Multiple lithic clasts in lunar breccia Northwest Africa 7948 and implication for the lithologic components of lunar crust

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(Received 05 June 2017; revision accepted 14 December 2017)

Abstract—This study presents the petrography, mineralogy, and bulk composition of lunar regolith breccia meteorite Northwest Africa (NWA) 7948. We identify a range of lunar lithologies including basaltic clasts (very low-titanium and low-titanium basalts), feldspathic lithologies (ferroan anorthosite, magnesian-suite rock, and alkali suite), granulites, impact melt breccias (including crystalline impact melt breccias, clast-bearing impact melt breccias, and glassy melt breccias), as well as regolith components (volcanic glass and impact glass). A compositionally unusual metal-rich clast was also identified, which may represent an impact melt lithology sourced from a unique Mg-suite parent rock. NWA 7948 has a mingled bulk rock composition (Al2O3 = 21.6 wt% and FeO = 9.4 wt%) and relatively low concentrations of incompatible trace elements (e.g., Th = 1.07 ppm and Sm = 2.99 ppm) compared with Apollo regolith breccias. Comparing the bulk composition of the meteorite with remotely sensed geochemical data sets suggests that the sample was derived from a region of the lunar surface distal from the nearside Th-rich Procellarum KREEP Terrane. Our investigations suggest that it may have been ejected from a nearside highlands-mare boundary (e.g., around Mare Crisium or Orientale) or a cryptomare region (e.g., Schickard-Schiller or Mare Smythii) or a farside highlands-mare boundary (e.g., Mare Australe, Apollo basin in the South Pole–Aitken basin). The distinctive mineralogical and geochemical features of NWA 7948 suggest that the meteorite may represent lunar material that has not been reported before, and indicate that the lunar highlands exhibit wide geological diversity.

INTRODUCTION

The global distribution of elements and minerals revealed by remote sensing missions has led to a generalized subdivision of the lunar surface into three distinct geologic terranes (1) the Procellarum KREEP Terrane (PKT), which is the region sampled by the Apollo and Lunar missions; (2) the South Pole–Aitken basin (SPA), the largest impact basin on the Moon; and (3) the Farside Highlands Terrane (FHT) (Jolliff et al. 2000; Gillis et al. 2003; Ohtake et al. 2012). The equatorial latitudes of the PKT have been sampled by the Apollo missions and the outer FHT portion of the eastern limb of the lunar nearside by the Luna missions. Our knowledge of the lunar crust has been greatly extended by the studies of lunar meteorites as they represent samples ejected from random locations across the lunar surface (e.g., Korotev 2005; Day et al. 2006; Yamaguchi et al. 2010; Gross et al. 2014).

To date, over 310 individual (named) lunar meteorites have been recovered from hot and cold deserts around the world including Oman, Northwest
Africa, and Antarctica (Meteoritical Bulletin Database, accessed October 1, 2017). Many of these samples are brecciated, consisting of mixtures of near-surface lithologies and mineral fragments sourced from a range of different types of lunar parent rock (e.g., Korotev et al. 2009; Joy and Arai 2013). Such brecciated meteorites could provide significant insights into the average compositions of their source regions, the lithological diversity within the lunar crust, and the geological evolution history of the Moon (e.g., Gnos et al. 2004; Korotev et al. 2009; Gross et al. 2014).

Lunar meteorites also have the potential to sample new lithologies (i.e., not sampled by the Apollo/Luna missions). For example, (1) in Dhofar 489, Takeda et al. (2006) identified two new lithologies (magnesian anorthosite [MAN] and spinel troctolite), which were thought to be unique samples from the farside crust of the Moon; (2) in lunar meteorite ALHA 81005, Gross and Treiman (2011) reported a new Mg-rich spinel-rich lithology, which has also been detected by the visible and near-infrared imaging spectrometer on the Chandrayaan-1 spacecraft (Pieters et al. 2011); (3) in impact melt breccia SaU 169, Lin et al. (2012) reported a new type of lithic clast of very high-K (VHK) KREEP lithology on the Moon; (4) in Dhofar 789, Nagaoka et al. (2014) reported several pure anorthosite clasts (>98% by mode of plagioclase), which are thought to be widely distributed across the Moon; and (5) in lunar meteorite MAC 88105, Joy et al. (2014) recognized a compositionally unusual clast, which either has a unique lunar magmatic source or has a nonlunar origin.

Northwest Africa (NWA) 7948, weighing 59.8 g, was recovered in 2013. It was classified as a mingled feldspathic regolith breccia (i.e., mixed highlands-mare materials; Korotev et al. 2009; Ruzicka et al. 2015) and is presumably paired with NWA 7834 clan (Korotev and Irving 2014). Currently, no detailed petrographic or mineralogical data have been reported on this lunar meteorite. Our preliminary observations show that a wide variety of lithic clasts from highland regions and mare basalts are presented in a single section (~3.6 cm²) of NWA 7948, making this meteorite a good target for further understanding the composition and lithology of the lunar crust. In this study, we report the detailed petrography, mineralogy, and geochemistry of NWA 7948 to (1) characterize its multiple lithic clast components, (2) constrain its possible launch location(s), and (3) discuss its implications for the lithologies within the lunar crust.

**SAMPLE AND METHODS**

A polished thick section (approximately 20 × 18 × 1 mm) was made for this study (Fig. 1a). The section was carbon-coated prior to backscatter electron (BSE) imaging. The BSE images were obtained using a Phillips XL30 FEG environmental scanning electron microscope (ESEM) at the University of Manchester, and a FEI-Scios field emission scanning electron microscope (FEG-SEM) at the Institute of Geochemistry, Chinese Academy of Sciences (Fig. 1b). The operating conditions were 15–20 kV accelerating voltage, 3.2–6.4 nA beam current, and 7–15 mm working distance. The X-ray elemental mapping was performed to identify fine-grained minerals using a Zeiss SEM at the University of Manchester, with an accelerating voltage of 20 kV, working distance of 12.6 mm, and a magnification of ×250. Qualitative element maps of C, O, Na, Mg, Al, Si, P, S, K, Ca, Ti, Cr, Fe, Co, Zr, and Ni were collected. A false-color X-ray element map of NWA 7948 is shown in Fig. 1c, where colors represent relative concentrations of different elements.

Quantitative chemical compositions of silicate minerals and bulk clasts were determined by using a Cameca SX100 electron microprobe (EMP) analyzer at the University of Manchester. For silicate mineral phases, the operating conditions were 15 kV accelerating voltage, 20 nA beam current, and a 1 μm focused beam. The typical detection limits for oxides of most elements are approximately 0.03 wt%. To estimate the bulk compositions of glass and fine-grained impact melt breccia clasts, the beam was defocused to a diameter of 10 and 20 μm, respectively, with the same current and voltage setting noted above. For each clast, an average composition is estimated from approximately 20 points randomly selected across the clasts. The FeNi metal grains in NWA 7948 were analyzed using a JXA 8230 EMP at the Guilin University of Technology. The operating conditions were 15 kV accelerating voltage, 20 nA beam current, and a 1 μm focused beam. Natural and synthetic standards were used. Mineral chemistry data are presented in Tables S1–S6 in supporting information.

Fourier transform infrared (FTIR) analyses of plagioclase grains within the polished section of NWA 7948 were obtained using a PerkinElmer Spotlight-400 FTIR spectrometer and adjoining microspectroscopy mapping unit (with a cooled Hg-Cd-Te detector) at the University of Manchester. Scans were made from 650 to 4000 cm⁻¹ at 4 cm⁻¹ resolution. Background calibration was conducted using a polished gold-coated aluminum standard at regular intervals (every 10–15 analyses) in order to minimize overall uncertainty related to changes in the thermal background of the surrounding environment. Minerals were analyzed using a spot size of 25 × 25 μm, integrated over 32 scans. The maximum degree of shock experienced by a plagioclase of interest can be determined via analysis of the resulting FTIR spectra. Here we follow the approach of Martin et al.
to calculate plagioclase mineral shock pressure. This approach is based on the disappearance of the 1126 cm$^{-1}$ plagioclase Reststrahlen Band feature (calculated using continuum removed spectra with tie points at 1075 and 1200 cm$^{-1}$) with increasing shock, calibrated using the relationship defined by experimentally shocked plagioclase to index shock pressure history (Johnson et al. 2002).

A ~200 mg piece of NWA 7948 was powdered using a clean agate pestle and mortar to determine the bulk rock trace composition using PerkinElmer ELAN DRC-e inductively coupled plasma mass spectrometry (ICP-MS) techniques at the Institute of Geochemistry, Chinese Academy of Sciences. The detailed analytical methods are reported in Qi et al. (2000). The powdered samples (50 mg) were dissolved in polytetrafluoroethylene (PTFE)-lined stainless steel bombs using a HF + HNO$_3$ mixture for 48 h at ~190 °C. An internal standard solution containing the single element Rh was used to monitor signal drift during counting. Three standard reference materials (AGV-2, AMH-1, and GBPG-1) were used for analytical quality control. The analytical precision for most of the analyzed elements ranges from 5% to 10% (Table S7 in supporting information).

RESULTS

Petrography and Mineral Chemistry

NWA 7948 is lithologically diverse with a mixture of white, gray, and light brown lithic clasts ranging in size from <0.1 to 9.5 mm within a dark gray matrix (Fig. 1a). Texturally and compositionally (Figs. 1b and 1c), these clasts include basaltic clasts, feldspathic clasts, evolved clasts, granulites, impact melt breccias, a compositionally unusual metal-rich clast, glass beads, and the mineral fragments. The studied lithic clasts in this work are representative, but not exhaustive, of every single fragment observed in the section. The petrography and major element mineral chemistry of the representative lithic clasts in NWA 7948 are provided in Figs. 2 and 3 and Table 1. The detailed mineralogy and mineral chemistry of the representative lithic clasts are described further below.

Basaltic Clasts

Basaltic clasts in the studied section of NWA 7948 exhibit a wide range of textures and mineralologies. The textures range from fine-grained porphyritic texture (clast B1; Figs. 2a and 2b), to subophitic texture (clasts B2, B3, and B4; e.g., Fig. 2c), poikilitic texture (clast B5; Fig. 2d), a zoned fragment (clast B6; Fig. 2e), and coarse-grained olivine-rich texture (clasts B7–B9; e.g., Fig. 2f).

The fine-grained porphyritic basaltic clast (clast B1). Clast B1 exhibits a porphyritic texture with large (up to 300 lm) mafic phenocrysts in a fine-grained (<90 lm) matrix (Fig. 2a). The mafic phenocrysts include subhedral pyroxene and anhedral to subhedral olivine. In this clast, pyroxene has a higher abundance (~67%, by area) and occurs as elongated laths that are zoned from Mg-rich cores to Fe-rich rims (Wo$_{6.7}$En$_{66.6}$ to Wo$_{30.2}$En$_{32.9}$; Fig. 4a; Table 1). The olivine occurs at relatively low abundances (~67%, by area) and occurs as elongated laths that are zoned from Mg-rich cores to Fe-rich rims (Wo$_{6.7}$En$_{66.6}$ to Wo$_{30.2}$En$_{32.9}$; Fig. 4a; Table 1). The olivine occurs at relatively low abundances (~5%) and shows limited compositional range (Fo$_{3.9}$–44.1; Table 1). The matrix is composed of acicular plagioclase (An$_{87.5}$–93.7), interstitial pyroxene grains, and small (<5 µm) Cr-spinel grains (Fig. 2b). Comparing Ti# (atomic Ti/[Ti + Cr]) against
Fe# (atomic Fe/[Mg + Fe]), the pyroxenes analyzed within clast B1 have a very low-titanium (VLT) mare basalt affinity (Fig. 5).

The subophitic basaltic clasts (clasts B2, B3, and B4). The subophitic clasts are coarse grained relative to the overall size of the clast, making the analyzed areas not representative of the parent lithology. They are predominantly composed of pyroxene (~40–60%) and plagioclase (~25–40%), with lesser (~15%) amounts of olivine, silica, or Ti-rich spinel grains (e.g., Fig. 2c). Compositionally, the pyroxenes in clasts B2 and B3 are strongly zoned (Wo14.6En50.3 to Wo25.1En32.9 and Wo15.9En38.1 to Wo27.5En9.5, respectively), with a Fe-rich pyroxene rim (Fig. 4a). An olivine in clast B2 is

Fig. 2. BSE images of representative lithic clasts in NWA 7948. a) Fine-grained porphyritic basaltic clast B1. b) A close-up of the region marked in (a), showing the detailed texture of clast B1. c–f) The representative basaltic clasts in NWA 7948, showing a wide range of textures and mineralogies. g–i) The representative feldspathic clasts in NWA 7948. j, k) Two evolved clasts including quartz monzodiorite (j) and alkali feldspar (k) fragments. The mineral phases are labeled: Ol = olivine; Px = pyroxene; Pl = plagioclase; Si = silica; Sp = spinel; Kfs = K-rich feldspar.
magnesian with narrow chemical variation (Fo62.8–66.8; Table 1). Conversely, the olivine grain in clast B3 is extremely Fe-rich (i.e., fayalite; Fo0.3–0.4; Table 1), likely forming part of a mesostasis assemblage. Basaltic clast B4 shows little compositional variation and contains similar proportions of orthopyroxene (Wo10.0En60.6 to Wo18.1En56.2) and plagioclase (An93.1–93.3). Comparing pyroxene Ti# versus Fe# (Fig. 5), these subophitic basaltic clasts B2–B4 have a VLT mare basalt affinity. The plagioclase in these clasts is calcic (Table 1), typical of VLT mare basalts (Papike et al. 1991), and occurs as elongated subhedral grains that are enclosed by pyroxene.

Clasts B5 and B6. The basaltic clast B5, with poikilitic texture, consists of similar proportions of plagioclase (An93.1–93.3) and augite (Wo33.9En24.5) with

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Fig. 3. BSE images of the representative lithic clasts in NWA 7498. a, b) The granulite clast exhibiting a granoblastic texture. c–e) BSE image of the crystalline impact melt clast (c), clast-bearing impact melt breccia (d), and glassy melt breccia clast (e). f, g) Large (~350 μm) volcanic glass bead (f) and impact glass sphere (g). h) A typical matrix area consisting of mineral debris. i) The shock pocket in NWA 7948. j, k) The plagioclase (j) and maskelynite (k) grain in the matrix. The mineral phases are labeled: Ol = olivine; Px = pyroxene; Pl = plagioclase; Sp = spinel; Si = silica; Tro = troilite; Mask = maskelynite.
low-Ca pyroxene (Wo\textsubscript{17.4}En\textsubscript{29.6}) found as exsolution lamellae (Fig. 2d; Table 1). Clast B6 consists of large (~800 μm) subhedral pyroxene grains (Fig. 2e), enclosing small (~50 μm) euhedral Cr-spinel grains. Pyroxenes in this clast show relatively larger chemical variations (Wo\textsubscript{11.9}En\textsubscript{58.2} to Wo\textsubscript{33.3}En\textsubscript{28.5}; Table 1). The Fe\# and Ti\# of pyroxene in both clasts are similar to the Apollo and Luna VLT mare basalts (Fig. 5).

The coarse-grained olivine-rich basaltic clasts (clasts B7, B8, and B9). The poikilitic clasts B7 and B8 are mainly composed of pyroxene (~55%), plagioclase (~13%), olivine (~27%), and accessory (~5%) Cr-spinel grains (Fig. 2f). Pyroxenes in clasts B7 and B8 display relatively large compositional variations (i.e., Wo\textsubscript{5.6}En\textsubscript{53.2} to Wo\textsubscript{33.5}En\textsubscript{24.5}; Table 1). The pyroxenes in this clast display little compositional variation (Wo\textsubscript{6.9}En\textsubscript{44.0} to Wo\textsubscript{6.9}En\textsubscript{44.5}; Table 1), while the olivine and plagioclase are relatively homogeneous (Fo\textsubscript{63.1} to Fo\textsubscript{63.6} and An\textsubscript{92.1} to An\textsubscript{92.6}, respectively; Table 1). Cr-spinel and pyroxene grains (up to ~50 μm) in these clasts are present in a minor phase and commonly present as anhedral or subhedral grains. Another coarse-grained olivine-rich basaltic clast B9 is predominantly composed of ~90% mafic minerals (olivine and pyroxene) and lesser amounts (~10%) of plagioclase and Cr-spinel.

The pyroxenes in this clast display little compositional variation (Wo\textsubscript{6.9}En\textsubscript{44.0} to Wo\textsubscript{6.9}En\textsubscript{44.5}; Table 1), while the olivine and plagioclase are relatively homogeneous (Fo\textsubscript{63.1} to Fo\textsubscript{63.6} and An\textsubscript{92.1} to An\textsubscript{92.6}, respectively; Table 1). The Ti\# and Fe\# of pyroxenes in these olivine-rich basaltic clasts B7–B9 are similar to low-Ti Apollo and Luna basalts (Fig. 5).

**Feldspathic Clasts: Anorthosite and Noritic/Troctolitic Anorthosite Clasts**

Five lithic clasts were recognized as being feldspathic on the basis that they have an abundance (~75%) of plagioclase (e.g., Figs. 2g–i). They have a wide range of clast sizes ranging from 0.25 to 0.6 mm in diameter.
diameter. Modally, these feldspathic clasts range from anorthosite (clasts F1, F2, and F3; e.g., Fig. 2g) to noritic/troctolitic anorthosite (clasts F4 and F5; Figs. 2h and 2i, respectively), although we note that such modes derived from such small fragments may not be representative of the parent lithology.

The anorthosite clasts (clasts F1, F2, and F3) contain >90% plagioclase and minor amounts (<10%) of irregular pyroxene and/or ilmenite grains (e.g., Fig. 2g). Plagioclase in these clasts is highly calcic (An$_{95.3-95.5}$, An$_{95.0-95.7}$, and An$_{94.0-95.3}$, respectively; Table 1). The pyroxenes have moderate Mg# values (= atomic 100 × Mg/[Mg + Fe]; Mg# = 56.5–70.4 for clast F1, Mg# = 60.1–67.6 for clast F2, and Mg# = 46.8–50.4 for clast F3; see Fig. 6).

The noritic/troctolitic anorthosite clasts (clasts F4 and F5; Figs. 2h and 2i) predominantly contain ~75% anorthitic plagioclase with <25% mafic minerals (olivine and/or pyroxene). The mafic minerals and plagioclase in these two clasts have significantly different compositions compared with anorthosite clasts F1–F3; mafic minerals in clasts F4 and F5 have relatively higher Mg# values (73.7–79.1 and 83.5–83.6, respectively; Fig. 6) and plagioclase grains have comparatively lower An contents (An$_{89.1-90.9}$ and An$_{88.4-94.2}$, respectively; Fig. 6).

**Evolved Clasts**

Clasts E1 and E2 represent evolved lithologies (Figs. 2j and 2k). Clast E1 is a quartz monzodiorite (QMD; Fig. 2j), whereas clast E2 is an alkali feldspar (Fig. 2k). The QMD clast E1 contains sodic plagioclase (An$_{41.1-48.5}$Mg$_{49.3-57.3}$Or$_{1.3-2.2}$), K-feldspar (An$_{3.1-14.9}$Ab$_{29.9-41.6}$Or$_{43.5-67.0}$), and silica (Fig. 4c; Table 1) in a granophyric intergrowth. Clast E2 is a large (~350 µm) Na-rich plagioclase fragment (An$_{32.2-56.8}$Ab$_{41.3-66.2}$Or$_{1.4-2.6}$; Fig. 4c; Table 1).

**Granulite Clast**

A large granulite fragment (clast R; ~0.4 × 1 mm in size) is also present in NWA 7948. It has a subrounded ellipse-shaped clast boundary (Fig. 3a), displaying a granoblastic texture and subrounded aggregates of mafic
silicates (Fig. 3b). Modally, this granulite clast is a noritic or troctolitic anorthosite, containing ~75% anorthitic plagioclase (An$_{92.0-94.0}$) with approximately similar proportions of low-Ca pyroxene (Wo$_{3.2}$En$_{81.1}$ to Wo$_{7.6}$En$_{69.0}$; Fig. 4b) and olivine (Fo$_{82.0-82.1}$), as well as accessory spinel (Table 1).

Impact Melt Breccia Clasts

Clasts produced by impact processes are common in the studied section. They range from ~500 µm up to 6 mm in size and have a variety of impact melt textures (Figs. 3c–e), including crystalline impact melt (e.g., clast IM1; Fig. 3c), clast-bearing impact melt breccia (e.g., clast IM2; Fig. 3d), and glassy melt breccia types (e.g., clast IM3; Fig. 3e).

The crystalline impact melts are texturally similar to crystalline igneous lithologies; however, they occasionally contain relict (xenolithic) mineral fragment clasts inherited from the target rock and also contain metallic components probably sourced from the impactor (Papike et al. 1998). Crystalline impact melt clast IM1 (Fig. 3c) exhibits a subophitic texture with subhedral plagioclase (An$_{95.7-96.4}$) enclosing anhedral to subhedral pyroxene (Wo$_{13.6}$En$_{57.6}$ to Wo$_{13.8}$En$_{56.0}$) and olivine (Fo$_{63.1}$) crystals as well as a minor component of small (~5 µm) FeNi metal blebs (Table 1). This clast has a FeO content of 1.63 (±2.19 wt% 1SD) and Al$_2$O$_3$ content of 31.8 (±3.8 wt% 1SD), suggesting that it formed from melting of feldspathic target rocks rather than basaltic or KREEP-rich lithologies (see Fig. 7 for context).

A large (5 × 6 mm) clast-bearing impact melt breccia clast (clast IM2; Fig 3d) has a lamellar structure (~100 to 700 µm thick) that contacts sharply with the matrix. The glassy matrix contains abundant fragments of plagioclase (An$_{88.2-89.5}$), olivine (Fo$_{73.0-73.3}$), and pyroxene (Wo$_{4.3}$En$_{69.3}$ to Wo$_{10.4}$En$_{66.0}$), as well as minor silica and FeNi metal grains (Table 1). This clast has a bulk Al$_2$O$_3$ and FeO content of 24.6 ± 4.3 wt% and 6.49 ± 3.64 wt%, respectively (1SD; Fig. 7). This composition is similar to the range of lunar highland materials (i.e., lunar highland meteorites and feldspathic impact melt; Cahill et al. 2004; Joy et al. 2010). One glassy melt breccia clast (clast IM3, measuring ~500 × 500 µm; Fig. 3e) has a heterogeneous texture, containing several large (up to 300 µm) plagioclase fragments (An$_{83.8-94.7}$; Table 1) fused together by glass with a MgO/Al$_2$O$_3$ ratio of about 0.66 (Table 2).

A Compositionally Unusual Metal-Rich Clast

One small (~200 × 200 µm) compositionally unusual metal-rich clast (clast UM) was observed in the section of
Table 2. Chemical composition (wt%) of glasses from lithic clasts within NWA 7948, compared with the Apollo 17 VLT picritic green glasses (Shearer and Papike 1993).

|                  | NWA 7948 | Apollo 17 VLT green glasses* |
|------------------|----------|-----------------------------|
|                  | Clast IM3 | Clast UM | Clast G1 | Clast G2 | Clast G3 | Clast IM3 | Clast UM | Clast G1 | Clast G2 | Clast G3 | Clast IM3 | Clast UM | Clast G1 | Clast G2 | Clast G3 |
|                  | (N = 4)  | (N = 4)  | (N = 9)  | (N = 6)  | (N = 3)  | VLT-1   | VLT-2   | VLT-3   |
| SiO₂             | 48.3 ± 0.36 | 74.8 ± 0.97 | 45.5 ± 0.24 | 44.1 ± 0.90 | 47.3 ± 0.23 | 46.3 | 46.0 | 45.9 |
| TiO₂             | 1.26 ± 0.04 | 1.92 ± 0.09 | 0.51 ± 0.02 | 0.59 ± 0.03 | 1.39 ± 0.03 | 0.55 | 0.86 | 0.88 |
| Al₂O₃            | 11.2 ± 0.40 | 12.2 ± 0.58 | 9.70 ± 0.10 | 9.02 ± 0.06 | 11.9 ± 0.20 | 9.82 | 10.2 | 9.98 |
| Cr₂O₃            | 0.22 ± 0.04 | 0.04 ± 0.03 | 0.47 ± 0.01 | 0.53 ± 0.04 | 0.23 ± 0.04 | 0.46 | 0.54 | 0.41 |
| FeO              | 17.9 ± 0.47 | 1.90 ± 0.18 | 18.6 ± 0.10 | 20.0 ± 0.33 | 18.4 ± 0.50 | 19.5 | 18.8 | 18.6 |
| MnO              | 0.26 ± 0.02 | 0.01 ± 0.01 | 0.24 ± 0.02 | 0.21 ± 0.06 | 0.19 ± 0.02 | 0.30 | 0.24 | 0.25 |
| MgO              | 7.45 ± 0.38 | 0.27 ± 0.03 | 14.5 ± 0.05 | 14.2 ± 0.07 | 6.24 ± 0.20 | 14.1 | 13.8 | 14.0 |
| CaO              | 12.1 ± 0.15 | 0.90 ± 0.57 | 9.64 ± 0.08 | 9.03 ± 0.06 | 12.3 ± 0.05 | 9.41 | 9.86 | 9.30 |
| Na₂O             | 0.31 ± 0.04 | 0.78 ± 0.32 | 0.25 ± 0.02 | 0.22 ± 0.02 | 0.30 ± 0.01 | 0.16 | 0.23 | 0.24 |
| K₂O              | 0.05 ± 0.01 | 5.17 ± 1.19 | b.d.       | 0.03 ± 0.02 | 0.01       |       |       |       |
| P₂O₅             | 0.04 ± 0.01 | 0.13 ± 0.24 | b.d.       | b.d.       | b.d.      |       |       |       |
| Mg#              | 42.6        | 20.3       | 58.1       | 55.8       | 37.6       | 56.3 | 56.7 | 57.3 |
| MgO/Al₂O₃        | 0.66        | 0.02       | 1.49       | 1.57       | 0.52       | 1.44 | 1.35 | 1.4  |

*Shearer and Papike (1993); N = number of EMP analyses; Errors for major elements are 1σ standard deviations; Mg# = atomic 100 × Mg/[Mg + Fe].

The typical detection limits for oxides of most elements are approximately 0.03 wt%.
b.d. = below detection limit.

Fig. 8. a, b) BSE (a) and X-ray composite (b) images of clast UM. c, d) A close-up of the regions marked in (a), showing the detailed textures of the clast UM. The mineral phases are labeled: Low-Ca = low-Ca pyroxene; High-Ca = high-Ca pyroxene; Ol = olivine; Pl = plagioclase; Tro = troilite; FeNi = FeNi metal; Sch = schreibersite; Ap =apatite. (Color figure can be viewed at wileyonlinelibrary.com.)
NWA 7948 (Fig. 8). The most distinctive petrographic features of clast UM are that it contains ~15% FeNi metal with a small amount (~1%) of troilite and schreibersite, with grain sizes ranging from ~10 to 50 μm (Fig. 8a). Other phases in this clast include pyroxene (~22%), plagioclase (~52%), and glassy mesostasis (~8%). Abundant tiny (<2 μm) metal grains are scattered in this clast and are always associated with the Si, K-rich glassy mesostasis (Fig. 8c).

Pyroxene grains in this clast are subhedral in form and are associated with the metal grains or are enclosed in the plagioclase (Figs. 8a and 8b). These grains are zoned (Fig. 8d) and include both low-Ca pyroxene (Wo3.3–8.5En79.4–87.8Fs8.7–14.1) and high-Ca pyroxene (Wo32.4–38.7En52.2–56.3Fs9.1–11.9) types (Fig. 4b; Table 1). Both of them have the highest Mg# values within this section, displaying compositional variations ranging from Mg# = 85.3–91.0 in low-Ca pyroxene to Mg# = 81.9–86.1 in high-Ca pyroxene (Fig. 6). The Fe/Mn ratios for these pyroxenes are 36.1 ± 6.7 (1SD), which is relatively lower than most lunar pyroxenes of 44–80 (see Figs. 9a and 9b). The plagioclase is calcic with a wide compositional range (An82.1–97.2; Fig. 6). Metal grains are kamacitic with Ni and Co concentrations of 2.7–4.0 wt% and 0.23–0.29 wt%, respectively (Fig. 9f). The Si- and K-rich glassy mesostasis has a relatively low Mg# value (20.3) and contains 74.8 wt% SiO₂, 5.17 wt% K₂O, 1.9 wt% FeO, 1.92 wt% TiO₂, and 12.2 wt% Al₂O₃ (Table 2).

Glass Beads

Three glass beads (clasts G1, G2, and G3) were observed in this section (Figs. 3f and 3g). They occur as subrounded to rounded spherules, ranging in size from ~200 to ~350 μm. Two processes are known to produce the glass beads on the Moon: impact melting of lunar surface materials (impact origin) and pyroclastic eruption (volcanic origin). We follow the criteria (e.g., the petrographic features and MgO/Al₂O₃ ratios) proposed by Delano (1986) and Zeigler et al. (2006) to distinguish these two different types of glasses.

Beads G1 and G2 display homogeneous textures containing several small (~30–60 μm) vesicles. Both display a narrow compositional variation (45.5 ± 0.24 wt% SiO₂ in clast G1, 44.1 ± 0.90 wt% SiO₂ in G2; 18.6 ± 0.10 wt% FeO in clast G1, 20.0 ± 0.33 wt% FeO in G2, 1SD; Table 2). The MgO/Al₂O₃ ratios of these two clasts are 1.49 and 1.57, respectively (Table 2). These higher MgO/Al₂O₃ ratios are consistent with the ratios of Apollo volcanic glasses (i.e., MgO/Al₂O₃ >1.25; Zeigler et al. 2006).

Clast G3 exhibits a heterogeneous texture, containing some relict mineral grains of plagioclase (Fig. 3g). Relative to beads G1 and G2, this clast has a lower MgO/Al₂O₃ ratio of 0.52 (Table 2), which is consistent with an impact origin (i.e., MgO/Al₂O₃ <1.25; Zeigler et al. 2006). Clast G3 has lower bulk Mg# (37.6), intermediate bulk Al₂O₃ content (11.9 wt%), and low to intermediate bulk TiO₂ content of 1.39 wt% (Table 2). These compositional characteristics indicate that clast G3 probably melted from a region containing a mix of low-Ti mare basalts and nonmare-highland rocks.

Mineral Fragments and Matrix

The matrix of the meteorite is relatively large-grained (up to 0.5 mm) and consists mostly of individual mineral fragments with shock veins and melt pockets (Figs. 3h and 3i). The silicate minerals (i.e., pyroxene, olivine, and plagioclase) are the main phases, while the nonsilicate minerals (e.g., FeNi metal, chromite, quartz, and troilite) are less common. The silicate fragments are commonly angular to subrounded in shape and have various grain sizes from <5 to ~500 μm. Pyroxene fragments usually have a large compositional range (Wo9.9En59.0 to Wo32.3En39.3; Fig. 4b; Table 1). The olivine grains show similar mineral composition with moderate Mg content (i.e., Fo# = 62.9–65.1; Table 1; Fig. 4c). In addition, plagioclase grains in the matrix are calcic with a large compositional range (An88.6–98.3; Fig. 4c).

Plagioclase FTIR Spectra

To get a good representation, we chose a selection of matrix plagioclase fragments with different shapes and morphological features (including some with microfractures and others that were homogeneous in BSE image) for in situ FTIR analysis. The analyzed plagioclases are all highly calcic (An94.97; Fig. 4c) and yet exhibit distinct FTIR spectra (Fig. 10). All spectra display a prominent reflectance band at ~930 cm⁻¹ (Fig. 10). Crystalline plagioclase spectra also display strong reflectance bands between ~1075 and 1200 cm⁻¹. Consistent with plagioclase, the Christensen Feature (i.e., the point of lowest reflectance; CF) position is situated at 1207 ± 9.3 cm⁻¹ (1SD uncertainty). One maskelynite crystal with a very smooth BSE appearance (Fig. 3k) was analyzed, displaying a broad reflectance feature at ~930 cm⁻¹ and a CF position of 1206 cm⁻¹. Maximum %Reflectance of the Reststrahlen bands averages at ~35–55%R for plagioclase and ~30%R for maskelynite (Fig. 10).

NWA 7948 Bulk Rock Composition

The bulk major elements and bulk trace elements of NWA 7948 are reported in Table 3. Our results are similar to the bulk composition determined by the INAA (instrumental neutron activation analysis) technique.
Korotev and Irving (2014). NWA 7948 has a “mingled” or intermediate bulk composition that is distinctive from the typical “endmember” feldspathic lunar meteorites and mare basalts. The $\text{Al}_2\text{O}_3$ and FeO contents are 21.6 and 9.4 wt% (Table 3), respectively, which fall between the composition of highland materials and mare basalts (Fig. 7). For the trace elements, NWA 7948 exhibits relatively low incompatible trace element concentrations ($\text{Th} = 1.07$ ppm, $\text{Sm} = 2.99$ ppm, and $\text{Sc} = 18.6$ ppm; Table 3) compared with high-K KREEP and other KREEP-bearing breccias. Chondrite-normalized rare earth element (REE) profiles exhibit a relative LREE-enriched pattern ($[\text{La}/\text{Lu}]_{\text{cn}} = 2.4$) with negative Eu-anomalies ($\text{Eu}/\text{Eu}^* = 0.8$, where $\text{Eu}/\text{Eu}^*$ is calculated as $\text{Eu}_{\text{cn}}/[\text{Sm}_{\text{cn}} \times \text{Gd}_{\text{cn}}]$; Fig. 11).

**DISCUSSION**

The anorthite content of most plagioclase (An $>90$), molar Fe-Mn trends in mafic minerals (Fig. 12), and petrographic features (e.g., igneous clasts, impact melt clasts, and impact glass beads) within NWA 7948 are similar to other lunar samples and strongly support the lunar classification of this meteorite (Sokol et al. 2008; Papike et al. 2009).

The relative abundance of larger clasts comprised of material not melted by impact processes indicates that NWA 7948 probably consolidated from a relatively immature regolith (McKay et al. 1991). However, this meteorite does contain a regolith component (i.e., the glass spherules from volcanic and impact sources) suggestive of a more mature regolith formation environment (McKay et al. 1991).

**Shock Effects of NWA 7948**

NWA 7948 is a polymict regolith breccia which must have been formed through impact mixing of lunar lithologies in a near-surface regolith environment. The observed impact-induced shock effects in NWA 7948...
mainly include glassy shock veins, melt pockets (Fig. 3i), and the fractured (cracked) minerals. Plagioclase fragments in the studied section notably exhibit a wide variety of shock effects. Some anorthite that have experienced lower shock stages are slightly fractured, but not melted (Fig. 3j), while the feldspars (An > 90) that have experienced higher shock stages display evidence of transformation into maskelynite (Fig. 3k). Maskelynite is easily identified by FTIR spectral data (Fig. 10) and displays a lack of absorption features expected of crystalline plagioclase. The conversion of plagioclase to maskelynite suggests that some plagioclase has experienced higher shock metamorphism, corresponding to a minimum shock pressure of about 20–35 GPa (Fritz et al. 2017).

Plagioclase FTIR spectra have been shown to change systematically with increasing shock (e.g., Johnson et al. 2002; Johnson 2012; Martin et al. 2017; Pernet-Fisher et al. 2017). Specifically, certain reflectance band features systematically decrease in % reflectance with increasing shock. Thus, the well-defined correlations between FTIR spectral features (such as band depths) of experimentally shocked plagioclase chips and their known peak shock pressure intensities can be used for estimating shock pressures for “unknown” plagioclase crystals. Here we follow the approach of Pernet-Fisher et al. (2017) in order to estimate peak shock for the plagioclase crystals investigated here. This method was adapted from Johnson et al. (2002) for plagioclase compositions relevant to the Moon. This method uses the disappearance of the 1126 cm\(^{-1}\) reflectance band feature (calculated using continuum removed spectra with tie points at 1075 and 1200 cm\(^{-1}\)) with increasing shock, based on the relationship defined by experimentally shocked plagioclase to index shock pressure history (see Pernet-Fisher et al. 2017). Plagioclase in this sample spans a range of shock states from unshocked (Pl-1, < 1 GPa; Fig. 10) to highly shocked (Pl-4, ~ 23 GPa; Fig. 10). The FTIR spectra for one feldspar that display a smooth appearance in BSE images (i.e., Fig. 3k) are consistent with maskelynite, displaying only one broad reflectance feature at ~ 900 cm\(^{-1}\) (Fig. 10). The CF positions of plagioclase and maskelynite are the same/similar (1207 and 1206 cm\(^{-1}\), respectively), confirming that this phase is maskelynite and not impact melt glass, whose CF position would shift to lower wavenumbers.

What Crustal Regions Were Sampled in the NWA 7948 Parent Regolith?

Anorthosite Clast Heritage

On the classic lunar crust classification tool of Mg\# in mafic minerals versus plagioclase An\# (Fig. 6), the anorthosite clasts (i.e., containing > 90% plagioclase; F1, F2, and F3) are most similar to rocks from the Apollo ferroan anorthosite (FAN) suite (Warren 1993). These clasts may represent the primary crustal rocks (i.e., FAN) that crystallized from a Lunar Magma Ocean (Shearer et al. 2006). In addition to the FAN clast group, another group of clasts (F4 and F5) falls clearly within the region of Apollo Mg-suite rocks (Fig. 6). This is significant as few meteorites have been reported as containing an Mg-suite lithic clast component (Treiman and Gross 2015).

Basaltic Clast Heritage

The basaltic clasts in NWA 7948 are VLT and low-Ti basalt affinity in nature. Six basaltic clasts (clasts B1–B6) are similar to the VLT basalts, while the other three basaltic clasts (clasts B7–B9) have the low-Ti basalt affinity (Fig. 5). These basaltic clasts show a variety of textures, indicating a range of crystallization histories. Compared with the lunar basalts sampled by Apollo missions and lunar meteorites, the groundmass texture of clast B1 (Figs. 2a and 2b) is similar to the reported “straw-texture” observed in both lunar breccia NWA 773 (Fagan et al. 2014) and Apollo 12/15 pigeonite basalts (Papike et al. 1998, see their figs. 16 and 17), suggesting that they have similar posteruption rapidly quenched crystallization histories.
Table 3. Bulk composition of NWA 7948, compared with mingled lunar meteorites DEW 12007, Dhofar 1180, QUE 94281, NWA 2996, EET 96008, Y-793274, and Calcalong Creek.

|       | NWA 7948 | NWA 7948 | DEW 12007 | Dhofar 1180 | QUE 94281 | NWA 2996 | EET 96008 | Y-793274 Calcalong Creek |
|-------|----------|----------|-----------|-------------|------------|-----------|-----------|--------------------------|
| Ref.  | This work| (1)      | (2)       | (3)         | (4)        | (5)       | (6)       | (7)                      | (8)                       |
| Major and minor elementsa (wt%) | | | | | | | | |
| SiO₂  | 45.1 ± 1.35 | 46.3 | 46.2 | 46.5 | 48.3 | 47.18 |
| TiO₂  | 0.49 ± 0.20 | 0.62 | 0.68 | 0.75 | 0.60 | 0.84 |
| Al₂O₃ | 21.6 ± 3.06 | 18.3 | 22.6 | 20.6 | 13.0 | 13.7 | 20.83 |
| Cr₂O₃ | 0.18 ± 0.06 | 1.6 | 1.65 | 0.23 | 0.24 | 0.29 | 0.17 |
| FeO   | 9.40 ± 2.73 | 9.5 | 12.6 | 6.31 | 13.2 | 9.75 | 18.1 | 15.2 | 9.69 |
| MnO   | 0.13 ± 0.07 | 0.163 | 0.15 | 0.24 | 0.22 | 0.14 |
| MgO   | 8.51 ± 3.02 | 8.13 | 8.08 | 7.72 | 9.00 | 7.11 |
| CaO   | 13.0 ± 1.86 | 12.9 | 12.7 | 13.5 | 11.2 | 12.2 | 13.31 |
| Na₂O  | 0.46 ± 0.13 | 0.40 | 0.4 | 0.51 | 0.36 | 0.46 | 0.49 |
| K₂O   | 0.07 ± 0.02 | 0.08 | 0.12 | 0.19 | 0.05 | 0.07 | 0.24 |
| P₂O₅  | 0.07 ± 0.04 | 0.07 | 0.14 | 0.07 | 0.14 |
| Total | 99.04 | 99.6 | 98.3 | 100.04 | 100 | |
| Trace elementsb (ppm) | | | | | | | | |
| Li    | 6.9 | 7.2 | | 4.39 | |
| Be    | 0.82 | 0.7 | | 0.82 | |
| Sc    | 18.6 | 17.7 | 28.8 | 15.53 | 28.4 | 18.8 | 45.4 | 31.9 | 21.24 |
| V     | 82 | 88 | | 103.4 | 55.3 |
| Cr    | 2110 | 1654 | 869 | 1764 | 1570 | 2530 | 2010 | 1170 |
| Co    | 45.3 | 36 | 15.68 | 45.3 | 34.1 | 41.4 | 24.82 |
| Ni    | 241 | 200 | 135 | 112 | 300 | 200 | 100 | 180 |
| Cu    | 8.48 | 9.1 | | 9.2 | |
| Zn    | 17.8 | | | 10.7 | 49 |
| Ga    | 3.81 | 4.5 | | 6.7 | 4.04 | 4.7 |
| Rb    | 1.76 | 1.45 | 5.1 | <5 | 1.4 | <2 | 9.37 |
| Sr    | 186 | 180 | 127 | 1973 | 119 | 164 | 112.4 | 100 | 149.2 |
| Y     | 22.3 | | 26.5 | | 33.4 | |
| Zr    | 82.8 | 91.6 | 47 | 100 | 137 | 112 | 81 | 354 |
| Nb    | 5.67 | 6.4 | | 6.85 | |
| Mo    | 0.11 | | | 0.12 | 1.79 |
| Sb    | 0.015 | | | | 0.048 |
| Cs    | 0.087 | 0.052 | 0.09 | 0.15 | 0.06 | 0.1 | 0.367 |
| Ba    | 185 | 180 | 112 | 594 | 78 | 173 | 80.2 | 97 | 257 |
| La    | 7.06 | 6.9 | 7 | 4.18 | 6.77 | 10.25 | 7.3 | 7 | 21.83 |
| Ce    | 17.6 | 18.1 | 10.67 | 18.1 | 27.3 | 19.7 | 17.9 | 54.1 |
| Pr    | 2.39 | 2.51 | | 2.84 | |
| Nd    | 11.1 | 11.6 | 6.7 | 10 | 16 | 12.7 | 12 | 29.5 |
| Sm    | 2.99 | 3.3 | 3.31 | 2.14 | 3.21 | 4.65 | 3.65 | 3.56 | 9.55 |
| Eu    | 0.82 | 0.92 | 0.9 | 0.856 | 0.85 | 1.07 | 0.9 | 0.96 | 1.303 |
| Gd    | 3.4 | 3.8 | | 4.42 | 4.19 | 10.5 |
| Tb    | 0.613 | 0.68 | 0.453 | 0.68 | 0.92 | 0.79 | 0.76 | 1.941 |
| Dy    | 3.94 | 4.61 | | 4.73 | 4.64 | 13.28 |
| Ho    | 0.821 | 0.96 | | 1.05 | 2.67 |
| Er    | 2.27 | 2.8 | | 2.89 | |
| Tm    | 0.337 | 0.4 | | 0.41 | 1.407 |
| Yb    | 2.13 | 2.2 | 2.44 | 1.711 | 2.45 | 3.16 | 2.86 | 2.73 | 7.5 |
| Lu    | 0.304 | 0.33 | 0.35 | 0.239 | 0.342 | 0.439 | 0.42 | 0.376 | 1.024 |
| Hf    | 1.95 | 2.28 | 1.55 | 2.54 | 3.61 | 2.42 | 2.96 | 7.15 |
| Ta    | 0.28 | 0.32 | 0.213 | 0.33 | 0.42 | 0.34 | 0.34 | 0.991 |
| W     | 0.383 | 0.18 | | 0.18 | 0.19 | 0.554 |
Evolved Clast Heritage

The evolved clasts (clasts E1 and E2) contain alkali sodic plagioclase, K-feldspar, and/or silica, but they are free of any incompatible trace element-rich accessory minerals (e.g., phosphate and zircon). These fragments could represent materials from the K-fraction of KREEP or late-stage precipitates of erupted basalts.

Granulite Clast Heritage

The olivine and pyroxene fragments in clast R have higher Mg# values (82.0–82.1 and 83.8–84.0, respectively; Fig. 7) than those of FAN lithologies (Mg# <70) and are more similar to the Apollo Mg-suite rocks (Fig. 7). This suggests that clast R likely represents a metamorphosed Mg-suite precursor.

Origin of the Compositionally Unusual Metal-Rich Clast “UM”

Compared with the known lithologies documented in lunar samples, clast UM exhibits several distinctive petrographic and compositional features. Mineralogically, it contains ~15% of FeNi metal grains ranging in size from <10 to 50 µm. The pyroxene Fe/Mn data fall within the range of compositions observed in Apollo samples (Fig. 9a), but do not follow the typical trend of lunar rocks: clast UM generally has lower Fe/Mn ratios (36.1 ± 6.7, 1σ; Fig. 9b) compared with other lunar samples (44–80; Papike et al. 2003). In addition to the low Fe/Mn ratios, the TiO2 and Cr2O3 abundances of the pyroxene grains are not an exact match with known lunar highland lithologies (Figs. 9c and 9d) (Bersch et al. 1991; Treiman and Gross 2015).

One possible source of clast UM is that it represents a meteoritic fragment from another planetary body. As shown in Fig. 9b, it is notable that clast UM is dissimilar to terrestrial and Martian samples on the Fe/Mn (atomic) versus An# diagram. The metal-rich nature of clast UM is also unlike that of the typical more oxidized terrestrial samples and Martian meteorites (Papike et al. 2009), suggesting that this clast likely did not originate from Earth or Mars. Although clast UM has a Fe/Mn (atomic) ratio and An# value similar to those of HED meteorites (Fig. 9b), the magnesian nature of the pyroxene grains (Fig. 9e) and metal-rich texture are not consistent with that currently reported in HED meteorites (McSween et al. 2011; Beck et al. 2012). Additionally, the FeNi metal grains in clast UM also have Ni and Co contents that were different from the HED meteorites (Papike et al. 2009).
and winonaites (McCoy et al. 1997; Benedix et al. 1998; Goodrich et al. 2011), the anorthitic nature of plagioclase (An$_{82.1-97.2}$) in clast UM is not consistent with that of these primitive achondrite meteorite groups (Fig. 9e).

Although the metal-rich texture of clast UM is not lunar-like, its mineral chemistry (Figs. 9b–d) may be consistent with the clast being derived from lunar rocks. Its magnesian nature potentially indicates a connection with the lunar Mg-suite. For the nonlunar-like Fe/Mn ratios of clast UM, several mechanisms (e.g., oxygen fugacity and crystallization or fractionation) could account for the clast’s unusual Fe/Mn ratios in pyroxene (see discussion in Joy et al. 2014).

Clast UM has petrographic texture characteristics that are similar to the lunar impact melt lithologies. The unequilibrated mineral composition and scattered tiny metal grains (Figs. 8c and 8d) suggest that clast UM crystallized with a fast cooling rate, which is consistent with the textures of lunar impact melt breccia clasts containing metal phases (e.g., Wittmann et al. 2014). The two-pyroxene equilibration temperature, calculated from the compositions of coexisting low-Ca and high-Ca pyroxenes, is about 1200 °C. We thus suggest that this clast was probably sourced from a Mg-suite lithology, but had been subsequently melted and recrystallized by impact processes. The Si,K-rich glassy mesostasis in clast UM is located at interstitial sites between the plagioclase and pyroxene (Fig. 8c), suggesting that this glassy mesostasis is more likely a last-stage differentiation product of impact melt. The lower Mg# value (20.3; Table 2) and higher incompatible element contents (e.g., 5.17 wt% K$_2$O and 1.92 wt% TiO$_2$; Table 2) of the glassy mesostasis also support this interpretation. In lunar meteorite MAC 88105 (Joy et al. 2014), a similar Si,K-rich glassy mesostasis has been observed in an unusual clast.

Possible Source Regions of NWA 7948

NWA 7948 is a mingled regolith breccia with approximately equal proportions of basaltic clasts (VLT and low-Ti basalt) and highland lithologies (FAN, Mg-suite, and alkali suite), indicating that the likely source region for NWA 7948 is an area on a mare-highland boundary or connected to a cryptomaria site (Sokol et al. 2008; Snape et al. 2011). Global remote sensing data (e.g., Clementine) revealed that the VLT and low-Ti basalts are mainly distributed on farside mare regions, peripheral regions of the nearside impact basins, and several basins within the PKT (e.g., northern regions of Oceanus Procellarum, Mare Frigoris, and Mare Serenitatis) (Lucey et al. 1998; Jolliff et al. 2000; Gillis et al. 2003). The absence of KREEP-rich impact melt clasts in NWA 7948 and its lower bulk Th content (1.07 ppm; Table 3) suggests that its parent lithology was likely sourced far from the types of regoliths that were sampled by the Apollo missions within the PKT (these have >5 ppm; Jolliff et al. 2000; Lawrence et al. 2003). In addition, NWA 7948 (FeO = 9.4 wt% and Th = 1.07 ppm; Table 3) is also different from the highly feldspathic (FeO = 3.28–4.06 wt%), KREEP-poor (Th = 0.06–0.16 ppm) farside highland meteorites (e.g., Dhofar 489, Yamato-86032, and its pairs; Takeda et al. 2006; Yamaguchi et al. 2010). Thus, this meteorite more likely originated in the
outer-Feldspathic Highlands Terrane (FHT-O; Jolliff et al. 2000).

The bulk composition for a regolith breccia could be used to compare with the remote sensing geochemical data (e.g., Lunar Prospector) to constrain its possible launch location(s) (see also the approach of Arai et al. 2010; Joy et al. 2010; Calzada-Diaz et al. 2015). Following the method of Joy et al. (2010), the Lunar Prospector 0.5° per pixel Th ppm (Lawrence et al. 2003) and FeO wt% (Lawrence et al. 2002) data sets were searched for pixels using the bulk composition of NWA 7948 (FeO = 9.4 ± 1 wt%, Th = 1.07 ± 1 ppm). Pixels that denote “region of interests” are colored yellow and have been overlain on a geographically corresponding Clementine cylindrical projection albedo map of the Moon (USGS, Map a Planet). Locations of the Apollo and Luna sample return missions are noted, along with the Chang’E-3 lander and rover landing site (Li et al. 2015). The map highlights with dashed outlines the main geochemical terranes defined by Jolliff et al. (2000). (Color figure can be viewed at wileyonlinelibrary.com.)

Comparison with Other Lunar Meteorites

NWA 7948 is a mixed mare-highlands breccia, with a relatively low KREEP component. In comparison with other reported mingled lunar meteorites (see Fig. 7; Table 3; Calcalong Creek, QUE 94281, EET 96008, Y-793274, Dhofar 1180, and DEW 12007; Koeberl et al. 1991; Jolliff et al. 1998; Anand et al. 2003; Hill and Boynton 2003; Zhang and Hsu 2009; Mercer et al. 2013; Collareta et al. 2016), NWA 7948 exhibits distinctive petrographic and mineralogical characteristics from these meteorites. Samples EET 96008, Y-793274, and QUE 94281 do not contain the VLT basaltic clasts and volcanic glasses (Koeberl et al. 1991; Jolliff et al. 1998; Anand et al. 2003), which are present in this section of NWA 7948 (Figs. 3f and 5). Sample DEW 12007 contains one KREEP-rich Mg-suite clast (e.g., clast L in DEW 12007; Collareta et al. 2016), which is absent within NWA 7948.

Although NWA 7948 has similar major element systematics to lunar meteorites Calcalong Creek and Dhofar 1180 (Fig. 7), there are significant differences in the REE compositions of these samples (Fig. 11). Calcalong Creek (La 93 × CI, Lu 42 × CI; Hill and Boynton 2003) contains more abundant REEs and incompatible elements than NWA 7948 (La 30 × CI, Lu 13 × CI; Fig. 11). Dhofar 1180 exhibits a positive Eu-anomaly, while NWA 7948 shows negative Eu-anomaly (Eu/Eu* = 0.8; Fig. 11). In addition, Dhofar 1180 (Zhang and Hsu 2009) does not contain the VLT
basaltic clasts which are common in NWA 7948. While this could indicate that these meteorites are not paired stones, it is important to consider that the samples may be heterogeneous on the scale of the individual hand specimen sizes.

Compared with NWA 2996 (Mercer et al. 2013), although the studied NWA 7948 section contains VLT volcanic glass beads that are possibly absent within NWA 2996, both meteorites contain similar lithologies (e.g., FAN clasts, VLT clasts, LT clasts, evolved clasts, and impact melt breccia), bulk FeO and Al₂O₃ composition (Fig. 7), and REE abundance (Fig. 11). On this basis, the stones may be paired, but exposure ages are needed to prove this connection.

By comparing with the recently reported lunar breccia NWA 10989 which was assumed to be paired with the NWA 7834 clan of meteorites (Korotev and Irving 2014; Ashcroft et al. 2017), NWA 7948 exhibits similar bulk composition (i.e., Th, Sc, and Sm contents) with the NWA 10989 stone. More detailed work should be carried out to investigate the pairing relationship between NWA 7948 and the NWA 7834 clan of meteorites.

Implications for the Lithologic Components of Lunar Crust

Geophysical, remote sensing, and sample analyses have revealed that the lunar crust consists of diverse lithologies and is laterally and vertically heterogeneous (Jolliff et al. 2000; Hawke et al. 2003; Lucey 2004; Korotev et al. 2009; Russell et al. 2014). The lithological diversity has been further extended by the study of lunar meteorites (e.g., Takeda et al. 2006; Gross and Treiman 2011; Joy et al. 2014). In NWA 7948, the occurrence of compositionally unusual metal-rich clasts (clast UM; Fig. 8) suggests that there is much to learn about the Moon’s geological diversity and petrological makeup.

The Mg-suite rocks are common at all of the Apollo landing sites (Warren 1993; Treiman et al. 2010). However, only a few true Mg-suite clasts have been recognized in the feldspathic lunar meteorites, strongly suggesting that the Mg-suite rocks are possibly localized around the PKT region (Gross et al. 2014; Treiman and Gross 2015). Within the studied section, three lithic clasts (clasts F4, F5, and R) have a strong affinity to the Mg-suite rocks (Fig. 6); these Mg-suite lithologies are likely to be formed at the FHT-O where the NWA 7948 meteorite originated (Fig. 13). This assumption is supported by remote sensing (e.g., Clementine NIR) observations, showing possible Mg-suite rock exposures surrounding Mare Australe, Crisium, and Procellarum (Cahill et al. 2009; Shearer et al. 2015). It is also possible that these Mg-suite fragments in NWA 7948 were transported by meteorite impacts from the PKT where Mg-suite material is relatively common (Treiman and Gross 2015). To reveal if the Mg-suite material is only closely associated with the PKT or produced Moon-wide, there clearly needs to be a search for more fragments of KREEP-free Mg-suite lithologies in future studies of lunar meteorites (Shearer et al. 2015).

The global distribution of Mg# (Ohtake et al. 2012) and sample analyses (e.g., Apollo samples and Dhofar 489; Lindstrom et al. 1986; Takeda et al. 2006) have highlighted that the primitive lunar feldspathic crust consists of both FAN and MAN. The FANs typically appear on the nearside, whereas the MANs occur more frequently on the lunar farside (Arai et al. 2008; Ohtake et al. 2012; Gross et al. 2014). Within the section NWA 7948 studied here, the anorthosite clasts are classified as FAN (Fig. 6), possibly supporting an origin within the FHT-O in mare-highland boundaries.

The KREEP-poor NWA 7948 meteorite contains a variety of VLT basaltic clasts (Fig. 5). In contrast, the VLT basaltic clasts are also common in other KREEP-poor meteorites that were not likely sourced from the PKT region (e.g., NEA 001, Kalahari 009, NWA 2996; Sokol et al. 2008; Snape et al. 2011; Mercer et al. 2013). This suggests that the composition of the lunar interior outside of the PKT may have predominantly VLT compositions, which may be derived from the partial melting of early cumulates of the magma ocean (e.g., Terada et al. 2007; Joy et al. 2008).

Lunar picritic glass could provide important constraints on volcanic activity and the magma evolution on the Moon (e.g., Shearer and Papike 1993). Over 100 lunar pyroclastic deposits have been identified across the lunar surface (Gustafson et al. 2012). Compared with the Apollo basalts and glasses, glass beads G1 and G2 within NWA 7948 have similar chemical compositions to VLT basalts and glasses (Fig. 14). Specifically, these glasses are more similar to the Apollo 17 green glass with respect to composition (Fig. 14; Table 2). However, NWA 7948 does not seem to be associated with the Apollo 17 landing site from the geochemical remote sensing results (Fig. 13). This indicates that the picritic glasses in NWA 7948 were possibly derived from a different pyroclastic deposit with a similar chemical composition to the Apollo 17 green glass.

CONCLUSIONS

NWA 7948 is a lunar mingled regolith breccia, predominately composed of a wide variety of crustal lithologies from the basalt (VLT and low-Ti basaltic clasts), feldspathic rocks (FAN, Mg-suite, and alkali
suite), impact melt clasts, and lunar regolith components (volcanic and impact glass). An unusual lithology, clast UM, was identified within the section investigated here. It exhibits a metal-rich texture, nonlunar-like Fe-Mn trend, and unusual mineral chemistry. This clast is not similar to meteorites sourced from other parent bodies, but most likely represents an impact lithology generated by melting of Mg-suite parent material.

The presence of both basaltic and feldspathic lithologies, mingled bulk composition, and the KREEP-poor nature of NWA 7948 suggest that this meteorite most likely originated from a mare region in the lunar highlands, i.e., a mare-highland boundary in FHT-O. The remote sensing data suggest that NWA 7948 is compositionally most similar to the regoliths on the nearside highlands-mare boundaries (e.g., Mare Crisium) or a cryptomare region (e.g., Schickard-Schiller) or a farside highlands-mare boundary (e.g., Apollo basin in the South Pole-Aitken region).

Multiple lithic clasts and the compositionally unusual clast UM within NWA 7948 reveal that the launch site of NWA 7948 has a complex geological diversity, and suggest that there is much to learn about the Moon’s petrological makeup. Future robotic/human sample return missions (e.g., Chang’E-5; Ling et al. 2017) and lunar meteorite studies will enable us to further understand the Moon’s geological and regolith archive (NRC 2007), and test our current ideas about its formation and evolution through the past 4.5 Ga years.

Acknowledgments—The authors thank Drs. Jon Fellowes, Greg McMahon, and Heath Bagshaw for assistance with the EMP and ESEM analyses at the University of Manchester. We acknowledge Yizhi Liu (Guilin University of Technology) and Jin Hu (Institute of Geochemistry, Chinese Academy of Sciences) for assistance with EMP analysis and ICP-MS measurement, respectively. We also thank Drs. J. Snape and J. Gross for their valuable comments that greatly improved this paper, and Drs. Akira Yamaguchi and A. J. Timothy Jull for their help as editors. This work benefited from the opportunity to visit the Isotope Geochemistry group at the University of Manchester for 6 months, supported by the NSFC (grants 41473067 and 41490630). K. H. J. acknowledges Royal Society grant RS/UF140190 and K. H. J. and J. P. F. acknowledge STFC grant ST/M001253/1 and D. M. is funded by an STFC studentship.

Editorial Handling—Dr. Akira Yamaguchi

REFERENCES
Anand M., Taylor L. A., Neal C. R., Snyder G. A., Patchen A., Sano Y., and Terada K. 2003. Petrogenesis of lunar meteorite EET 96008. Geochimica et Cosmochimica Acta 67:3499–3518.
Anders E. and Grevesse N. 1989. Abundances of the elements—Meteoritic and solar. Geochimica et Cosmochimica Acta 53:197–214.
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., Takeda H., Yamaguchi A., and Ohtake M. 2008. A new model of lunar crust: Asymmetry in crustal
composition and evolution. Earth, Planets and Space 60:433–444.

Arai T., Hawke B. R., Giguere T. A., Misawa K., Miyamoto M., and Kojima H. 2010. Antarctic lunar meteorites Yamato-793169, Asuka-881757, MIL 05035, and MET 01210 (YAMM): Launch pairing and possible cryptomare origin. Geochimica et Cosmochimica Acta 74:2231–2248.

Ashcroft H. O., Anand M., Korotev R. L., Greenwood R. C., Franchi I. A., and Strekopytov S. 2017. NWA 10989—A new lunar meteorite with equal proportions of feldspathic and VLT material (abstract #1481). 48th Lunar and Planetary Science Conference. CD-ROM.

Beck A. W., Welten K. C., McSween H. Y., Viviano C. E., and Caffee M. W. 2012. Petrologic and textural diversity among the PCA 02 howardite group, one of the largest pieces of the Vestan surface. Meteoritics & Planetary Science 47:947–969.

Benidex G., McCoy T. J., Keil K., Bogard D. D., and Garrison D. H. 1998. A petrologic and isotopic study of winonaites: Evidence for early partial melting, brecciation, and metamorphism. Geochimica et Cosmochimica Acta 62:2535–2553.

Bersch M. G., Taylor G. J., Keil K., and Norman M. D. 1991. Mineral compositions in pristine lunar highland rocks and the diversity of highland magmatism. Geophysical Research Letters 18:2085–2088.

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. Meteoritics & Planetary Science 41:A31.

Cahill J., 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.

Cahill J., Lucey P., and Wieczorek M. 2009. Compositional variations of the lunar crust: Results from radiative transfer modeling of central peak spectra. Journal of Geophysical Research 114:1–17.

Calzada-Diaz A., Joy K. H., Crawford I. A., and Nordheim T. A. 2015. Constraining the source regions of lunar meteorites using orbital geochemical data. Meteoritics & Planetary Science 15:214–228.

Collareta A., D’Orazio M., Gemelli M., Pack A., and Folco L. 2016. High crustal diversity preserved in the lunar meteorite Mount Dewitt 12007 (Victoria Land, Antarctica). Meteoritics & Planetary Science 51:351–371.

Day J. M. D., Floss C., Taylor L. A., Anand M., and Patchen A. D. 2006. Evolved mare basalt magmatism, high Mg/Fe feldspathic crust, chondritic impactors, and the petrogenesis of Antarctic lunar breccia meteorites Meteorite Hills 01210 and Pecora Escarpment 02007. Geochimica et Cosmochimica Acta 70:5957–5989.

Delano J. W. 1986. Pristine lunar glasses: Criteria, data, and implications. Journal of Geophysical Research: Solid Earth 91:201–213.

Fagan T. J., Kashima D., Wakabayashi Y., and Suginoahara A. 2014. Case study of magmatic differentiation trends on the Moon based on lunar meteorite Northwest Africa 773 and comparison with Apollo 15 quartz monzodiorite. Geochimica et Cosmochimica Acta 133:97–127.

Fritz J., Greshake A., and Fernandes V. A. 2017. Revising the shock classification of meteorites. Meteoritics & Planetary Science 52:1216–1232.

Gillis J. J., Jolliff B. L., and Elphic R. C. 2003. A revised algorithm for calculating TiO2 from Clementine UVVIS data: A synthesis of rock, soil, and remotely sensed TiO2 concentrations. Journal of Geophysical Research (Planets) 108:5009–5027.

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.

Goldstein J. I. and Yakowitz H. 1971. Metallic inclusions and metal particles in the Apollo 12 lunar soil. Proceedings, 2nd Lunar Science Conference. p. 177.

Goodrich C. A., Kita N. T., Spicuzza M. J., Valley J. W., Zipfel J., Mikouchi T., and Miyamoto M. 2011. The Northwest Africa 1500 meteorite: Not a ureilite, maybe a brachinite. Meteoritics & Planetary Science 45:1906–1928.

Goodrich C. A., Kita N. T., Yin Q. Z., Sanborn M. E., Williams C. D., Nakashima D., Lane M. D., and Boyle S. 2017. Petrogenesis and provenance of ungrouped achatonite Northwest Africa 7325 from petrology, trace elements, oxygen, chromium and titanium isotopes, and mid-IR spectroscopy. Geochimica et Cosmochimica Acta 203:381–403.

Gross J. and Treiman A. H. 2011. Unique spinel-rich lithology in lunar meteorite ALH81005: Origin and possible connection to M3 observations of the farside highlands. Journal of Geophysical Research 116:E9.

Gross J., Treiman A. H., and Mercer C. N. 2014. Lunar feldspathic meteorites: Constraints on the geology of the lunar highlands, and the origin of the lunar crust. Earth and Planetary Science Letters 388:318–328.

Gustafson J. O., Iii J. F. B., Gaddis L. R., Hawke B. R., and Giguere T. A. 2012. Characterization of previously unidentified lunar pyroclastic deposits using Lunar Reconnaissance Orbiter Camera (LROC) data. Journal of Geophysical Research 117:1733.

Hawke B., Peterson C., Blewett D., Bussey D., Lucey P., Taylor G., and Spudis P. 2003. Distribution and modes of occurrence of lunar anorthosite. Journal of Geophysical Research 108:5050.

Hill D. H. and Boynton W. V. 2003. Chemistry of the Calcagno Creek lunar meteorite and its relationship to lunar terranes. Meteoritics & Planetary Science 38:595–626.

Johnson J. R. 2012. Thermal infrared spectra of experimentally shocked andesine anorthosite. Icarus 221:359–364.

Johnson J. R., Hörz F., Christensen P., and Lucey P. G. 2002. Thermal infrared spectroscopy of experimentally shocked anorthosite and pyroxenite: Implications for remote sensing of Mars. Journal of Geophysical Resources 107:1–14.

Jolliff B. L., Korotev R. L., and Rockow K. M. 1998. Geochemistry and petrology of lunar meteorite Queen Alexandra Range 94281, a mixed mare and highland regolith breccia, with special emphasis on very-low-titanium mafic components. Meteoritics & Planetary Science 33:581–601.

Jolliff B. L., Gillis J. J., Haskin L. A., Korotev R. L., and Wieczorek M. A. 2000. Major lunar crustal terranes: Surface expressions and crust-mantle origins. Journal of Geophysical Research 105:4197–4216.
Joy K. H. and Arai T. 2013. Lunar meteorites: New insights into the geological history of the Moon. *Astronomy & Geophysics* 54:4–28.

Joy K. H., Crawford I. A., Anand M., Greenwood R. C., Franchi I. A., and Russell S. S. 2008. The petrology and geochemistry of Miller Range 05035: A new lunar gabbroic meteorite. *Geochimica et Cosmochimica Acta* 72:3822–3844.

Joy K. H., Crawford I. A., Russell S. S., and Kearsley A. T. 2010. Lunar meteorite regolith breccias: An in situ study of impact melt composition using LA-ICP-MS with implications for the composition of the lunar crust. *Meteoritics & Planetary Science* 45:917–946.

Joy K. H., Crawford I. A., Huss G., Nagashima K., and Taylor G. J. 2014. An unusual clast in lunar meteorite MacAlpine Hills 88105: A unique lunar sample or projectile debris? *Meteoritics & Planetary Science* 49:677–695.

Koeberl C., Kurat G., and Brandstätter F. 1991. Lunar meteorite Yamato-793274: Mixture of mare and highland components, and barringerite from the Moon. *Proceedings of the NIPR Symposium on Antarctic Meteorites* 4:33–55.

Korotev R. L. 2005. Lunar geochemistry as told by lunar meteorites. *Chemie der Erde* 65:297–346.

Korotev R. L. and Irving A. J. 2014. Keeping up with the lunar meteorites—2014 (abstract #1405). 45th Lunar and Planetary Science Conference. CD-ROM.

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., Zeigler R. A., Jolliff B. L., Irving A. J., and Bunch T. E. 2009. Compositional and lithological diversity among brecciated lunar meteorites of intermediate iron concentration. *Meteoritics & Planetary Science* 44:1287–1322.

Lawrence D. J., Feldman W. C., Elphic R. C., Little R. C., Prettyman T. H., Maurice S., Lucey P. G., and Binder A. B. 2002. Iron abundances on the lunar surface as measured by the Lunar Prospector gamma-ray and neutron spectrometers. *Journal of Geophysical Research* 107:5130.

Lawrence D. J., Elphic R. C., Feldman W. C., Prettyman T. H., Gaspault O., and Maurice S. 2003. Small-area thorium features on the lunar surface. *Journal of Geophysical Research* 108:5102.

Li C., Liu J., Ren X., Zuo W., Tan X., Wen W., Li H., Mu L., Su Y., Zhang H., Yan J., and Ouyang Z. 2015. The Chang’E 3 mission overview. *Space Science Reviews* 190:85–101.

Lin Y., Shen W., Liu Y., Xu L., Hofmann B. A., Mao Q., Tang G. Q., Wu F., and Li X. H. 2012. Very high-K KREEP-rich clasts in the impact melt breccia of the lunar meteorite SaU 169: New constraints on the last residue of the Lunar Magma Ocean. *Geochimica et Cosmochimica Acta* 85:19–40.

Lindstrom M. M., Lindstrom D. J., Korotev R. L., and Haskin L. A. 1986. Lunar meteorite Yamato-791197: A polymict anorthositic norite from the lunar highlands. *Memoirs of the National Institute of Polar Research* 41:58–75.

Ling Z. C., Liu C. Q., Jolliff B. L., Zhang J., Li B., Sun L. Z., Chen J., and Liu J. Z. 2017. Spectral and mineralogical analysis of Chang’E-5 candidate landing site in Northern Oceanus Procellarum (abstract #2079). 48th Lunar and Planetary Science Conference. CD-ROM.

Lucey P. G. 2004. Mineral maps of the Moon. *Geophysical Research Letters* 31:08701–08705.

Lucey P. G., Blewett D. T., and Hawke B. R. 1998. Mapping the FeO and TiO2 content of the lunar surface with multispectral imagery. *Journal of Geophysical Research* 103:3679–3699.

Martin D. J., Pernet-Fisher J. F., Joy K. H., Wegelius R. A., Morlok A., and Hiesinger H. 2017. Investigating the shock histories of lunar meteorites Miller Range 090034, 090070, and 090075 using petrography, geochemistry, and micro-FTIR spectroscopy. *Meteoritics & Planetary Science* 52:1103–1124.

McCoy T. J., Keil K., Clayton R. N., Mayeda T. K., Bogard D. D., Garrison D. H., and Wieler R. 1997. A petrologic and isotopic study of lodranites: Evidence for early formation as partial melt residues from heterogeneous precursors. *Geochimica et Cosmochimica Acta* 61:623–637.

McKay D. S., Heiken G., Basu A., Blanford G., Simon S., Reedy R., French B. M., and Papike J. 1991. The lunar regolith. In *Lunar sourcebook*, edited by Heiken G., Vaniman D., and French B. M. Cambridge: Cambridge University Press. pp. 286–356.

McSween H., Mittlefehldt D., Beck A., Mayne R., and McCoy T. 2011. HED meteorites and their relationship to the geology of Vesta and the Dawn mission. *Space Science Reviews* 163:141–174.

Merce C. N., Treiman A. H., and Joy K. H. 2013. New lunar meteorite Northwest Africa 2996: A window into farside lithologies and petrogenesis. *Meteoritics & Planetary Science* 48:289–315.

Nagaoka H., Takeda H., Karouji Y., Ohtake M., Yamaguchi A., Yoneda S., and Hasebe N. 2014. Implications for the origins of pure anorthosites found in the feldspathic lunar meteorites, Dhofar 489 group. *Earth, Planets and Space* 66:1–14.

Neal C. R. and Taylor L. A. 1992. Petrogenesis of mare basalts—A record of lunar volcanism. *Geochimica et Cosmochimica Acta* 56:2177–2211.

Nielsen R. L. and Drake M. J. 1978. The case for at least three mare basalt magmas at the Luna 24 landing site. In *Mare Crisium: The view from Luna 24*, edited by Merrill R. B. and Papike J. J. New York: Pergamon Press. pp. 419–428.

NRC (National Research Council). 2007. *The scientific context for the exploration of the Moon*. Washington, D.C.: National Academies Press.

Ohtake M., Takeda H., Matsunaga T., Yokota Y., Haruyama J., Morota T., Yamamoto S., Ogawa Y., Hiroi T., Karouji Y., Saiki K., and Lucey P. G. 2012. Asymmetric crustal growth on the Moon indicated by primitive farside highland materials. *Nature Geoscience* 5:384–388.

Papike J., Taylor L., and Simon S. 1991. Lunar minerals. In *The lunar sourcebook*, edited by Heiken G., Vaniman D., and French B. M. Cambridge: Cambridge University Press. pp. 121–181.

Papike J. J., Ryder G., Shearer C. K. 1998. Lunar samples. In *Planetary materials*, edited by Papike J. J. Reviews in Mineralogy, vol. 36. Washington, D.C.: Mineralogical Society of America. pp. 5.1–5.234.

Papike J. J., Karner J. M., and Shearer C. K. 2003. Determination of planetary basalt parentage: A simple
technique using the electron microprobe. *American Mineralogist* 88:469–472.

Papike J. J., Karner J. M., Shearer C. K., and Burger P. V. 2009. Silicate mineralogy of Martian meteorites. *Geochimica et Cosmochimica Acta* 73:7443–7485.

Pernet-Fisher J. F., Joy K. H., Martin D. J. P., and Hanna K. L. D. 2017. Assessing the shock state of the lunar highlands: Implications for the petrogenesis and chronology of crustal anorthosites. *Scientific Reports* 7:5888.

Pieters C. M., Besse S., Boardman J., Buratti B., Check L., Clark R. N., Combe J. P., Dhingra D., Goswami J. N., Green R. O., Head K. W., Isaacson P., Klima R., Kramer G., Lundeen S., Malaret E., McCord T., Mustard J., Nettles J., Petro N., Runyon C., Staid M., Sunshine J., Taylor L. A., Thaisen K., Tompkins S., and Whitten J. 2011. Mg-spinel lithology: A new rock type on the lunar farside. *Journal of Geophysical Research* 116:E00G08.

Qi L., Hu J., and Gregoire D. C. 2000. Determination of trace elements in granites by inductively coupled plasma mass spectrometry. *Talanta* 51:507–513.

Russell S. S., Joy K. H., Jeffries T. E., Consolmagno G. J., and Kearsley A. 2014. Heterogeneity in lunar anorthosite meteorites: Implications for the lunar magma ocean model. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences* 372:20130241.

Ruzicka A., Grossman J., Bouvier A., Herd C. D. K., and Agee C. B. 2015. The Meteoritical Bulletin, No. 102. *Meteoritics & Planetary Science* 50:1662.

Shearer C. K. and Papike J. J. 1993. Basaltic magmatism on the Moon: A perspective from volcanic picritic glass beads. *Geochimica et Cosmochimica Acta* 57:4787–4812.

Shearer C. K., Hess P. C., Wieczorek M. A., Pritchard M. E., Parmentier E. M., Borg L., Longhi J., Elkins-Tanton L. T., Neal C. R., Antonenko I., Canup R. M., Halliday A. N., Grove T. L., Hager B. H., Less D.-C., and Wiechert U. 2006. Thermal and magmatic evolution of the Moon. In *New views of the Moon*, edited by Jolliff B. L., Wieczorek M. A., Shearer C. K., and Neal C. R. *Reviews in Mineralogy and Geochemistry* 60:365–518.

Shearer C. K., Elardo S. M., Petro N. E., Borg L. E., and McCubbin F. M. 2015. Origin of the lunar highlands Mg-suite: An integrated petrology, geochemistry, chronology, and remote sensing perspective. *American Mineralogist* 100:294–325.

Snape J. F., Joy K. H., and Crawford I. A. 2011. Characterization of multiple lithologies within the lunar feldspathic regolith breccia meteorite Northeast Africa 001. *Meteoritics & Planetary Science* 46:1288–1312.

**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of this article:

Table S1. Pyroxene composition.
Table S2. Olivine composition.
Table S3. Plagioclase composition.
Table S4. Glass composition.
Table S5. Metal composition.
Table S6. Bulk clast composition.
Table S7. The measured and reference values of reference materials.