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Investigation of mare basalts with the Lunar Reconnaissance Orbiter Camera (LROC)

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Introduction: Most lunar mare basalts occur on the lunar nearside within large impact structures, but a much smaller number is also present on the lunar farside [1]. Absolute radiometric age data are still not available for most of the lunar basalts. However, remote sensing techniques allow us to derive relative and absolute model ages for unsampled regions. For example, inspection and interpretation of the superposition of geologic units, including embayment and crosscutting relationships as seen with high-resolution Apollo and Lunar Orbiter images, were used to derive relative ages for lunar surface units [e.g., 2]. In addition, crater degradation stages and crater size-frequency distribution measurements, calibrated to the Apollo and Luna landing sites, are useful for the derivation of relative and absolute model ages [e.g., 3-14]. In previous papers, we reported on ages based on crater size-frequency distribution measurements [e.g., 11-14] for nearly all lunar nearside mare basalts. Those ages represent the most comprehensive data set on lunar mare basalt ages and provide important constraints for boundary conditions of the thermal and petrologic evolution of the Moon. In particular, our ages can be correlated with compositional data from Lunar Prospector and Clementine in order to study the mineralogical evolution of mare basalts with time. Also, in some cases, distinctive kinks in the cumulative crater size frequency distribution were used to estimate the thickness of lava flows [14,15]. These thicknesses allow us to estimate the flux of lunar mare basalts over time in order to constrain the thermal evolution of the Moon.

Scientific Questions: ***(1) Mare volcanism in space and time:*** Despite the undisputed scientific value of the returned samples from six Apollo and three Luna landing sites, these data are insufficient to completely explain the thermal evolution of the Moon. For example, based on samples alone, the onset and extent of mare volcanism are not well defined (summarized by [16]). Lunar samples studied in laboratories indicate that mare volcanism was active at least between ~3.9 and 3.1 b.y. [17,18]. Some basaltic clasts in older breccias point to an onset of mare volcanism prior to 3.9 b.y. [19], perhaps as early as 4.2–4.3 b.y. in the Apollo 14 region [16,20,21]. Such early volcanism is also supported by remote-sensing data of dark halo craters, which have been interpreted as impacts into older basaltic deposits now buried underneath a veneer of basin or crater ejecta [e.g., 22-24]. Therefore, these so-called cryptomare basalts might be among the oldest basalts on the Moon, implying that volcanism was active prior to ~3.9 b.y. ago. In addition, early volcanism is also supported by radiometric ages of the lunar meteorite Kalahari 009, which revealed that volcanism was already active at least 4.35 b.y. ago [25]. The crater degradation ages of Boyce [6] and Boyce and Johnson [26] indicate that volcanism might have begun at 3.85±0.05 b.y. and lasted until 2.5±0.5 b.y. ago. Support for such young basalt ages comes from a recently collected lunar meteorite, Northwest Africa 032, which shows an Ar-Ar whole rock age of ~2.8 b.y. [27]. Schultz and Spudis [8] made crater size-frequency distribution measurements for basalts embaying the Copernican crater Lichtenberg, and concluded that these basalts might be less than 1 b.y. old. On the basis of our crater counts we found that lunar volcanism on the nearside started at ~4 b.y. and ended at ~1.1 b.y. ago. Most of the investigated basalts on the lunar nearside erupted during the late Imbrian Period between ~3.3-3.8 b.y. and there is possibly a second period of enhanced volcanic activity at ~2.0-2.2 b.y. ago. Crater counts of about 15 basalt occurrences on the lunar

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farside also revealed a long-lived volcanic activity and ages of 3.85-2.44 b.y. [28].

(2) Mineralogical evolution of the Moon: The presence of basaltic deposits on planetary surfaces is indicative of the thermal activity and volcanic evolution of the body [29-32]. For our understanding of the geologic evolution of a planetary body, it is crucial to know when basaltic volcanism was active and how the mineralogy varied with time. Lunar basalts show a wide range in TiO_2 abundances, which allows us to separate different basalt types with both laboratory and remote sensing techniques. However, it is well known that not all basalt types are represented in the sample collection [31]. In the sample collection, three major groups of basalts can be identified: high-Ti (9-14 wt% TiO_2), low-Ti (1-5 wt% TiO_2), and very-low-Ti (< 1 wt% TiO_2) basalts. The samples show a distinctive bimodal distribution of titanium concentrations of basalts with peaks at ~2.5-3 and 12-13 wt% TiO_2. On the other hand, remote sensing data suggest that there is a continuous distribution from very low-Ti to high-Ti mare basalts [33]. On the basis of the returned samples, it has been suggested that early Ti-rich basalts flooded large regions in the eastern lunar hemisphere (Ap11, Ap17) in the early Imbrian Period (3.3-3.8 b.y.) [1]. These basalts were followed by widespread eruptions of less Ti-rich basalts of middle to late Imbrian age (Ap12, Ap15). Finally Ti-rich basalts, which have not been sampled so far, flooded parts of Mare Imbrium and Oceanus Procellarum in the early Eratosthenian Period (2.5-3.0 b.y.) [1]. If we combine our absolute model ages with mineralogical data from spacecraft (e.g., Clementine, Lunar Prospector), we can study possible relationships between mineralogy and age of basalts. Our investigation of lunar nearside basalts showed that there is no systematic relationship between the age and the Ti abundance of lunar basalts. On the basis of our investigation of ~220 basalt units in 9 different mare regions, we see that Ti-rich basalts were erupting simultaneously with Ti-poor basalts. We do not find any evidence that older basalts are systematically more Ti-rich than younger basalts.

(3) Flux and thermal evolution of the Moon: Understanding the flux of mare basalts is crucial for the investigation of the thermal evolution of the Moon. In order to derive the volumes and flux of erupted basalts, one has to know the thickness of individual flows. Previous work on basalt flow thicknesses relied on (1) shadow measurements in high-resolution images that were taken under low-sun conditions to enhance the subtle surface morphology of flow units [e.g., 34-36]; (2) in situ observations of basalts exposed at the walls of Hadley Rille at the Apollo 15 landing site [37], and (3) studies of chemical kinetic aspects of lava emplacement and cooling [38]. Neukum and Horn [39] demonstrated that lava flow processes could be identified by their characteristic effects on crater size-frequency distributions without the direct identification of individual flows in images. In fact, the emplacement of a young lava flow on top of an old flow preferentially destroys small craters and hence results in a characteristic deflection in the cumulative crater curve. The crater diameters at which these deflections occur can be used to calculate the thickness of the young flow. Once these diameters are derived, the flow unit height is estimated using the rim height/diameter relationship of [40]. On the basis of our measurements of the flow heights of ~70 mare units exposed within the nearside mare, we found an average thickness of ~30-60 m with a variation between 20 and 220 m. Combined with the size of our units, this yields flow volumes in the range of 30 to 7700 km^3, averaging 590-940 km^3 [14].

LROC: In June 2009, the Lunar Reconnaissance Orbiter will be launched to investigate the lunar surface in unprecedented detail [41]. On board the spacecraft are two narrow angle cameras (NAC) and a wide-angle camera (WAC), providing global coverage at about 100 m/pixel and coverage of large areas at spatial resolutions of less than 1 m/pixel. The illumination geometry was chosen in order to emphasize subtle morphologic details. Hence, the global WAC and the local/regional NAC data sets will be extremely valuable for crater counts, particularly on the farside. At the extremely high resolution of the LROC NAC, we will be able to derive reliable crater counts for much smaller areas compared to crater size-frequency measurements on 50-100 m resolution Lunar Orbiter images. We have specified more

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than 1800 targets covering mare basalts in scientifically interesting locations for investigation with LROC. Our targets were selected based on the count areas of our previous papers [11-14], which represent spectrally homogeneous areas. Within each of those old larger areas, we now specified several subunits that can realistically be covered with LROC NAC images. We particularly endeavor to avoid secondary craters, wrinkle ridges, ejecta blankets, etc., that could influence our crater counts. Because mare basalts are flat-lying and exhibit few morphologic features, we rarely request the acquisition of geometric or photometric stereo images. In order to make full use of the high-resolution capabilities of the NAC to measure small craters, binning of the data should only be applied if absolutely necessary.

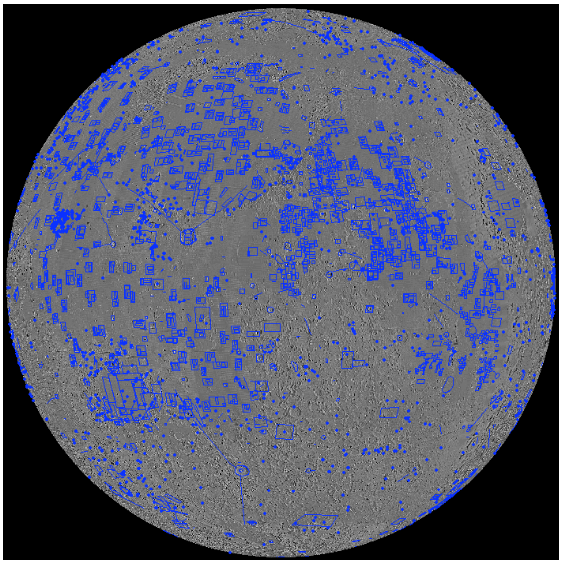

Fig. 1. The lunar nearside with potential targets, including numerous mare basalts, for LROC.

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