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Petrography, geochronology and source terrain characteristics of lunar meteorites Dhofar 925, 961 and Sayh al Uhaymir 449

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Abstract

Dhofar (Dho) 925, 961 and Sayh al Uhaymir (SaU) 449 are brecciated lunar meteorites consisting of mineral fragments and clasts from a range of precursor lithologies including magnesian anorthositic gabbronorite granulites; crystalline impact melt breccias; clast-bearing glassy impact melt breccias; lithic (fragmental) breccias; mare basalts; and evolved (silica-rich) rocks. On the similarity of clast type and mineral chemistry the samples are likely grouped, and were part of the same parent meteorite. Phosphate Pb–Pb ages in impact melt breccias and matrix grains demonstrate that Dho 961 records geological events spanning ~500 Ma between 4.35 and 3.89 Ga. These Pb–Pb ages are similar to the ages of 'ancient' intrusive magmatic samples and impact basin melt products collected on the lunar nearside by the Apollo missions. However, the samples' bulk rock composition is chemically distinct from these types of samples, and it has been suggested that they may have originated from the farside South Pole-Aitken impact basin (i.e., Jolliff et al., 2008). We test this hypothesis, and conclude that although it is possible that the samples may be from the South Pole-Aitken basin, there are other regions on the Moon that may have also sourced these complex breccias.

1. INTRODUCTION

The Moon is a witness plate to Solar System processes and preserves a record of the geological evolution of small planetary bodies (NRC, 2007). Manned and unmanned missions to the Moon returned ~382 kg of lunar rocks and soils (Vaniman et al., 1991). These were collected from within and around the nearside Procellarum KREEP Terrane (PKT) by the Apollo missions, and from equatorial latitudes on the eastern limb by the Luna missions. Therefore, interpretations of the Moon's past have mostly been derived from a geographically restricted dataset on the lunar nearside. Lunar meteorites, which are sourced from potentially anywhere on the Moon's surface, however, provide a better global representation of the geological and chronological history of the Moon (Korotev, 2005; Joy and Arai, 2013). To date, there have been ~185 individual (named) lunar meteorites collected on Earth as hot and cold

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desert finds. These originated from perhaps as few as 40–50 source craters on the Moon (Basilevsky et al., 2010). Radiogenic isotope studies indicate that the majority of known lunar meteorites have been launched from the Moon in the last 10 Myr, and all have been launched in the last 20 Myr probably from small craters only a few kilometres or less in diameter (Warren, 1994; Head et al., 2002).

Remote sensing datasets provide information about the chemical and mineralogical diversity of the lunar surface (i.e., Lunar Prospector and the Kaguya gamma-ray spectrometer chemical data, Clementine, Chandrayaan-1 Moon Mineralogy Mapper, and the Kaguya Spectral Profiler spectral datasets). Although the spatial scales of these mapping efforts are often on the scale of hundreds of metres to tens of kilometre (depending on the method), many previous studies have used these datasets to test chemical and mineralogical similarities with lunar meteorite and infer potential source regions. For example, feldspathic lunar meteorites (i.e., samples with bulk rock FeO <7 wt%: Korotev et al., 2009) have been linked to origins in the highlands on the farside of the Moon (Palme et al., 1991; Korotev et al., 2003; Warren, 2005; Warren et al., 2005; Nyquist et al., 2006; Takeda et al., 2006; Arai et al., 2008; Yamaguchi et al., 2010; Joy et al., 2010a; Fritz, 2012). Basaltic meteorites (i.e., bulk rock FeO >17 wt%) have been linked to different mare basalt lava flow units predominantly on the nearside of the Moon (Joy et al., 2008; Fernandes et al., 2009; Arai et al., 2010; Robinson et al., 2012). Meteorites of intermediate-Fe composition (i.e., with bulk compositions between 7 and 17 FeO wt%) and with high concentrations of thorium (>2 ppm) and other incompatible trace elements (ITEs) have previously been linked with high-Th regoliths on the nearside of the Moon in the Procellarum KREEP Terrane (Gnos et al., 2004; Joy et al., 2011a), and tentatively with the South Pole-Aitken (SPA) impact basin on the farside of the Moon (Hill and Boynton, 2003; Korotev et al., 2007; Mercer et al., 2013).

Lunar meteorites Dhofar (Dho) 925 and 961 and Sayh al Uhaymir (SaU) 449 are breccias of intermediate-Fe composition (Demidova et al., 2005, 2007; Korotev et al., 2009; Korotev, 2012). Henceforth, this group of stones will be collectively referred to here as the Dhofar group. They were collected in Oman and are thought to have originated in the same meteorite fall, and are also grouped with the Dho 960 stone (Demidova et al., 2005, 2007; Korotev et al., 2010; Korotev, 2012). All stones are formally classified as impact melt breccias (Russell et al., 2004, 2005; Connolly et al., 2007). The meteorites have elevated concentrations of Th (1–3 ppm: Table 1) compared with many other intermediate-Fe brecciated lunar meteorites, indicating inclusion of an ITE-rich component. Previous studies of Dho 961 (e.g., Jolliff et al., 2007, 2008, 2009; Korotev et al., 2007, 2009, 2010; Zeigler et al., 2010a, 2010b, 2013) report that the bulk rock composition is not consistent with Apollo samples sourced from the Procellarum KREEP Terrane. Zeigler et al. (2013 and Refs. therein) argue that the meteorite may have originated from the South Pole-Aitken basin, which is the other notable Th-rich (i.e., ITE-rich) region of the Moon (Jolliff, 1998).

Here we report the composition, mineralogy and chronology of the Dhofar group of meteorites to investigate their geological history, and test the hypothesis that the samples represent South Pole-Aitken basin material. A launch locality in SPA would be significant, as geological samples from this massive impact basin are expected to hold the answer to several key lunar science questions (NRC, 2007; Jolliff et al., 2010) including: (i) the age of the basin, which is believed to be the largest and one of the oldest impact basins on the Moon (Wilhelms et al., 1987; Spudis, 1993). Defining its age will help to constrain the early lunar bombardment record, which may help to anchor the early Earth-Moon impact flux chronology (NRC, 2007; Norman, 2009); (ii) determine the extent and nature of products of the Moon's differentiation by studying igneous rock samples from the lunar farside (e.g., Arai et al., 2008; Ohtake et al., 2012; Gross et al., 2014); (iii) characterise products of impact melt sheet differentiation (e.g., Vaughan et al., 2012; Vaughan and Head, 2014; Hurwitz and Kring, 2014); (iv) determine the composition and timing of farside mare volcanism to shed light on the magmatic history of the Moon (e.g., Hagerty et al., 2011); (v) directly sample lunar mantle material, which may have been excavated during the SPA basin-forming event (Pieters et al., 1997; Yamamoto et al., 2010; Potter et al., 2012), helping to characterise the stratification of the mantle and address models of lunar differentiation and evolution (Elardo et al., 2011; Elkins-Tanton et al., 2011).

2. SAMPLES AND METHOD

We obtained three authenticated meteorite chips (EA1.1 to EA1.3) of Dho 925 (0.136 g), Dho 961 (0.331 g) and SaU 449 (0.764 g). Two 100 μm thick sections (named Dho 925,1, Dho 925,2 and Dho 961,1 and Dho 961,2) and a 30 μm thin section (named Dho 925,3 and Dho 961,3) were prepared from each of the Dho 925 and 961 stones using Buehler Epo-Thin resin. The SaU 449 sample was split into two chips, and the larger portion (0.535 g) was prepared as two 100 μm thick sections (named SaU 449,2 and SaU 449,3) and a 30 μm thin section (named SaU 449,1) using Buehler Epo-Thin resin. Water was not used during the section making process. The samples were studied and photographed using an optical Leica M205C microscope with a Leica DFC 490 camera at NASA Johnson Space Center (JSC).

The Dho 925,1, Dho 961,1 and SaU 449,3 sections (Fig. 1, EA1.1–EA1.3) were all analysed in further detail for mineral chemistry by electron microprobe. Sections Dho 925,1 and Dho 961,1 were also analysed for trace element composition using *in situ* laser ablation inductively coupled mass spectrometry (LA-ICP-MS). U–Pb chronology by ion microprobe was conducted on Dho 961,1.

2.1. Petrography and mineral chemistry methodology

The sections were carbon coated and mapped using the NASA JSC JEOL 7600f Field Emission Gun Scanning Electron Microscope (FEG-SEM) with a beam current of 20 to 30 nA and an accelerating voltage of 15 kV. The SEM has a faraday cup, so we can set the sample current