surface where micrometeorites accumulate over time, enriching the soil in siderophile elements. A near surface origin seems to be inconsistent with

Table 8. Minor and trace element concentrations (ppm) of olivine, pyroxene, plagioclase, impact-melt glass, and apatite in SaU 300.

	Olivine			Pyroxene			Plagioclase			Glass		Apatite	
Na										2175 ± 4	2070 ± 5	502 ± 5	
K										373 ± 2	350 ± 3	50 ± 1	
Sc	29.3 ± 0.3	26.2 ± 0.4		55.0 ± 0.3	86.9 ± 0.6		15.6 ± 0.3	12.9 ± 0.1		29 ± 0.3	29 ± 0.4	1.1 ± 0.1	
Ti	378 ± 5	176 ± 4		6845 ± 23	11342 ± 39		156 ± 4	555 ± 4		1429 ± 11	1455 ± 15	1991 ± 29	
V	43.0 ± 0.5	34.7 ± 0.6		86 ± 1	174 ± 1		7.7 ± 0.3	5.6 ± 0.1		56 ± 1	57 ± 1	1.2 ± 0.2	
Cr	1797 ± 4	1017 ± 4		1662 ± 3	2316 ± 4		44.1 ± 0.9	9.9 ± 0.1		1243 ± 4	1212 ± 5	6.3 ± 0.4	
Mn	4507 ± 7	4281 ± 9		2866 ± 5	1911 ± 6		158 ± 2	167 ± 1		918 ± 4	869 ± 5	252 ± 4	
Ni	23.4 ± 0.7	29.4 ± 0.9		26.3 ± 0.7	81.8 ± 1.5		55.0 ± 1.4	62.4 ± 0.6		81 ± 1	102 ± 2	786 ± 21	
Rb	34.1 ± 1.0	33.1 ± 1.3		1.14 ± 0.05	0.70 ± 0.05		1.0 ± 0.2	0.18 ± 0.01		5.3 ± 0.5	5.7 ± 0.6	0.2 ± 0.2	
Sr	70 ± 1	32.3 ± 0.7		60.4 ± 0.8	31.6 ± 0.7		291 ± 2	252 ± 1		90 ± 1	94 ± 1	243 ± 4	
Y	4.4 ± 0.1	1.2 ± 0.1		35.3 ± 0.3	94.3 ± 0.6		0.8 ± 0.1	12.3 ± 0.1		9.9 ± 0.2	9.6 ± 0.2	1400 ± 6	
Zr										96 ± 1	121 ± 1	2813 ± 21	
Ba	2.5 ± 0.1	1.3 ± 0.1		3.2 ± 0.1	6.4 ± 0.2		7.4 ± 0.2	84.5 ± 0.2		27.8 ± 0.3	26.4 ± 0.3	4.6 ± 0.2	
La				0.829 ± 0.028	3.336 ± 0.074		0.179 ± 0.019	5.066 ± 0.041		2.54 ± 0.05	2.44 ± 0.07	642 ± 2	
Ce				3.280 ± 0.061	12.81 ± 0.16		0.510 ± 0.031	13.13 ± 0.071		5.80 ± 0.09	5.93 ± 0.12	1698 ± 4	
Pr				0.628 ± 0.024	2.328 ± 0.061		0.053 ± 0.009	1.714 ± 0.023		0.75 ± 0.03	0.77 ± 0.04	321 ± 2	
Nd				3.745 ± 0.064	14.46 ± 0.16		0.234 ± 0.020	7.815 ± 0.054		3.52 ± 0.07	3.59 ± 0.09	1370 ± 3	
Sm				1.950 ± 0.061	7.533 ± 0.156		0.048 ± 0.017	2.174 ± 0.042		1.05 ± 0.05	1.12 ± 0.07	386 ± 3	
Eu				0.059 ± 0.011	0.150 ± 0.021		0.560 ± 0.030	1.192 ± 0.023		0.59 ± 0.03	0.59 ± 0.04	1.6 ± 0.2	
Gd	0.09 ± 0.023	0.026 ± 0.018		3.251 ± 0.110	11.52 ± 0.27		0.104 ± 0.021	2.240 ± 0.061		1.31 ± 0.07	1.38 ± 0.10	348 ± 4	
Tb	0.035 ± 0.006	0.014 ± 0.005		0.743 ± 0.028	2.407 ± 0.066		0.018 ± 0.006	0.348 ± 0.013		0.26 ± 0.02	0.24 ± 0.03	32.9 ± 0.6	
Dy	0.393 ± 0.020	0.088 ± 0.012		6.070 ± 0.080	17.77 ± 0.18		0.081 ± 0.012	2.782 ± 0.034		1.70 ± 0.05	1.68 ± 0.06	329 ± 2	
Ho	0.151 ± 0.013	0.021 ± 0.005		1.507 ± 0.041	4.105 ± 0.089		0.021 ± 0.006	0.625 ± 0.016		0.39 ± 0.02	0.42 ± 0.03	61.6 ± 0.9	
Er	0.617 ± 0.027	0.091 ± 0.014		4.368 ± 0.073	10.76 ± 0.15		0.086 ± 0.014	1.484 ± 0.027		1.14 ± 0.04	1.11 ± 0.05	150 ± 2	
Tm	0.134 ± 0.011	0.012 ± 0.005		0.743 ± 0.028	1.561 ± 0.052		0.017 ± 0.008	0.211 ± 0.010		0.18 ± 0.02	0.16 ± 0.02	15.7 ± 0.4	
Yb	1.240 ± 0.038	0.169 ± 0.017		5.234 ± 0.080	11.32 ± 0.16		0.049 ± 0.011	1.603 ± 0.028		1.14 ± 0.04	1.22 ± 0.06	85.7 ± 1.9	
Lu	0.258 ± 0.019	0.045 ± 0.009		0.792 ± 0.035	1.545 ± 0.066		0.016 ± 0.005	0.183 ± 0.011		0.18 ± 0.02	0.21 ± 0.03	15.8 ± 0.7	

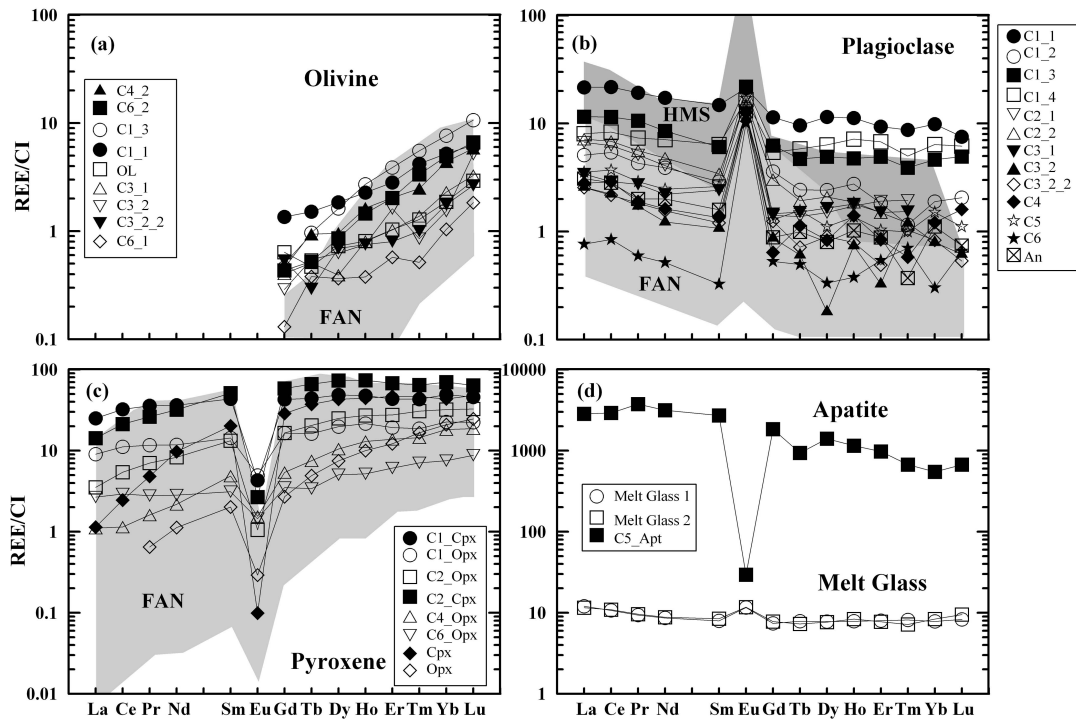


Fig. 9. REE microdistributions in olivine (a), plagioclase (b), pyroxene (c), apatite, and melt glass (d) of SaU 300. FAN and HMS envelopes are adopted from Floss et al. (1998), Papike et al. (1996, 1997), and Cahill et al. (2004).

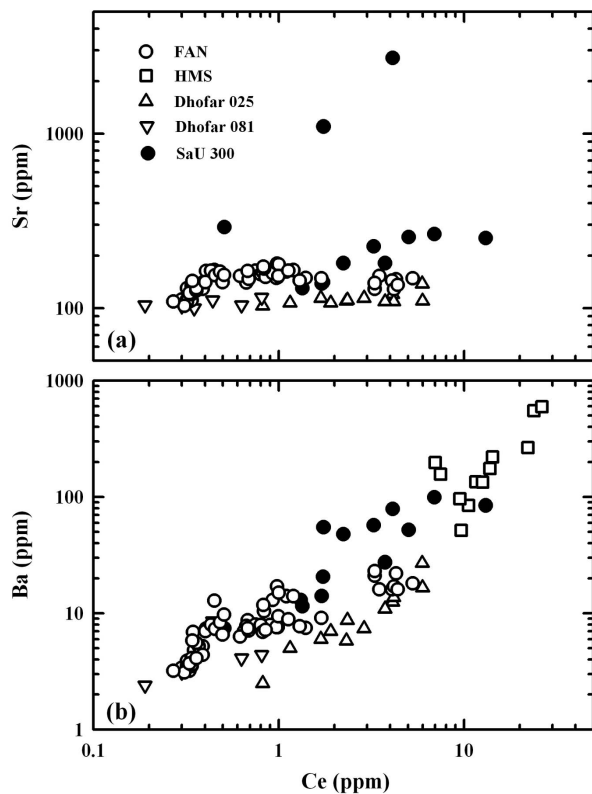


Fig. 10. Sr (a), Ba (b) and Ce concentrations of plagioclase in SaU 300 in comparison to lunar highlands meteorites Dhofar 025 and 081 (Cahill et al. 2004) and FAN and HMS rocks (Floss et al. 1998; Papike et al. 1996, 1997).

low concentrations of solar-wind gases in SaU 300 (unpublished data). An explanation is that the low solar wind contents in SaU 300 are due to the loss of noble gases by the extensive impact heating on the surface. The CI-normalized siderophile abundances of SaU 300 show a Co enrichment relative to Ni (Fig. 14b), consistent with results from other lunar samples (Warren et al. 1989). This is due to the fact that on the Moon, Co is not only a siderophile element but also shows partly lithophile and chalcophile tendencies. The Ni/Ir ratio of SaU 300 is close to chondritic, indicating a contribution from chondritic particles that struck the lunar surface. With an Ir concentration of 20 ppb, SaU 300 could contain ~3% chondritic material. Korotev et al. (2007) suggested H-chondrite affinity for the metal in SaU 300 and estimated that a 2.5% component of H chondrite could account for the siderophile compositions in SaU 300.

It has been previously noted that meteorites from hot and cold deserts are susceptible to terrestrial weathering (Croaz and Wadhwa 2001; Croaz et al. 2003). Secondary minerals, such as calcite and gypsum, fill pores and fractures within meteorites during prolonged exposure time in deserts. This results in alteration of the REE concentrations and an enrichment of Ca, Sr, and Ba in the bulk rock. SaU 300 contains a relatively elevated Sr (~550 ppm) concentration compared to other lunar meteorites and Apollo and Luna samples (Fig. 15). The Ba concentration (~50 ppm) of SaU 300 falls within the lower range observed in lunar meteorites and Apollo and Luna samples (Papike et al. 1996, 1997; Floss et al. 1998; Cahill et al. 2004) (Fig. 10b). Such a distribution

Table 9. *Continued.* Bulk composition (ppm) of SaU 300 and comparison with other lunar meteorites and Apollo soils.

Elements	SaU 300				Calcalong Creek				ALH 81005			
	0.0301 g		0.0605 g		0.0563 g		feldspathic breccia		feldspathic regolith breccia		Average Highland regolith	
	ICP-MS	s.d.	TXRF	s.d.	INAA	s.d.	(1)	(2)	(2)	(2)	(3)	(2)
Sm	1.07	0.07			1.11	0.06	9.55	0.95	3.34	0.131	15.1	15.1
Eu	0.604	0.038			0.64	0.05	1.303	0.69	0.97	0.769	1.89	1.89
Gd	1.42	0.12					10.5					
Tb	0.255	0.016			0.24	0.02	1.941	0.21	0.71	0.036	3.6	3.6
Dy	1.74	0.11			2.20	0.17	13.28	1.33	4.45		20	20
Ho	0.373	0.025			<0.6		2.67					
Er	1.15	0.07										
Tm	0.168	0.012					1.407					
Yb	1.20	0.08			1.30	0.07	7.5	0.84	2.51	0.16	10.7	10.7
Lu	0.167	0.012			0.170	0.009	1.024	0.12	0.37	0.014	1.54	1.54
Hf					0.90	0.05	7.15	0.72	2.56	0.126	12.8	12.8
Ta					0.108	0.009	0.991	0.09	0.31		1.35	1.35
Ir (ppb)	21	2			19	1	3	6.8	10.1	0.351	5.6	5.6
Pt (ppb)	38	4			<4							
Au (ppb)					7	1	3	2.3	5.2	0.441	2.4	2.4
Pb	0.581	0.065	<1.2									
Th	0.473	0.033	<1.0		0.45	0.05	4.28	0.29	1.27	0.036	5.2	5.2
U					0.22	0.02	1.18	0.1	0.4		1.68	1.68

Data sources: (1) Hill and Boynton (2003); (2) Warren (2003); (3) Cahill et al. (2004).

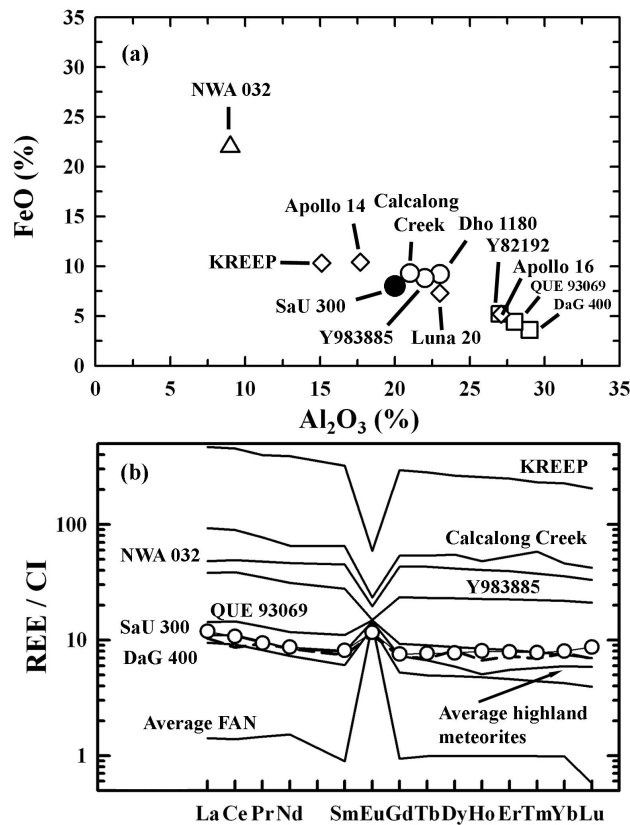


Fig. 11. a) Major element and b) REE abundances of lunar meteorites, lunar soils and KREEP rocks. Open circles in (b) represent the glass veins in SaU 300. The dashed line is for the bulk composition of SaU 300. The REE pattern of SaU 300 is similar to that of highland feldspathic breccias. Data sources are from Fagan et al. (2003), Hill and Boynton (2003), Koeberl (1988), Korotev et al. (1996, 2003), Korotev (2005), Warren (2003).

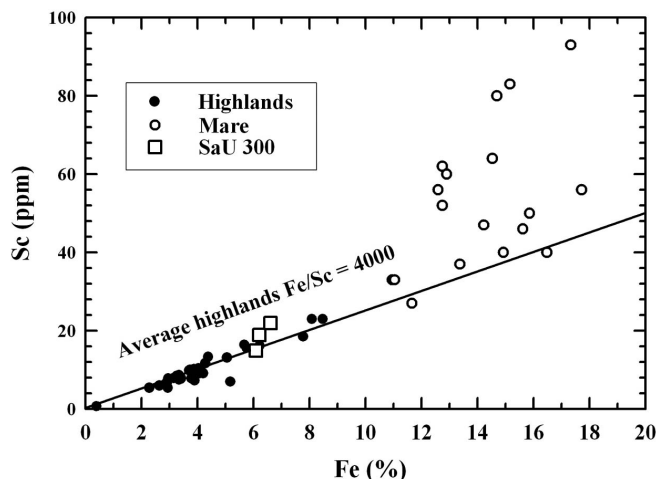


Fig. 12. Whole rock Fe versus Sc for mare basalts and highlands breccias. The composition of SaU 300 falls into the range of highland lithologies. Its Fe/Sc ratio is also close to the typical highland average of 4000. Data are from Palme et al. 1991, Koeberl et al. (1996), Fagan et al. (2003), Korotev et al. (2003), Warren (2003), Cahill et al. (2004), Cohen et al. (2004).

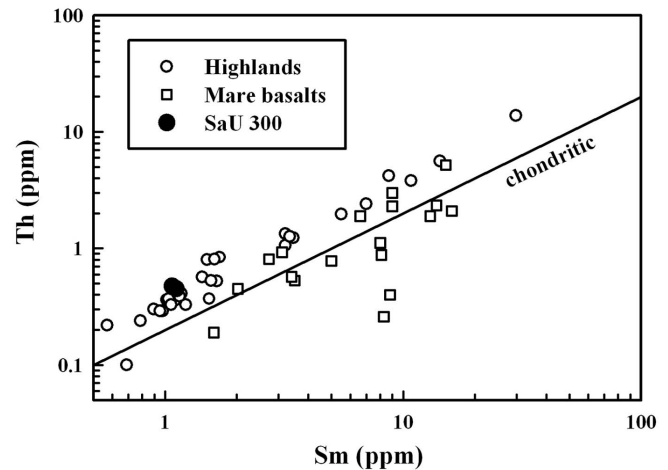


Fig. 13. Correlation between highly incompatible elements Th and Sm among lunar meteorites. SaU 300 falls at the lower end of the trend. Data are from Koeberl et al. (1996), Fagan et al. (2003), Korotev et al. (2003), Warren (2003), Cahill et al. (2004), Cohen et al. (2004).

pattern has been seen in individual mineral grains. As mentioned above, some plagioclase grains in SaU 300 contain an extremely high Sr concentration compared to other highlands meteorites and Apollo samples. Enrichment of Ba was not observed in mineral grains of SaU 300. SaU 300 has experienced moderate terrestrial weathering. Indeed, we did not observe widespread weathering mineral phases.

LUNAR PROVENANCE

Recent Clementine and Lunar Prospector missions have revealed that the radioactive and geochemically incompatible elements, such as K and Th, are largely concentrated in the NW quadrant of the nearside, coincident with the Procellarum terrane (Lawrence et al. 1998, 2000). On the basis of the remote sensing data provided by these missions, Jolliff et al. (2000) recognized three distinct geochemical and petrologic terranes on the lunar surface: Procellarum KREEP Terrane (PKT), Feldspathic Highlands Terrane (FHT), and South Pole-Aitken Terrane (SPAT). The PKT is rich in Th (>3.5 ppm) and coincides with the largely resurfaced area in the Procellarum-Imbrium region. The FHT covers most of the lunar surface (>60%), including the bulk of the lunar far side. It is poor in Th (0.2 to 1.5 ppm) and FeO (~5%), dominated by feldspathic components. The SPAT is moderately rich in FeO (~10%) and Th (~2 ppm). It is the largest impact basin (~2600 km) in the solar system. These terranes represent distinctive lunar provinces and indicate unique geologic histories. Haskin (1998) noted a relationship between Th abundance and distance from the Imbrium basin. Th concentration decreases from the edge of the Imbrium basin (~5 ppm) to a distance of 4000–5000 km (<1 ppm). This finding was confirmed by the Lunar Prospector gamma-ray spectrometer spectra (Lawrence et al. 1998). The impact that

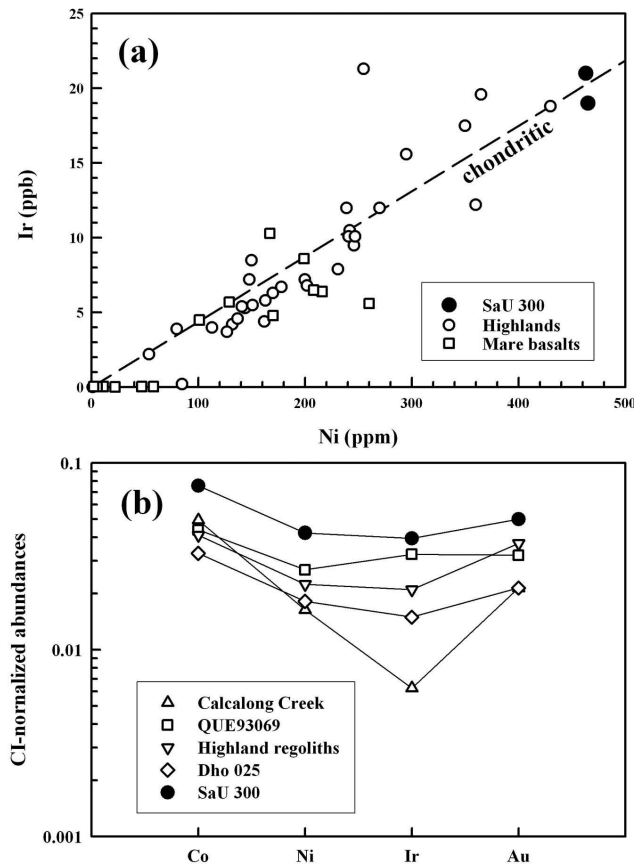


Fig. 14. a) Correlation between highly siderophile elements Ni and Ir among lunar meteorites. SaU 300 plots at the high end of the trend, indicating a source close to the lunar surface that accumulates micrometeorites with time. b) CI-normalized siderophile element abundances of lunar meteorites. SaU 300 has a similar pattern to that of the highland regolith. Data are from Koeberl et al. (1996), Fagan et al. (2003), Korotev et al. (2003), Warren (2003), Cahill et al. (2004), Cohen et al. (2004).

formed the Imbrium basin would have excavated and melted a large amount of Th-rich material that was subsequently distributed over most of the lunar surface.

Lunar meteorite SaU 169 is an impact-melt breccia that is extremely enriched with K, REEs, and P (Th 33 ppm, U 8.6 ppm, K₂O 0.54 wt%), (Gnos et al. 2004). It has a strong link to the Imbrium basin and was inferred to have been derived from the Lalande impact crater (Gnos et al. 2004). Two other feldspathic breccias, Y-983885 and Calalong Creek, are relatively rich in Th (2 and 4 ppm, respectively). They contain clasts of Th-rich impact melt breccias. These meteorites could be related to or derived from an area close to the PKT and SPAT areas (Hill and Boynton 2003; Korotev et al. 2003; Arai et al. 2005; Korotev 2005). However, most lunar feldspathic meteorites do not contain Th-rich impact-melt breccias. They most likely originated from the FHT, probably from the lunar far side (Cahill et al. 2004; Takeda et al. 2006). SaU 300 is dominated by feldspathic components with a small HMS contribution and a dearth of KREEPy

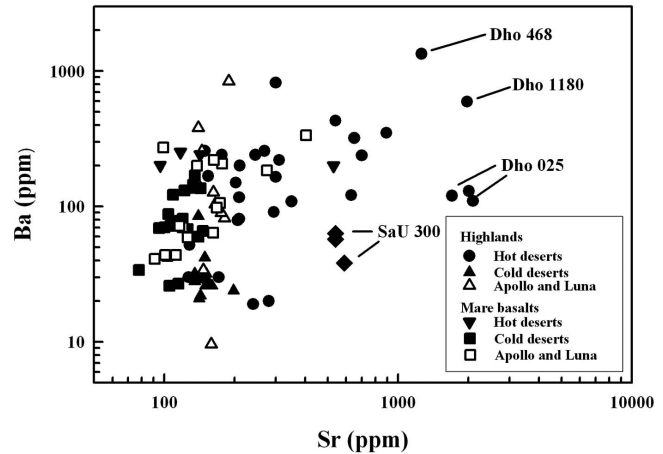


Fig. 15. Bulk concentrations of Sr and Ba in lunar meteorites and Apollo samples. These elements are susceptible to terrestrial weathering. SaU 300 has an elevated Sr concentration, but a low Ba concentration relative to Apollo and Luna samples, indicating that SaU 300 has experienced moderate terrestrial weathering. Data are from Cahill et al. (2004), Korotev et al. (2003), Warren (2003, 2005).

characteristics, very similar to lunar highlands meteorites Dho 025 and Dho 081 (Cahill et al. 2004). The remote-sensing data from Clementine and Lunar Prospector reveal that the northern far side surface consists almost exclusively of feldspathic highland terrain with little HMS and KREEP components, and that the near side includes feldspathic highlands, HMS, and KREEP rocks. Dho 489 was inferred to have derived from the lunar far side highlands on the basis of the depletion of Th (0.05 ppm) and FeO (~3 wt%) (Takeda et al. 2006). SaU 300 has relatively higher Th and FeO contents than Dho 489. SaU 300 is unique amongst the Apollo suite rocks and the lunar meteorites recovered thus far and it may represent an unexplored region on the lunar surface, which is almost free from KREEP and mare basalt contamination. It is worth noting that there is very little exposure of mare basalt on the northern far side of the Moon. The eastern near-side is also far distant from the PKT and has some areas of feldspathic highlands, but the abundance of mare basalt and “cryptomare” or partially buried mare basalt results in the development of higher FeO in regolith than on the northern far side highlands. Therefore, it is possible that the source region of SaU 300 is within the FHT, at a great distance from the PKT, probably on the far side of the Moon.

SUMMARY

SaU 300 is dominated by a fine-grained crystalline matrix surrounding mineral fragments and lithic clasts. Lithic clasts are mainly anorthositic to noritic. Mare basalt and KREEPy rocks are absent. A second impact event generated veins and glassy impact melts whose compositions are close to anorthositic norite. SaU 300 is a feldspathic impact-melt breccia.

Major element concentrations of SaU 300 are very similar to those of mingled lunar meteorites (e.g., Calalong Creek and Y-983885). However, SaU 300 is largely free of mare basalt and KREEP rocks. It is mainly composed of highlands feldspathic rocks with a small amount of mafic rocks. With 8.16 wt% FeO, SaU 300 is more mafic than other nominally feldspathic highlands meteorites. The bulk REE abundances of SaU 300 are significantly lower than those of Calalong Creek and Y-983885, but resemble those of feldspathic highlands meteorites and the average lunar highlands crust. SaU 300 is a unique lunar meteorite and represents a lunar surface composition distinct from any other known lunar meteorites.

SaU 300 also contains high siderophile abundances with a chondritic Ni/Ir ratio, indicating its source region close to the lunar surface. Bulk Sr concentration is relatively elevated in SaU 300 compared to other lunar meteorites and Apollo and Luna samples. But Ba concentration in SaU 300 falls within the lower field observed for lunar meteorites and Apollo and Luna samples. The elevated Sr concentration indicates that SaU 300 has experienced moderate terrestrial weathering.

On the basis of the low Th concentration (0.46 ppm) and the lack of KREEPy and mare basaltic components, the source region of SaU 300 could have been within the FHT at a significant distance from the PKT, probably on the lunar far side.

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REFERENCES

- Armstrong J. T. 1982. New ZAF and α -factor correction procedures for the quantitative analysis of individual microparticles. In *Microbeam analysis*, edited by Heinrich K. F. J. San Francisco Press. pp. 175–180.
- Anand M., Taylor L. A., Patchen A., Cahill J. T., and Nazarov M. A. 2002. New minerals from a new meteorite Dhofar 280 (abstract #1653). 33rd Lunar and Planetary Science Conference. CD-ROM.
- Arai T., Takeda H., and Warren P. H. 1996. Four lunar mare meteorites: Crystallization trends of pyroxenes and spinels. *Meteoritics & Planetary Science* 31:877–892.
- Arai T., Otsuki M., Ishii T., Mikouchi T., and Miyamoto M. 2005. Mineralogy of Yamato-983885 lunar polymict breccia with KREEP basalt, a high-Al basalt, a very low-Ti basalt and Mg-rich rocks. *Antarctic Meteorite Research* 18:17–45.
- Bickel C. E. and Warner J. L. 1978. Survey of lunar plutonic and granulitic lithic fragments. Proceedings, 9th Lunar and Planetary Science Conference. pp. 629–652.
- Bunch T. E., Wittke J. H., and Korotev R. L. 2006. Petrology and composition of lunar feldspathic breccias NWA 2995, Dhofar 1180, and Dhofar 1428 (abstract). *Meteoritics & Planetary Science* 41:A31.
- Cahill J. T., Floss C., Anand M., Taylor L. A., Nazarov M. A., and Cohen B. A. 2004. Petrogenesis of lunar highlands meteorites: Dhofar 025, Dhofar 081, Dar al Gani 262, and Dar al Gani 400. *Meteoritics & Planetary Science* 39:503–529.
- Cohen B. A., James O. B., Taylor L. A., Nazarov M. A., and Barsukova L. D. 2004. Lunar highland meteorite Dhofar 026 and Apollo sample 15418: Two strongly shocked, partially melted, granulitic breccias. *Meteoritics & Planetary Science* 39:1419–1447.
- Crozaz G. and Wadhwa M. 2001. The terrestrial alteration of Saharan shergottites Dar al Gani 476 and 489: A case study of weathering in a hot desert environment. *Geochimica et Cosmochimica Acta* 65:971–978.
- Crozaz G., Floss C., and Wadhwa M. 2003. Chemical alteration and REE mobilization in meteorites from hot and cold deserts. *Geochimica et Cosmochimica Acta* 67:4727–4741.
- Fagan T. J., Taylor G. J., Keil K., Hicks T. L., Killgore M., Bunch T. E., Wittke J. H., Mittlefehldt D. W., Clayton R. N., Mayeda T. K., Eugster O., Lorenzetti S., and Norman M. D. 2003. Northwest Africa 773: Lunar origin and iron-enrichment trend. *Meteoritics & Planetary Science* 38:529–554.
- Floss C., James O. B., McGee J. J., and Crozaz G. 1998. Lunar ferroan anorthosite petrogenesis: Clues from trace element distributions in FAN subgroups. *Geochimica et Cosmochimica Acta* 62:1255–1283.
- Gnos E., Hofmann B. A., Al-Kathiri A., Lorenzetti S., Eugster O., Whitehouse M. J., Villa I., Jull A. J. T., Eikenberg J., Spettel B., Krähenbühl U., Franchi I. A., and Greenwood G. C. 2004. Pinpointing the source of a lunar meteorite: Implications for the evolution of the Moon. *Science* 305:657–659.
- Greim L., Motamedi K., and Niedergesäß R. 1976. Ein Rechenprogramm zur Auswertung der Messungen bei der instrumentellen Multielement-Neutronenaktivierungsanalyse. GKSS 76/E/49.
- Haskin L. A. 1998. The Imbrium impact event and the thorium distribution at the lunar highlands surface. *Journal of Geophysical Research* 103:1679–1689.
- Heiken G. H., Vaniman D. T., and French B. M. 1991. *Lunar sourcebook—A user's guide to the moon*. Cambridge: Cambridge University Press. 753 p.
- Hill D. H. and Boynton W. V. 2003. Chemistry of the Calalong Creek lunar meteorite and its relationship to lunar terranes. *Meteoritics & Planetary Science* 38:595–626.
- Hsu W., Guan Y., Wang H., Leshin L. A., Wang R., Zhang W., Chen X., Zhang F., and Lin C. 2004. The Iherzolitic shergottite Grove Mountains 99027: Rare earth element geochemistry. *Meteoritics & Planetary Science* 39:701–709.
- Hsu W., Guan Y., Ushikubo T., Bartoschewitz R., Zhang A., Kurtz Th., and Kurtz P. 2006. Petrology and REE geochemistry of the lunar meteorite Sayh al Uhaymir 300 (abstract). *Meteoritics & Planetary Science* 41:A79.
- Hsu W., Zhang A., Guan Y., Ushikubo T., and Bartoschewitz R. 2007. Sayh al Uhaymir 300: Petrology, mineralogy, and trace element geochemistry (abstract #1149). 38th Lunar and Planetary Science Conference. CD-ROM.
- Hudgins J. A., Walton E. L., and Spray J. G. 2007. Mineralogy, petrology, and shock history of lunar meteorite Sayh al Uhaymir 300: A crystalline impact-melt breccia (abstract #1674). 38th Lunar and Planetary Science Conference. CD-ROM.
- Jolliff B. L., Gillis J. J., Haskin L. A., Korotev R. L., and Wieczorek M. A. 2000. Major lunar crustal terranes: Surface expressions and crustal mantle origins. *Journal of Geophysical Research* 105: 4197–4216.

- Karouji Y., Arai T., and Ebihara M. 2006. Chemical composition of another KREEP-rich lunar regolith breccia Yamato 983885 (abstract #1919). 37th Lunar and Planetary Science Conference. CD-ROM.
- Koeberl C. 1988. Trace element geochemistry of lunar meteorites Yamato-791197 and 82192. *Proceedings of the NIPR Symposium on Antarctic Meteorites* 1:122–134.
- Koeberl C., Kurat G., and Brandstätter F. 1996. Mineralogy and geochemistry of lunar meteorite Queen Alexandra Range 93069. *Meteoritics & Planetary Science* 31:897–908.
- Korotev R. L., Jolliff B. L., and Rockow K. M. 1996. Lunar meteorite Queen Alexandra Range 93069 and the iron concentration of the lunar highlands surface. *Meteoritics & Planetary Science* 31:909–924.
- Korotev R. L., Jolliff B. L., Zeigler R. A., Gillis J. J., and Haskin L. A. 2003. Feldspathic lunar meteorites and their implications for compositional remote sensing of the lunar surface and the composition of the lunar crust. *Geochimica et Cosmochimica Acta* 67:4895–4923.
- Korotev R. L. 2005. Lunar geochemistry as told by lunar meteorites. *Chemie der Erde* 65:297–346.
- Korotev R. L., Bartoschewitz R., Kurtz Th., and Kurtz P. 2007. Sayh al Uhaymir 300—The most mafic of the feldspathic lunar meteorites. *Meteoritics & Planetary Science* 42:A86.
- Korotev R. L., Irving A. J., and Bunch T. E. 2008. Keeping up with the lunar meteorites—2008 (abstract #1209). 39th Lunar and Planetary Science Conference. CD-ROM.
- Lawrence D. J., Feldman W. C., Barraclough B. L., Binder A. B., Elphic R. C., Maurice S., and Thomsen D. R. 1998. Global elemental maps of the Moon: The Lunar Prospector gamma ray spectrometer. *Science* 281:1484–1489.
- Lawrence D. J., Feldman W. C., Barraclough B. L., Binder A. B., Elphic R. C., Maurice S., Miller M. C., and Prettyman T. H. 2000. Thorium abundances on the lunar surface. *Journal of Geophysical Research* 105:20,307–20,331.
- Lindstrom M. M. and Lindstrom D. J. 1986. Lunar granulites and their precursor anorthositic norites of the early lunar crust. *Proceedings, 17th Lunar and Planetary Science Conference*. pp. D263–276.
- Nazarov M. A., Demidova S. I., Patchen A., and Taylor L. A. 2002. Dhofar 301, 302, and 303: Three new lunar highland meteorites from Oman (abstract #1293). 33rd Lunar and Planetary Science Conference. CD-ROM.
- Norman M. D. 1981. Petrology of suevitic lunar breccia 67016. *Proceedings, 12th Lunar and Planetary Science Conference*. pp. 235–252.
- Palme H., Spettel B., Jochum K. P., Dreibus G., Weber H., Weckwerth G., Wonke H., Bishoff A., and Stöffler D. 1991. Lunar highland meteorites and the composition of the lunar crust. *Geochimica et Cosmochimica Acta* 55:3105–3122.
- Papike J. J. 1998. Comparative planetary mineralogy: Chemistry of melt-derived pyroxene, feldspar, and olivine. In *Planetary materials*, edited by Papike J. J. Washington, D. C.: Mineralogical Society of America. pp. 7.1–7.11.
- Papike J. J., Fowler G. W., and Shearer C. K. 1996. Ion microprobe investigation of plagioclase and orthopyroxene from lunar Mg suite norites: Implications for calculating parental melt REE concentrations and for assessing post crystallization REE redistribution. *Geochimica et Cosmochimica Acta* 60:3967–3978.
- Papike J. J., Fowler G. W., and Shearer C. K. 1997. Evolution of the lunar crust: SIMS study of plagioclase from ferroan anorthosites. *Geochimica et Cosmochimica Acta* 61:2343–2350.
- Semenova A. S., Nazarov M. A., Konokova N. N., Patchen A., and Taylor L. A. 2000. Mineral chemistry of lunar meteorite Dar al Gani 400 (abstract #1252). 31st Lunar and Planetary Science Conference. CD-ROM.
- Takeda H., Yamaguchi A., Bogard D. D., Karouji Y., Ebihara M., Ohtake M., Saiki K., and Arai T. 2006. Magnesian anorthosites and a deep crustal rock from the farside crust of the moon. *Earth and Planetary Science Letters* 247:171–184.
- Warren P. H. 1985. The magma ocean concept and lunar evolution. *Annual Review of Earth and Planetary Sciences* 13:201–240.
- Warren P. H. 2003. The Moon. In *Meteorites, comets and planets*, edited by Davis A. M., Treatise on Geochemistry, vol. 1. Amsterdam: Elsevier. pp. 559–599.
- Warren P. H. and Kallemeyn G. W. 1991. Geochemical investigation of five lunar meteorites: Implications for the composition, origin and evolution of the lunar crust. *Proceedings of the NIPR Symposium on Antarctic Meteorites* 4:91–117.
- Warren P. H., Jerde E. A., and Kallemeyn G. W. 1989. Lunar meteorites: Siderophile element contents, and implications for the composition and origin of the Moon. *Earth and Planetary Science Letters* 91:245–260.
- Warren P. H., Ulf-Möller F., and Kallemeyn G. W. 2005. “New” lunar meteorites: impact-melt and regolith breccias and large-scale heterogeneities of the upper lunar crust. *Meteoritics & Planetary Science* 41:989–1014.
- Zhang A. and Hsu W. 2006. Petrographic and mineralogical studies of the lunar meteorite Dhofar 1180. *Meteoritics & Planetary Science* 41:A197.
- Zhang A. and Hsu W. 2007. A KREEP clast in the lunar meteorite Dhofar 1180 (abstract #1108). 38th Lunar and Planetary Science Conference. CD-ROM.