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Basalt



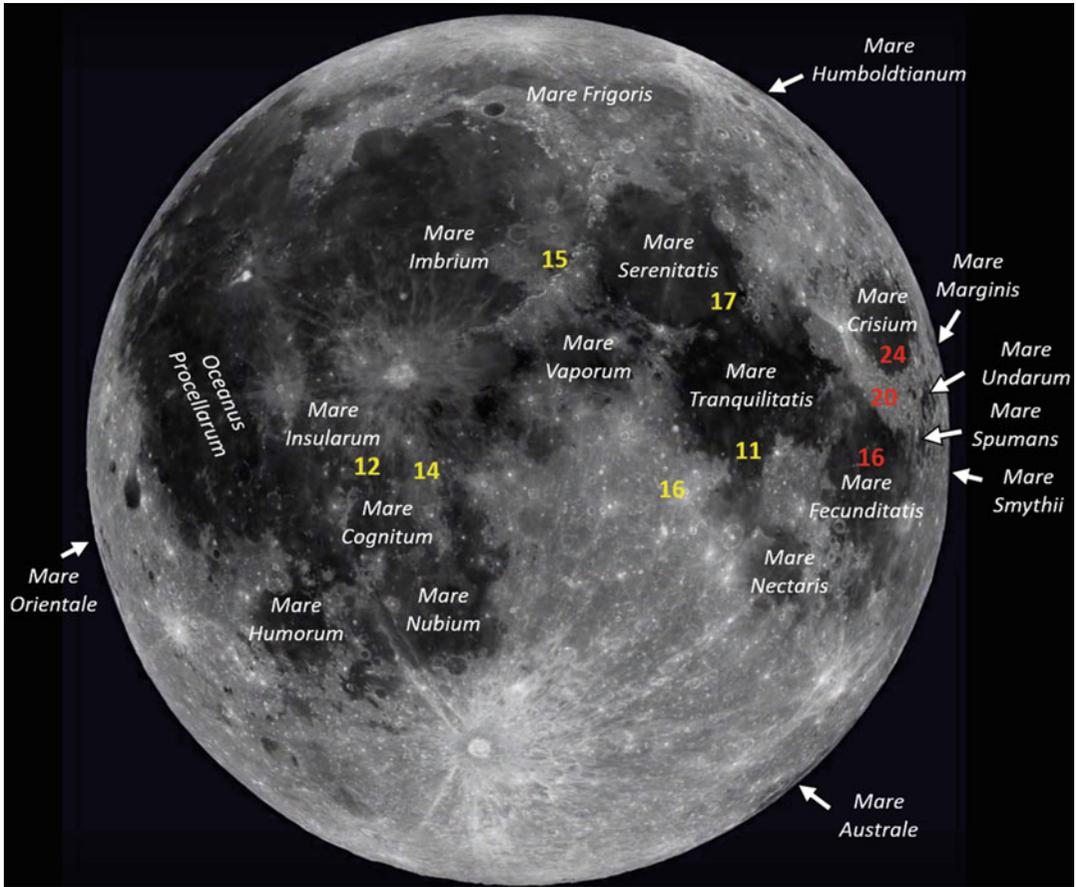
Aleksandra J. Gawronska and Claire L. McLeod
Department of Geology & Environmental Earth
Science, Miami University, Oxford, OH, USA

Introduction

Basalt is the fine-grained, mafic igneous rock produced as a result of extrusive basaltic magmatism, one of the fundamental processes that shape the interiors and surfaces of differentiated planetary bodies. Mineralogically, basalt is characterized by relatively high proportions of olivine, pyroxene, and calcic plagioclase feldspar, the crystallization of which produces volcanic products with overall low SiO₂ (<52 wt. %), low alkali (typically <5 wt. % Na₂O + K₂O), high MgO (often >5 wt. %), and high CaO (up to ~10 wt. %) contents. Basaltic lavas are often emplaced during effusive eruptions and form outflows that can be broadly characterized as either ‘a’ā or pāhoehoe (BVSP 1981; Self et al. 1998; Wilson 2009). On the Moon, basaltic outflows collectively cover ~17% of the lunar surface (see Fig. 1; Head 1976; for more information, the reader is referred to Ma 2018). Many of the basaltic units observed on the lunar surface are confined to the lunar near side, where they form great outflows termed mare (plural maria) from the Latin word for “sea.” Questions remain regarding the exact reason for the lower abundance of basalts on the lunar far

side (e.g., Jolliff et al. 2000; Shearer et al. 2006). Potential explanations for this dichotomy include the observation that the crust on the lunar far side is thicker and may have trapped melt at rheological boundaries, precluding it from erupting (e.g., Wieczorek et al. 2006; Wilson and Head 2017), or that the near side mantle was heterogeneously heated by a concentration of heat-producing elements (i.e., within the Procellarum KREEP Terrane, Jolliff et al. 2000).

Primary basaltic magmas are produced through partial melting of planetary mantles and can thus provide insights into the characteristics of planetary interiors (e.g., Papike et al. 1976, 1991; Neal 2001; Shearer et al. 2006; Taylor et al. 2006; Hallis et al. 2010, 2014; Ogawa 2018). As products of partial melting, the compositions of lunar basalts specifically have been utilized as probes of not only the chemical make-up of the lunar interior, but also as a window into differentiation processes occurring during and after the solidification of a lunar magma ocean (LMO; e.g., Taylor 1982; Snyder et al. 2000; Taylor et al. 2006; Wieczorek et al. 2006; Grove and Krawczynski 2009; Hallis et al. 2014). During the final stages of LMO solidification, relatively incompatible elements became concentrated in a geochemical reservoir enriched in potassium (K), rare earth elements (REEs), and phosphorus (P). This reservoir, referred to as urKREEP (Warren and Wasson 1979; Shearer et al. 2006), has yet to be sampled directly but has been shown to influence the geochemical compositions of some of the mare

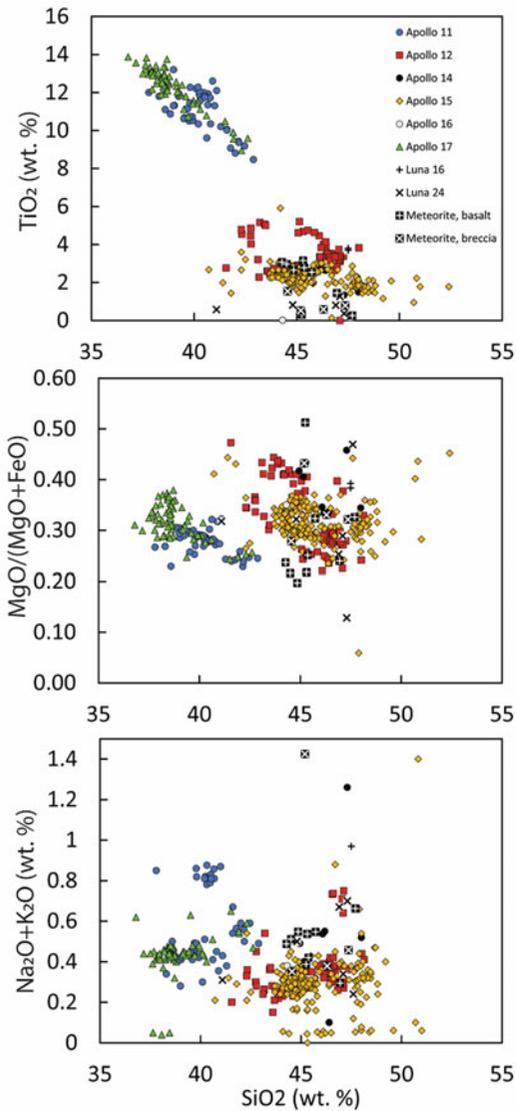


Basalt, Fig. 1 Map of the lunar near side showing locations of lunar maria. Not shown: Mare Ingenii and Mare Moscoviense, which reside on the lunar far side. Locations of missions which returned materials from the lunar surface

are numbered in yellow for the Apollo missions, and in red for the Luna missions. Original image from NASA Goddard Space Flight Center; Arizona State University

basalts emplaced on the lunar surface. Basaltic partial melts generated either at depth or over a range of depths (Wieczorek et al. 2006; Wilson and Head 2017) within the lunar mantle likely rose as molten diapirs and may have reached rheological traps where they crystallized and differentiated prior to eruption (e.g., Wilson and Head 2017). This resulted in a range of bulk geochemical compositions throughout the erupted mare basalt suite (e.g., Fig. 2) which ultimately reflect compositional variations associated with lunar mantle source regions, the degree of partial melting, potentially variable assimilation of crustal and KREEPy material during ascent, and accompanying crystal fractionation and accumulation (Snyder et al. 1992; Shearer et al. 2006;

Wieczorek et al. 2006; Grove and Krawczynski 2009; Hallis et al. 2014). Considering the entirety of the lunar interior, the mare basalts may only have been derived from the upper 20% of the LMO cumulate pile (Snyder et al. 1992; Münker 2010) leaving the majority of the lunar interior as an untapped, unmelted reservoir left over from primary LMO differentiation. The reader is referred to the relevant LMO chapters in this encyclopedia for specific discussions of LMO processes.



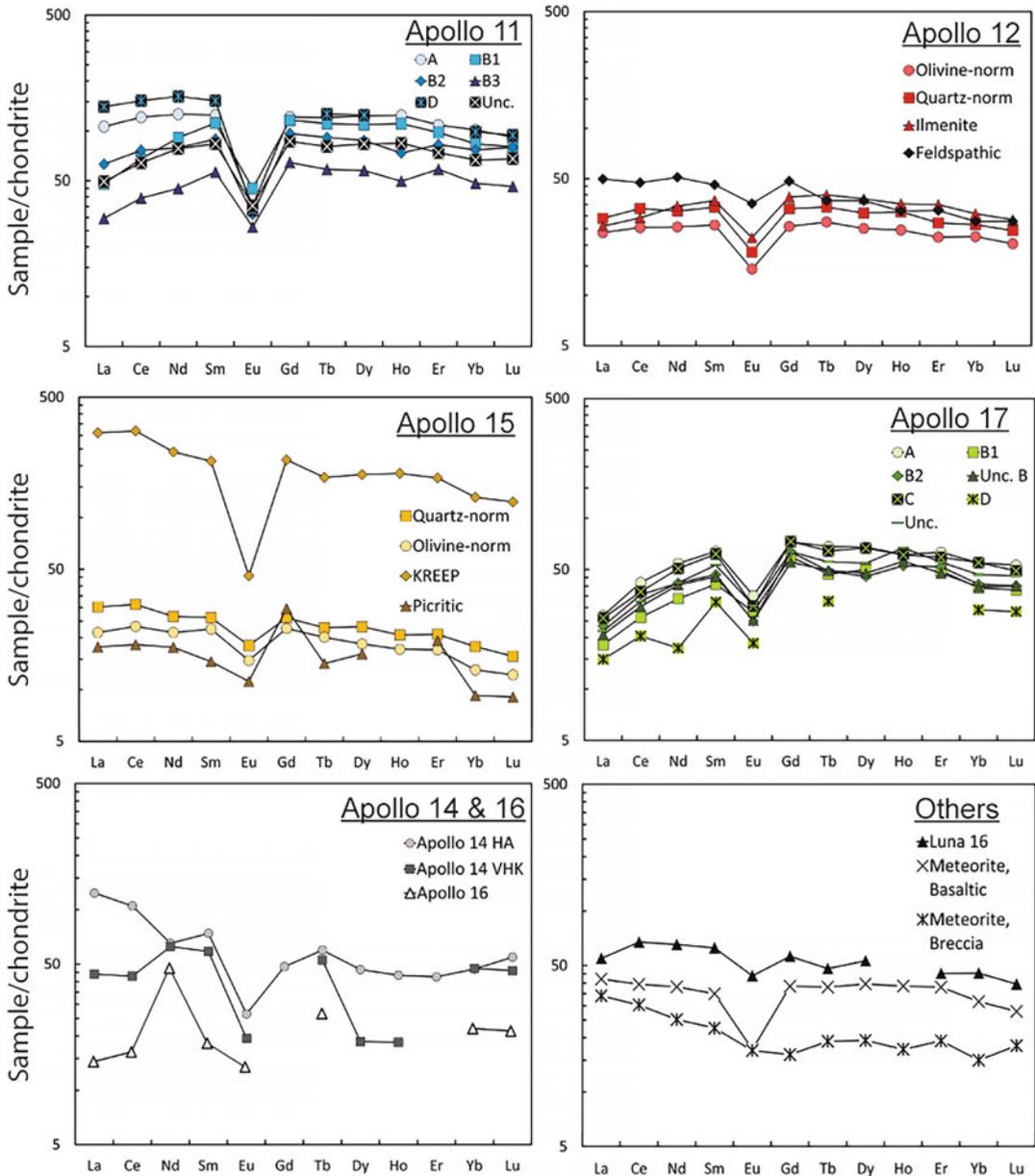
Basalt, Fig. 2 Plots depicting the whole rock major element oxide compositions of various lunar basaltic samples. Original published data was downloaded from the Astromaterials Data System data repository (AstroMat; www.astromat.org) using the “whole rock” criterion for Apollo and Luna missions, and “whole rock” and “clast” criteria for meteorites. Note that the ratio plotted in the middle graph was calculated from values in wt. %

Sample Studies

In the late 1960s and early 1970s, the geographically constrained Apollo and Luna sampling missions (Fig. 1) returned 382 kg and 321 g, respectively, of lunar material. Collectively, the

lunar basaltic samples record a bimodal distribution of bulk wt. % TiO_2 contents (Fig. 2); hence, TiO_2 content is often utilized as a geochemical parameter for evaluating the petrogenesis of sampled lunar basalts (e.g., Neal and Taylor 1992; Papike et al. 1998; Shearer et al. 2006; Münker 2010). Due to the range in TiO_2 contents, lunar basaltic samples are traditionally described as either having very low Ti (VLT; <1 wt. % TiO_2), low-Ti (1–6 wt. % TiO_2), or high-Ti content (>6 wt. % TiO_2) (e.g., Neal and Taylor 1992; Papike et al. 1998). Describing a sample with 6 wt. % TiO_2 as “low-Ti,” is arguably a little misleading; hence, it is recognized here that the nomenclature reported in Le Bas (2001) in which samples are referred to as Ti-poor, medium-Ti, and Ti-rich, respectively, may be more appropriate. Nonetheless, the traditional nomenclature will continue to be used here. Samples returned through the Apollo 12 and 15, and Luna 16 and 24 missions fit largely into either the VLT or low-Ti bracket while the Apollo 11 and 17 missions largely define the high-Ti group (Fig. 2). While Apollo 14 and 16 samples did not land in mare regions, basaltic material from both of these suites is generally low-Ti.

The mare basalts are generally depleted in both the alkalis (e.g., Cs, Rb, K) and volatiles (e.g., S, Cl, CO) relative to terrestrial basalts (Shearer et al. 2006; Wiczorek et al. 2006). With respect to other broad chemical signatures, the lunar mare basalts are collectively observed to be depleted in Eu relative to the ferroan anorthosites (Fig. 3), indicating extensive prior fractionation of plagioclase and consistent with the early establishment of the anorthositic lunar crust (Taylor 1982; Neal 2001; Shearer et al. 2006). Sampled pristine mare basalts also generally contain low concentrations of incompatible trace elements (ITEs) relative to the KREEP materials (e.g., Shearer et al. 2006; Wiczorek et al. 2006), consistent with derivation from a lunar mantle source also depleted in these elements. This source is likely residual lunar mantle olivine and pyroxene cumulates (Papike et al. 1976; Longhi 1992; Neal and Taylor 1992; Neal 2001; Shearer et al. 2006; Grove and Krawczynski 2009; Münker 2010). For detailed information regarding the isotopic contents of



Basalt, Fig. 3 Plots depicting the average whole rock REE spidergrams of lunar basaltic sample groups normalized to chondrite. Original published data was downloaded from the Astromaterials Data System data repository (AstroMat; www.astromat.org) using the “whole rock” criterion for Apollo and Luna missions, and “whole rock”

lunar basaltic samples, see Shearer et al. (2006) and Warren and Taylor (2014).

and “clast” for meteorites. Data was then separated into sample groups as defined by previous authors (e.g., Ryder 1985, 1990; Neal et al. 1990, 1994; Jerde et al. 1994; Neal and Kramer 2006; Robinson et al. 2012; Roberts and Neal 2019). Apollo 17 Unc. group indicates basalts collected during this mission that have not been categorized

Basaltic Samples Collected through the Apollo Missions

Based on chronology and elemental abundances, the Apollo 11 and Apollo 17 basalts can be

broadly considered as older (3.85 to 3.7 Ga), high-Ti (8 to 14 wt. % TiO_2) representatives of lunar basaltic magmatism (Papike et al. 1976; Jerde et al. 1994; Snyder et al. 2000; Snape et al. 2019). Both the Apollo 11 and 17 suites are characteristically light REE-depleted relative to the heavy REEs (Fig. 3; BVSP 1981; Papike et al. 1998; Shearer et al. 2006; Wieczorek et al. 2006). Both suites also have generally non-chondritic high field strength element (HFSE) signatures, likely due to the addition of ilmenite cumulates to previously chondritic source regions (Neal 2001; Wieczorek et al. 2006). Specifically, the Apollo 11 basalts were collected in southern Mare Tranquilitatis (Fig. 1). The Apollo 11 basalts have been categorized into six groups based on compositions and textures, as outlined by Jerde et al. (1994). Although all groups are high in TiO_2 (>6 wt. %; Fig. 2), Apollo 11 group A basalts are additionally enriched in K and the REEs, and have been used to support the existence of a KREEP-rich layer at depth within the lunar interior (Jerde et al. 1994; Hallis et al. 2014). Most of the remaining Apollo 11 groups (B1, B2, B3) are depleted in REEs relative to group A (Fig. 3). Meanwhile, Apollo 17 basaltic samples were collected from lunar mare flows which seem to underlie the Taurus-Littrow Valley in south-east Mare Serenitatis (Fig. 1) and were at least partially exhumed through impact (Jolliff et al. 1996). Apollo 17 samples have been classified into groups based on two different schemes: texturally (types 1A, 1B, and 2) and compositionally (groups A, B, C, and potentially a D group, Ryder 1990); a detailed summary of the textural and geochemical classifications of these basalts is provided in Neal et al. (1990). Variation in bulk chemical compositions within each of the compositionally classified Apollo 17 groups can be explained by simple closed-system fractional crystallization (Neal et al. 1990), but the differences between these groups are more likely to be due to source region heterogeneities (Neal et al. 1990; Paces et al. 1991; Hallis et al. 2014). Paces et al. (1991) evaluated the chronology of the Apollo 17 basalts and concluded that while the eruptions which emplaced the Apollo 17 lavas onto the lunar surface may have occurred

contemporaneously, the primary basaltic magma was derived from sources which formed separately and at separate times. Such source heterogeneities could originate from contamination of the Apollo 17 source regions by a volatile-rich fluid (Paces et al. 1991; Hallis et al. 2014).

In contrast, the Apollo 12 and 15 basalts represent the younger (3.35 to 3.15 Ga), relatively low-Ti (<5.5 wt. % TiO_2) group of lunar basalts (Papike et al. 1976; Snyder et al. 2000; Snape et al. 2019). Collectively, the Apollo 12 and 15 basalts are compositionally similar (Papike et al. 1976; Neal and Taylor 1992; Shearer et al. 2006; Hallis et al. 2014). Both suites record HFSE values that indicate their source regions contained chondritic HFSE values (Neal 2001; Wieczorek et al. 2006). The Apollo 12 basalts were collected at the southern edge of Mare Insularum at the eastern flank of Oceanus Procellarum (Fig. 1). The Apollo 12 basalts have been classified into several groups (olivine-normative, quartz-normative, ilmenite, and feldspathic basalts; Neal et al. 1994), and are generally understood to have been produced during a relatively short-lived pulse of magmatism, over ~70,000 years from 3.22 to 3.15 Ga (Snyder et al. 2000; Hiesinger et al. 2011). A comprehensive overview of their petrogenesis is provided in Neal et al. (1994). Unlike Apollo 11 basalts, the observed geochemical range in the Apollo 12 suite cannot be generated through the variable involvement of a KREEP-like reservoir (e.g., Neal and Taylor 1992; Hallis et al. 2014). In addition, the separate groups of Apollo 12 basalts cannot be reconciled through fractional crystallization or accumulation. This suite of samples is therefore interpreted to be derived from physically separate, chemically distinct mantle sources (Neal et al. 1994). In this scenario, the compositional variety that exists within the sample groups can also be accounted for (e.g., Neal and Taylor 1992; Neal et al. 1994; Hallis et al. 2014). The Apollo 15 mission landed near Hadley Rille, at the base of the Apennine Mountain front in eastern Mare Imbrium (Fig. 1), and returned a diverse suite of basaltic samples. The mare basalts found here are primarily grouped into olivine-normative and quartz-normative (or pigeonite) groups (e.g., Ryder

1985), but additional samples include highly enriched KREEP basalts and depleted picritic basalts. Bulk rock geochemical analyses of Apollo 15 samples indicate that the basaltic magmas which produced this suite of basalts were likely generated by partial melting of separate, distinct mantle sources with common major phase compositions (Neal and Taylor 1992; Hallis et al. 2014). Compositional variation within the olivine- and quartz-normative suites may be due to either unrepresentative sampling or fractional crystallization of olivine for the olivine-normative basalts and pigeonite for the quartz-normative basalts (e.g., Neal and Taylor 1992; Ryder and Schuraytz 2001).

While the Apollo 14 and 16 missions did not specifically land in mare terrain, basaltic materials were still returned through both missions. The Apollo 14 mission sampled the Fra Mauro formation (Fig. 1) and collected a number of basaltic breccias. Since collection, these have been categorized as either high alumina (HA) or very high potassium (VHK) basalts. The HA basalts are 4.3 to 3.9 Ga (see summary in Neal and Kramer 2006), while the VHKs are approximately 3.95 to 3.85 Ga (see summary in Roberts and Neal 2019). The generation of the compositional variety in the HA basalt suite requires fluctuating degrees of assimilation of materials with varying compositions. The most likely assimilant is some mixture of KREEP-rich quartz monzogabbros and granites found at the Apollo 14 site (Neal and Kramer 2006; Hui et al. 2011). Regolith may also have been incorporated as the lava flowed on the lunar surface (Hui et al. 2011). Meanwhile, a comprehensive overview of VHK petrogenesis can be found in Roberts and Neal (2019). Roberts and Neal (2019) concluded that two groups of VHKs exist: one produced endogenously, the other exogenously. The endogenous VHK basalts likely formed when HA melt assimilated granitic material, while the exogenous group formed during impact, where a melt sheet covered HA basalts mixed in with granitic clasts. This caused partial melting and variable assimilation of K-rich material by HA basalts (e.g., Neal et al. 1989; Roberts and Neal 2019). The Apollo 16 mission traveled to anorthositic terrain near the crater Descartes,

but did return mare basalt chips that were likely deposited there as ejecta. Basaltic clasts identified are both high- and low-Ti and may be traced back to nearby maria (e.g., Zeigler et al. 2006, and references therein).

Basaltic Samples Collected through the Luna Missions

While the six Apollo missions sampled the lunar surface through crewed missions, the Soviet Luna missions utilized robotic landers to return cores of material to Earth, summarized in Robinson et al. (2012) and in Stooke (2017). Of the three Luna sample return missions, two landed within the basaltic maria: Luna 16 which sampled Mare Fecunditatis, and Luna 24 which sampled Mare Crisium (Fig. 1). The third mission, Luna 20, sampled the lunar highlands between these two sites and returned samples similar to the anorthositic material collected during Apollo 16. Material sampled by Luna 16 is approximately 3.4 Ga (Stöffler et al. 2006), generally VLT to low-Ti (~5 wt. %), and high in Al_2O_3 (~13 to 14 wt. %, Robinson et al. 2012, and references therein). The Mare Crisium core sampled by Luna 24 is similar in age at approximately 3.6 to 3.22 Ga (Robinson et al. 2012, and references therein). Luna 24 samples are neither high in Al_2O_3 nor TiO_2 , with TiO_2 contents at <1 wt. % (Stöffler et al. 2006; Robinson et al. 2012, and references therein). Basalts with <1 wt. % TiO_2 have been sampled only at the Luna 24 and Apollo 17 sites, although they are comparatively not as abundant at the Apollo 17 site (Robinson et al. 2012).

Lunar Basaltic Meteorites

While the crewed missions to the surface of the Moon provide spatially constrained insights into the nature of basaltic magmatism, returned samples are limited to regions at and/or near the selected landing sites. Meanwhile, basaltic lunar meteorites collected on Earth have the potential to provide additional information regarding magmatic units not sampled in situ. For example, lunar basaltic meteorites have provided additional constraints regarding the timing of volcanism on the Moon – basaltic clasts from many lunar meteorites have yielded ages as old as 4.4 Ga to as

young as 1 Ga (Korotev 2005, and references therein). This age range is currently not represented by the basaltic suite returned by crewed exploration of the lunar surface. Compositionally, the meteorite suite provides a more extensive sampling of the lunar surface because the meteorites have arrived from many locations on the lunar surface. For more information, see Korotev (2005) and Zhou (2017).

Remote Sensing

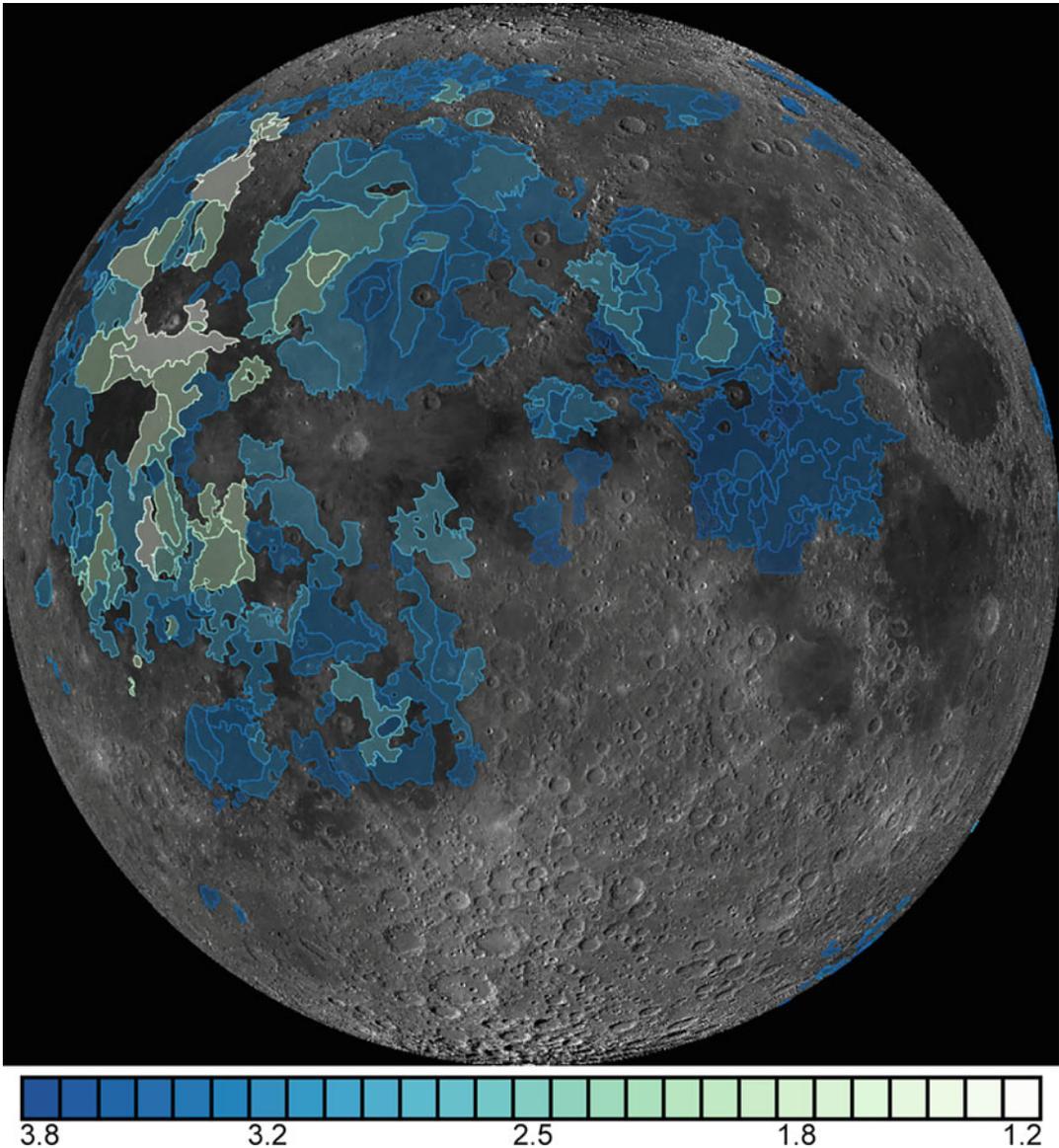
Returned and meteoritic samples provide critical groundtruthing to remote studies (e.g., Gillis et al. 2004). However, it is worth noting that while the basaltic materials within the lunar sample collection continue to provide new insights on the nature of magmatism on extraterrestrial planetary objects, this sample suite may be quite limited within the context of capturing the true diversity of lunar basaltic magmatism (e.g., Neal and Taylor 1992; Taylor et al. 2006). Remote sensing data has allowed further characterization of all maria through missions such as the Lunar Prospector, Clementine, (e.g., Gillis et al. 2004), and the Selenological and Engineering Explorer (SELENE/Kaguya; e.g., Oshigami et al. 2014). For more information, see the relevant mission chapters in this volume. Through remote sensing analyses, it is understood that the global distribution of TiO₂ content is unimodal and continuous, with a mean of 3 wt. % TiO₂ (Giguere et al. 2000; Gillis et al. 2003, 2004; Shearer et al. 2006). Specifically, Gillis et al. (2003) found mare regions that supplement the gap in TiO₂ composition that exists in the returned sample suite between ~6 wt. % and ~9.5 wt. % (see Fig. 2; Neal and Taylor 1992; Giguere et al. 2000). Distribution of Th and K elemental abundances, two elements associated with KREEP, are similarly unimodal (Gillis et al. 2004). FeO has also been mapped extensively and shows elevated concentrations spatially correlated to regions dominated by mare basalts (e.g., Gillis et al. 2003; Naito et al. 2018).

Regarding the ages and chronology of basaltic units, the returned sample suite is also not

representative of the complete history of volcanism on the Moon. For example, crater size-frequency distribution calculations have allowed for the estimation of ages for individual basaltic units across the lunar surface. From this, lunar volcanism likely lasted for more than ~3 Ga, from at least 4.0 Ga to 1.0 Ga (Fig. 4; Hiesinger et al. 2011; Oshigami et al. 2014). However, as described above, the HA samples record ages up to 4.3 Ga indicating that basaltic volcanism was likely occurring even earlier in lunar history, and that the resulting basalts were later obscured by impact. Such obscured mare basalt units are referred to as cryptomaria (e.g., Whitten and Head 2015). Based on both sample-based and remote sensing studies, the majority of volcanic activity occurred early in the Moon's history, with the greatest volume likely being erupted between 3.7 and 3.3 Ga (Hiesinger et al. 2011). At this point in lunar history, volcanic activity may have been voluminous enough to briefly produce a transient atmosphere (Needham and Kring 2017).

Conclusions

Overall, investigations of lunar basalts on both the micro and macro scale have provided critical information regarding the evolution and differentiation of the Moon (Head 1976; Papike et al. 1976; BVSP 1981; Haskin and Warren 1991; Papike et al. 1991; Neal and Taylor 1992; Giguere et al. 2000; Shearer et al. 2006; Hallis et al. 2014). Specifically, the distinct bulk wt. % TiO₂ contents of basalts from the Apollo 11 and 17 suites, and those from the Apollo 12 and 15 suites, are inferred to have resulted from the variable presence of Fe-Ti oxides (such as ilmenite and armalcolite) in the lunar mantle source regions. Where present, these oxides are modelled to have been involved in LMO density-driven overturn, where olivine and pyroxene cumulates rose diapirically and variably incorporated oxides. Many of the diapirs likely remained at rheological traps, but partial melts of these regions propagated via dikes to produce the basaltic mare outflows (e.g., Shearer et al. 2006; Wilson and Head 2017). This implies that the lunar mantle is laterally (and



Basalt, Fig. 4 Figure depicting the approximate ages of mare units in billions of years (Ga) overlain on an image of the lunar near side (image credit: NASA Goddard Space Flight Center; Arizona State University). Figure adapted

from LROC *Quickmap* (<https://quickmap.lroc.asu.edu>); data originally from Hiesinger et al. (2011). See Hiesinger et al. (2011) and references therein for a description of the individual units

vertically) mineralogically heterogeneous (Grove and Krawczynski 2009; Hallis et al. 2010, 2014; see also the lunar mantle chapters in this volume). This variability could also account for the differences observed in bulk major and trace element signatures observed throughout the lunar sample suite (Papike et al. 1998; Münker 2010). The ages and bulk geochemical compositions of lunar

basalts imply that magmatism and the resulting volcanism began in shallow cumulate-dominated source regions which experienced greater interaction with ilmenite during mantle overturn (represented by the Apollo 11 and 17 samples; Snyder et al. 1992; Hallis et al. 2010; Münker 2010). The younger basaltic magmas are interpreted to be derived from deeper, ilmenite-

poor sources where mantle partial melting was still possible following advanced cooling of the lunar exterior (represented by Apollo 12 and 15 basalts; e.g., Snyder et al. 2000; Grove and Krawczynski 2009; Wilson and Head 2017). Further insights into the evolution of lunar basaltic magmas and the lunar mantle will be gained through continued analysis of already collected samples. Additional information necessary to comprehensively evaluate lunar magmatic processes could be attained via continued collection of basaltic meteorites and direct sampling of basaltic materials during future crewed and robotic missions, e.g., the continued Chang'e program and the future Artemis program. When combined with remote sensing, these sample-based programs will be invaluable to furthering our understanding of magmatic and volcanic processes across the Solar System.

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