Mineralogy and petrogenesis of lunar magnesian granulitic meteorite
Northwest Africa 5744

Jeremy J. KENT1*, Alan D. BRANDON2, Katherine H. JOY3, Anne H. PESLIER4, Thomas J. LAPEN2, Anthony J. IRVING5, and Daniel M. COLEFF6

1GeoControl Systems, Jacobs J.E.T.S. Contract, NASA-Johnson Space Center, Mail Code XI2, Houston, Texas 77058, USA
2University of Houston, Department of Earth and Atmospheric Sciences, Houston, Texas 77004, USA
3School of Earth and Environmental Sciences, University of Manchester, Oxford Road, Manchester M13 9PL, UK
4Jacobs, NASA-Johnson Space Center, Mail Code X13, Houston, Texas 77058, USA
5University of Washington, Department of Earth and Space Sciences, Seattle, Washington 98195, USA
6HX5, Jacobs J.E.T.S. Contract, NASA-Johnson Space Center, Mail Code X12, Houston, Texas 77058, USA

*Corresponding author. E-mail: jeremy.j.kent@nasa.gov

(Received 08 March 2017; revision accepted 26 April 2017)

Abstract—Lunar meteorite Northwest Africa (NWA) 5744 is a granulitic breccia with an anorthositic troctolite composition that may represent a distinct crustal lithology not previously described. This meteorite is the namesake and first-discovered stone of its pairing group. Bulk rock major element abundances show the greatest affinity to Mg-suite rocks, yet trace element abundances are more consistent with those of ferroan anorthosites. The relatively low abundances of incompatible trace elements (including K, P, Th, U, and rare earth elements) in NWA 5744 could indicate derivation from a highlands crustal lithology or mixture of lithologies that are distinct from the Procellarum KREEP terrane on the lunar nearside. Impact-related thermal and shock metamorphism of NWA 5744 was intense enough to recrystallize mafic minerals in the matrix, but not intense enough to chemically equilibrate the constituent minerals. Thus, we infer that NWA 5744 was likely metamorphosed near the lunar surface, either as a lithic component within an impact melt sheet or from impact-induced shock.

INTRODUCTION

Rock and regolith samples returned by the Apollo and Luna missions provide invaluable data on the composition and structure of the lunar crust, but the lithologies they sampled represent only about 4.7% of the lunar surface (Warren et al. 1989). Lunar meteorites, however, are rocks that originate from random locations on the Moon’s surface, many of which are likely distant from the landing sites of the Apollo and Luna missions (see Korotev [2005] for a review). Therefore, lunar meteorites may provide more information on the lithologic diversity of the lunar surface and provide evidence that helps constrain lunar evolution (e.g., Korotev et al. 2003; Cahill et al. 2004; Warren et al. 2005; Arai et al. 2008; Joy et al. 2010; Joy and Arai 2013; Gross et al. 2014).

Lunar meteorite Northwest Africa (NWA) 5744, found in Mali in 2009 (Weisberg et al. 2009), is classified as an anorthositic troctolite granulitic breccia. It is composed primarily of plagioclase (partially converted to maskelynite), olivine, and low-Ca pyroxene, with accessory high-Ca pyroxene (augite) and titaniferous chromite. Based on petrologic and geochemical comparisons, NWA 5744 is paired with at least six other lunar anorthositic troctolite granulitic breccias (NWA 8599, NWA 8687, NWA 10140, NWA 10178, NWA 10318, and NWA 10401; Korotev and Irving 2016; The Meteoritical Bulletin Database 2017) (Table 1). Most of these paired stones are reported to contain accessory troilite and/or taenite except for NWA 10401 (Hilton et al. 2016). Modal abundances of major minerals are not similar between the paired stones; for example, pyroxene varies from <5% in NWA 8687 to as much as 20% in NWA 10318, and plagioclase/maskelynite and olivine abundances also vary accordingly (The Meteoritical Bulletin Database 2017).
Kuehner et al. (2010) noted that metal grains in NWA 5744 are rare and the rock has a bulk Ni/Co ratio of ~3.5 (compared to chondritic ratios between 19.4 and 21.1; Wasson and Kallemeyn 1988). They also found that NWA 5744 has lower concentrations of incompatible trace elements (ITEs) than Apollo granulites (e.g., Ma and Schmitt 1982; Goodrich et al. 1984; Lindstrom and Lindstrom 1986; Salpas et al. 1988). Northwest Africa 5744 is also more magnesian than Apollo granulites, with bulk Mg# (molar Mg/[Mg + Fe] × 100) of ~79. Thus, NWA 5744 appears to represent a crustal lithology distinct from those observed at the Apollo and Luna sites and merits detailed investigation (Kuehner et al. 2010; Korotev 2017).

These anorthositic troctolite granulitic breccias are intriguing because they appear unrelated to observed FAN and Mg-suite plutonics, which have long been considered the representative lithologies of the early lunar crust of >4.2 Ga ago (Korotev and Jolliff 2001; McCleod et al. 2016). Magnesian feldspathic granulites are present as clasts in many lunar meteorites (e.g., Allan Hills 81005, Queen Alexandra Range 93069, MacAlpine Hills 88104 and 88105, Dhofar 026 and paired stones; Lindstrom et al. 1991; Koeberl et al. 1996; Treiman et al. 2010; Hudgins et al. 2011a; Gross et al. 2014) and Apollo rocks (e.g., 60035, 67415, 72275, 76503, 79215; Ma and Schmitt 1982; Lindstrom and Lindstrom 1986; Salpas et al. 1988; Jolliff et al. 1996; Hudgins et al. 2008), suggesting they are an important widespread component of the ancient lunar crust. However, they are typically chemically distinct from the FAN and mare basalt igneous rocks that are prevalent at the Apollo and Luna landing sites. They are, therefore, likely to have formed in a region distant from those sites with differing local geology (Lindstrom and Lindstrom 1986; Korotev et al. 2003; Treiman et al. 2010; Hilton et al. 2016).

This study reports on petrological and elemental analyses of NWA 5744, which are used to infer details about the formation process of the protolith(s) of NWA 5744 and their subsequent metamorphism.

### METHODS

We studied a thin section and a polished chip of NWA 5744 weighing 527 mg. The chip of NWA 5744 was a wedge-shaped slab approximately 1.5 cm in length, 1 cm in width, with a thickness ranging from 0.5 to 2 mm. These samples were analyzed by four different techniques in order to obtain two- (2-D) and three-dimensional (3-D) backscatter, elemental, and density maps and elemental abundances in the constituent phases.

#### Sample Mapping

X-ray computed tomography (CT) is a nondestructive method for acquisition of a 3-D density map of both the surface and interior of a sample. We performed this analysis on the slab of NWA 5744 using an XTECH XT H 225 machine at Shell BTC Research Facility in Houston using a method similar to that of Tsuchiyama et al. (2002). Instrument settings of 60 kV for penetration, 100 μA for current, optimized at 2947 projections, and an exposure of 1 frame per second with 16 frames averaged per projection were used. Indexing with a 3-pixel offset was used to minimize ring artifacts.

### Table 1. Mineral compositions of the Northwest Africa (NWA) 5744 lunar meteorite pairing group.

|            | NWA 5744 | NWA 8599 | NWA 8687 | NWA 10140 | NWA 10178 | NWA 10318 | NWA 10401 |
|------------|----------|----------|----------|-----------|-----------|-----------|-----------|
| Olivine    |          |          |          |           |           |           |           |
| Fa         | 20.7     | 23.3–23.5| 21.7 ± 2.2| 23.4 ± 2.8| 22.7–23.0 | 26.4 ± 0.6| 18.6 ± 2  |
| FeO/MnO    | 76.9–94.5| 81–83    | 88 ± 5   | 90 ± 4    | 87–91     | 97        | 88.1 ± 8.3|
| Low-Ca Pyx|          |          |          |           |           |           |           |
| Fs         | 16.6     | 18.9–19.6| 19.6 ± 2.3| 20.5 ± 1.1| 18.7–18.8 | 21.8 ± 0.7| 15.5 ± 2  |
| Wo         | 9.7      | 5.2–4.7  | 3.5 ± 1.4| 3.7 ± 0.9 | 2.9–3.2   | 5.0 ± 2   | 3.1 ± 0.6 |
| FeO/MnO    | 50       | 53–58    | 54 ± 3   | 56 ± 6    | 47–61     | 54        | 49.3 ± 6  |
| High-Ca Pyx|         |          |          |           |           |           |           |
| Fs         | 9.8      |          |          |           |           |           | 9.0 ± 1.4 |
| Wo         | 40.6     |          |          |           |           |           | 41.3 ± 7.9|
| FeO/MnO    | 59       |          |          |           |           |           | 37.2 ± 4  |
| Plagioclase|          |          |          |           |           |           |           |
| An         | 97.9     | 97.0–97.1| 96.7 ± 0.8| 97.1 ± 1.0| 95.9–97.4 | 97.1 ± 0.6| 96.6 ± 0.3|
| Or         | 0.1      | 0.1      | 0.2 ± 0.0| 0.2 ± 0.0 | 0         | 0.1 ± 0.05|

All data are from the Meteoritical Bulletin Database. NWA 5744, 8599, and 10178 data contributed to the database by A. Irving and S. Kuehner. NWA 8687 and 10140 data contributed to the database by C. Agee and N. Mittik. NWA 10318 data contributed to the database by A. Bischoff and S. Ebert. NWA 10401 data contributed by J. Gross and A. Hilton.
due to stage rotation. This produced a 3-D volumetric density map with cubic voxels (volumetric pixels) 10.4 μm across on each side (Fig. 1). This spatial resolution was too coarse to resolve the small (<5 μm) mafic mineral grains embedded in the matrix, but was sufficient to identify the larger plagioclase and olivine grains.

Backscatter electron (BSE) and elemental maps of the thin section and polished slab surfaces were obtained on a JEOL JSM-7600F field emission scanning electron microscope (FEG-SEM) at NASA-Johnson Space Center using a focused <0.01 μm electron beam at 15 kV accelerating potential, beam current of 30 nA (as measured on a Faraday cup), and count times of ~6 μs per pixel. The spatial resolution of the backscatter maps was ~3.3 μm per pixel. A silicon drift X-ray detector (SD) with an ultra-thin window was used to acquire energy dispersive spectra for each point, and ThermoElectron NSS software was used to collect and reduce the data. All elemental maps were extracted from hyperspectral image data sets and were background corrected.

Mineral Analysis

Optical microscopy was used on the thin section to identify the primary mineral components and visible textures. Nikon Eclipse LV100 POL microscopes were used at both the University of Houston and NASA-Johnson Space Center.

The slab of NWA 5744 was split into two similarly sized pieces, and each was mounted on a 2.54-cm round slide using carbon tape. Because of the wedge shape, more carbon tape was used under one end of each slab piece than the other, in order to have the sample surface perpendicular to the electron beam of the electron microprobe; the samples were verified to be flat using a reflected light optical microscope. Major element concentrations of all principal mineral phases were measured by electron probe microanalysis (EPMA) using the Cameca SX100 electron microprobe at NASA-Johnson Space Center. Analyses were obtained with an electron beam of 1 μm at 15 kV and 20 nA, except for plagioclase/maskelynite where the beam was defocused to 10 μm. The following well-characterized standards were used for calibration of electron microprobe (EMP) measurements on all phases: troilite for S, apatite for P, rutile for Ti, chromite for Cr, NiO for Ni, rhodonite for Mn, cobalt metal for Co, and oligoclase for Na. For plagioclase/maskelynite: orthoclase for K and Si, olivoclase for Al and Na, hypersthene for Fe, diopside for Mg, plagioclase for Ca. For olivine: fayalite for Si and Fe, forsterite for Mg, chromite for Al, and diopside for Ca. For pyroxene: diopside for Si, Ca, and Mg; olivoclase for Al; and hypersthene for Fe. For chromite: chromite for Al, Fe, Cr, and Mg; olivine for Si; and diopside for Ca. Sodium, potassium, and phosphorus were always measured simultaneously first to minimize the effect of their loss from beam interaction with the sample. Analyses were validated by running standards as unknowns. Compositions of each measured spot location using EPMA are provided in Appendix S1 in supporting information.

Trace element concentrations were determined on the same mineral phases measured by EPMA on the slab of NWA 5744 by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Houston using a Varian 810 quadrupole ICP-MS with a PhotonMachines Analyte.193 ArF excimer laser, using He as a carrier gas. In preparation for trace element analyses, the CT volume of the NWA 5744 slab was used in this study to help select desirable ablation locations with low risk of breaching a grain boundary. Candidate grains were selected from BSE images, located in the CT volume, and were then only ablated if they extended at least 50 μm below the...
surface of the slab. Trace element compositions for each measured spot location using LA-ICP-MS are provided in Appendix S2 in supporting information.

For all trace element measurements, calcium concentrations measured by EPMA were used as internal standards for plagioclase, while magnesium contents measured by EPMA were used for olivine, pyroxene, and bulk ablations. The United States Geological Survey (USGS) standard reference material BHVO-2G glass was used to correct for instrumental fractionation and drift using the commercial data reduction software package Glitter (http://www.glitter-gemoc.com). Cracks containing greater levels of calcium than the surrounding plagioclase (as seen in elemental mapping) were avoided for all ablation sites to minimize terrestrial contamination. The USGS SRM BIR-1G glass was used to monitor external reproducibility. The BIR glass data are compared to reference values as a means of assessing accuracy. The 2–10% RSD was achieved for all elements except tantalum, thorium, and uranium. Lanthanum background was high during two experiments. Poikiloblastic olivines enclosing <5 μm plagioclase or maskelynite are present but rare (Fig. 2C). There are no FeO-zoned grains exhibit MgO or Na2O zoning (Fig. 4D). Many of these large plagioclase grains are poikilitic and enclose small olivine grains (<5 μm) that tend to be located near the plagioclase grain rims. Some large plagioclase crystals exhibit compositional zoning from core to rim. The rims of all large plagioclase grains analyzed (Fig. 4) tend to have enhanced FeO (>0.3 wt% at the edge, compared to 0.10–0.15 wt% several tens of microns within the grain interior). MgO and Na2O concentrations are mostly constant, but exhibit localized compositional variation only within ~10 μm of plagioclase/maskelynite grain rims (Fig. 4). The FeO concentrations in the rims are variable both in degree of enrichment and distance from the grain boundary; moreover, not all FeO-zoned grains exhibit MgO or Na2O zoning (Fig. 4D). This zoning over tens of microns is unlikely to be due to hitting olivine or pyroxene inclusions or surrounding grains because a 1-μm focused spot size was used and the spot locations were closely inspected for any defects or inclusions.

Plagioclase and Maskelynite

Maskelynite in the matrix of NWA 5744 is relatively homogeneous and has the composition of stoichiometric plagioclase (Table 3; Figs. 2–4; ). The An values (percent anorthite content, measured as molar Ca/[Ca + Na + K] × 100) range from 93.6 to 97.4 with a mean of 96.0 ± 1.3 (2 SD). Some large plagioclase grains (≥120 μm) have visible twinning and birefringence (Fig. 5A), often with undulose extinction indicating partial transformation to maskelynite (Fig. 5). Most large plagioclase grains, whether they contain maskelynite or not, have rounded edges (Fig. 4). Many of these large plagioclase grains are poikilitic and enclose small olivine grains (<5 μm) that tend to be located near the plagioclase grain rims. Some large plagioclase grains exhibit compositional zoning from core to rim. The rims of all large plagioclase grains analyzed (Fig. 4) tend to have enhanced FeO (>0.3 wt% at the edge, compared to 0.10–0.15 wt% several tens of microns within the grain interior). MgO and Na2O concentrations are mostly constant, but exhibit localized compositional variation only within ~10 μm of plagioclase/maskelynite grain rims (Fig. 4). The FeO concentrations in the rims are variable both in degree of enrichment and distance from the grain boundary; moreover, not all FeO-zoned grains exhibit MgO or Na2O zoning (Fig. 4D). This zoning over tens of microns is unlikely to be due to hitting olivine or pyroxene inclusions or surrounding grains because a 1-μm focused spot size was used and the spot locations were closely inspected for any defects or inclusions.

Plagioclase is enriched in light rare earth elements (LREE) relative to heavy rare earth elements (HREE) (Cl-normalized La/Lu ratio of 11.2–24.6, averaging 13.9; Fig. 6C) and contains positive europium anomalies, typical of lunar highland rocks (Table 4).

Olivine

Olivine is distributed relatively evenly in the matrix as anhedral grains with rounded rims ranging in size from 5 to 15 μm (Fig. 2A). Larger subhedral 80–400 μm olivine grains are also present (Fig. 2B). Most olivine grains have fractures, with the larger grains generally being more heavily fractured (Fig. 2B). Poikiloblastic olivines enclosing <5 μm plagioclase or maskelynite are present but rare (Fig. 2C). There are small differences in Mg# between the large and small olivine grains: those >100 μm across have Mg# from
Fig. 2. A) Backscattered electron (BSE) image of an olivine within NWA 5744, surrounded by plagioclase/maskelynite matrix, darker pyroxene, lighter smaller olivines, and white specks of Ti-chromite. B) BSE image of a plagioclase and an olivine grain which were ablated in this study for trace element analyses. The plagioclase has rounded edges and is typical of most of the relict plagioclase grains analyzed. The olivine is among the largest seen on the surface of the NWA 5744 slab, measuring about 400 μm across. Compositionally, it was similar to others ablated, but all others were 150 μm across or less. The white areas around the olivine are where the carbon coating on the slab had been damaged. C) BSE image of a rare poikiloblastic olivine within the slab of NWA 5744 enclosing <5 μm plagioclase or maskelynite. A small shock vein cuts diagonally through the image, skirting the edge of the poikiloblastic olivine. D) BSE image of the largest pyroxene found in the slab of NWA 5744. Its composition is primarily low-Ca pyroxene (~95%) with some lighter colored high-Ca pyroxene within it, both in small anhedral blebs and thin parallel lamellae-like structures.

Fig. 3. A) Backscattered electron image of a portion of the slab of NWA 5744 studied here. B) Elemental map of the same slab portion with Mg colored in red, Ca in green, and Al in blue. Plagioclase is light blue, olivine is bright red, pyroxene is dark burgundy, and terrestrial calcite in the major cracks is bright green. C) Elemental map of the same slab portion with Mg in red, Ca in green, and Fe in blue. Plagioclase is dull green, olivine is bright pink, pyroxene is darker purple, and terrestrial calcite in the major cracks is bright green. (Color figure can be viewed at wileyonlinelibrary.com.)
Table 2. Average major element composition for Northwest Africa (NWA) 5744 primary minerals and bulk rock, where the bulk rock has been calculated from the volumetric modal proportions of different phases.

| Analyses | Na₂O | MgO | Al₂O₃ | SiO₂ | P₂O₅ | K₂O | SO₂ | CaO | TiO₂ | MnO | FeO | Cr₂O₃ | NiO | Total | Mg# | Proportion (vol%) |
|----------|------|-----|-------|------|------|-----|-----|-----|------|-----|-----|-------|-----|--------|-----|------------------|
| Plag (wt%) | 842  | 0.42| 0.09  | 35   | 44.69| 0.02| 0.01| 19.09| 0.02| 0.01| 0.34| 0.01| 0.01| 99.73| 32.1 | 67               |
| Olv      | 145  | 0.02| 41.75 | 0.12 | 38.54| 0.01| 0.02| 0.01| 0.19| 0.16| 0.24| 18.86 | –   | –     | 99.92| 79.8 | 26.3            |
| Low-CaPx | 52   | 0.01| 27.67 | 0.92 | 54.97| 0.01| 0.01| 0.01| 2.55| 0.45| 0.26| 13.09 | –   | –     | 99.96| 79   | 6.3             |
| Aug      | 19   | 0.05| 18.62 | 2.14 | 52.27| 0.04| 0.01| 0.02| 18.47| 1.09| 0.18| 6.45  | –   | –     | 99.32| 83.7 | 0.3             |
| Tri-chm  | 3    | –   | 8.27  | 12.86| 0.25 | –   | –   | –   | 0.39| 6.88 | 0.3 | 27.43| 41.57 | –   | 97.95 | 35   | 0.1             |
| Bulk     | 0.29 | 12.85| 23.56 | 43.7 | 0.02 | 0.02| 0.01| 13.06| 0.09| 0.09| 6.06 | 0.05 | <0.01| 99.79| 79.1 | 100            |

Table 3. Plagioclase and maskelynite major element data (wt%). Plagioclase data are averages for that grain.

| Plag 1 | Plag 2 | Plag 3 | Plag 4 | Plag 5 | Plag 6 | Plag 7 | Plag 8 | Plag 9 | Mask |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|------|
| SiO₂   | 44.41  | 44.57  | 45.23  | 44.84  | 44.60  | 44.44  | 43.59  | 43.93  | 44.30 |
| Al₂O₃  | 35.31  | 35.24  | 35.08  | 35.21  | 35.20  | 35.05  | 35.63  | 35.58  | 35.43 |
| FeO    | 0.11   | 0.14   | 0.05   | 0.13   | 0.09   | 0.01   | 0.07   | 0.07   | 0.14  |
| MgO    | 0.07   | 0.10   | 0.01   | 0.13   | 0.01   | 0.01   | 0.07   | 0.07   | 0.14  |
| CaO    | 19.27  | 19.28  | 19.20  | 19.25  | 19.20  | 19.27  | 19.79  | 19.76  | 19.67 |
| Na₂O   | 0.29   | 0.35   | 0.04   | 0.39   | 0.04   | 0.04   | 0.32   | 0.04   | 0.33  |
| K₂O    | 0.02   | 0.02   | 0.02   | 0.02   | 0.02   | 0.02   | 0.02   | 0.02   | 0.03  |
| Total  | 99.48  | 99.70  | 100.17 | 99.87  | 99.59  | 99.34  | 99.57  | 99.84  | 100.05 |
| An     | 97.28  | 96.75  | 96.38  | 96.62  | 96.55  | 96.54  | 97.04  | 96.91  | 96.89 |
| Mg#    | 54.49  | 55.46  | 64.25  | 58.80  | 57.54  | 54.66  | 42.64  | 48.31  | 60.29 |

Uncertainties reported are the averaged 1σ analytical uncertainties for all EMP measurements on the specific grain. Standard deviations for the averages are all less than 0.01.
78.0 to 79.3 (average 78.7 ± 0.8; Table 5), and those of 5–50 µm across are more magnesian with Mg# from 79.2 to 82.1 (average 80.3 ± 0.8). Because of the heavy fracturing, rim to rim profiles could not be obtained for olivine grains. However, individual points do not exhibit any heterogeneity of major elements within a given olivine grain. Olivine trace element concentrations are presented in Table 5.

Olivine grains have low LREE concentrations (Fig. 6D) near the LA-ICP-MS detection limit (Appendix S2 in supporting information), but have HREE concentrations that are comparatively higher than the instrument detection limit. Olivine LREE concentrations are relatively flat (CI-normalized La/Lu ratio of 0.39–5.53, averaging 2.20; Fig. 6D). The HREE in the olivine shows a strong positive slope (CI-normalized La/Lu ratio of 0.04–0.56, averaging 0.22).

Pyroxene

Rare >80 µm low-Ca pyroxene grains are present in addition to the common ~5 µm matrix grains (Figs. 2A–C). A few of these larger pyroxenes show distorted <3 µm scale high-Ca exsolution lamellae (Fig. 2D). The vast majority (95%) of the pyroxenes are low-Ca matrix grains, and larger grains share the same composition (En77.8-81.2, Fs14.7-17.6, Wo2.0-6.0; Table 6, Fig. 7). One larger grain showed a small increase in CaO at the rim (1.71–3.80 wt%). Augite accounts for the remaining 5% of the pyroxenes (En48.1-52.4, Fs8.1-10.2, Wo37.4-43.8; Fig. 7). Augite is present as both lamellae and distinct grains within the matrix. In low-Ca pyroxene, Mg# ranges from 80.9 to 84.3 (average 82.4 ± 1.3); in augite, Mg# ranges from 83.4 to 86.2 (average 84.7 ± 2.3). All augite grains found and analyzed (Fig. 7) were <5 µm across, and they were also all in direct contact with low-Ca pyroxene. The pyroxenes are LREE depleted, with a negative europium anomaly (Table 7).

The pyroxene trace element compositions each show a bulk (e.g., mix of high and low-Ca exsolution, Fig. 1D) smooth pattern with a gradual increase in CI-normalized concentration from the LREE to the HREE (CI-normalized La/Lu ratio of 0.12–0.15, averaging 0.13), with negative Eu/Eu* anomalies (0.027–0.086) (Figs. 6A–B).
Four distinct large pyroxene grains with coexisting (i.e., in contact) low-Ca pyroxene and high-Ca pyroxene (augite) were identified for two-pyroxene thermometry. The Lindsley (1983) Ca-Mg thermometer gives a very broad range of temperatures from 800 °C to 1270 °C at 1 atm. The Ca-Mg two-pyroxene thermometer of Brey and Kohler (1990) also shows a wide range in temperatures at 1 atm, from 835 to 1379 °C.

Ti-chromite

Ti-chromite is present in the sample matrix as a minor component, accounting for 0.1% of the rock volume, with a typical grain size of ~1 μm or less. Three ~3-μm Ti-chromites were analyzed by EPMA (Table 6), but were not large enough for laser ablation analysis.

Accessory Phases

All other accessory phases identified were too small and/or had surfaces that were too irregular to get acceptable major element compositions using EPMA. Troilite has been previously observed in NWA 5744 (Weisberg et al. 2009; Kuehner et al. 2010). Only one instance of a phase with significant sulfur and nickel content was observed in our samples, and is likely a grain of troilite (from EDS spectral identification). It is present as an inclusion within a large plagioclase grain. Two other instances of an iron-bearing, sulfur-poor phase with nickel and cobalt levels in excess of 5 and 3 wt%, respectively, according to WDS measurements were also observed, both within fractures of large olivines; however, these phases were too small to measure accurately and did not produce stoichiometrically balanced results. Two <5-μm phosphates were identified in the available sample material, but they were too small to collect EPMA data. One ~10-μm phosphate was also identified within a hole where a grain appears to have been plucked out when the slab was cut or polished, but the irregular and nonlevel surface did not allow for EMP measurement either.

Calcite is present in most of the largest cracks (Fig. 3—green colored vein networks) and presumably records terrestrial contamination/alteration. This terrestrial contamination does not appear to be present in any of the smaller fractures in the rock, or within any of the previously described mineral phases.

Shock Features

Northwest Africa 5744 has shock features similar to those of other lunar granulitic meteorites, such as NWA 3163 (Hudgins et al. 2011a, 2011b), including a matrix composed largely of maskelynite. Almost all pyroxene is present in the matrix as elongated, amoeboid, or otherwise anhedral ~5-μm grains (Figs. 2 and 5), which suggests these phases were deformed under ductile conditions (Warren and Rubin 2010). Open fractures cut through nearly all of the olivine and all of the large pyroxene grains. Large plagioclase grains show little or no fracturing, and those fractures tend only to be very fine cracks.

Shock-induced melt veins are present in NWA 5744 and run roughly along planes throughout the sample in a variety of orientations for hundreds to thousands of microns. Thicknesses of the veins vary along their lengths, from as much as 15 μm to less than 1 μm (Fig. 2C). The average measured shock vein major features.

Fig. 5. Cross-polarized microscope photographs of NWA 5744 in thin section. Left) Relatively unshocked relict plagioclase grain, with maskelynitized plagioclase matrix around it. Right) Relict plagioclase grains exhibiting shock features including undulatory extinction, mosaicism, and planar fractures. (Color figure can be viewed at wileyonlinelibrary.com.)
element composition is also given in Table 6, but it does change with location. The shock veins cut through large plagioclase grains, maskelynite, and pyroxenes and tend to follow the edges of olivines with some smearing of the olivine into the veins. The shock veins are cut by some later fractures.

**Bulk Composition**

A major element modal recombination bulk composition was estimated using average plagioclase, olivine, pyroxene, and Ti-chromite compositions (Table 2) and the mineral mode estimated by pixel counting in
Adobe Photoshop on SEM compositional maps. All other minerals were neglected in this bulk estimate due to their low abundance and/or small grain size.

The bulk trace element composition of NWA 5744 was derived using two approaches. (1) By averaging the modal abundance of the matrix material area (91.6%) and the large grains of plagioclase (7.7%), olivine (0.6%), and pyroxene (0.1%) (Table 7—“Modal Bulk”). (2) Trace element concentrations were acquired in eight different places throughout fine-grained matrix of the meteorite using broad 176-μm spot ablations. We avoided major cracks (to avoid terrestrial contamination) and large mineral or lithic grains (to avoid biasing the results toward the composition of these grains). These results were then averaged together to approximate a bulk rock trace element composition (Table 7—“Matrix”). Our modal mineralogy bulk rock estimate (Table 7—“Modal Bulk”) is likely to be more representative of the rock as a whole because it is calculated using a larger surface area of the rock than was measured in matrix ablations alone and accounts for any compositional differences between large grains and matrix material.

DISCUSSION

Petrographic and Compositional Observations

Northwest Africa 5744 is primarily composed of what appears to be a metamorphic matrix of <30 μm olivines and <10 μm pyroxenes surrounded by maskelynite (Fig. 5). The presence of maskelynite and irregular fractures within olivines both indicate that the rock was subjected to high pressure shock (Stöffler et al. 1991; Hiesinger and Head 2006). The larger 80-μm olivine, plagioclase, and pyroxene grains do not exhibit the same metamorphic textures as the smaller, amoeboid, and anhedral matrix grains. Most of these larger grains seem to have retained at least some protolith texture, morphology, and composition; we will refer to these as porphyroclastic or “relict grains.”

The chemical zoning observed in relict plagioclase grains may indicate partial chemical equilibration during metamorphism. Since all of the augite compositions in Fig. 7 plot in a mixing line between higher and lower Ca-types, and all grains analyzed were <5 μm across and in direct content with low-Ca pyroxene, they are, therefore, suspected of being measurements of some mixture between the true augite composition and that of the low-Ca pyroxene.

Although shock veins typically represent localized and preferential melting of the material they cut through, their major element compositions may still approximate that of the bulk rock (Walton and Spray 2003; Walton and Herd 2007). However, when comparing the calculated bulk composition using the mineral compositions and their modes, the average for the shock vein composition (Table 6) is about 8% and 4% lower for MgO and FeO, respectively, and about 8% and 4% in excess for Al2O3 and CaO, respectively. This is consistent with the shock veins probably containing too little melted olivine and/or pyroxene material to represent an accurate bulk rock composition, given that the shock veins tend to go around the edges of olivine grains rather than cut directly through them (Fig. 2C). Hence, we propose that the bulk compositions measured from large spot size LA-ICP-MS ablations (Table 7) or calculated using the major mineral compositions and modes (Table 2) are likely more representative than shock vein composition for this sample.

Comparison of NWA 5744 with Apollo Lunar Highlands Lithologies

Major Elements

Ferroan anorthosites and the Mg-suite of pristine lunar crustal rocks define separate fields on a diagram of anorthite content in plagioclase versus Mg# of mafic minerals in equilibrium with one another (Fig. 8) (see Warren and Wasson 1977; Goodrich et al. 1984; Warren 1993; Treiman et al. 2010). Minerals in NWA 5744 plot on the edge of the Mg-suite field in the Fig. 8 diagram. The range of An content appears to be centered on the field of expected FAN compositions, which also seems to be true for most other lunar magnesian feldspathic granulites (Fig. 8), with the exception of lunar meteorite Dhofar 733 which contains more sodic plagioclase (Foreman et al. 2008) and is more likely related to an ITE-rich Mg-suite protolith. Olivine in NWA 5744 and other magnesian feldspathic granulites have Mg# similar to Mg-suite rocks (Fig. 8). The calculated bulk rock Mg# of 79 (Table 2) is higher than FAN samples, but also most similar to samples from the Mg-Suite. However, the mafic mineral Mg# and An content for NWA 5744 do not completely overlap with those of many other lunar magnesian feldspathic granulites, which may indicate diversity in their respective source materials.

Both Ni and Co concentrations in NWA 5744 matrix material (Table 7) are low compared to chondrites, falling well within the range of pristine Apollo highlands rocks and soils (Wasson and Kallemeyn 1988). In materials with Ni and Co dominantly obtained through impactor contamination, the Ni/Co ratio should approach 20 (Wasson and Kallemeyn 1988), but in NWA 5744 matrix, the ratios are all less than 5. Thus, although the sample is granulite in nature, there is no indication of significant siderophile-element-rich impactor contribution to NWA 5744.
| Spot (µm) | Ablations | Co (ppm) | Ni | Cu | Ga | Sr | Y | Zr | Nb | Ba | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu | Hf | Ta | Th | U |
|----------|-----------|----------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 30       | 14        | 52.5     | 179 | 121 | 14  | 112 | 15.8| 15.3| 0.564 | 6.6 | 0.623 | 1.93 | 0.381 | 2.49 | 1.14 | 0.537 | 1.91 | 0.369 | 2.73 | 0.599 | 1.79 | 0.26 | 0.27 | 0.609 | 0.038 | 0.03 | 0.016 |
| 30       | 6         | 52.90    | 165.35 | 126.77 | 15.77 | 101.92 | 13.33 | 12.52 | 0.499 | 6.20 | 0.549 | 1.884 | 0.351 | 2.193 | 0.981 | 0.481 | 1.514 | 0.300 | 2.142 | 0.493 | 2.335 | 1.491 | 0.225 | 0.316 | 0.472 | 0.031 | 0.027 | 0.015 |
| 8        | 1σ       | 1.58     | 1.24 | 1.95 | 2.37 | 1.77 | 1.73 | 2.00 | 2.07 | 1.881 | 0.302 | 0.555 | 0.103 | 0.071 | 0.138 | 0.746 | 0.133 | 0.024 | 0.010 | 0.018 | 0.547 | 1.271 | 0.971 | 2.856 | 0.011 | 0.016 | 7.102 |
| 30       | %RSD     | 0.13     | 18.60 | 5.58 | 0.34 | 5.22 | 0.32 | 0.21 | b.d. | 11.81 | 0.025 | 0.048 | 0.013 | 0.071 | 0.047 | 0.064 | 0.035 | 0.007 | 0.024 | 0.041 | 0.009 | 0.009 | 8.889 | 0.007 | 0.007 | 0.032 |
| 30       | lσ      | 1.39      | 32.42 | 1.57 | 5.22 | 2.06 | 5.07 | 51.24 | b.d. | 12.34 | 0.265 | 0.633 | 0.090 | 0.403 | 0.172 | 0.138 | 0.133 | 0.024 | 0.041 | 0.019 | 0.029 | 12.29 | b.d. | 2.856 | 0.007 | 0.016 | 7.102 |
| 30       | %RSD    | 0.15   | 93.30 | 1.63 | 3.36 | 0.38 | 3.46 | 0.21 | b.d. | 101.55 | 0.24 | 0.45 | 0.065 | 0.065 | 0.053 | 0.064 | 0.035 | 0.007 | 0.041 | 0.019 | 0.029 | 12.29 | b.d. | 2.856 | 0.007 | 0.016 | 7.102 |
| 30       | lσ    | 101.41 | 50.75 | 12.36 | 14.44 | 3.65 | 157.63 | 30.75 | 51.24 | b.d. | 16.313 | 13.413 | 17.927 | 17.613 | 20.683 | 32.19 | 32.19 | 20.538 | 19.558 | 42.262 | 24.421 | 19.195 | 19.195 | 12.29 | 0.007 |
| 30       | %RSD  | 0.55  | 0.12 | 1.47 | 0.45 | 3.65 | 8.08 | 0.49 | b.d. | 1.026 | 2.417 | 0.290 | 1.118 | 0.222 | 0.172 | 0.138 | 0.133 | 0.024 | 0.041 | 0.019 | 0.029 | 12.29 | b.d. | 2.856 | 0.007 | 0.016 | 7.102 |
| 30       | lσ | 98.34 | b.d. | 41.91 | 24.96 | 1.42 | 159.99 | 13.76 | b.d. | b.d. | 6.025 | 7.799 | 11.467 | 11.697 | 23.610 | 22.810 | 20.891 | 25.941 | 20.05 | 19.558 | 42.262 | 24.421 | 19.195 | 19.195 | 12.29 | 0.007 |
| 30       | %RSD | b.d. | b.d. | 72.53 | 16.08 | 10.52 | 2.00 | 0.47 | 0.47 | 0.55 | 0.076 | 0.076 | 0.076 | 0.076 | 0.076 | 0.076 | 0.076 |

Table 4. Plagioclase trace element data.
Table 4. Continued. Plagioclase trace element data.

|   | Plag 5 |   | %RSD | Plag 6 |   | %RSD | Plag 7 |   | %RSD | Plag 8 |   | %RSD | Plag 9 |   | %RSD |
|---|--------|---|------|--------|---|------|--------|---|------|--------|---|------|--------|---|------|
| Spot (μm) | 30 | 1σ | 84 |   | %RSD | 84 |   | %RSD | 84 |   | %RSD | 84 |   | %RSD |
| Ablations | 3 |   | 2 |   |   | 2 |   |   | 1 |   |   | 2 |   |   |
| Co (ppm) | b.d. |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Ni | b.d. |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Cu | b.d. |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Ga | 2.03 | 0.42 | 21.76 | 1.80 | 0.10 | 32.57 | 1.21 | 0.06 | 26.09 | 1.63 | 0.09 | 2.23 | 0.12 | 9.92 |   |
| Sr | 154.05 | 10.72 | 0.21 | 111.36 | 5.28 | 29.08 | 89.48 | 4.71 | 29.20 | 104.10 | 5.60 | 138.34 | 7.62 | 3.97 |   |
| Y | 0.46 | 0.05 | 6.92 | 0.33 | 0.02 | 20.73 | 0.20 | 0.02 | 35.53 | 0.15 | 0.01 | 0.10 | 0.01 | 5.82 |   |
| Zr | 0.67 | 0.23 | 0.00 | 0.87 | 0.08 | 34.77 | 0.40 | 0.05 | 16.68 | b.d. | – | 0.37 | 0.07 | 41.45 |   |
| Nb | b.d. |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Ba | 8.19 | 0.64 | 5.54 | 12.51 | 0.56 | 31.31 | 6.18 | 0.26 | 44.88 | 8.38 | 0.35 | 21.17 | 0.90 | 17.04 |   |
| La | 0.212 | 0.021 | 0.964 | 0.588 | 0.026 | 30.943 | 0.222 | 0.014 | 47.209 | 0.189 | 0.013 | 0.082 | 0.007 | 4.481 |   |
| Ce | 0.526 | 0.044 | 5.319 | 1.401 | 0.056 | 30.682 | 0.523 | 0.032 | 45.182 | 0.382 | 0.024 | 0.193 | 0.014 | 12.333 |   |
| Pr | 0.079 | 0.012 | 7.966 | 0.181 | 0.009 | 30.657 | 0.064 | 0.004 | 40.054 | 0.050 | 0.004 | 0.029 | 0.003 | 5.973 |   |
| Nd | 0.349 | 0.059 | 4.940 | 0.770 | 0.044 | 28.702 | 0.298 | 0.019 | 38.567 | 0.232 | 0.016 | 0.093 | 0.011 | 3.813 |   |
| Sm | 0.143 | 0.048 | 7.402 | 0.135 | 0.015 | 24.677 | 0.070 | 0.007 | 43.019 | 0.040 | 0.006 | 0.030 | 0.006 |   |   |
| Eu | 0.674 | 0.081 | 6.809 | 0.513 | 0.028 | 28.798 | 0.428 | 0.022 | 29.387 | 0.521 | 0.027 | 0.630 | 0.034 | 4.438 |   |
| Gd | 0.100 | 0.037 | 10.448 | 0.106 | 0.012 | 25.824 | 0.062 | 0.006 | 46.770 | 0.037 | 0.005 | 0.036 | 0.006 | 30.243 |   |
| Tb | b.d. |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Dy | 0.273 | 0.046 | 4.820 | 0.056 | 0.009 | 23.290 | 0.045 | 0.005 | 45.924 | 0.033 | 0.005 | 0.028 | 0.005 |   |   |
| Ho | 0.027 | 0.008 | 8.700 | 0.012 | 0.002 | 25.435 | 0.008 | 0.001 | 25.452 | 0.005 | 0.001 | 0.005 | 0.001 | 17.131 |   |
| Er | 0.072 | 0.035 | 0.215 | 0.029 | 0.006 | 2.215 | 0.014 | 0.003 | 34.834 | 0.016 | 0.003 | b.d. | – |   |   |
| Tm | b.d. |   |   |   |   |   |   |   |   |   |   | b.d. |   |   |   |
| Yb | b.d. |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Lu | b.d. |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Hf | b.d. |   |   |   |   |   |   |   |   |   |   | b.d. |   |   |   |
| Ta | b.d. |   |   |   |   |   |   |   |   |   |   | 8.609 | 0.002 | 0.001 | 41.120 | b.d. | – |   |
| Th | b.d. |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| U | 0.013 | 0.007 | 0.003 | 0.001 | 19.531 | 0.002 | <0.001 | 2.236 | 0.001 | <0.001 | 0.003 | 0.001 | 0.007 | 0.003 | 8.535 |   |

%RSD is the percent relative standard deviation for each element across all averaged ablations. 1σ uncertainty for plagioclase is the averaged analytical uncertainty for that particular grain. Where more than one ablation was performed on a particular grain or on matrix material, the %RSD across all averaged measurements is reported. When only one ablation measured a given element above the detection limit, %RSD cannot be calculated. b.d. = below detection limits.
Table 5. (a) Olivine major element data, averaged for each olivine grain.  (b) Olivine trace element data

| (a) Element | Olv 1 | 1σ | Olv 2 | 1σ | Olv 3 | 1σ | Olv 4 | 1σ | Olv 5 | 1σ | Olv 6 | 1σ | Olv 7 | 1σ |
|-------------|------|----|------|----|------|----|------|----|------|----|------|----|------|----|
| SiO₂ (wt. %) | 39.13 | 0.20 | 39.32 | 0.20 | 39.16 | 0.20 | 39.11 | 0.20 | 38.74 | 0.22 | 38.66 | 0.19 | 38.71 | 0.20 |
| TiO₂ | b.d. | – | 0.05 | – | 0.17 | – | b.d. | – | 0.04 | – | 0.06 | – | b.d. | – |
| Al₂O₃ | 0.04 | 0.02 | b.d. | – | 0.05 | 0.02 | b.d. | – | 0.04 | 0.01 | 0.03 | 0.02 | 0.07 | 0.02 |
| FeO | 19.93 | 0.32 | 19.70 | 0.32 | 19.65 | 0.32 | 20.19 | 0.32 | 20.30 | 0.34 | 19.24 | 0.32 | 20.21 | 0.32 |
| MgO | 41.16 | 0.32 | 41.54 | 0.32 | 41.31 | 0.32 | 41.14 | 0.32 | 41.62 | 0.21 | 41.24 | 0.32 | 40.13 | 0.31 |
| CaO | 0.10 | 0.03 | 0.08 | 0.02 | 0.09 | 0.02 | 0.09 | 0.02 | 0.07 | 0.02 | 0.12 | 0.02 | 0.12 | 0.02 |
| MnO | 0.26 | 0.05 | 0.25 | 0.05 | 0.27 | 0.05 | 0.24 | 0.05 | 0.26 | 0.06 | 0.23 | 0.05 | 0.25 | 0.05 |
| NiO | b.d. | – | b.d. | – | b.d. | – | b.d. | – | b.d. | – | b.d. | – | b.d. | – |
| Cr₂O₃ | b.d. | – | 0.05 | 0.03 | 0.08 | 0.03 | b.d. | – | b.d. | – | b.d. | – | b.d. | – |
| Total | 100.70 | 101.03 | 100.82 | 100.86 | 101.13 | 99.64 | 99.57 | |
| Mg' | 78.63 | |

| (b) | Olv 1 | 1σ | Olv 2 | 1σ | Olv 3 | 1σ | Olv 4 | 1σ | Olv 5 | 1σ | % RSD | Olv 6 | 1σ | Olv 7 | 1σ |
|------|------|----|------|----|------|----|------|----|------|----|--------|------|----|------|----|
| Spot (µm) | 84 | 84 | 84 | 84 | 84 | 176 | 84 | 84 |
| Ablations | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Co (ppm) | 80.18 | 3.01 | 75.34 | 2.84 | 71.95 | 2.72 | 77.23 | 2.94 | 52.84 | 3.82 | 0.30 | 70.36 | 2.55 | 76.65 | 2.66 |
| Ni | 204.34 | 8.11 | 125.54 | 5.11 | 160.90 | 6.61 | 140.65 | 5.79 | 112.66 | 6.32 | 1.58 | 123.26 | 6.00 | 129.35 | 9.84 |
| Cu | 8.61 | 0.38 | 6.30 | 0.28 | 8.78 | 0.40 | 6.41 | 0.29 | 5.10 | 0.36 | 1.01 | 5.77 | 0.28 | 6.59 | 0.53 |
| Ga | 0.18 | 0.01 | 0.70 | 0.04 | 2.02 | 0.10 | 0.24 | 0.02 | 0.30 | 0.04 | 117.66 | 0.18 | 117.66 | 0.18 |
| Sr | 6.37 | 0.27 | 5.10 | 0.22 | b.d. | – | 2.97 | 0.13 | 3.91 | 0.28 | 43.90 | 0.18 | 14.18 | 2.02 |
| Y | 0.51 | 0.03 | 0.42 | 0.03 | 0.72 | 0.04 | 0.25 | 0.02 | 0.32 | 0.10 | 10.45 | 0.07 | 0.54 | 0.14 |
| Zr | 2.14 | 0.12 | 2.44 | 0.15 | 2.69 | 0.17 | 0.79 | 0.07 | 1.57 | 0.30 | 17.17 | 0.19 | 0.95 | 0.35 |
| Nb | 0.427 | 0.021 | 0.224 | 0.013 | 0.326 | 0.019 | 0.029 | 0.003 | 0.224 | 0.026 | 11.82 | 0.254 | 0.147 | 0.025 |
| Ba | b.d. | – | b.d. | – | 13.94 | 0.52 | 7.91 | 0.30 | b.d. | – | – | 11.64 | 0.48 | b.d. | – |
| La | 0.055 | 0.004 | 0.016 | 0.002 | 0.174 | 0.012 | 0.028 | 0.003 | 0.025 | 0.007 | 19.051 | 0.085 | 0.113 | 0.015 |
| Ce | 0.209 | 0.012 | 0.142 | 0.009 | 0.442 | 0.025 | 0.091 | 0.006 | 0.121 | 0.015 | 8.936 | 0.357 | 0.397 | 0.042 |
| Pr | 0.024 | 0.002 | 0.010 | 0.001 | 0.054 | 0.004 | 0.008 | 0.001 | 0.012 | 0.002 | 1.732 | 0.041 | 0.039 | 0.007 |
| Nd | 0.099 | 0.009 | 0.031 | 0.006 | 0.181 | 0.017 | 0.039 | 0.005 | 0.046 | 0.014 | 10.241 | 0.246 | 0.308 | 0.040 |
| Sm | 0.028 | 0.006 | b.d. | – | 0.051 | 0.009 | 0.022 | 0.004 | 0.017 | 0.005 | 10.001 | 0.093 | 0.050 | 0.021 |
| Eu | 0.006 | 0.001 | 0.007 | 0.002 | b.d. | – | 0.003 | 0.001 | 0.005 | 0.001 | 38.442 | 0.011 | 0.007 | 0.013 |
| Gd | 0.051 | 0.006 | 0.018 | 0.004 | 0.058 | 0.008 | 0.016 | 0.004 | 0.025 | 0.008 | 10.602 | 0.089 | 0.068 | 0.027 |
| Tb | 0.009 | 0.001 | 0.002 | 0.001 | 0.009 | 0.002 | 0.001 | 0.001 | 0.004 | 0.002 | 50.943 | 0.021 | 0.007 | 0.005 |
| Dy | 0.067 | 0.007 | 0.037 | 0.006 | 0.101 | 0.011 | 0.028 | 0.005 | 0.037 | 0.012 | 35.224 | 0.133 | 0.036 | 0.038 |
| Ho | 0.016 | 0.002 | 0.014 | 0.002 | 0.021 | 0.003 | 0.009 | 0.001 | 0.011 | 0.004 | 17.184 | 0.036 | 0.016 | 0.008 |
Table 5. Continued. (a) Olivine major element data, averaged for each olivine grain. (b) Olivine trace element data.

|        | Olv 1 | 1σ    | Olv 2 | 1σ    | Olv 3 | 1σ    | Olv 4 | 1σ    | Olv 5 | 1σ    | %RSD  | Olv 6 | 1σ    | Olv 7 | 1σ |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|----|
| Er     | 0.067 | 0.007 | 0.053 | 0.007 | 0.116 | 0.012 | 0.038 | 0.005 | 0.042 | 0.014 | 18.215| 0.109 | 0.015 | 0.067 | 0.028 |
| Tm     | 0.015 | 0.002 | 0.014 | 0.002 | 0.027 | 0.003 | 0.012 | 0.001 | 0.010 | 0.003 | 10.142| 0.021 | 0.003 | 0.015 | 0.005 |
| Yb     | 0.147 | 0.010 | 0.154 | 0.011 | b.d.  | 0.122 | 0.009 | b.d.  | 0.199 | 0.020 | 0.107 | 0.030 |
| Lu     | 0.029 | 0.003 | 0.041 | 0.003 | 0.062 | 0.005 | 0.029 | 0.002 | 0.024 | 0.005 | 5.685 | 0.039 | 0.005 | 0.035 | 0.007 |
| Hf     | 0.076 | 0.007 | 0.041 | 0.006 | 0.052 | 0.007 | 0.022 | 0.004 | 0.041 | 0.009 | 4.995 | 0.109 | 0.013 | 0.017 | 0.016 |
| Ta     | 0.041 | 0.003 | 0.014 | 0.002 | 0.017 | 0.003 | b.d.  | 0.020 | 0.002 | 8.821 | 0.016 | 0.003 | 0.008 | 0.003 |
| Th     | 0.048 | 0.004 | 0.015 | 0.002 | 0.025 | 0.003 | 0.008 | 0.001 | 0.022 | 0.006 | 89.735| 0.024 | 0.004 | 0.030 | 0.004 |
| U      | 0.015 | 0.001 | 0.011 | 0.001 | 0.008 | 0.001 | 0.020 | 0.001 | 0.009 | 0.001 | 12.576| 0.019 | 0.002 | 0.027 | 0.001 |

*aUncertainties reported are the averaged 1σ analytical uncertainties for all EMP measurements on the specific grain. b.d. = below detection limits.

Table 6. Average of pyroxene, average shock vein, and titanium chromite major element data.

|                  | Pyroxene 1 |                  | Pyroxene 2 |                  | Pyroxene 3 |                  | Avg. Shock Vein |                  | Ti-Chromite |
|------------------|------------|-----------------|------------|-----------------|------------|-----------------|-----------------|-----------------|------------|
|                  | LCP Core   | 1σ              | LCP Rim    | 1σ              | Aug        | 1σ              | LCP Core        | 1σ              | LCP Rim    | 1σ              | Total       | 1σ              |
|                  |            |                 |            |                 |            |                 |                 |                 |            |                 |             |                 |
| SiO2 (wt %)      | 55.48      | 0.24            | 55.39      | 0.24            | 51.88      | 0.23            | 53.48           | 0.46            | 50.62      | 0.43            | 54.48       | 0.32            |
| TiO2             | 0.30       | 0.02            | 0.40       | 0.03            | 1.19       | 0.04            | 0.69            | 0.06            | 1.27       | 0.07            | 0.44        | 0.04            |
| Al2O3            | 0.78       | 0.02            | 0.87       | 0.02            | 2.29       | 0.04            | 1.07            | 0.04            | 2.06       | 0.06            | 1.29        | 0.03            |
| FeO              | 12.30      | 0.27            | 11.20      | 0.25            | 6.34       | 0.18            | 12.29           | 0.40            | 6.24       | 0.27            | 11.69       | 0.51            |
| MgO              | 29.32      | 0.33            | 28.22      | 0.32            | 17.91      | 0.21            | 29.27           | 0.41            | 17.77      | 0.27            | 28.83       | 0.38            |
| CaO              | 1.71       | 0.07            | 3.80       | 0.11            | 19.17      | 0.30            | 2.49            | 0.13            | 20.17      | 0.44            | 2.77        | 0.09            |
| Na2O             | b.d.       | b.d.            | b.d.       | b.d.            | b.d.       | b.d.            | b.d.            | b.d.            | b.d.       | b.d.            | 0.33        | 0.05            |
| MnO              | 0.24       | 0.04            | 0.23       | 0.04            | 0.19       | 0.04            | 0.26            | 0.08            | 0.17       | 0.08            | 0.28        | 0.06            |
| Cr2O3            | b.d.       | b.d.            | b.d.       | b.d.            | b.d.       | b.d.            | b.d.            | b.d.            | b.d.       | b.d.            | 0.33        | 0.05            |
| SO2              | b.d.       | b.d.            | b.d.       | b.d.            | b.d.       | b.d.            | b.d.            | b.d.            | b.d.       | b.d.            | 0.08        | 0.03            |
| Total            | 100.14     | 100.10          | 98.97      | 100.00          | 99.06      | 100.35          | 99.89           | 99.77           | 97.96      | 100.10          | 99.06       | 100.35          |
| Mg#              | 77.38      | 78.34           | 80.21      | 77.37           | 80.35      | 77.97           | 77.88           | 75.45           | 30.20      | 77.37           | 80.35       | 77.97           |
| En                | 75.83      | 75.83           | 50.82      | 77.12           | 49.69      | 77.25           | 75.83           | 75.83           | 75.83      | 75.83           | 75.83       | 75.83           |
| Fs                | 17.02      | 17.02           | 10.09      | 18.17           | 9.79       | 17.61           | 17.02           | 17.02           | 17.02      | 17.02           | 17.02       | 17.02           |
| Wo                | 7.15       | 7.15            | 39.09      | 4.71            | 40.53      | 5.14            | 7.15            | 7.15            | 7.15       | 7.15            | 7.15        | 7.15            |

*LCP = low-Ca pyroxene; Aug = augite; b.d. = below detection limits.

Uncertainties reported are the averaged 1σ analytical uncertainties for all EMP measurements on the specific grain or across all shock vein measurements.
Mineral Trace Elements

Plagioclase is readily affected by terrestrial chemical modification processes, which elevate Ba and Sr concentrations (Tera et al. 1970). However, in NWA 5744, the Ba and Sr contents of plagioclase are similar to that of pristine Apollo FAN (Fig. 6C); this is a strong indication a terrestrially added component to these analyzed phases is minimal.

The rare earth element (REE) CI-normalized patterns of NWA 5744 (Fig. 6C) overlap with those of “pristine” Apollo FAN plagioclase compositions (Papike et al. 1997; Floss et al. 1998), and have lower REE concentrations relative to the plagioclases from Mg-suite samples (Papike et al. 1996; Shervais and McGee 1998). There is also a large spread in REE abundance between individual NWA 5744 grains, spanning about one order of magnitude (Fig. 6C). Although Eu abundances also overlap with those of FAN (Fig. 9B), the Eu/Sm ratios of NWA 5744 plagioclase (Fig. 9A), which are a function of the magnitude of the positive Eu-anomalies, are higher than those for the FAN suite, and overlap with the Eu/Sm ratios in Mg-suite plagioclases with the same An contents (Fig. 9). This is also true of plagioclase from other feldspathic lunar meteorites (e.g., Russell et al. 2014). Plagioclase from the Mg-suite displays a broader range of An (Fig. 8) and trace element content, but generally has higher concentrations of ITE than either FAN or the NWA 5744 plagioclase (see CI-normalized La/Yb in Fig. 9). The NWA 5744 data tend to plot on the periphery of the field of Mg-suite plagioclase in each case, rather than distinctly within the field.

The composition of NWA 5744 overlaps broadly, in terms of plagioclase and low-Ca pyroxene trace elements, with that of FAN suite lithologies (Figs. 6A–C). The mineral major element composition (Figs. 7 and 8) appears as an extension of the FAN suite toward more magnesian compositions (Figs. 6C, 8, and 9). Rare earth element contents are similar to those of Apollo FAN material as well as some other lunar meteorites (e.g., Dhofar 081 and Dhofar 908; Russell et al. 2014). Rare earth element concentrations of NWA 5744 pyroxenes fall within the range for FAN pyroxenes and some Mg-suite orthopyroxenes (Figs. 6A–B) (Papike et al. 1994; Floss et al. 1998; Shervais and McGee 1999a).

In summary, the plagioclase major and trace element compositions of NWA 5744 are most similar to those of the Apollo pristine FAN suite. Northwest Africa 5744 olivine, pyroxene, and plagioclase, and bulk rock (Table 2), however, are as Mg rich as those from Mg-suite lithologies.

Major elements in magnesian feldspathic granulites from Apollo samples 60035, 67415, 72275, 76230, and 79215 (Ma and Schmitt 1982; Lindstrom and Lindstrom 1986; Salpas et al. 1988), as well as both major and trace elements from Mg-rich granulate clasts in lunar meteorites ALH 81005, Dhofar 309, and Dhofar 489 (Takeda et al. 2006; Treiman et al. 2010), are similar to those of NWA 5744 (Figs. 6C, 8, and 9). As noted in Hilton et al. (2016) about NWA 5744 and its paired stones, this group of meteorites is the most magnesian of all the feldspathic lunar meteorites recovered to date.

Bulk Rare Earth Element Composition

The average measured bulk matrix REE content (Table 7) is about 2–4 times greater than the bulk composition calculated by modal recombination and relict grain REE content, except for La and Eu which are closer to the average LA-ICP-MS measurements (Fig. 10, Table 7). The lower La concentration is explained by the two bulk (matrix) ablation spot measurements with background readings too high to resolve La from the background signal. For Eu, the average measured bulk composition is a close match to the calculated modal recombination values. Phosphate minerals could account for some of the excess REE if some were ablated in the matrix material, but their rarity in the surfaces examined here makes it unlikely that they were present in all of the matrix ablations unless they are submicron scale. A more likely explanation for the difference is simply that the matrix maskelynite, olivine, and pyroxene are more enriched in REEs than the relict grains.

Kuehner et al. (2010) performed instrumental neutron activation analysis (INAA) on clean saw cuttings from NWA 5744. Their data are similar to both our average matrix and modal bulk calculations (Fig. 10), though not an exact match for either. The differences are a small excess in LREE content and lower HREE content compared to our data, which can be explained by observed heterogeneities in major mineral abundance observed throughout NWA 5744 as well as among grouped stones. Measurements of La, Sm, Eu, and Yb concentrations in paired stone NWA 10401 (Hilton et al. 2016) are lower than those we report here, but are within the total range of all the matrix laser ablation spots we measured. Given the established heterogeneity of NWA 5744 and its pairings, our calculated modal bulk REE composition is within the published range of data.

All the bulk rock trace element determinations for NWA 5744 record higher REE concentrations than those of the magnesian feldspathic granulate clasts in lunar meteorites Dhofar 489 (Takeda et al. 2006), ALH 81005, or Dhofar 309 (Treiman et al. 2010) (Fig. 10, light gray field), with compositions dissimilar to Apollo magnesian feldspathic granulites (Fig. 10, dark gray field). Bulk REE patterns of magnesian feldspathic granulate clasts
Fig. 7. Pyroxene composition for NWA 5744, compared with pyroxene from ferroan anorthosite (FAN) and Mg-suite rocks (Papike et al. 1994; Floss et al. 1998; Shervais and McGee 1999a). High calcium pyroxene in NWA 5744 is rare (<5% of observed pyroxene) and classified as augite. Low calcium pyroxene is common (>95% of all pyroxene) and contains too little Ca to be classified as pigeonite. Lunar FAN and Mg-suite data are not from metamorphosed rocks and are only shown for direct compositional comparison. Endmembers on the plot are diopside (Di), hedenbergite (Hd), enstatite (En), and ferrosillite (Fs). (Color figure can be viewed at wileyonlinelibrary.com.)

Table 7. Pyroxene, matrix material, and calculated NWA 5744 bulk rock trace element compositions.

| Spot (µm) | Pyx 1 | 1σ | %RSD | Pyx 2 | 1σ | %RSD | Pyx 3 | 1σ | %RSD | Matrix | 1σ | %RSD | Modal Bulk | Relict Avg | Uncertainty is the averaged analytical uncertainty for that particular grain, and for matrix material is the averaged analytical uncertainty across all matrix ablations. Where more than one ablation was performed on a particular grain or on matrix material, the %RSD across all averaged measurements is reported. Modal bulk content was calculated by averaging the matrix, large plagioclase, large olivine, and large pyroxene compositions by their modal abundances. Relict average is the calculated average rare earth element content of relict grains only, according to the modal abundance. |
from Apollo 16 sample 67415 (Lindstrom et al. 1991) also do not resemble those of NWA 5744.

Overall, the modal bulk REE concentrations in NWA 5744 are higher than those of most other magnesian feldspathic granulite meteorites, but lower than those of Apollo magnesian granulites (Fig. 10). Assuming that the modal NWA 5744 bulk composition calculated in this study is representative of the protolith(s), NWA 5744, like many lunar meteorites, is sampling protolith material in the lunar crust that was different from the Apollo landing sites (see also Takeda et al. 2006).

Igneous History of NWA 5744

The differences in trace element content between the fine-grained metamorphic matrix of NWA 5744 and larger relict grains (Fig. 10), and between individual relict grains (Fig. 6) imply that the meteorite was not sourced from a single igneous protolith. Trace element contents appear to be greater in the matrix than in larger relict grains (Figs. 6, 9, and 10). This may be explained if the matrix contains trace amounts of phosphate or other REE-rich minerals that are too small to be observed in our elemental maps. Two of the laser ablation spots in the matrix did show phosphorus levels 2–5 times higher than the other matrix spots (Appendix S2), so it is possible there are some phosphates present. However, the other six matrix spots did not show any elevated phosphorus content compared to the relict olivine ablations, yet they still exhibited elevated REE content.

Alternatively, the difference in trace element content may indicate that the matrix comes from different source materials than the relict grains, although that would make NWA 5744 a polymict breccia. If the matrix simply came from a later evolutionary stage of the same magma that produced the relict grains, it is unclear how such variation observed in the trace element content of the relict grains could have been established (Figs. 6 and 9).

Were the NWA 5744 Protolith(s) Ferroan or Magnesian Types of Anorthosite?

What are the source(s) of the NWA 5744 protolith? The relict grain mineral component of Northwest Africa 5744 formed from an anorthositic protolith(s) that was likely part of the lunar feldspathic crust formed during the earliest period of lunar evolution. This would require an impact event to excavate the material from depth within the lunar crust prior to exposure at the lunar surface and later ejection (see the Excavation of Protolith and Metamorphic Heat Source section). Hilton et al. (2016) show that paired stone NWA 10401 is not sufficiently rich in K, rare earth elements, and P (KREEP) to have originated on the lunar nearside within the Procellarum KREEP Terrane, and our new trace element analysis of NWA 5744 is in agreement (Table 7). The REE composition of the meteorite (Fig. 10) is also lower than those magnesian granulites from the Apollo landing sites. This would also mean NWA 5744 represents an altogether different crustal lithology from those observed at the Apollo and Luna sites.

Were the NWA 5744 relict grains formed from lunar magma ocean primary crust? During the crystallization of a hypothesized lunar magma ocean (LMO) (Warren 1985, 1990; Snyder et al. 1992), plagioclase flotation could not have occurred until the LMO melt became denser than plagioclase (2.74 g/cm³; Campbell et al. 1978) after the substantial crystallization of early mafic silicates. Experiments and modeling suggest that plagioclase first precipitated after the LMO reached ~70–86% of complete crystallization, dependent on the chemistry, density, and water content of the melt (see Snyder et al. 1992; Lin et al. 2017; references therein), and where co-forming mafic minerals had compositions <75 Mg# (Snyder et al. 1992). Since the Mg values of the mafic phases are all greater than 75 (Fig. 6), the protolith of NWA 5744 cannot have originated from this sort of ferroan LMO flotation cumulate model that accounts for the Apollo FAN rocks.

If the protolith(s) originated in the upper crust, they could have been magnesian anorthosite, a rock type common in lunar meteorites lacking KREEP content and postulated to predominantly originate from the farside feldspathic highlands terrane (Takeda et al. 2006; Arai et al. 2008; Gross et al. 2012, 2014). Longhi and Ashwal (1985) and Longhi (2003) suggested that these rocks formed as a result of serial magmatism rather than as primary flotation cumulates in the late stages of the LMO. However, these types of proposed diapir magma bodies and any crystals entrained within them should be well-equilibrated, and the broad range of REE contents in NWA 5744 between relict grains of major phases fails to reflect the expected equilibration from this sort of slowly cooled protolith (Fig. 6).

It may be that NWA 5744 and other similar magnesian feldspathic granulites do originate from primary crustal FAN suite protoliths, and the FAN field in Figs. 8 and 11 should be extended up to partially overlap with the Mg-suite. This would imply that the initial LMO flotation crust may not have been as ferroan as previously believed (see experimental results of Lin et al. 2017), or at least not as uniformly so (see also Takeda et al. 2006; Arai et al. 2008; Gross et al. 2012, 2014; Pernet-Fisher and Joy 2016). Models for LMO composition and crystallization would need to
be adjusted to make the magma more magnesian, yet still allow for plagioclase flotation. In this scenario, NWA 5744 would represent an early batch of flotation cumulate from the LMO when the liquid had just become dense enough, and before compositions had progressed to becoming more ferroan.

**Could the NWA 5744 Protolith(s) Have Formed as a Mix of Ferroan and Magnesian Anorthosite Materials?**

There are alternative scenarios to explain the composition of NWA 5744 if it originated from the lunar farside highlands (as suggested by Hilton et al. 2016). Arai et al. (2008) proposed a model for the lunar crust to explain remote sensing data that indicate variations in the Moon's surface composition and crustal thickness. They noted that the nearside crust is thinner and more noritic, while the farside crust is thicker (except for the South Pole–Aitken [SPA] basin) and more troctolitic (see also Crites and Lucey 2015). Such variations between the near and farside crust could have been caused by a variety of mechanisms including asymmetric crystallization of the LMO (driven by thermal convection), or the SPA basin-forming impact ejecta mixing deep crust/upper mantle (Potter et al. 2012).

Given the magnesian composition and the similarities NWA 5744 has to FAN suite material (Figs. 6, 8, and 9), it may be suggested to represent (1) a hybridized magma composed of mixed FAN and either Mg-suite or magnesian anorthosite source materials which were melted by an impact event, or (2) brecciated products of the FAN suite and either Mg-suite or magnesian anorthosite materials mixed together in the deep lunar megaregolith. However, both scenarios, with partial contribution from an Mg-suite protolith source, seem unlikely as both would predict major and trace element compositions to be intermediate between the FAN and Mg-suites, which is not what is observed in NWA 5744 relict plagioclase (Figs. 6, 8, 10). Bulk rock alumina contents and Mg# are more similar to Mg-suite material (Fig. 11), also casting doubt on either scenario with a partial FAN source, although it does not rule out a mixture of ferroan anorthosite and KREEP-poor Mg-rich mantle material. Scenario (2) would also make NWA 5744 distinctly a polymict breccia, and the only potential indication of differing composition is the trace element content difference between the matrix and relict grains. There are no other indications of any clasts of differing rock type within NWA 5744, ferroan or otherwise. We conclude that the protolith of NWA 5744 is unlikely to originate from solely the Apollo FAN or Mg-suite and is also unlikely to be some physical combination of the two suites.

**Metamorphic History of NWA 5744**

**Pyroxene Thermometry and Characteristics of Metamorphism**

The broad range of temperatures derived from Lindsley (1983) and Brey and Kohler (1990) may indicate that many of the high-Ca and low-Ca pyroxene pairs in the relict mineral grains are not in equilibrium because periods of thermal metamorphism were not sufficiently intense to equilibrate them. Pyroxene compositions for NWA 5744 are shown in Fig. 7 and compared with pyroxenes from the FAN and Mg suites. The data for NWA 5744 plot on the magnesian side of the pyroxene quadrilateral. Low-Ca pyroxene is uniform...
in composition other than one outlier point, but augite present in NWA 5744 has considerable variation in Ca content. This may indicate that Ca did not reach equilibrium in the augite during metamorphism, because Ca diffuses slower than Mg or Fe in pyroxene (Cherniak and Dimanov 2010). However, it may also be due to mixed EMP measurements when attempting to measure only augite composition in <5 μm grains. The highest-Ca augite measurement would indicate a temperature of ~800 °C, but if the augite measurements do lie on a mixing line between the true augite composition and low-Ca pyroxene, then there is no indication that even the highest-Ca augite measurement necessarily represents the augite endmember composition.

The lamellae in the NWA 5744 pyroxene vary slightly in thickness along their length and are somewhat wavy rather than straight and parallel (Fig. 2D). This may be indicative of a brief reheating event post lamellae formation, but could also simply be related to the perspective of the section and possible dislocation planes. Calculations for the duration of metamorphism can be made using average grain size of the granulite, but are highly and inversely dependent on the peak metamorphic temperature (Cushing et al. 1993). However, if metamorphism occurred at 1000 °C, which Cushing et al. (1993) suggest is the minimum expected peak temperature for lunar feldspathic granulites, a conservatively large average metamorphic olivine grain size of 15 μm is used, then an approximation for a maximum metamorphic duration of no more than 1000 yr is calculated where temperatures are sufficient to recrystallize olivine (Cushing et al. 1993). Using average pyroxene grain sizes of <10 μm would make the maximum duration for their recrystallization even shorter, on the order of 100s of years at most. A lower estimate for peak metamorphic temperature of 800 °C (McGee et al. 1978) would increase the duration of metamorphism to a maximum of ~10^4 yr. The ~5 μm average width of matrix pyroxenes would indicate rapid cooling after metamorphism, perhaps over a duration as brief as 15–1500 yr using the approach of Cushing et al. (1993, 1999). It is, therefore, possible that NWA 5744 was metamorphosed at or near the lunar surface, where heat dissipation could have been rapid enough to accommodate these calculated durations.

One possible scenario of the rock’s evolution begins with the hypothesis that the relict grains were part of
one parent material, composed of magnesian anorthosite that formed deep in the crust. One or more impacts excavated that material, while also disaggregating it and abrading the constituent pieces. These loose grains were mechanically intermixed with material at a shallower crustal depth that contained greater FeO and REE abundance and that had been pulverized into much finer grains due to being closer to the excavating impact(s) and perhaps some smaller, earlier impacts. As the sample matrix has low concentrations of bulk Ni and Co and there are only reports of metal found in rare instances in other portion(s) of NWA 5744 (Kuehner et al. 2010) and paired stones (The Meteoritical Bulletin Database 2017), it is likely that this substrate was not a metal-rich impact melt or formed from surficial regolith material.

Following the formation of the protolith(s), NWA 5744 was subjected to one or more metamorphic events. This metamorphism would have initiated equilibration and elemental diffusion between the matrix and relict grains. Equilibration appears to have been incomplete as indicated by the spread in REE abundance between individual relict plagioclase and olivine grains (Fig. 6), as well as the major element zoning within plagioclase (Fig. 4). Incomplete plagioclase equilibration and small average pyroxene grain size indicate that the duration of metamorphism was too brief to allow for REE diffusion beyond the rims of minerals in the rock. This also supports the theory that metamorphism occurred near the surface where cooling would have been more rapid (Cushing et al. 1999; Hudgins et al. 2011a). If that is the case, then the elevated FeO content of the maskelynite compared with the relict plagioclase grains (Table 3), as well as greater REE abundance in the matrix compared to the relict grains (Fig. 10), would be an indication that the matrix and relict grains do not come from the same precursor rock.

**Excavation of Protolith and Metamorphic Heat Source**

If the NWA 5744 protolith was formed deep within the crust, below the impact-modified megaregolith environment, a significant excavation process would have been required to bring it near the surface, prior to metamorphism and later lunar ejection. Using a formula published by Cintala and Grieve (1998), an impact that produces a 98-km diameter crater would be necessary to fully excavate material from a depth of 17 km, or half of the minimum crustal thickness (Wieczorek et al. 2013). For material from a maximum crustal depth of 43 km (Wieczorek et al. 2013), an impact producing a 186-km diameter crater would be required. An upper crustal origin would, of course, have smaller impactor requirements.

Basin-forming and cratering impact processes dominated the history of the Moon prior to 3.7 Ga (Stöffler and Ryder 2001) and may even have continued in the inner solar system until 2.5 Ga (Bottke et al. 2012), excavating, remelting, and mixing the lunar crust. According to Stöffler and Ryder (2001), at 4.1–4.2 Ga, many craters larger than 1 km were formed per 2 km² of the lunar surface, and this rate slowed down to one crater of diameter >1 km per 330 km² by the end of the

---

**Fig. 10.** CI chondrite normalized (Anders and Grevesse 1989) bulk rare earth element (REE) content of NWA 5744 compared to those of magnesian anorthositic granulites (MAGs). Dotted line with square symbols represents the average of eight individual 176-μm laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) matrix ablations of NWA 5744 (Table 7; Appendix S1). Dashed line with diamond symbols represents the calculated average REE content of the large relict mineral grains in proportion to modal abundance. Dashed black line with triangular symbols represents the calculated bulk rock REE content in proportion to matrix and large relict grain modal abundances. Solid line represents INAA measurements on saw cuttings (Kuehner et al. 2010); the white circles represent data points and all elements without points on this line are interpolated. Dark gray–shaded region represents the following Apollo magnesian feldspathic granulites: 67415; 60035 (average of 27, 30, 59A, and 59B); 67415 (average of 33A and 33B); 67955 (average of 74A and 74B); 76230; average 79215; 72275,439/495; 76503,7021; and 76503,7052 (Ma and Schmitt 1982; Salpas et al. 1988; Lindstrom et al. 1991; Jolliff et al. 1996; Hudgins et al. 2008). Light gray–shaded region represents the following magnesian feldspathic granulite meteorites with REE content distinct from Apollo samples: average Dhofar 489; average ALH 81005; average Dhofar 309 (Warren and Kallemeyn 1991; Takeda et al. 2006; Treiman et al. 2010). Magnesian feldspathic granulite clast MAC 88105,W3 (Treiman et al. 2010) falls entirely within the Apollo MAGs field and was excluded.
basin-forming epochs. It is notable though that craters 10 times smaller were about 100 times more common per unit area of the lunar surface (Barlow 1990). Thermal modeling by Bottke et al. (2012) indicates that large-scale inner solar system bombardment may have lasted even longer, with about 15 basin-forming impacts striking Earth between 2.5 and 3.7 Gyr ago, some of which may have resulted in craters as large as the Nectaris Basin on the Moon (860 km diameter; Stöffler et al. 2006). Since 100+ km basin impact events have occurred over the Moon's history, one such event, or a closely timed cluster of events, may have excavated NWA 5744 from the lower crust.

One plausible metamorphic heat source would be an impact melt sheet on the lunar surface. Alternatively, the metamorphism could be shock-induced. In anorthosite, plagioclase begins to transform into maskelynite in small patches at pressures of 25–27 GPa, with near-complete maskelynitization at pressures >30 GPa (Johnson and Hörz 2003). Because the matrix is almost fully maskelynitized but the relict plagioclase is not, it seems unlikely that shock pressures exceeded 30 GPa. Typical shock pressures of 10–60 GPa in rock surrounding an impact typically generate temperatures from 500 °C to 3000 °C (French 1998), which would be more than sufficient to produce the range of temperatures seen in the pyroxene thermometry. Shock may well have provided the heat to metamorphose the source rock that produced NWA 5744. If NWA 5744 was excavated close to the surface prior to metamorphism, it seems logical that the same impact or impacts could have generated a melt sheet that served as the metamorphic heat source. Mineral textures (rounded relict grain boundaries, amoeboid olivines, ductile appearance of pyroxenes in the matrix; Figs. 2–4), plagioclase zoning (Fig. 4), a wide range of matrix (Fig. 10), plagioclase (Fig. 6C), and olivine (Fig. 6D), REE profiles, and wavy pyroxene lamellae (Fig. 2D) all support a hypothesis that the metamorphism of the relict grains was intense, but insufficient to completely equilibrate the rock and thus homogenize the textures or elemental concentrations. This could be indicative of a brief metamorphic duration. Hudgins et al. (2011a) proposed that lunar granulites containing olivine grains with zoning in the major elements may have been metamorphosed by melt sheets over time scales of less than 13,000 yr that were (1) <1 km thick; (2) of lower initial temperature than the modeled ~2000 °C; and/or (3) buried deeper than 110 m or 350 m below modeled melt sheets of 1000 and 5000 m thickness, respectively. A similar metamorphic history for NWA 5744 may explain the zoning in its plagioclase, although the Mg closure temperature is lower in plagioclase than in olivine (Onorato and Uhlmann 1978; Van Orman et al. 2012), so metamorphism of NWA 5744 probably occurred for a shorter duration and/or at lower temperature than in models presented by Hudgins et al. (2011a).

If metamorphism was caused by an impact melt sheet, the melt sheet must have been small enough or its proximity distant enough for the heat to dissipate before the minerals could equilibrate. If the protolith did originate from the deep crust, then the impact(s) which excavated it must have been very large and either the shock from the excavation was sufficient to cause the observed metamorphism by itself or the excavation preceded a later, smaller impact which caused the metamorphism by either shock or an impact melt sheet.

CONCLUSIONS

The lunar meteorite NWA 5744 has mineralogical features similar to those of other magnesian anorthositic granulites, which do not allow it to be clearly classified into any major suite of lunar crustal rocks. This meteorite bears bulk compositional correlations and discrepancies with both the lunar crustal FAN (i.e., primary crust) and Mg-suites (i.e., secondary crust intrusive magmatics). In terms of major element concentrations, NWA 5744 resembles Mg-suite rocks, while the trace elements are more akin to those of the FAN, tentatively placing it and similar Mg granulites in a category of highland lunar crust lithology of their own. Its protolith(s) would have been too magnesian to have formed as part of the primary ferroan anorthosite crust according to classical models (e.g., Warren 1985; Snyder et al. 1992). This protolith composition was most likely magnesian anorthosite, which is also unrelated to the Apollo Mg-suite. The data obtained in this study show that NWA 5744 is distinct from samples obtained from the Apollo landing sites, indicating NWA 5744 likely originated in a different region of the Moon than those locales. The data are also consistent with a deep crustal origin for the igneous protolith of NWA 5744, and if that is the case, then there is a strong likelihood that it was excavated by a major impact event away from the Apollo and Luna sites. The meteorite records a complex history of crustal formation and subsequent impacts and metamorphism on the Moon.

Thermal metamorphism appears to have been intense, but short-lived, almost certainly occurring near the lunar surface. Contact metamorphism from an igneous intrusion is not an impossible explanation for the source of the heat that triggered NWA 5744 metamorphism, but is highly unlikely given how rapidly it would have had to cool. Our observations are more consistent with a series of impacts beginning...
with one or more very large impacts to excavate the protolith of NWA 5744 followed by relatively rapid dissipation of the heat away from the impact site that affected this rock. A relatively small impact melt sheet could have followed and served as a heat source for the metamorphism, because a small volume of melt would have a low thermal inertia and cool quickly on the lunar surface. It is also possible for NWA 5744 to have been metamorphosed largely due to shock-induced heating, without the presence of a significant impact melt sheet.

Acknowledgments—This research was supported by NASA grants NNX12AD06G, NNX10AB37G, and the Lunar and Planetary Science Institute to AB, NNX09AC06G to TJL, and STFC Grant ST/M001253/1 and Royal Society grant RS/UF140190 to KHJ. We acknowledge the excellent resources of Randy Korotev’s Lunar Meteorite List website and NASA’s Lunar Meteorite Compendium. We are grateful to Kent Ross at JSC for help on the SEM. We thank Drs. Arai, Treiman, and Wittmann for undertaking very detailed reviews on a previous version of the manuscript, also to Dr. Jeff Taylor for his helpful review, and Drs. Floss and Spray for editorial support.

Editorial Handling—Dr. A. J. Timothy Jull

REFERENCES

Anders E. and Grevesse N. 1989. Abundances of the elements: Meteoritic and solar. Geochimica et Cosmochimica Acta 53:197–214.

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.

Barlow N. G. 1990. The Late Heavy Bombardment crater size-frequency distribution in the inner solar system. Proceedings, International Workshop on Meteorite Impact on the Early Earth. pp. 6–7.

Botke W. F., Vokrouhlicky D., Minton D., Nesvorny D., Morbidelli A., Brasser R., Simonson B., and Levison H. F. 2012. An Archean heavy bombardment from a destabilized extension of the asteroid belt. Nature 485:78–81.

Brey G. P. and Kohler T. 1990. Geothermobarometry in four-phase lherzolites II. New thermobarometers, and practical assessment of existing thermometers. Journal of Petrology 31:1353–1378.

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.

Campbell I. H., Roeder P. L., and Dixon J. M. 1978. Plagioclase buoyancy in basaltic liquids as determined with a centrifuge furnace. Contributions to Mineralogy and Petrology 67:369–377.

Cherniak D. J. and Dimanov A. 2010. Diffusion in pyroxene, mica, and amphibole. Reviews in Mineralogy & Geochemistry 72:641–690.

Cintala M. J. and Grieve R. A. F. 1998. Scaling impact melting and crater dimensions: Implications for the lunar cratering record. Meteoritics & Planetary Science 33:889–912.

Crites S. T. and Lucey P. G. 2015. Revised mineral and Mg# maps of the Moon from integrating results from the Lunar Prospector neutron and gamma-ray spectrometers with Clementine spectroscopy. American Mineralogist 100:973–982.

Cushing J. A., Taylor G. J., Norman M. D., and Keil K. 1993. The granulite suite: Impact melts and metamorphic
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.

Pernet-Fisher J. F. and Joy K. H. 2014. Heterogeneity in lunar anorthosite meteorites: Implications for the inner solar system. *American Mineralogist* 99:796–800.

Potter R. W. K., Collins G. S., Kiefer W. S., McGovern P. J., and Kring D. A. 2012. Constraining the size of the South Pole–Aitken basin impact. *Icarus* 220:730–743.

Russell S. S., Joy K. H., Jeffries T. E., Consolmagno G. J., and Kearsley A. 2014. Magnesium diffusion in plagioclase (abstract #1467). 43rd Lunar and Planetary Science Conference. CD-ROM.

Shervais J. W. and McGee J. J. 1998. Ion microprobe study of troctolites, norite, and anorthosites from Apollo 14: Evidence for urKREEP assimilation during petrogenesis of Apollo 14 Mg-suite rocks. *Geochimica et Cosmochimica Acta* 62:3009–3023.

Shervais J. and McGee J. J. 1999a. Petrology of the western highland province: Ancient crust formation at the Apollo 14 site. *Journal of Geophysical Research* 104:5891–5920.

Snyder G. A., Taylor L. A., and Neal C. R. A. 1992. Chemical model for generating the sources of mare basalts: Combined equilibrium and fractional crystallization of the lunar magmasphere. *Geochimica et Cosmochimica Acta* 56:3809–3823.

Stöffler D. and Ryder G. 2001. Stratigraphy and isotope ages of lunar geologic units: Chronological standard for the inner solar system. *Space Science Reviews* 96:9–54.

Stöffler D., Knöll H.-D., Marvin U. B., Simonds C. H., and Warren P. H. 1980. Recommended classification and nomenclature of lunar highland rocks—a committee report. Proceedings, Lunar Highlands Crust Conference. pp. 51–70.

Stöffler D., Keil K., and Scott E. R. D. 1991. Shock metamorphism of ordinary chondrites. *Geochimica et Cosmochimica Acta* 55:3845–3867.

Takeda H., Yamaguchi A., Bogard D. D., Karouji Y., Ebihara M., Ohtake M., Kaiki 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.

Tera F., Eugster O., Burnett D. S., and Wasserburg G. J. 1970. Comparative study of Li, Na, K, Rb, Cs, Ca, Sr, and Ba abundances in achondrites and in Apollo 11 lunar samples. *Proceedings, Apollo 11 Lunar Science Conference* 2:1657–1657.

The Meteoritical Bulletin Database. 2017. http://www.lpi.usra.edu/meteor/mbull.php. Accessed January 5, 2017.

Van Orman J. A., Cherniak D. J., and Kita N. T. 2012. Magnesium diffusion in plagioclase (abstract #1467). 43rd Lunar and Planetary Science Conference. CD-ROM.

Warren P. H. 1985. The magma ocean concept and lunar chronology. *American Mineralogist* 70:431–465.

Warren P. H. and Wasson J. T. 1977. Pristine nonmare rocks and the nature of the lunar crust. Proceedings, 8th Lunar Science Conference. pp. 2215–2235.
SUPPORTING INFORMATION

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

Appendix S1: NWA 5744 major element data.
Appendix S2: NWA 5744 trace element data.
Video S1: Panning through the X-ray CT scan volume of NWA 5744 slab.