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Constraining the source regions of lunar meteorites using orbital geochemical data

A. CALZADA-DIAZ[1,2*], K. H. JOY[3], I. A. CRAWFORD[1,2], and T. A. NORDHEIM[2,4]

[1]Department of Earth and Planetary Sciences, Birkbeck College, London WC1E 7HX, UK
[2]Centre for Planetary Sciences UCL/Birkbeck, London WC1E 6BT, UK
[3]School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Manchester M13 9PL, UK
[4]Mullard Space Science Laboratory, University College London, Dorking RH5 6NT, UK
[*]Corresponding author. E-mail: acalza01@mail.bbk.ac.uk

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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

nd = 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.	TiO2 (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
Kahalari 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

nd = 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, TiO_2, 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., $\pm 2\sigma$ 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, TiO_2, 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;

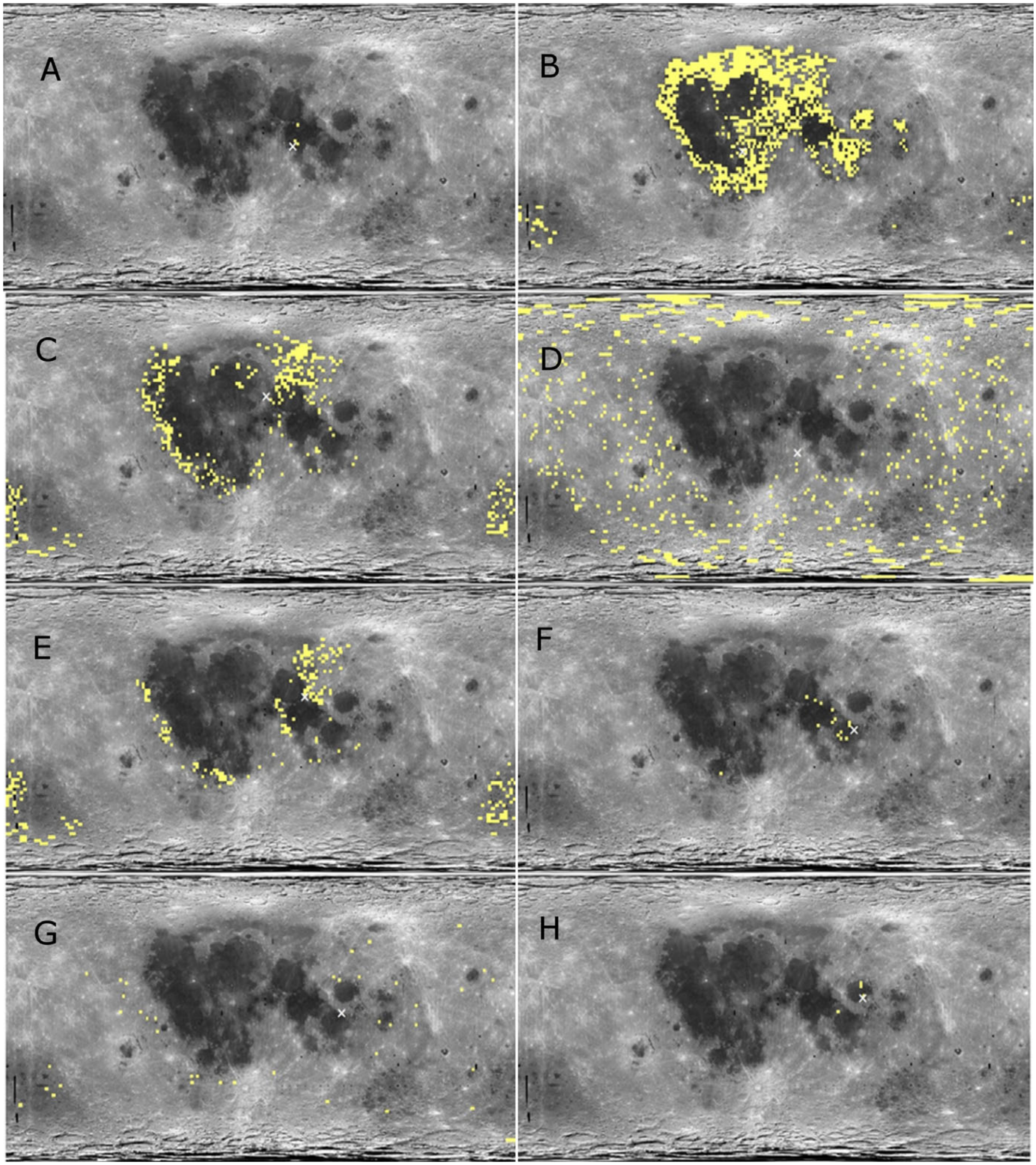

Fig. 1. Apollo and Luna returned samples validation. Identification of lunar regolith with similar composition to (A) Apollo 11, (B) Apollo 12, (C) Apollo 15, (D) Apollo 16, (E) Apollo 17, (F) Luna 16, (G) Luna 20, and (H) Luna 24 soils and regolith breccias. Matching composition to the inputs + 2σ standard 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^o longitude and 0° latitude in the center.

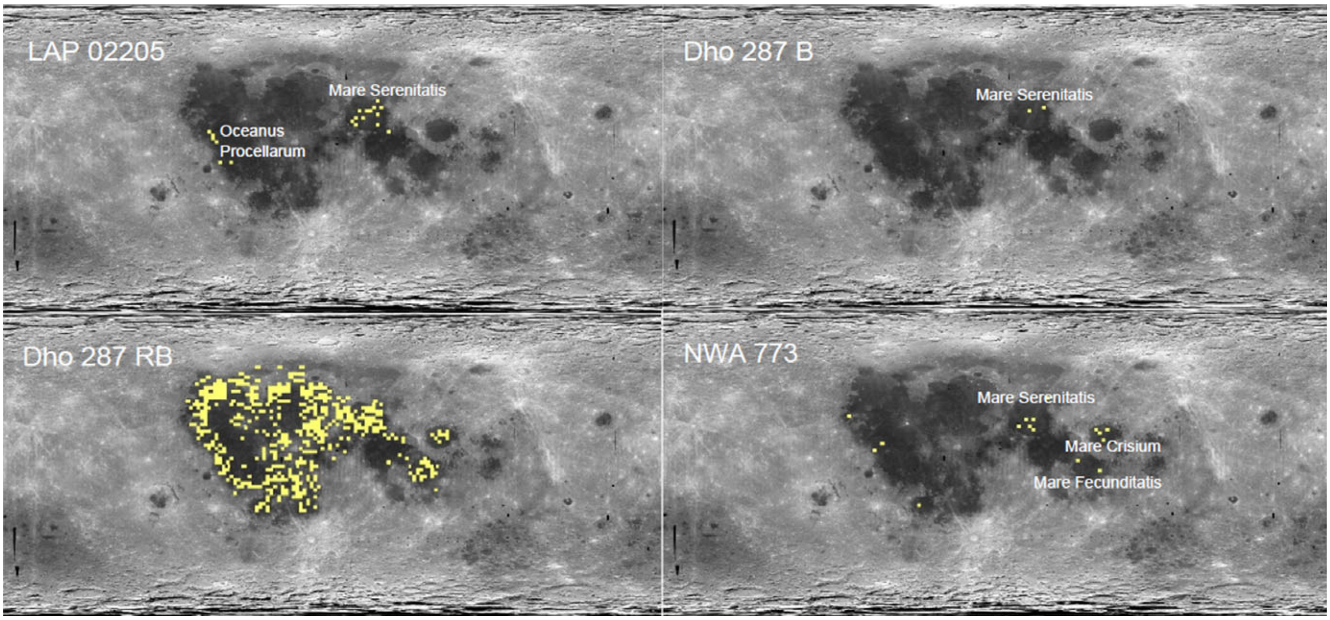

Fig. 2. Identification of lunar regolith with similar compositions to crystalline basalts: LAP 02005 ± 3 standard deviations (3σ); Dho 287 basalt component ±2σ; Dho 287 regolith breccia component (RB) ±2σ; and NWA 773 ± 3σ. Matching compositions are shown in yellow.

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. 2008). 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-^{30}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-^{39}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,

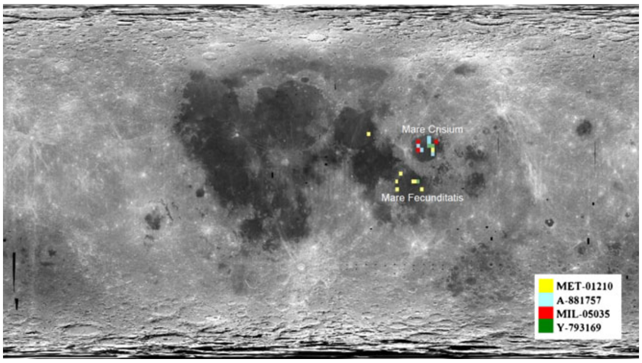

Fig. 3. Identification of lunar regolith with similar compositions to the YAMM group: Crystalline basalts Yamato-793169 ± 5σ (green), Asuka-881757 ± 4σ (blue), MIL 05035 ± 8σ (red), and regolith breccia MET 01210 ± 5σ (yellow). All the crystalline basalts are located in Mare Crisium observing some overlapping in the results; the regolith breccia is mainly located in Mare Fecunditatis.

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

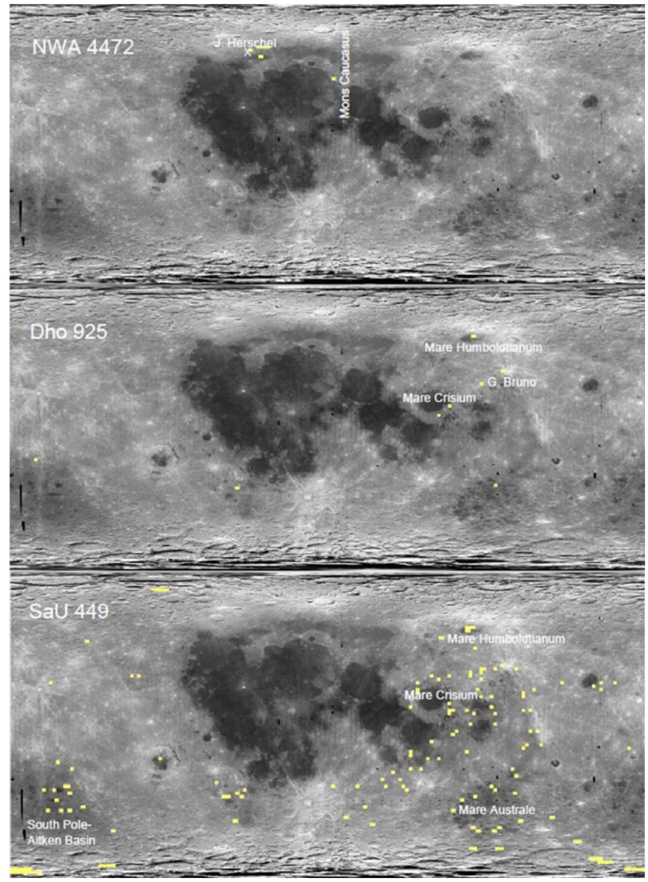

Fig. 4. Image showing the areas where surface regolith composition measurements match the analytical composition of the ITE-rich mingled regolith breccia: NWA 4472 ± 2σ, Dho 925 ± 2σ (blue), and SaU 449 ± 2σ standard deviation (yellow) ITE-rich lunar meteorites.

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

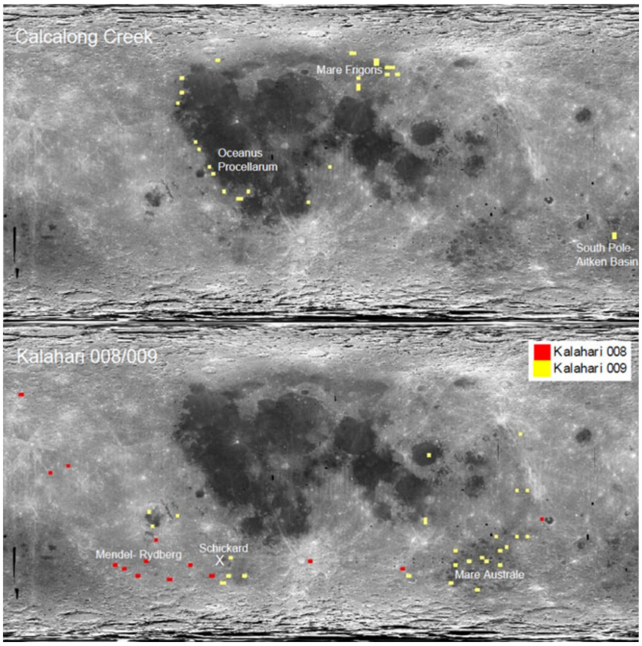

Fig. 5. Identification of lunar regolith with similarities in composition to the mingled regolith breccias: top, Calcalong Creek ±2σ and bottom, Kalahari 008 (red) and Kalahari 009 (yellow) ±2σ.

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 TiO_2, 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 gabbronorite 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,

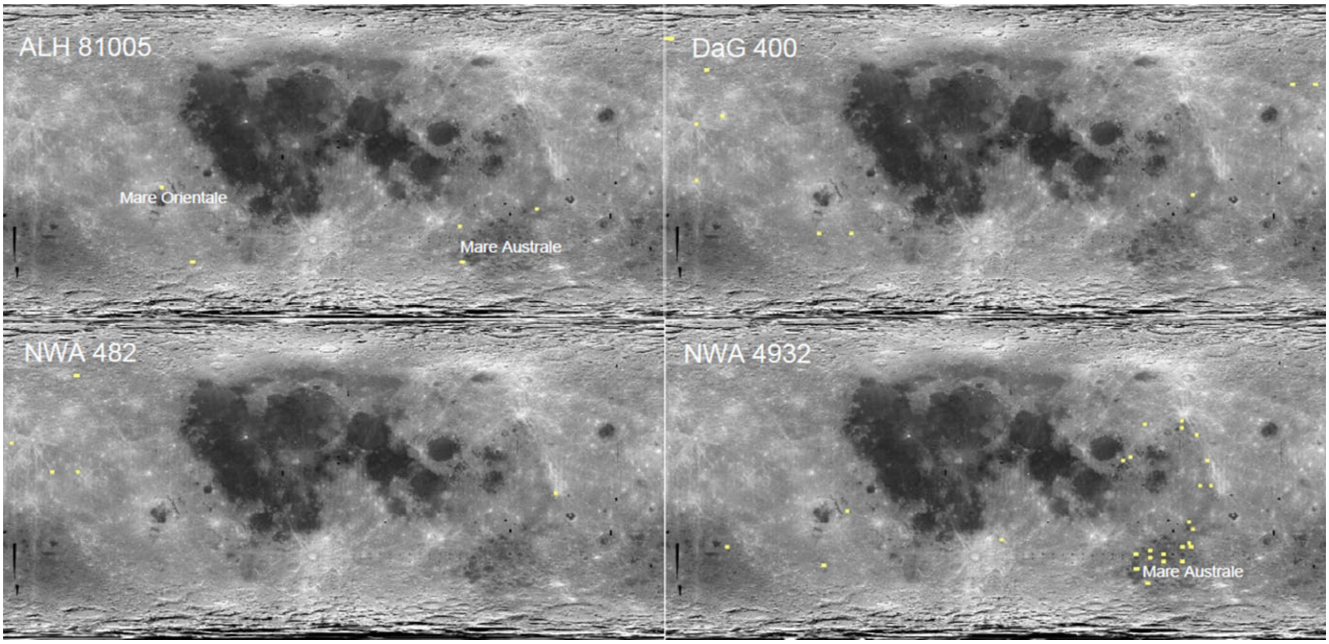

Fig. 6. Identification of lunar regolith with similarities to the feldspathic meteorites: ALH 81005 ± 2σ standard deviation, DaG 400 ± 2σ, NWA 482 ± 2σ, and NWA 4932 ± 2σ.

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., ±0.018 for Ti, ±0.291 for Fe, and ±0.24 for Th instead of ±1 wt% for Fe and ±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 cataclastites. 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 (Arai 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 km^2; 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-Rydberg 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 magnesian 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.

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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.