Constraining the source regions of lunar meteorites using orbital geochemical data

A. CALZADA-DIAZ1,2*, K. H. JOY3, I. A. CRAWFORD1,2, and T. A. NORDHEIM2,4

1Department of Earth and Planetary Sciences, Birkbeck College, London WC1E 7HX, UK
2Centre for Planetary Sciences UCL/Birkbeck, London WC1E 6BT, UK
3School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Manchester M13 9PL, UK
4Mullard Space Science Laboratory, University College London, Dorking RH5 6NT, UK

*Corresponding author. E-mail: acalza01@mail.bbk.ac.uk

(Received 30 July 2014; revision accepted 06 November 2014)

Abstract—Lunar meteorites provide important new samples of the Moon remote from regions visited by the Apollo and Luna sample return missions. Petrologic and geochemical analysis of these meteorites, combined with orbital remote sensing measurements, have enabled additional discoveries about the composition and age of the lunar surface on a global scale. However, the interpretation of these samples is limited by the fact that we do not know the source region of any individual lunar meteorite. Here, we investigate the link between meteorite and source region on the Moon using the Lunar Prospector gamma ray spectrometer remote sensing data set for the elements Fe, Ti, and Th. The approach has been validated using Apollo and Luna bulk regolith samples, and we have applied it to 48 meteorites excluding paired stones. Our approach is able broadly to differentiate the best compositional matches as potential regions of origin for the various classes of lunar meteorites. Basaltic and intermediate Fe regolith breccia meteorites are found to have the best constrained potential launch sites, with some impact breccias and pristine mare basalts also having reasonably well-defined potential source regions. Launch areas for highland feldspathic meteorites are much less well constrained and the addition of another element, such as Mg, will probably be required to identify potential source regions for these.

INTRODUCTION

The Moon provides valuable information to understand the early history of the solar system as it preserves the geological record of the processes that have shaped the formation and evolution of the Earth–Moon system. Also, it is the only planetary body from which samples have been returned (382 kg returned by the Apollo and Luna 16, 20, and 24 missions), and these have shed considerable light on the age and composition on the Moon (see Vaniman et al. 1991; Shearer et al. 2006; Jaumann et al. [2012] for comprehensive reviews). The analysis of soils and regolith samples returned by the Apollo and Luna localities (e.g., Rhodes et al. 1977; Laul et al. 1981; Morris et al. 1983; Simon et al. 1985; McKay et al. 1986a, 1986b; Jerde et al. 1990) has been invaluable in calibrating data returned from orbital remote sensing missions (McEwen and Robinson 1997; Gillis et al. 2004; Prettyman et al. 2006; Pieters et al. 2008; Swinyard et al. 2009; Isaacson et al. 2013; Peplowski and Lawrence 2013). However, the Apollo and Luna missions were restricted geographically to low latitude near-side localities, and so do not provide a fully comprehensive view about the geological diversity of the whole Moon.

Lunar meteorites are additional sources of rocks from the Moon. It is believed that they were ejected from random locations on the surface within the last 20 Myr, the vast majority in the last 2 Myr (Korotev 2005). They have probably originated from small shallow impact craters less than a few km in size and, therefore, they sample the upper layer of the lunar surface (Warren 1994; Basilevsky et al. 2010). Petrologic and geochemical analysis of these meteorites reveals a wide range of compositional variations that can be broadly classified into pristine mare basalts, basaltic breccias, feldspathic breccias, and intermediate Fe breccias. There are currently (as of July 2014) 183...
individual lunar meteorite stones that have been classified according to the Meteoritical Bulletin (http://www.lpi.usra.edu/meteor/metbull.php), with terrestrial pairings reducing the number to ~92 meteorites. However, the interpretation of these samples is limited by the fact that we do not know the source region of any individual lunar meteorite. In this paper, we report on an investigation of the source regions of lunar meteorites to determine the local geological context of these samples. The ultimate goal, which will be addressed in future work, was to use this contextual information to better understand the evolution of the lunar crust and mantle in regions not sampled by the Apollo and Luna missions.

Remote sensing missions provide key insights to the chemical, mineralogical, and geophysical diversity of the Moon. For example, the Clementine mission spectral reflectance (CSR) and Lunar Prospector mission gamma ray spectrometer (LP-GRS) data have enabled the estimation of global concentrations of rock-forming elements which differentiate the major lunar crustal terranes (Elphic et al. 1998; Lawrence et al. 1998; Jolliff et al. 2000; Gillis et al. 2004). Such data have also been used to help identify the location of specific types of lunar rocks, aiding our understanding of the regional variation in magmatic processes (e.g., Hagerty et al. 2006, 2011; Kramer et al. 2008). Other instruments, such as the Moon Mineralogy Mapper (M3) on Chandrayaan-1 and the Diviner Lunar Radiometer on board the NASA’s Lunar Reconnaissance Orbiter (LRO), are being used to understand the mineralogy of the Moon and have led to new insights into the lunar petrology. The identification of silica-rich and olivine-rich lithologies, the distribution of low-Ca pyroxene exposures, and the detection of unusual Mg-spinel lithologies are some examples of how these remote sensing data sets have expanded our knowledge about the geology of the Moon (Glotch et al. 2010; Greenhagen et al. 2010; Klima et al. 2011; Pieters et al. 2011).

The LP-GRS instrument measured the abundance of major rock-forming elements (O, Si, Fe, Ti, Mg, Al, and Ca) within the upper few tens of centimeters of the surface by detecting gamma-ray emission induced by the cosmic ray background, as well as from the decay of radioactive incompatible elements (Th and K; Lawrence et al. 1998; Feldman et al. 1999). These data have led to the production of global maps of the composition of the lunar regolith (Binder 1998; Lawrence et al. 1998, 2000, 2002; Shkuratov et al. 2005; Prettyman et al. 2006). Previous work, on which we elaborate here, has demonstrated the usefulness of using LP-GRS data to constrain the source of some lunar meteorites (Gnos et al. 2004; Jolliff et al. 2008, 2009; Corrigan et al. 2009; Arai et al. 2010a, 2010b; Joy et al. 2010, 2011, 2014; Robinson et al. 2012; Mercer et al. 2013).

**METHODOLOGY**

Adapting a method of Joy et al. (2010, 2011), we have developed a new software application in the Python programming language that matches input elemental compositions with elemental remote sensing data sets. In the present work, we have used bulk rock composition measurements from different literature sources to calculate the average FeO, TiO$_2$, and Th concentrations of soils and lunar regolith breccias collected by the Apollo and Luna missions, as well as lunar meteorites. We have calculated the 1σ standard deviation of averaged analytical measurements listed in Tables 1 and 2 and the online supplement to this article.

The LP-GRS data set (Prettyman et al. 2006) provides global FeO, TiO$_2$, and Th compositions with a spatial resolution of 2 × 2 degrees (i.e., 60 × 60 km) across the lunar surface. This data set was chosen due to a combination of an adequate compositional accuracy and an acceptable spatial resolution. Fe allows us to distinguish between mare basalts and highland lithologies, Ti discriminates between different types of basalts, and Th differentiates Procellarum KREEP Terrain (PKT) materials. In this initial analysis, we have not included other elements, such as Mg, because of the generally poorer precision of the LP-GRS instrument for other elements (Prettyman et al. 2006; Wöhler et al. 2011). However, the technique is easily adapted to using additional elements, and we plan to do so in future work.

The software matches the composition of samples with the elemental compositions reported by the LP-GRS data set, taking into account the uncertainty of the LP-GRS measurements as well as the standard deviation of the sample compositions. In general, we consider it a match if the LP-GRS values for all three elements lie within two standard deviations (2σ) of the average sample compositions. However, for some meteorites, 2σ defines a very narrow threshold and our software did not report any matches. As discussed below, mismatches greater than 2σ between the sample compositions and the GRS data are not unexpected owing to the very different spatial scales involved. In these cases, we increased the compositional range of the search by increasing the number of σ on the sample compositions until the first matches with the GRS data set appeared. Our software produces a text file with the matching coordinates and a shapefile layer compatible with most of the geographic information systems including ArcGIS™ that allows for convenient visualization of the outcome.
Table 1. Average Apollo and Luna landing sites bulk soil and regolith breccia compositions used for the validation exercise of this study ± the analytical 1σ standard deviation. Data obtained from Rhodes and Blanchard (1981), Morris et al. (1983), Simon et al. (1985), McKay et al. (1986a, 1986b), Jerde et al. (1987, 1990), and Korotev (1997).

|          | FeO (wt%) | Std. Dev. | TiO$_2$ (wt%) | Std. Dev. | Th (ppm) | Std. Dev. |
|----------|-----------|-----------|---------------|-----------|----------|-----------|
| Apollo 11| 16.34     | 0.71      | 8.02          | 0.52      | 2.12     | 0.76      |
| Apollo 12| 14.63     | 3.66      | 2.44          | 1.06      | 7.01     | 7.64      |
| Apollo 14| 10.43     | 0.92      | 1.64          | 0.25      | 13.72    | 1.13      |
| Apollo 15| 14.98     | 3.3       | 1.46          | 0.34      | 3.35     | 1.55      |
| Apollo 16| 4.95      | 0.69      | 0.52          | 0.11      | 2.36     | 2.65      |
| Apollo 17| 13.01     | 3.47      | 4.96          | 3.16      | 1.77     | 1.06      |
| Luna 16  | 16.75     | 0.09      | 3.3           | 0.1       | nd       | nd        |
| Luna 20  | 7.46      | 0.47      | 0.5           | 0.06      | 0.97     | 0.03      |
| Luna 24  | 19.55     | 0.62      | 1.04          | 0.15      | 0.4      | 0.09      |

$\text{nd} = \text{not detected.}$

Table 2. Average bulk meteorite composition of the lunar meteorites NWA 883; Dho 287 basaltic and Dho 287 regolith breccia portion; Yamato-793169; Asuka-881757; LAP 02205, 02224, 02436; MET 01210; MIL 05035; NWA 4472; SaU 449; Dho 925, 961; Calcalong Creek, Kalahari 008, 009; ALHA81005; DaG 400; NWA 482; NWA 4932; Yamato-86032, 82192, 82193 ± the analytical 1σ standard deviation of averaged measurements (Boynton and Hill 1983; Korotev et al. 1983, 2003, 2009; Laul et al. 1983; Palme et al. 1983; Fukukoa et al. 1986; Bischoff et al. 1987; Eugster et al. 1989; Koeberl et al. 1989; Yanai and Kojima 1991; Jolliff et al. 1993, 2003; Koeberl et al. 1993; Lindstrom et al. 1991; Warren and Kallemeyn 1993; Daubar et al. 2002; Anand et al. 2003, 2006; Demidova et al. 2003, 2007; Fagan et al. 2003; Hill and Boynton 2003; Karouji et al. 2004; Righter et al. 2005; Zeigler et al. 2005, 2007; Day et al. 2006; Joy et al. 2006, 2008a, 2008b, 2010; Nyquist et al. 2006; Day and Taylor 2007; Sokol et al. 2008; Liu et al. 2009; Arai et al. 2010a, 2010b; Korotev 2012; Korotev and Irving 2013).

|          | FeO (wt%) | Std. Dev. | TiO$_2$ (wt%) | Std. Dev. | Th (ppm) | Std. Dev. |
|----------|-----------|-----------|---------------|-----------|----------|-----------|
| NWA 773  | 19.67     | 1.02      | 0.62          | 0.31      | 1.63     | 0.45      |
| Dho 287  | 20.38     | 2.02      | 2.64          | 0.22      | 0.90     | 0.21      |
| Dho 287 regolith breccia | 18.95 | 4.49 | 2.48 | 1.33 | nd | nd |
| Y-793169 | 22.29     | 1.67      | 1.94          | 0.37      | 0.71     | 0.04      |
| A-881757 | 22.55     | 2.07      | 2.44          | 0.49      | 0.44     | 0.10      |
| LAP 02205| 22.03     | 1.43      | 3.29          | 0.34      | 2.10     | 0.22      |
| LAP 02224| 22.28     | 0.63      | 3.03          | 0.28      | 2.08     | 0.21      |
| LAP 02436| 21.90     | 0.79      | 2.89          | 0.23      | 1.76     | 0.26      |
| MET 01210| 16.25     | 0.31      | 1.48          | 0.10      | 0.86     | 0.20      |
| MIL 05035| 21.35     | 0.46      | 1.17          | 0.38      | 0.28     | 0.07      |
| NWA 4472,4485 | 9.26 | 0.09 | 1.28 | 0.26 | 6.99 | 0.08 |
| SaU 449  | 7.86      | 0.72      | 0.31          | 0.06      | 0.87     | 0.20      |
| Dho 925  | 8.09      | 0.96      | 0.31          | 0.06      | 0.94     | 0.01      |
| Dho 961  | 11.14     | 1.06      | 0.63          | 0.13      | 2.86     | 0.66      |
| Calcalong Creek | 9.52 | 1.10 | 0.79 | 0.12 | 3.92 | 0.43 |
| Kalahari 008 | 4.87 | 0.28 | 0.40 | 0.16 | 0.18 | 0.01 |
| Kalahari 009 | 16.43 | 1.56 | 0.26 | 0.05 | 0.20 | 0.05 |
| ALHA81005 | 5.50 | 0.08 | 0.30 | 0.04 | 0.30 | 0.06 |
| DaG 400  | 3.67      | 0.10      | 0.18          | 0.01      | 0.23     | 0.08      |
| NWA 482  | 3.57      | 0.50      | 0.16          | 0.03      | 0.24     | 0.01      |
| NWA 4932 | 8.55      | 0.78      | 0.31          | 0.07      | 0.50     | 0.12      |
| Y-86032  | 4.33      | 0.35      | 0.16          | 0.08      | 0.20     | 0.03      |
| Y-82192  | 5.89      | 0.35      | 0.27          | 0.19      | 0.20     | 0.03      |
| Y-82193  | 5.30      | 0.47      | 0.25          | 0.03      | 0.20     | 0.00      |

$\text{nd} = \text{not detected.}$
The lunar surface has not suffered large-scale disturbances in the last 2–3 Ga, and so the surface composition mostly represents the composition of the underlying rocks (Heiken et al. 1991). However, the lithologies of an area may vary over short distances and with depth, so the regolith compositions measured by the GRS may be a mixture of several types of rock and soil. In the cases of regolith breccia (i.e., consolidated soil), the samples themselves may have averaged much of this compositional heterogeneity and comparison with the GRS data is more straightforward. The approach, however, becomes more uncertain when it is applied to other types of material (e.g., pristine basalts, impact melt breccias, magmatic rocks, etc.) which may lay beneath the lunar surface and be out of the detection range of the LP-GRS instrument, or may represent very localized geological materials within a single GRS pixel. In addition, unavoidable uncertainties occur owing to the large difference in scale from lunar meteorites, which are cm in scale, to GRS data that comprises 60 × 60 km square pixels in the case of the 2 degree LP-GRS data set. The limiting effect of spatial resolution is especially clear in the case of Th for which small spatial scale variations are known to occur (Lawrence et al. 1998, 2003, 2007; Hagerty et al. 2006).

### APOLLO AND LUNA LANDING SITES VALIDATION

We first validated our approach by comparing the compositions of the Apollo and Luna bulk regolith returned samples (Table 1; Rhodes and Blanchard 1981; Morris et al. 1983; Simon et al. 1985; McKay et al. 1986a, 1986b; Jerde et al. 1987, 1990; Korotev 1997), with the abundances of FeO, TiO₂, and Th reported by the 2 degree per pixel spatial resolution (i.e., 60 km per pixel) LP-GRS data set (Prettyman et al. 2006). We obtained good correlations (i.e., ±2σ standard deviation) for most of the landing sites (Fig. 1). In particular, for Apollo 11, 12, 17, and Luna 24, we find that the method correctly matches the landing site location average regolith sample compositions with the corresponding LP-GRS pixels, although unsurprisingly other areas of the lunar surface are also found to have similar compositions.

For Apollo 15, our method matches areas approximately 60 km (1 pixel) away from the actual landing site. In the case of the Apollo 16 and Luna 16, we obtain matches in the general vicinity of the landing sites (i.e., <120 km, 2 pixels), however, not at the exact landing sites. In the Luna 16 case, the closest matches are considered as being too far from the landing site (>500 km) to be accepted as a valid result. As discussed in the Methodology section, we consider that these discrepancies are probably related to the spatial resolution of the Prettyman et al. (2006) data set and, therefore, heterogeneities in the area will affect the results. In the case of the Apollo 14 landing site, the average Th compositions are larger (up to 13.72 ppm) than those reported in the LP-GRS data set (in which highest measurement is 11.64 ppm), so we did not obtain a direct match; again, the discrepancy is most likely due to the relatively coarse spatial resolution of the LP-GRS compared with the ~1.5 km sampling scale of the Apollo 14 mission (Philpotts et al. 1972; Papike et al. 1982; Jerde et al. 1987; Heiken et al. 1991; Lawrence et al. 2007).

### LUNAR METEORITES

Having verified the method with the Apollo and Luna landing sites, we next applied our approach in a study of lunar meteorites (see Table 2 and the online supplement) to constrain their likely source regions. Previous work has attempted to locate the launch sites of certain lunar meteorites (Gnos et al. 2004; Corrigan et al. 2009; Fernandes et al. 2009; Joy et al. 2010, 2011; Mercer et al. 2013; Jolliff et al. 2014), but to our knowledge, this is the first time that such an exercise has been undertaken in a systematic manner for all the lunar meteorites with reported bulk rock compositions.

Of the 96 meteorites (grouped from 185 individual stones) recovered to date, 10 are pristine mare basalts and the rest are different types of breccias (12 are basaltic breccias, 48 are feldspathic breccias, 20 are breccias of intermediate Fe composition, and 6 represent mafic breccias with Th > 2 ppm (see Randy Korotev’s list at http://meteorites.wustl.edu/lunar/moon_meteorites_list_alumina.htm).

The number of meteorites covered in this study, which is 48 excluding paired stones, is set by the availability of published geochemical data. We first created a database of lunar meteorite compositional measurements, and for each composition, we obtained the average of the published FeO, TiO₂, and Th compositions, and their associated standard deviations. This database and references are available in the online supplement of this article. We subdivided these into three different categories based on their bulk composition: basaltic meteorites, breccias of intermediate Fe composition, and feldspathic meteorites.

The meteorites presented in the following sections were selected as being representative of each category and their compositions are represented in Table 2.

#### Basaltic Meteorites

LaPaz Icefield (LAP) 02005 is a holocrystalline basalt with low-Ti content, Table 2 (Righter et al. 2005;
Fig. 1. Apollo and Luna returned samples validation. Identification of lunar regolith with similar composition to (A) Apollo 11, (B) Apollo 12, (C) Apollo 15, (D) Apollo 16, (E) Apollo 17, (F) Luna 16, (G) Luna 20, and (H) Luna 24 soils and regolith breccias. Matching composition to the inputs $+2\sigma$ standard deviations in Table 1 are shown in yellow. Apollo and Luna landing sites locations are denoted as white crosses. Underlying albedo images of the Moon is a Clementine image in a cylindrical projection with 0° longitude and 0° latitude in the center.
Zeigler et al. 2005; Anand et al. 2006; Day et al. 2006; Joy et al. 2006) and a crystallization age of \(~3\) Ga (Fernandes et al. 2009). Our analysis shows mainly two areas as possible source regions: the Mare Serenitatis and the western area of Oceanus Procellarum (Fig. 2). In this case, the relatively young crystallization age \(~3\) Ga may suggest that the launch site is more likely to lie within the young basaltic lava flows \(~3.3\)–\(~3.5\) Ga) in the western Oceanus Procellarum (Hiesinger et al. 2003), rather than older basalts \(~3.3\)–\(~4.0\) Ga) within Mare Serenitatis.

Dhofar (Dho) 287 is an unbrecciated basalt with a smaller portion of regolith breccia attached. The basalt clast has low-Ti content and a higher concentration of LREE elements compared with other low-Ti basalts, see Table 2. The regolith breccia portion contains low-Ti basalts, impact melt breccia fragments, and glass and mineral fragments, but no evidences of anorthositic lithologies (Anand et al. 2003; Demidova et al. 2003). Sm-Nd and U-Pb analysis of the basalt clast give ages of \(3.4\) Ga (Shih et al. 2002; Terada et al. 2003). We have differentiated both lithologies and plotted them independently to observe any variation in the results. We show that for the basalt composition, Mare Serenitatis is a plausible launch region (Fig. 2). However, when Fe and Ti content in the regolith breccia portion are plotted its composition would be consistent with most of the mare areas in the nearside (Fig. 2). We could not use Th in this case due to the lack of Th data reported for this sample.

Northwest Africa (NWA) 773 is a mafic volcanic breccia with high incompatible trace elements (ITE) and enriched in LREE/HREE, see Table 2. It is formed of two lithologies: a predominately volcanic, polymict fragmental regolith breccia and a cumulate olivine gabbro (Fagan et al. 2003; Jolliff et al. 2003, 2014). \(^{40}\)Ar-\(^{39}\)Ar chronology studies of the cumulate and breccia portions have given an approximate crystallization age of \(2.91\) Ga (Fernandes et al. 2003). Our results suggest Mare Serenitatis, Crisium, and Fecunditatis as plausible compositional source regions for this meteorite, with some sparse areas within the western boundary of Oceanus Procellarum also being possible (Fig. 2d). However, \(^{40}\)Ar-\(^{36}\)Ar studies performed in Luna 16 basalts suggest older crystallization ages for Fecunditatis basalts \(~3.5\) Ga; Fernandes and Burgess 2005; Hiesinger et al. 2006) and this older age would exclude Mare Fecunditatis from consideration (Hiesinger et al. 2000, 2003; Fernandes and Burgess 2005).

Miller Range (MIL) 05035 is a crystalline mare basalt with gabbroic texture and low Ti and low ITE concentrations (Zeigler et al. 2007; Joy et al. 2008a, 2008b; Liu et al. 2009; Arai et al. 2010a, 2010b). MIL 05035 composition, mineralogy, and texture are similar to the basaltic meteorites Asuka (A)-881757 and Yamato (Y)-793169 (Warren and Kallemeyn 1993; Joy et al. 2008a, 2008b; Arai et al. 2010a, 2010b; Zeigler et al. 2012) and to regolith breccia Meteorite Hills (MET) 01210 (Arai et al. 2005), Table 2. These meteorites are often referred to as the YAMM group,
and are believed to be launch-paired stones, forming a stratigraphic section from the upper regolith layer, represented by the regolith breccia MET 01210, to the underlying lava flows (Joy et al. 2008a, 2008b, 2010; Arai et al. 2010a, 2010b). Isotopic studies indicate crystallization ages of ~3.84 Ga, ~3.76 Ga, and ~3.81 Ga for MIL 05035, A-881757, and Y-793169, respectively (Fernandes et al. 2009). When we plotted the MIL 05035, A-881757, and Y-793169 averaged compositions, the outcome revealed Mare Crisium as a possible source area, although the regolith breccia MET-01210 has a better match with Mare Fecunditatis (Fig. 3). As discussed in the Methodology section, regolith breccias are probably more appropriate for comparison with the LP-GRS data set, as they represent the uppermost layer of the lunar crust, so we may consider that the entire YAMM group could have been originated within Mare Fecunditatis. This result agrees with the late Imbrian crystallization ages obtained from the basaltic samples (Fernandes and Burgess 2005; Hiesinger et al. 2006).

Intermediate Fe Composition Breccias

NWA 4472, and its paired stone NWA 4485 (Connolly et al. 2007), are regolith breccias with a high content of KREEP elements. Its bulk Th concentration is up to 7 ppm, see Table 2 (Kuehner et al. 2007; Korotev et al. 2009; Joy et al. 2011). U-Pb and Pb-Pb zircon age analysis reveals that the oldest age of these rocks is 4.35 Ga, corresponding to episodes of early KREEP magmatism. Phosphate U-Pb and Pb-Pb age dating also show impact resetting events between 3.9 and 4.0 Ga, agreeing with the time of basin formation of the Moon (Arai et al. 2010a, 2010b; Joy et al. 2011). Our results indicate that the highlands in the vicinity of the John Herschel crater and Mons Caucasus in the north and east of the Procellarum KREEP Terrain (PKT) are the most probable sources of these meteorites (Fig. 4). These results are consistent with the interpretation that NWA 4472 represents Imbrium basin ejecta (Joy et al. 2011).

Dho 925 is a polymict breccia with highland and mare clasts in an impact melt-rich matrix. Lithic clasts include anorthositic, very low-Ti (VLT) mare, and KREEP-related material (Russell et al. 2004; Demidova et al. 2007; Korotev et al. 2009; Joy et al. 2014). Dho 925 is considered to be paired with Dho-960, 961 (Demidova et al. 2005), and with Sayh al Uhaymir (SaU) 449 (Korotev et al. 2009) based on petrographic and compositional similarities (see Table 2). We find that the highlands in the vicinity of Mare Crisium, Giordano Bruno crater, Mare Humboldtianum, Mare Australe, and a few other areas in the highland terrane provide the best matches to the composition of Dho 925 (Fig. 4). Similar results were obtained for SaU 449, but
in this case, we obtained many more matches that include areas within the South Pole–Aitken Basin (SPA) terrane and the near-side highlands. To a much lesser extent, some matches were also found in the farside highlands (Fig. 4).

Calcalong Creek is a polymict regolith breccia that includes fragments from anorthositic and mare lithologies. The analysis of major elements shows intermediate values for FeO and TiO₂, and the Th analysis shows values ranging between 3 and 4 ppm (Table 2). This is indicative of a mixed nature intermediate between low-Ti mare, highlands, and KREEP compositions (Hill and Boynton 2003; Korotev et al. 2009). Our analysis suggests that the western boundary of Oceanus Procellarum or the eastern boundary of Mare Frigoris are the most probable source regions of this meteorite (Fig. 5). A match is also found for a small area of SPA, and it has previously been suggested that the SPA is a possible source region for this meteorite (Corrigan et al. 2009). Two possibilities have been proposed to explain the Calcalong Creek composition: one model suggests that the meteorite is a mixture of anorthosite, KREEP, and mare basalt rocks which would agree with a PKT boundary origin. The other possibility is the meteorite being a gabbro-norite with moderate concentration of incompatible elements that would be consistent with a SPA origin (Pieters et al. 2001; Corrigan et al. 2009; Korotev et al. 2009). Our results are not sufficient to confirm or dismiss SPA as the source; however, we obtained more matches within the PKT boundaries.

Kalahari 008 is an anorthositic regolith breccia (Sokol et al. 2008; Korotev et al. 2009). Kalahari 009 is a basaltic fragmental breccia with a low FeO content for mare basalts (~16 wt%; see Table 2), and a crystallization age of approximately 4.3 Ga, making it one of the oldest lunar basalts reported to date (Terada et al. 2007; Sokol et al. 2008). Kalahari-008 and -009 are considered paired based on similar fayalite content in olivines, initial Hf isotope compositions, and the proximity of the locations where they were collected in Botswana (Sokol et al. 2008). We plotted the meteorites separately on Fig. 5b. In the case of Kalahari-008, most of the matches are restricted to the Mendel-Rydberg cryptomare region, in contrast to Kalahari-009 whose matches are mainly in Mare Australe, with some matches in the Schickard cryptomare region close to the Mendel-Rydberg basin (Fig. 5). Considering that our approach returns better results using regolith breccia material, we suggest that Kalahari-009 represents a cryptomare sample from Mendel-Rydberg basin, covered by anorthositic regolith formed by ejecta from the Orientale event represented by Kalahari-008. This is also consistent with the ages reported by previous works suggesting a cryptomare origin for Kalahari-009 (Terada et al. 2007; Sokol et al. 2008).

Feldspathic Meteorites

Allan Hills (ALH) 81005 is a polymict regolith breccia with clasts of anorthosite, norite, troctolite, low-Ti and high-Ti mare basalts, and impact melt, as well as soil components and mineral and glass fragments (Boynton and Hill 1983; Kallemeyn and Warren 1983; Korotev et al. 1983; Laul et al. 1983; Verkouteren et al. 1983; Warren et al. 1983; Palme et al. 1991; Treiman et al. 2010). It has very low bulk rock Na, Ti, and ITE concentrations (Table 2) suggesting an origin far from the Apollo and Luna landing sites and close to the Procellarum KREEP Terrain. Consistent with this interpretation, when we plotted this meteorite (Fig. 6), we obtained matches in the Mare Orientale and the surroundings of Mare Australe.

Dar al Gani (DaG) 400 is a polymict anorthositic regolith breccia comprising lithic and mineral fragments fused in a glassy matrix. Most of the clasts (up to 95%) are anorthositic with nearly pure anorthite compositions, see Table 2. Other clasts present are norites and troctolites with anorthite-rich feldspars (Zipfel et al. 1998; Korotev et al. 2003; Cahill et al. 2004; Warren et al. 2005; Joy et al. 2010). Our results show that this meteorite was likely launched from the farside Feldspathic Highland Terrane (FHT); however,
some other highland areas should be considered as well (Fig. 6). Previous work performed on this meteorite by Joy et al. (2010) obtained a wider range of possible source areas. We were able to reduce the spatial extent of composition matches using three elements instead of two (Fe and Th) and smaller search thresholds (e.g., \( \pm 0.018 \) for Ti, \( \pm 0.291 \) for Fe, and \( \pm 0.24 \) for Th instead of \( \pm 1 \) wt% for Fe and \( \pm 1 \) ppm for Th used previously).

NWA 482 is a highly anorthositic crystalline impact melt breccia (Table 2). The rock presents clasts formed mainly by ferroan anorthosites, spinel troctolites, and cataclasites. Mare basalts, KREEP, and Mg-suite lithologies are absent (Daubar et al. 2002; Korotev et al. 2003; Warren et al. 2005). Our results show that the most probable source for this meteorite is the farside FHT region (Fig. 6). This region of the Moon has been previously proposed to be possibly dominated by magnesian feldspathic lithologies (Araki et al. 2008; Ohtake et al. 2012) rather than ferroan rocks like NWA 482. Therefore, our result of a ferroan meteorite originating from within the FHT could imply that this interpretation of the farside crust’s composition and evolution needs further investigation.

NWA 4932 is a crystalline impact melt breccia which is anorthositic in composition and has intermediate FeO content (~8 wt%), see Table 2. This meteorite represents a type of lunar material not observed neither in the Apollo and Luna samples nor in the meteorite collection (Korotev et al. 2009). Our results (Fig. 6) show matches mainly in Mare Australe and also in the eastern boundary of the FHT on the farside.

**DISCUSSION**

Despite the successful validation of our approach with the Apollo and Luna samples, and the apparently sensible outcomes obtained from the lunar meteorites, there are several issues that we consider need to be taken into account when using our approach. These concerns are mainly related to the remote sensing instrument limitations as pointed out in the Methodology section and the type of lunar material that is being studied.

In some cases, the Th content in the sample is extremely high and our approach does not return any matches with the LP-GRS data, as for the Apollo 14 and SaU 169 samples. The upper limit of the Th measurements in the remote sensing data set is 11.6 ppm, smaller than the 15 ppm measured in Apollo 14 regolith samples, and far below the 32.7 ppm measured in the SaU-169 impact melt breccia (Morris et al. 1983; Heiken et al. 1991; Gnos et al. 2004; see online supplement). It is observed that Th abundances larger than 7 ppm in the lunar surface are usually restricted to small regions (<150 km²; Lawrence et al. 2000, 2007); therefore, it is likely that SaU 169 derives from a restricted area with unusually high Th content that is unresolved in the 2 degree per pixel data set.

Pristine basalts are relatively well constrained by our technique, though we found that it is necessary to
use relatively broad compositional range (i.e., a large number of standard deviations around the mean compositional analyses) to obtain the first matches returned by our software. We may reduce this uncertainty by adding other types of information, such as lava ages deduced from crater counts as was discussed for LAP 02005. In this case, we were able to further link the composition of a meteorite with the age estimates of a lava flow obtained by crater counting techniques (Hiesinger et al. 2000, 2003). Performing this exercise in all basaltic meteorites will allow us a better understanding of the compositional evolution of the magma reservoirs on the Moon. Our technique also allows us to restrict the provenance of Kalahari-008/009 meteorites, placing their source within the Mendel-Ryder basin suggesting that this area was volcanically active ~4.3 Ga ago.

Our technique shows that NWA 4472/4485 and SaU 169 may derive from different areas of the Imbrium ejecta blanket (see Fig. 4 and Appendix S1). Previously, these and Apollo 12 impact melt samples have given a similar age for an impact event at 3.92 Ga, which likely dates the Imbrium basin forming event (Gnos et al. 2004; Arai et al. 2010a, 2010b; Joy et al. 2011; Liu et al. 2012).

Identification of SPA basin samples would be an important step to understand the nature of the basin floor and to elucidate whether it penetrates into the noritic lower crust (Wieczorek et al. 2006). Several meteorites have been previously considered to have originated from the SPA basin using Clementine and LP-GRS data: Dho 961, NWA 2995, 4819, 5153, and 5207, Y-983885 (Jolliff et al. 2009; Korotev et al. 2009; Mercer et al. 2013; Joy et al. 2014). For these meteorites, we obtained areas within the SPA where regolith matches meteorite compositions. However, these results are not conclusive as there are other areas that present positive matches, particularly in the surroundings of the nearside eastern basins.

Our approach is not sensitive to the differences among the highland feldspathic suites (see Appendix S1). Although it is able to broadly distinguish among farside FHT, outer FHT (FHT-O), and the central nearside highlands, it is not able to restrict them in a precise way. Distinguishing these terranes is key to understanding the mechanisms leading to the formation and evolution of the lunar crust (Arai et al. 2008; Gross et al. 2014). Based on Apollo 16 ferroan anorthositic samples (FAN) and the Mg-rich (MAN) Dho 489 sample, Arai et al. (2008) proposed a model where the lunar crust is characterized by a ferroan southern nearside and a northern farside dominated by magnesium lithologies (Ohtake et al. 2012; Gross et al. 2014). It disagrees with the results we obtained for the meteorite NWA 482 (FAN) that shows the farside central highlands as a possible origin. Furthermore, our results for Dho 489 (MAN) are not conclusive to establish whether the rock derived from the nearside or the farside, therefore, we cannot dismiss the possibility of a nearside origin for this sample. This uncertainty might be further addressed with the inclusion of the element Mg into our approach (Warren 1985; Shearer and Papike 2005; Prettyman et al. 2006), although the abundance precision for this element in the LP-GRS data set is relatively low with uncertainties up to 5.2 wt% (Prettyman et al. 2006). We plan to investigate this possibility in future work.

**CONCLUSIONS**

We have shown that comparing the analyzed bulk compositions of samples with element abundances obtained by lunar remote sensing instruments is a potentially valuable tool for constraining the source localities of lunar meteorites. We have validated our approach using regolith and soil samples returned during the Apollo and Luna missions (Fig. 1), and then performed analyses for the 48 lunar meteorites with published element compositions (Figs. 2–6; Appendix S1). Our technique shows plausible matches for regolith breccia meteorites. Results for pristine basalts must be taken cautiously as these materials may not represent the actual composition of the regolith as mapped by the LP-GRS. When applied to feldspathic meteorites, our approach is not very sensitive to the differences among highland feldspathic suites.

However, there are several factors that must be taken into account when using this approach. The most important are the measurement uncertainties and spatial resolution of the instrument data used for matching. In addition, care must be taken when considering certain types of sample material, in particular, we suggest that regolith breccias are the most appropriate sample type to compositionally compare with remote sensing data sets.

Our technique is easily adaptable for use with other elements (i.e., Mg) and may be expanded to include additional remote sensing data sets. Future work will explore these possibilities as well as the use of mineralogical data to further constrain matches for different types of lunar material.

**Acknowledgments**—This research is funded by the UK Science and Technology Facilities Council (STFC). KHJ additionally acknowledges funding from the Leverhulme Trust, UK (grant 2011-569). We thank Dr. David Lawrence and Tom Prettyman for providing LP data and errors. We acknowledge the resources available through the NASA’s Lunar Meteorite
Compendium (http://curator.jsc.nasa.gov/antmet/lmc/),
Dr. Randy Korotev’s Lunar Meteorite List (http://
meteorites.wustl.edu/lunar/), and the Lunar Meteoritical
Bulletin (http://lpi.usra.edu/ meteor/metbull.php). We
thank our two referees, David Lawrence and Yang Liu,
and the Associate Editor, Cyrena Goodrich, for very
helpful comments which have improved the paper.

Editorial Handling—Dr. Cyrena Goodrich

REFERENCES

Anand M., Taylor L. A., Misra K. C., Demidova S. I., and
Nazarov M. A. 2003. KREEPy lunar meteorite Dhofar
287A: A new lunar mare basalt. Meteoritics & Planetary
Science 38:485–499.

Anand M., Taylor L. A., Floss C., Neal C. R., Terada K.,
and Tanikawa S. 2006. Petrology and geochemistry of
LaPaz Icefield 02205: A new unique low-Ti mare-basalt
meteorite. Geochimica et Cosmochimica Acta 70:246–264.

Arai T., Misawa K., and Kojima H. 2005. A new lunar
meteorite MET 01210: Mare breccia with a low-Ti
ferrobasalt (abstract #2361). 38th Lunar and Planetary
Science Conference. CD-ROM.

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

Arai T., Yoshihata M., Tomiyama T., Nihara T., Yokoyama T.,
Kaiden H., Misawa K., and Irving A. J. 2010b. Support for a prolonged KREEP magmatism: U-Pb age
dating of zircon and baddeleyite in lunar meteorite
NWA4485 (abstract #2379). 41st Lunar and Planetary
Science Conference. CD-ROM.

Baslevsky A. T., Neukum G., and Nyquist L. 2010. The spatial and
temporal distribution of lunar mare basalts as
deduced from analysis of data for lunar meteorites.
Planetary and Space Science 58:1900–1905.

Binder A. B. 1998. Lunar Prospector: Overview improved
gravity field of the moon from lunar prospector. Science
281:1475–1476.

Bischoff A., Palme H., Weber H. W., Stöffler D., Braun O.,
Spettel B., Begemann F., Winke H., and Ostertag R.
1987. Petrography, shock history, chemical composition
and noble gas content of the lunar meteorites Yamato-
82192 and -82193. National Institute of Polar Research
NI-Electronic Library Service 46:21–42.

Boynton W. V. and Hill D. H. 1983. Composition of bulk
samples and a possible pristine clast from Allan Hills
A81005. Geophysical Research Letters 10:837–840.

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. doi:10.1111/j.1945-5100.2004.tb00916.x.

Connolly H. C., Zupfel J., Folco L., Smith C., Jones R. H.,
Benedix G., Righter K., Yamaguchi A., Chennaoui
Aoudjehane H., and Grossman J. N. 2007. The
Meteoritical Bulletin, No. 91. 2007 March. Meteoritics &
Planetary Science 42:413–466.

Corrigan C. M., Dombard A. J., Spudis D., Bussey D. B. J.,
and McCoy T. J. 2009. Candidate source regions for the
lunar meteorites (abstract #5375). 72nd Annual
Meteoritical Society Meeting.

Dauber J. J., Kring D. A., Swindle T. D., and Timothy Jull
A. J. 2002. Northwest Africa 482: A crystalline impact-
melt breccia from the lunar highlands. Meteoritics &
Planetary Science 37:1797–1813.

Day J. M. D. and Taylor L. A. 2007. On the structure of
mare basalt lava flow from textural analysis of the LaPaz
Icefield and Northwest Africa 032 lunar meteorites.
Meteoritics & Planetary Science 42:3–17.

Day J. M. D., Taylor L. A., Floss C., Patchen A. D., Schnare D.
W., and Graham Pearson D. 2006. Comparative petrology,
geochemistry, and petrogenesis of evolved, low-Ti lunar
mare basalt meteorites from the LaPaz Icefield, Antarctica.
Geochimica et Cosmochimica Acta 70:1581–1600.

Demidova S. I., Nazarov M. A., Anand M., and Taylor L.
A. 2003. Lunar regolith breccia Dhofar 287B: A record of lunar
volcanism. Meteoritics & Planetary Science 38:501–514.

Demidova S. I., Nazarov M. A., Kurat G., Brandstätter F.,
and Ntaflos T. 2005. New lunar meteorites from Oman:
Dhofar 925, 960 and 961 (abstract #1607). 36th Lunar and
Planetary Science Conference. CD-ROM.

Demidova S. I., Nazarov M. A., Lorenz C. A., Kurat G.,
Brandstätter F., and Ntaflos T. 2007. Chemical
composition of lunar meteorites and the lunar crust.
Petrology 15:386–407.

Elphic R. C., Lawrence D. J., Feldman W. C., Barrarclough B.
L., Maurice S., Binder A. B., and Lucey G. 1998. Lunar
Fe and Ti abundances: Comparison of Lunar Prospector
and Clementine data. Science 281:1493–1496.

Eugster O., Niedermann S., Burger M., Krahenbuhl U.,
Weber H., Clayton R. N., and Mayeda T. K. 1989.
Preliminary report on the Yamato-86032 lunar meteorite:
III. Ages, noble gas isotopes, oxygen isotopes and
chemical abundances. Proceedings of the NIPR Symposium
on Antarctic Meteorites 2:25–35.

Fagan T. J., Taylor G. J., Keil K., Hicks T. L., Killgore M.,
Bunch T. E., Wittke J. H., Mittlefehldt D. W., Clayton R.
N., Mayeda T. K., Eugster O., Lorenzetti S., and Norman
M. D. 2003. Northwest Africa 773: Lunar origin and
iron-enrichment trend. Meteoritics & Planetary Science
38:529–554.

Feldman W. C., Barrarclough B. L., Fuller K. R., Lawrence D.
J., Maurice S., Miller M. C., Prettyman T. H., and Binder
A. B. 1999. The Lunar Prospector gamma-ray and neutron
spectrometers. Nuclear Instruments and Methods in Physics
Research A 422:562–566.

Fernandes F. A. and Burgess R. 2005. Volcanism in Mare
Fecunditatis and Mare Crisium: Ar-Ar age studies.
Geochimica et Cosmochimica Acta 69:4919–4934.

Fernandes V. A., Burgess R., and Turner G. 2003. 40Ar–39Ar
chronology of lunar meteorites Northwest Africa 032 and
773. Meteoritics & Planetary Science 38:555–564.

Fernandes V. A., Burgess R., and Morris A. 2009. 40Ar–39Ar
age determinations of lunar basalt meteorites Asuka
881757, Yamato 793169, Miller Range 05035, La Paz
Icefield 02205, Northwest Africa 479, and basaltic breccia
Elephant Moraine 96008. Meteoritics & Planetary Science
44:805–821.
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., Burgess R., Hinton R., Fernandes V. A., Crawford I. A., Kearsley A. T., and Irving A. J. 2011. Petrogenesis and chronology of lunar meteorite Northwest Africa 4472: A KREEPy regolith breccia from the Moon. Geochimica et Cosmochimica Acta 75:2420–2452.

Joy K. H., Nemchin A., Grange M., Lapen T. J., Peslier A. H., Ross D. K., Zolensky M. E., and Kring D. A. 2014. Petrography, geochronology and source terrain characteristics of lunar meteorites Dhofar 925, 961 and Sayh al Uhaymir 449. Geochimica et Cosmochimica Acta 144:299–325.

Killeeney G. W. and Warren H. 1983. Compositional implications regarding the lunar origin of the ALHA81005 meteorite. Geophysical Research Letters 10:833–836.

Karouji Y., Ebihara M., and Yamaguchi A. 2004. Chemical characterization of lunar meteorites, Yamato 86032 and Dhofar 489 (abstract). 28th NIPR Symposium on Antarctic Meteorites, pp. 29–30.

Klima R. L., Pieters C. M., Boardman J. W., Green R. O., Head J. W. III, Isaacsen P. J., Mustard J. F., Nettles J. T., Petro N. E., Staid M. I., Sunshine J. M., Taylor L. A., and Tompkins S. 2011. New insights into lunar petrology: Distribution and composition of prominent low-Ca pyroxene exposures as observed by the Moon Mineralogy Mapper (M 3). Journal of Geophysical Research 116:E00G06.

Koeberl C., Warren H., Lindstrom M. M., Spettel B., and Fukukoa T. 1989. Preliminary examination of the Yamato-86032 lunar meteorite. II- Major and trace element chemistry. Proceedings of the NIPR Symposium on Antarctic Meteorites 2:15–24.

Koeberl C., Kurat G., and Brandstätter F. 1993. Gabbroic lunar mare meteorites Asuka-881757 (Asuka 31) and Yamato-793169: Geochemical and mineralogical study. Proceedings of the NIPR Symposium on Antarctic Meteorites 6:14–34.

Korotev R. L. 1997. Some things we can infer about the Moon from the composition of the Apollo 16 regolith. Meteoritics & Planetary Science 32:447–478.

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

Korotev R. L. 2012. Lunar meteorites from Oman. Meteoritics & Planetary Science 47:1365–1402.

Korotev R. L. and Irving A. J. 2013. Keeping up with the lunar meteorites-2013 (abstract #1216). 44th Lunar and Planetary Science Conference. CD-ROM.

Korotev R. L., Lindstrom M., Lindstrom D. J., and Haskin A. 1983. Antarctic meteorite ALHA81005—Not just another lunar anorthositic norite. Geophysical Research Letters 10:829–832.

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.

Kramer G. Y., Jolliff B. L., and Neal C. R. 2008. Distinguishing high-alumina mare basalts using Clementine UVVIS and Lunar Prospector GRS data: Mare Moscovienne and Mare Nectari. Journal of Geophysical Research 113:E01002.

Kuehner S. M., Irving A. J., Korotev R. L., Hupé G. M., and Rulew S. 2007. Zirconium-baddeleyite-bearing silica-feldspar granophyric clasts in KREEP-rich lunar breccias Northwest Africa 4472 and 4485 (abstract #1516). 38th Lunar and Planetary Science Conference. CD-ROM.

Lauf J. C., Papike J. J., and Simon S. B. 1981. The lunar regolith: Comparative studies of the Apollo and Luna sites. Chemistry of soils from Apollo 17, Luna 16, 20 and 24. Proceedings, 12th Lunar and Planetary Science Conference. pp. 389–407.

Lauf L. C., Smith M. R., and Schmitt R. A. 1983. ALHA 81005 meteorite: Chemical evidence for lunar highland origin. Geophysical Research Letters 10:825–828.

Lawrence D. J., Feldman W. C., Barraclough B. L., Binder A. B., Elphic R. C., Maurice S., and Thomsen D. R. 1998. Global elemental maps of the moon: The Lunar Prospector gamma-ray spectrometer. Science 281:1484–1489.

Lawrence D. J., Feldman W. C., Barraclough B. L., Binder A. B., Elphic R. C., Maurice S., Miller M. C., and Prettyman T. H. 2000. Thorium abundances on the lunar surface. Journal of Geophysical Research 105:20307–20331.

Lawrence D. J., Feldman W. C., Elphic R. C., Little R. C., Prettyman T. H., Maurice S., Lucey 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 107:5130–5156.

Lawrence D. J., Elphic R. C., Feldman W. C., Prettyman T. H., Gassault O., and Maurice S. 2003. Small-area thorium features on the lunar surface. Journal of Geophysical Research 108:5102–5127.

Lawrence D. J., Paquet R. C., Elphic R. C., Feldman W. C., Hagerty J. J., Prettyman T. H., and Spudis P. D. 2007. Global spatial deconvolution of Lunar Prospector Th abundances. Geophysical Research Letters 34:L03201.

Lindstrom M. M., Mittlefehl dt D. W., Martinez R. R., Lipscutz M. E., and Wang M.-S. 1991. Geochemistry of Yamato-82192, -86032 and -793274. Proceedings of the NIPR Symposium on Antarctic Meteorites 4:12–32.

Liu D., Jolliff B. L., Zeigler R. A., Korotev R. L., Wan Y., Xie H., Zhang Y., Dong C., and Wang W. 2012. Comparative zircon U-Pb geochronology of impact melt breccias from Apollo 12 and lunar meteorite SaU 169, and implications for the age of the Imbrium impact. Earth and Planetary Science Letters 319–320:277–286.

Liu Y., Floss C., Day J. M. D., Hill E., and Taylor L. A. 2009. Petrogenesis of lunar mare basaltic meteorite Miller Range 05035. Meteoritics & Planetary Science 44:261–284.

McEwen A. S. and Robinson M. S. 1997. Mapping of the Moon by Clementine. Advances in Space Research 19:1523–1533.

McKay D. S., Bogard D. D., Morris R. V., Korotev R. L., Johnson P., and Wentworth S. J. 1986a. Apollo 16 regolith breccias: Characterization and evidence for early formation in the mega-regolith. Proceedings, 7th Lunar Science Conference, pp. D277–D303.

McKay G., Wagstaff J., and Yang S.-R. 1986b. Zirconium, Hafnium, and rare earth element partition coefficients for ilmenite and other minerals in high-Ti lunar mare basalts: An experimental study. Journal of Geophysical Research 91:229–237.

Mercer 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.
Morris R. V., Score R., Dardano C., and Heiken G. 1983. *Handbook of lunar soils*. Houston, Texas: Planetary Materials Branch, NASA.

Nyquist L., Bogard D., Yamaguchi A., Shih C.-Y., Karouji Y., Ebihara M., Reese Y., Garrison D., McKay G., and Takeda H. 2006. Feldspathic clasts in Yamato-86032: Remnants of the lunar crust with implications for its formation and impact history. *Geochimica et Cosmochimica Acta* 70:5990–6015.

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.

Palme H., Spettel B., Weckwerth G., and Wanke H. 1983. Antarctic meteorite ALHA81005, a piece from the ancient lunar crust. *Geophysical Research Letters* 10:817–820.

Palme H., Spettel B., Jochum K., Dreibus G., Weber H., Weckwerth G., Wanke H., Bischoff A., and Stöffler D. 1991. Lunar highland meteorites and the composition of the lunar crust. *Geochimica et Cosmochimica Acta* 55:3105–3122.

Papike J. J., Simon S. B., and Laul J. C. 1982. The Lunar Regolith: Chemistry, mineralogy, and petrology. *Reviews of Geophysics and Space Physics* 20:761–826.

Peplowski N. and Lawrence D. J. 2013. New insights into the global composition of the lunar surface from high-energy gamma rays measured by Lunar Prospector. *Journal of Geophysical Research: Planets* 118:671–688.

Philpotts J. A., Schnetzler C. C., Nava D. F., Bottino M. L., Fullagar D., Thomas H. H., Schuhmann S., and Kouns C. W. 1972. Apollo 14: Some geochemical aspects. *Proceedings, 3rd Lunar Science Conference*. pp. 1293–1305.

Pieters C. M., Head J. W., Gaddis L., Jolliff B., and Duke M. 2001. Rock types of South Pole-Aitken basin and extent of basaltic volcanism. *Journal of Geophysical Research* 106:28,001–28,022.

Pieters C. M., Head J. W., Isaacscon Petro N., Runyon C., Ohtake M., Föing B., and Grande M. 2008. Lunar international science coordination/calibration targets (L-ISCT). *Advances in Space Research* 42:248–258.

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., Isaacscon 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., Thaïsen K., Tompkins S., and Whitten J. 2011. Mg-spinel lithology: A new rock type on the lunar farside. *Journal of Geophysical Research* 116:E00G08.

Prettyman T. H., Hagerty J. J., Elphic R. C., Feldman W. C., Lawrence D. J., McKinney G. W., and Vaniman D. T. 2006. Elemental composition of the lunar surface: Analysis of gamma ray spectroscopy data from Lunar Prospector. *Journal of Geophysical Research* 111:E12007.

Rhodes J. M. and Blanchard D. 1981. Apollo 11 breccias and soils: Aluminous mare basaltic or multi-component mixtures? *Proceedings Lunar Planetary Science* 12B:607–620.

Rhodes J. M., Blanchard D., Duncan M. A., Brannon J. C., and Rodgers K. V. 1977. Chemistry of Apollo 12 mare basalts: Magma types and fractionation processes. Proceedings, 8th Lunar Science Conference. pp. 1305–1338.

Righter K., Collins S. J., and Brandon A. D. 2005. Mineralogy and petrology of the LaPaz Icefield lunar mare basaltic meteorites. *Meteoritics & Planetary Science* 40:1703–1722.

Robinson K. L., Treiman A. H., and Joy K. H. 2012. Basaltic fragments in lunar feldspathic meteorites: Connecting sample analyses to orbital remote sensing. *Meteoritics & Planetary Science* 47:387–399.

Russell S. S., Folco L., Grady M. M., Zolensky M. E., Jones R., Righter K., Zipfel J., and Grossman J. N. 2004. The Meteoritical Bulletin, No. 88. *Meteoritics & Planetary Science* 39:A215–A272.

Shearer C. K. and Papike J. J. 2001. Early crustal building processes on the moon: Models for the petrogenesis of the magnesian suite. *Geochimica et Cosmochimica Acta* 69:3445–3461.

Shearer C. K., Hess P. C., Wieczorek M. A., Pritchard M. E., Parmentier E. M., Borg L. E., Longhi J., Elkins-Tanton L. T., Neal C. R., Antonenko I., Canup R. M., Halliday A. N., Grove T. L., Hager B. H., Lee 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 & Geochemistry* 60:365–518.

Shih C.-Y., Nyquist L. E., Reese Y., Wiesmann H., Nazarov M. A., and Taylor L. A. 2002. The chronology and petrogenesis of the mare basalt clast from lunar meteorite Dhofar 287: Rb-Sr and Sm-Nd isotopic studies (abstract #1344). 33rd Lunar and Planetary Science Conference. CD-ROM.

Shkuratov Y. G., Kaydash V. G., Stankevich D. G., Starukhina L. V., Pinet C., Chevrel S. D., and Daydou Y. H. 2005. Derivation of elemental abundance maps at intermediate resolution from optical interpolation of lunar prospector gamma-ray spectrometer data. *Planetary and Space Science* 53:1287–1301.

Simon S. B., Papike J. J., Gosselin D. C., and Laul J. C. 1985. Petrology and chemistry of Apollo 12 regolith brecias. *Journal of Geophysical Research* 90:D75–D86.

Sokol A. K., Fernandez V. A., Schulz T., Bischoff A., Burgess R., Clayton R. N., Münker C., Nishizumi K., Palme H., Schultz L., Weckwerth G., Mezger K., and Horstmann M. 2008. Geochemistry, petrology and ages of the lunar meteorites Kalahari 008 and 009: New constraints on early lunar evolution. *Geochimica et Cosmochimica Acta* 72:4845–4873.

Swinyard B. M., Joy K. H., Kellet B. J., Crawford I. A., Grande M., Howe C. J., Fernandez V. A., Gasnault O., Lawrence D. J., Russell S. S., Wieczorek M. A., Foing B. H., and The SMART-1 team. 2009. X-ray fluorescence observations of the moon by SMART-1/D-CIXS and the first detection of Ti Kα from the lunar surface. *Planetary and Space Science* 57:744–750.

Terada K., Anand M., Sokol A. K., Bischoff A., and Sano Y. 2007. Cryptomare magmatism 4.35 Gyr ago recorded in lunar meteorite Kalahari 009. *Nature* 450:849–852.

Terada K., Sasaki Y., Anand M., Sano Y., Taylor L. A., and Hori K. 2008. Uranium–lead systematics of low-Ti basaltic meteorite Dhofar 287A: Affinity to Apollo 15 green glasses. *Earth and Planetary Science Letters* 270:119–124.

Treiman A. H., Maloy A. K., Shearer C. K., and Gross J. 2010. Magnesian anorthositic granulites in lunar meteorites Allan Hills A81005 and Dhofar 309: Geochemistry and global significance. *Meteoritics & Planetary Science* 45:163–180.
Vaniman D., Dietrich J., Taylor G. J., and Heiken G. 1991. Exploration, samples, and recent concepts of the Moon. In Lunar sourcebook: A user’s guide to the Moon, edited by Heiken G. H., Vaniman D. T., and French B. M. New York: Cambridge University Press. pp. 5–26.

Verkouteren R. M., Dennison J. E., and Lipschutz M. E. 1983. Siderophile, lithophile and movile trace elements in the lunar meteorite Allan Hills 81005. Geophysical Research Letters 10:821–824.

Warren P. H. 1985. The magma ocean concept and lunar evolution. Annual Reviews Earth and Planetary Science 13:201–240.

Warren P. H. 1994. Lunar and Martian meteorite delivery services. Icarus 111:338–363.

Warren P. H. and Kallemeyn G. W. 1993. Geochemical investigation of two lunar mare meteorites: Yamato-793169 and Asuka-881757. Proceedings of the NIPR Symposium on Antarctic Meteorites 6:35–57.

Warren P. H., Taylor G. J., and Keil K. 1983. Regolith breccia Allan Hills A81005: Evidence of lunar origin, and petrography of pristine and nonpristine clasts. Geophysical Research Letters 10:779–782.

Warren P. H., Ulf-Møller F., and Kallemeyn G. W. 2005. “New” lunar meteorites: Impact melt and regolith breccias and large-scale heterogeneities of the upper lunar crust. Meteoritics & Planetary Science 40:989–1014.

Wieczorek M. A., Jolliff B. L., Khan A., Pritchard M. E., Weiss B. P., Williams J. G., Hood L. L., Righter K., Neal C. R., Shearer C. K., Stewart McCallum L., Tompkins S., Hawke B. R., Peterson C., Gillis J. J., and Bussey B. 2006. The constitution and structure of the lunar interior. Reviews in Mineralogy and Geochemistry 60:221–364.

Wöhler C., Bereznnyov A., and Evans R. 2011. Estimation of elemental abundances of the lunar regolith using Clementine UVVIS+NIR data. Planetary and Space Science 59:92–110.

Yanai K. and Kojima H. 1991. Varieties of lunar meteorites recovered from Antarctica. Proceedings of the NIPR Symposium on Antarctic Meteorites 4:70–90.

Zeigler R. A., Korotev R. L., Jolliff B. L., and Haskin L. A. 2005. Petrography and geochemistry of the LaPaz Icefield basaltic lunar meteorite and source crater pairing with Northwest Africa 032. Meteoritics & Planetary Science 40:1073–1101.

Zeigler R. A., Korotev R. L., and Jolliff B. L. 2007. Miller Range 05035 and Meteorite Hills 01210: Two basaltic lunar meteorites, both likely source-crater paired with Asuka 881757 and Yamato 793169 (abstract #2110). 38th Lunar and Planetary Science Conference. CD-ROM.

Zeigler R. A., Korotev R. L., and Jolliff B. L. 2012. Pairing relationships among feldspathic lunar meteorites from Miller Range, Antarctica (abstract #2377). 43rd Lunar and Planetary Science Conference. CD-ROM.

Zipfel J., Spettel B., Palme H., Wolf D., Franchi I., Sexton A., S., Pillinger C. T., and Bischoff A. 1998. Dar al Gani 400: Chemistry and petrology of the largest lunar meteorite. Meteoritics & Planetary Science 33:A171.

SUPPORTING INFORMATION

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

Appendix S1. Table: Bulk rock reported compositions of the meteorites and paired stones of this study ± the analytical 1σ standard deviation of averaged measurements.

Results: Regions were the given meteorite compositional data matches the regolith compositions underlying a Clementine lunar albedo map in cylindrical projection.