The distribution and purity of anorthosite across the Orientale basin: New perspectives from Moon Mineralogy Mapper data

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[1] The Orientale basin is a multiring impact structure on the western limb of the Moon that provides a clear view of the primary lunar crust exposed during basin formation. Previously, near-infrared reflectance spectra suggested that Orientale’s Inner Rook Ring (IRR) is very poor in mafic minerals and may represent anorthosite excavated from the Moon’s upper crust. However, detailed assessment of the mineralogy of these anorthosites was prohibited because the available spectroscopic data sets did not identify the diagnostic plagioclase absorption feature near 1250 nm. Recently, however, this absorption has been identified in several spectroscopic data sets, including the Moon Mineralogy Mapper (M3), enabling the unique identification of a plagioclase-dominated lithology at Orientale for the first time. Here we present the first in-depth characterization of the Orientale anorthosites based on direct measurement of their plagioclase component. In addition, detailed geologic context of the exposures is discussed based on analysis of Lunar Reconnaissance Orbiter Narrow Angle Camera images for selected anorthosite identifications. The results confirm that anorthosite is overwhelmingly concentrated in the IRR. Comparison with nonlinear spectral mixing models suggests that the anorthosite is exceedingly pure, containing >95 vol % plagioclase in most areas and commonly ~99–100 vol %. These new data place important constraints on magma ocean crystallization scenarios, which must produce a zone of highly pure anorthosite spanning the entire lateral extent of the 430 km diameter IRR.


1. Introduction

[2] The Orientale basin, on the western limb of the Moon, is the youngest and most well-preserved multiring impact structure on the lunar surface [e.g., Hartmann and Kuiper, 1962; Head, 1974, 1977, 2012; Howard et al., 1974; Moore et al., 1974; McCauley, 1977; Scott et al., 1977; Croft, 1981; Wilhelms et al., 1987; Spudis, 1993]. Lunar Orbiter Laser Altimeter (LOLA) topography of the basin, shown in Figure 1, reveals three prominent concentric rings associated with Orientale: (1) the ~930 km diameter Cordillera Ring, (2) the ~620 km diameter Outer Rook Ring (ORR), and (3) the ~430 km diameter Inner Rook Ring (IRR). The Cordillera Ring forms an inward facing relatively continuous scarp, while the ORR forms a continuous to discontinuous set of inward facing massifs and scarp mantled by the Montes Rook Formation. The IRR consists of isolated massifs and clusters of massifs, similar in morphology to central peaks in complex craters and to rings and clusters of peaks in peak-ring basins [e.g., Baker et al., 2011, 2012a]. The IRR are draped and surrounded by the Maunud Formation, interpreted to be impact melt deposits.

[3] The excellent morphological preservation of the Orientale basin rings offers a clear window into the composition of the highland crust that was exposed during basin formation [e.g., Head et al., 2010a]. Lunar magma ocean (LMO) models predict an extensive zone of anorthosite, a rock type consisting of ~90 vol % plagioclase [Stöffler et al., 1980], in the Moon’s upper crust [e.g., Smith et al., 1970; Wood et al., 1970; Herbert et al., 1977; Longhi, 1977; Warren and Wasson, 1980; Warren, 1985, 1990; Snyder et al., 1992; Elkins-Tanton et al., 2011]. As primary crystallization products of the LMO, anorthosites hold key information regarding magma ocean composition and crystallization history (see Shearer et al. [2006] for a recent synthesis). However, early basin-forming impacts along with continued bombardment from smaller bodies [e.g., Wilhelms et al., 1987; Head et al., 2010b; Fassett et al., 2012] produced a compositionally mixed “megaregolith” layer several kilometers thick across the Moon’s surface [e.g., McGetchin et al., 1973; Hartmann, 1980; Hörr et al., 1991; Hawke et al., 2003; Petro and Pieters, 2008]. This mixed layer of impact
ejecta obscures the anorthosites, as well as other ancient crustal lithologies such as the Mg-suite, from view by remote instruments. Exposures of igneous crustal materials are therefore mostly limited to the uplifted central peaks and peak rings of craters and basins that excavated primary crustal material from below the megaregolith [e.g., Tompkins and Pieters, 1999; Matsunaga et al., 2008; Cahill et al., 2009].

Numerous studies, discussed below, have noted the presence of anorthosite in the Orientale basin rings, particularly the IRR. The work described here represents the first dedicated analysis of the Orientale anorthosites that is based solely on exposures displaying the diagnostic plagioclase absorption feature, centered near 1250 nm. To distinguish these exposures from the bright, spectrally featureless materials discussed in previous studies, we refer to the present identifications as “crystalline anorthosite.” Our specific goals are (1) to map the distribution of discrete crystalline anorthosite exposures throughout the Orientale basin, as indicated by the presence of a 1250 nm absorption in Moon Mineralogy Mapper (M3) spectra, and (2) to estimate the “purity,” or plagioclase abundance, of the various anorthosite exposures by comparing the relative strengths of the plagioclase and mafic mineral absorptions in M3 spectra.

2. Background

2.1. Indirect Spectral Evidence for Anorthosite

Spectral evidence for anorthosite in large craters and basins, including Orientale, has been documented previously using Earth-based telescopic data, the Clementine UVVIS camera, and the Galileo solid-state imager [e.g., Spudis et al., 1984, 1989; Pieters, 1986; Hawke et al., 1991, 2003; Head et al., 1993; Pieters et al., 1993; Bussey and Spudis, 1997, 2000]. Importantly, these instruments did not readily detect the diagnostic plagioclase absorption feature near 1250 nm, which would uniquely identify plagioclase or a plagioclase-dominated lithology. Instead, they identified areas that were consistent with anorthosite based on spectra that exhibited other characteristics of plagioclase-dominated rocks, namely, (1) a high albedo and (2) a lack of mafic mineral absorptions, indicating low modal proportions of olivine and pyroxene. The interpretation that these bright, mafic-poor regions were rich in plagioclase was supported by lower resolution orbital geochemical data, which noted high aluminum and low iron abundances in similar highland...
areas covered by the Apollo 15 and 16 spacecraft [e.g., Adler et al., 1972a, 1972b; Spudis and Davis, 1986].

Within the Orientale basin, evidence for anorthosite was found primarily in the IRR; other units in the basin appeared to have higher proportions of mafic minerals [e.g., Spudis et al., 1984; Bussey and Spudis, 2000]. The distribution of these bright, spectrally featureless materials are shown in M3 data for Orientale in Figures 2 and 3. In particular, Figure 2 demonstrates that the brightest pixels in the Orientale region, those with the highest reflectance values at 1489 nm, are concentrated in basin rings. Variations in the 1000 nm absorption strength, which is related to the abundance of mafic minerals, predominately pyroxene, is illustrated in Figure 3. The most feldspathic, mafic-poor materials (dark in Figure 3) are clearly located in the nonmare portions of the basin interior. Upon closer inspection, the areas with the lowest proportion of mafic minerals in the scene correspond to the massifs of the IRR. The observation that different rings of the basin may have exposed different crustal lithologies makes Orientale a compelling laboratory for studying the distribution of primary products of the lunar magma ocean within the Moon’s crust.

2.2. The Diagnostic Plagioclase Absorption

[7] Anorthosites, which are dominated by a single mineral, should be easily identifiable on the lunar surface by near-infrared (NIR) spectrometers because plagioclase has a diagnostic crystal field absorption near 1250 nm. This absorption is caused by electronic transitions in Fe$^{2+}$ cations substituting for Ca$^{2+}$ in an irregular eightfold to 12-fold site [e.g., Conel and Nash, 1970; Bell and Mao, 1973; Adams and Goullaud, 1978]. Figure 4 illustrates the ~1250 nm absorption in example plagioclase spectra. Only trace amounts of FeO (~0.1 wt%) in the crystal structure are necessary to generate the plagioclase absorption.

[8] The plagioclase absorption is easily distinguished from the diagnostic ferrous absorptions of common lunar mafic minerals. For example, pyroxene absorptions occur near 1000 and 2000 nm [e.g., Hazen et al., 1978; Cloutis and Gaffey, 1991; Klima et al., 2007, 2011], whereas olivines typically display a composite absorption centered near 1050 nm [e.g., Burns, 1970, 1993; Hazen et al., 1977]. Importantly, the relatively low concentration of iron in plagioclase coupled to the transparent nature of the mineral causes the 1250 nm absorption feature to appear very weak in comparison with the mafic silicate absorptions. Laboratory and modeling studies of mineral mixtures have shown that the diagnostic plagioclase absorption feature is distinguishable only if plagioclase comprises more than ~85 vol% of the bulk material measured by the spectrometer (assuming intimate mixture with typical lunar minerals such as olivine or pyroxene) [Nash and Conel, 1974; Crown and Pieters, 1987; Cheek and Pieters, 2012]. The dominant effect of small amounts of pyroxene on bulk spectral properties is demonstrated in Figure 5. Here terrestrial laboratory mixtures consisting of 95 and 98 vol% plagioclase (remainder pyroxene) are shown. In this example, the laboratory mixture containing only 2 vol% pyroxene results in a ~1000 nm pyroxene absorption that is comparable in strength to the 1250 nm plagioclase absorption. Figure 5 also shows calculated mixtures of 95 and 98% plagioclase produced using the method described in section 3. These calculated mixtures are discussed in more detail below.

[9] The absence of the diagnostic plagioclase feature in telescopic data for the Moon, which commonly has high spectral resolution covering the 1250 nm region, has typically been
attributed to the effects of shock metamorphism on plagioclase crystals [e.g., Spudis et al., 1984]. Relatively low shock pressures (between ~ 10 and 30 GPa) are known to cause internal fragmentation in feldspars [e.g., Stöffler, 1971; Hörz and Quaide, 1973]. Such fragmentation in transparent materials is expected to subdue crystal field absorptions by increasing light scattering and decreasing the effective path length for photons passing through mineral grains [e.g., Pieters, 1983]. In addition, beginning at moderate pressures of ~25 GPa, plagioclase crystals transform to a diaplectic glass called maskelynite [e.g., von Engelhardt and Stöffler, 1968; Stöffler, 1971]. Because maskelynite does not have the plagioclase structure necessary to generate the crystal field electronic absorption at ~1250 nm, increasing proportions of this amorphous phase produced by extensive shock causes the strength of the diagnostic plagioclase band to progressively weaken and ultimately disappear [Adams et al., 1979; Bruckenthal and Pieters, 1984; Johnson and Hörz, 2003]. Importantly, diaplectic glasses are only known to form in tectosilicates such as feldspars and quartz; olivines and pyroxenes, by contrast, retain their spectral features even when subjected to relatively high shock pressures (e.g., ~60 GPa for pyroxene) [e.g., Hörz and Quaide, 1973; Adams et al., 1979; Hörz et al., 1991].

Recently, the Multiband Imager (MI) and Spectral Profiler (SP) on board Japan’s Kaguya mission have identified the plagioclase absorption in numerous locations across the Moon, including Orientale [e.g., Matsunaga et al., 2008; Ohtake et al., 2009; Yamamoto et al., 2012]. Observations from M3 have also identified the plagioclase absorption in the IRR of Orientale [Pieters et al., 2009], and a thorough global assessment of crystalline plagioclase at numerous basins and craters has recently been undertaken using M3 data [Donaldson Hanna et al., 2012; also Global assessment of pure crystalline plagioclase across the Moon and implications for evolution of the primary crust, Journal of Geophysical Research, in review, 2013]. Because plagioclase must occur in high abundances in order to be distinguished spectroscopically in a bulk material (e.g., Figure 5), identification of the ~1250 nm plagioclase absorption in numerous locations across the Moon, including Orientale, provides significant insights into the mineralogical and tectonic history of the lunar highlands.

Figure 4. Example plagioclase spectra showing the diagnostic broad plagioclase absorption feature near 1250 nm (arrow indicates 1250 nm). Top spectrum in both Figures 4a and 4b is a plagioclase separate from a lunar highland soil (particles <125 μm) (RELAB ID: LR-CMP-183), and the bottom spectrum (with symbols) is a plagioclase separate from the Stillwater complex (particles <500 μm) (RELAB ID: SW-CMP-012). (a) Bidirectional reflectance measured in RELAB and (b) single-scattering albedo calculated using the approach described in section 3.
The images were processed and projected using the U.S. Geological Survey Integrated Software for Imagers and Spectrometers, imported into Environmental Systems Research Institute’s Geographic Information System software ArcMap, and georeferenced with M3 data.Overlaying the M3 data on NAC images reveals meter-scale information about the terrain contained in individual M3 pixels. The specific NAC images examined are given in Table S1 of the supporting information.

3.2. Spectroscopy of Plagioclase-Pyroxene Mixtures

A major goal of this paper is to estimate the relative plagioclase abundances in crystalline anorthosite exposures within Orientale. Our approach is based on comparing the relative strengths of the ~1000 nm pyroxene absorption and the ~1250 nm crystalline plagioclase absorption in individual M3 spectra. First, spectra are classified into three groups based on relative plagioclase and pyroxene absorption strength. The range of plagioclase abundances predicted for each group is then estimated by comparison with calculated spectra of different proportions of well-characterized end-members. Nonlinear calculations are required in order to account for the disproportionate effect of the pyroxene component on bulk spectral properties. Our approach for calculating mixture spectra involves the following:

1. Converting end-member reflectance values (technically, radiance coefficient) to single-scattering albedo (ω) with a look-up table that uses equation (37) from Hapke [1981] for reflectance and the H-function approximations from Hapke [2002].
2. Combining the ω spectra linearly over a range of mixture proportions weighted by the relative geometric cross section of each component, and
3. Converting the resulting ω spectrum for each mixture to reflectance again using equation (37) from Hapke [1981], which assumes that the two components are intimately mixed and that particles are spherical, closely spaced, and large compared to the wavelength of light (e.g., particles that are tens of microns in diameter). We have also assumed an isotropic phase function and a backscattering term of zero.

Assuming that the two end-member components have approximately the same particle size, their relative geometric cross sections are equal to volume fraction [see Hapke, 1981, p. 105].

Table 2. Spectral Classes of Exposures Examined Across the Orientale Basin*

<table>
<thead>
<tr>
<th>Spectral Class</th>
<th>Absorptions Present</th>
<th>Dominant Absorption</th>
<th>Estimated Plagioclase Content (vol %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>~1250 nm (plagioclase)</td>
<td>~1250 nm (plagioclase)</td>
<td>99–100</td>
</tr>
<tr>
<td>B</td>
<td>~1250 nm (plagioclase) and ~1000 nm (pyroxene)</td>
<td>~1250 nm (plagioclase), and ~1000 nm (pyroxene)</td>
<td>96–98</td>
</tr>
<tr>
<td>C</td>
<td>~1250 nm (plagioclase) and ~1000 nm (pyroxene)</td>
<td>~1000 nm (pyroxene)</td>
<td>≤95</td>
</tr>
</tbody>
</table>

*The three spectral classes, defined by which mineral absorption is the most prominent in an M3 spectrum over the 1000–1500 nm region.

**Estimated plagioclase contents for each class based on the results of the nonlinear mixing analyses using lunar highland plagioclase and low-calcium pyroxene spectral end-members (Figure 7).
equation (17)]. Thus, plagioclase percentages discussed in this section and throughout the paper refer to volume proportions. We note that although the “mixing” step (step 2) is carried out linearly using single-scattering albedo, we refer to the approach broadly as “nonlinear mixing” because the relationship between single-scattering albedo and measured reflectance is highly nonlinear.

This modeling approach was tested by calculating mixture spectra for terrestrial plagioclase and pyroxene end-members that could be validated against laboratory-prepared mixtures of the same end-members. The compositions for these terrestrial end-members are shown in Table 3. Two laboratory-prepared mixtures of these end-members are compared to the corresponding mixtures calculated using the forward modeling approach (described above) in Figure 5. Additionally, we calculated mixtures in 0.1 vol% increments from 80 to 100 vol% plagioclase and found the calculated spectrum with the lowest root mean square error to the measured reflectance spectra of the laboratory-prepared mixtures containing 98 and 95% plagioclase. The best fit to the laboratory-prepared spectra for the 98 and 95% plagioclase mixtures are the calculated mixture spectra for 97.8 and 94.8% plagioclase, respectively. For these two examples, the mixture modeling approach is accurate to better than half a percent of plagioclase volume proportion. We emphasize that the end-members used in the calculation shown in Figure 5 are not intended to be lunar analog spectra, and so their absorption strengths may not represent the specific mineral compositions or textures at Orientale.

Because the nonlinear mixing approach described above is shown to be successful in modeling controlled mixtures prepared in the laboratory, we have confidence in using this approach to produce modeled mixtures of lunar sample input spectra, for which laboratory mixtures cannot be prepared. Using lunar sample end-members with mineral compositions similar to those found in lunar anorthosites improves the fidelity of the modeled spectral characteristics to those observed at Orientale. The modeled mixtures produced from laboratory spectra of lunar end-members are described in section 4.

4. Results

4.1. Exposures With Discrete Mineral Absorptions

Many lunar surface materials consist of well-developed soils, and crystal field absorptions of constituent minerals are commonly subdued by prolonged exposure to the space environment [e.g., Adams and McCord, 1970, 1973; Pieters et al., 2000]. In this analysis, we focus instead on nonmare regions of Orientale with spectra displaying clear absorption features that can be confidently assigned to either mafic minerals or plagioclase. Small, discrete exposures are distinguished from background soils using a combination of spectral parameters, described in Table 1, that are designed to highlight pixels with prominent NIR absorptions due to plagioclase, pyroxene, olivine, or spinel in M$^3$ data. The 1000 nm absorption strength map in Figure 3 shows that nonmare basin materials generally lack strong ferrous absorptions on a regional scale, indicating...
Table 3. Major Element Compositions (Oxide wt %) of End-Members in Figures 5 and 7

<table>
<thead>
<tr>
<th>Validation Samples (Figure 5)</th>
<th>Lunar Samples (Figure 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyroxene</td>
<td>Plagioclase</td>
</tr>
<tr>
<td>SiO₂</td>
<td>57.43</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.06</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.15</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.01</td>
</tr>
<tr>
<td>FeO</td>
<td>7.90</td>
</tr>
<tr>
<td>MnO</td>
<td>0.05</td>
</tr>
<tr>
<td>MgO</td>
<td>33.96</td>
</tr>
<tr>
<td>CaO</td>
<td>0.29</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.01</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>99.86</td>
</tr>
<tr>
<td>En</td>
<td>88</td>
</tr>
<tr>
<td>Fs</td>
<td>11</td>
</tr>
<tr>
<td>Wo</td>
<td>1</td>
</tr>
<tr>
<td>An</td>
<td>n/a</td>
</tr>
</tbody>
</table>

- Compositions of the terrestrial samples were obtained by electron microprobe at Brown University, and compositions of the lunar end-members were obtained from the RELAB database. En' = molar [Mg/(Mg + Fe + Ca)] in pyroxene. Fs' = molar [Fe/(Mg + Fe + Ca)] in pyroxene. Wo' = molar [Ca/(Mg + Fe + Ca)] in pyroxene. An' = molar [Ca/(Ca + Na + K)].

- Lunar pyroxene is a green pyroxene separate from 15058, <125 µm particulate, RELAB ID: LR-CMP-173 [Joaacoen et al., 2011]. Lunar plagioclase is a separate from highland soil 62241, <125 µm particulate, RELAB ID: LR-CMP-183 [Taylor et al., 2001, 2010].

4.2. Spectral Classes

The discrete areas across the basin with distinct NIR absorptions can be broadly classified into three types based on their relative plagioclase and pyroxene absorption depths. These three spectral types include (1) spectra that are dominated by a crystalline plagioclase absorption near 1250 nm and lack evidence for a pyroxene absorption near 1000 nm (Class A); (2) spectra that display composite absorptions (a “w” shape), in which the pyroxene ~1000 nm absorption is approximately subequal to the plagioclase ~1250 nm absorption (Class B); and (3) spectra with a ~1000 nm pyroxene absorption that dominates or is clearly stronger than the plagioclase absorption (Class C). These classes of nonmare materials across Orientale are described in Table 2, and a spectrum representing each spectral type is shown in Figure 6. In this analysis, we have focused mainly on the ~1000 nm pyroxene band, rather than on both the ~1000 and ~2000 nm pyroxene absorptions, because of the difficulty in accurately measuring subtle ~2000 nm absorptions due to possible residual thermal emission contributions to the spectrum.

4.3. Plagioclase Abundances

Comparison of each spectral class with calculated mixtures of lunar plagioclase and pyroxene spectra demonstrates that many spectra from the Orientale basin represent very high plagioclase abundances. Model spectra calculated from lunar end-members using the nonlinear method described in section 3 are shown in Figure 7. The lunar sample end-members for this calculation were selected to be within the compositional range expected for the plagioclase and pyroxene in lunar anorthosites based on the sample collection [e.g., Ryder and Norman, 1978; Warren and Wasson, 1980; James et al., 1989; McGee, 1993; Warren, 1993]. Specifically, we have chosen a plagioclase end-member with uniformly pyroxene-dominated, but a detailed investigation of these locations in the context of other mafic-rich basin materials warrants further study.

a feldspathic character. Individual massifs or small craters, however, often exhibit small areas with distinct NIR absorption features. Inspection of the spectra for these areas suggests that the dominant mafic mineral is pyroxene, and the short-wavelength positions of the pyroxene absorptions indicate a low-Ca composition. Olivine and spinel are uncommon or absent in the region. Thus, characterizing the varying abundances of plagioclase across the basin (below) predominately involves comparing the relative strengths of the plagioclase and low-Ca pyroxene absorptions.

When the three parameters in Table 1 are viewed simultaneously in an RGB image and stretched to highlight the strongest absorptions, areas that contain pure plagioclase are generally distinguished from areas with spectra displaying only pyroxene absorptions. Spectra that contain a combination of the plagioclase and pyroxene absorptions (e.g., a composite feature between 1000 and 1500 nm), are also apparent. Ignoring well-developed soils with weak features (absorption strengths less than ~1%) and small-scale mixed materials, we have identified nearly 800 representative discrete areas across the region with clear absorptions attributable to either plagioclase, pyroxene, or both. Individual spectra of these areas were evaluated for internal consistency and classified as described below. The locations of these discrete exposures, irrespective of their relative plagioclase and pyroxene absorption strengths, are shown in Figure S1 of the supporting information. We note that the region exterior to the Cordillera Ring in the southwestern portion of the scene displays an interesting concentration of small, mafic-rich craters that have not been mapped here. We have focused on a representative selection of these materials since they appear to be
0.1 wt % FeO from highland soil 62241 and a low-calcium pyroxene separate (En64Fs29Wo7) from basalt 15058. The use of a basaltic low-calcium pyroxene rather than a spectrum of an anorthositic pyroxene was dictated by the availability of measured lunar pyroxene separates in the Reflectance Experiment Laboratory (RELAB) database. The major element compositions of the lunar sample end-members used in the mixture calculations are described in Table 3. A discussion of other factors such as mineral composition and grain size that may influence the modeling of absorption features is given in Appendix A. Although it is difficult to quantify the absolute error associated with each of these additional factors, their effect on relative absorption strengths is likely small and should not significantly affect the results described here.

As demonstrated in Figures 5 and 7, pyroxene is the optically dominant component in a plagioclase-pyroxene mixture. The addition of small amounts of pyroxene to the bulk mixture leads to systematic effects on bulk spectral properties. Calculated spectra for only the 99% and 100% plagioclase mixtures lack a detectable ~1000 nm pyroxene absorption and are analogous to Class A spectra from Orientale. Calculated spectra corresponding to 96–98% plagioclase are analogous to Orientale Class B spectra because they contain composite absorptions with ~1000 nm pyroxene features that are subequal in strength to the ~1250 nm plagioclase feature. Class A and Class B both clearly represent highly pure anorthosite, containing <5% pyroxene. In the following discussions we refer to Classes A and B collectively as “anorthosite.” We emphasize that the distinction between Classes A and B is defined only in terms of their spectral properties. The differences in mineralogy represented by these two classes is small but detectable with the current spectroscopic data.

For Class C spectra, however, the dominant absorptions are due to pyroxene. Locations exhibiting Class C spectra have not been further analyzed for mafic content but can represent a variety of compositions that are <95 vol% plagioclase. We note that many Class C locations may therefore also represent anorthosites, in a strict sense, and we believe this to be the case for many of the exposures within the basin rings.
Figure 9. Nonmare locations with strong mineral absorption features, shown classified according to their spectral properties. Class A (99–100% plagioclase) are represented by red symbols, and Class B (96–98% plagioclase) are represented by yellow symbols. The remaining locations (black) are Class C (≤95% plagioclase).

4.4. Local Geologic Context of Crystalline Anorthosite Exposures

[27] Crystalline anorthosite exposures in Orientale are commonly small (<1 km), which likely precluded their identification in Earth-based telescopic data that have spatial resolutions typically between 2 and 10 km [see Ohtake et al., 2009]. As illustrated with high spatial resolution NAC images in Figure 8 and the supporting information, the exposures principally occur on massif crests and in small fresh craters. Analysis of the NAC images showed that the plagioclase detections are typically, but not exclusively, correlated with morphologically fresh material such as meter-scale blocks or small bright craters. In nearly all cases the plagioclase detections are surrounded by spectrally featureless material rather than mafic material. In Figure 8a, M³ pixels containing crystalline anorthosite are highlighted based on the IBD1250 parameter and overlain on a portion of a coregistered NAC image. M³ spectra corresponding to each of the six locations annotated in Figure 8a are shown in Figure 8b, and continuum-removed spectra are shown in Figure 8c. A selection of four additional NAC images, with M³ plagioclase detections overlain, is provided in the supporting information.

4.5. Distribution of Crystalline Anorthosite Exposures

[28] The distribution of nonmare exposures with strong mineral absorptions that were examined in this analysis is shown in Figure 9, with each location color coded to indicate the spectral class based on the criteria in Table 2. Exposures estimated to contain more than 95% plagioclase, namely Class A and Class B, are represented by red and yellow symbols, respectively. The remaining locations (black symbols) are classified as Class C and are estimated to contain less than 95% plagioclase. Crystalline anorthosite with more than 95% plagioclase is shown to be overwhelmingly concentrated in the IRR, although a few examples can be found in the ORR, near the Cordillera Ring, and associated with large craters such as Mauder, Kopff, and Schlüter. Further, Figure 9 also demonstrates that the majority of crystalline anorthosite exposures in Orientale are of the highest purity distinguishable by NIR spectroscopy (Class A) and are estimated to contain 99–100 vol % plagioclase on the basis of nonlinear spectral modeling.

5. Discussion

5.1. Implications for Orientale Basin Formation

5.1.1. Crystalline Anorthosite

[29] The distinctly crystalline nature of the numerous, small anorthosite exposures described here offers insight into the formation of the complex but well-preserved Orientale basin. Specifically, a strong 1250 nm absorption in spectra of these exposures requires that most of the plagioclase in the local target rocks either (1) never experienced shock pressures sufficient to produce maskelynite during the basin-forming impact (~25–30 GPa) or (2) transformed into maskelynite during the impact event but later recrystallized back into feldspar. Determining the peak shock pressures experienced by the rocks of the IRR requires additional detailed modeling of peak-ring formation, and resulting estimates will depend heavily on the location, relative to the sub-impact point, from which these complex structures were derived. Numerical simulations of the terrestrial Chicxulub impact basin (180 km in diameter) do suggest that peak shock pressures experienced by material uplifted to form its peak ring could exceed 25 GPa [e.g., Morgan et al., 2011]. On the Moon, such peak shock pressures would be sufficient to enable transformation of plagioclase to maskelynite, although it is unclear how such estimates would scale to an Orientale-sized impact. For example, some numerical simulations of the Orientale impact suggest that sampling depths for the IRR could be in the lower crust and mantle [e.g., Potter et al., 2013], seemingly inconsistent with the abundance of highly pure anorthosite described here.

[30] A number of experimental studies have shown that annealing maskelynite at temperatures of ~800–1000°C results in a restoration to the original plagioclase structure in under an hour [Arndt et al., 1982; Ostertag and Stöffler, 1982]. This type of recrystallization was invoked by Gibson and Reimold [2005] in describing the shock pressures experienced by the granofelses in the center of the Vredefort impact structure. While the apparently high postshock temperatures in the Vredefort dome maybe related to subsequent magmatic events [Gibson and Reimold, 2005], it is prudent to consider recrystallization having occurred in lunar craters and basins as well. Ultimately however, if the effects of recrystallization could be well-characterized by estimating the postshock thermal environment of the rings of Orientale, these undisputed observations of the presence of crystalline plagioclase can be used to constrain a lower limit for the distribution of peak shock pressures within the basin.
5.1.2. Spectrally Featureless Anorthosite

[31] Bright, spectrally featureless materials, which have been previously attributed to “shocked” anorthosite [e.g., Spudis et al., 1984], nevertheless occur commonly throughout the basin (Figures 2 and 3). In fact, M^3 pixels displaying the crystalline plagioclase absorption feature are typically surrounded by spectrally featureless materials rather than by materials displaying mafic mineral absorption features (e.g., Figure 8). In the 12 different NAC images examined, spectrally featureless M^3 pixels always correspond to well-developed, relatively block-free regions or soils. Examples of four of the NAC images examined are described in the supporting information. This observation suggests that other processes in addition to shock metamorphism of plagioclase grains (e.g., fracturing or transformation to maskelynite) may contribute to the origin of spectrally featureless material within Orientale. For instance, the production of abundant nanophase iron on soil grains by prolonged exposure to the space environment is also known to substantially weaken absorption bands [Pieters et al., 2000; Hapke, 2001; Lucey, 2002; Noble et al., 2007], suggesting that soil maturation processes may play an important role. However, these processes must be somewhat limited in the Orientale areas in order to remain consistent with the observed brightness of the IRR [e.g., Pieters et al., 2000; Hapke, 2001]. More extensive analyses of the spatial relationship between crystalline exposures and spectrally featureless anorthositic terrain may reveal clues about the complex shock history experienced by basin materials.

5.1.3. Peak-Ring Formation

[32] Regardless of the shock history of the anorthosite in Orientale, the concentration of the crystalline plagioclase-dominated materials within the inner ring of the basin must be linked to its formation. The overall lack of mafic minerals observed in Orientale nonmare basin materials has long suggested that the impact event did not expose and eject significant amounts of material from deep in the lower crust or mantle [e.g., Head et al., 1993, 2010a; Pieters et al., 1993, 2009], even if the transient cavity may have penetrated to those depths [e.g., Head, 2010; Baker et al., 2011, 2012a]. It is important to note that the IRR shares key properties with peak rings of smaller peak-ring basins—two-ringed basin structures that characterize the transition from complex craters (smaller) to multiring basins (larger). Recent studies of peak-ring basins characterized on the basis of new LRO LOLA data and LROC images [Baker et al., 2011, 2012a] show that over the diameter range from ~200 to ~600 km, many morphometric characteristics change in substantial ways. Trends are observed for peak-ring basins [Baker et al., 2011, 2012a] that are consistent with a model in which, at the onset diameter of peak-ring basins, the volume and depth of melting affects the interior morphology of the basin and suppresses central peak formation [Cintala and Grieve, 1998; Head, 2010; Baker et al., 2012b]. Peak rings are thought to be associated with centro-symmetric collapse and bulking of the collapsing transient crater rim, which is rotated into position by extreme uplift of the crater floor. An important prediction of this model is that the sampling depths of peak rings should be relatively shallow, predominantly in the upper crust [e.g., Baker et al., 2012b]. Such a perspective for the formation of the Orientale basin is consistent with our findings of upper crustal anorthosite being the dominant component of the Inner Rook Ring (Table 2 and Figure 9). It is important to note that several other lunar basins, such as Nectaris, Grimaldi, and Humorum have also been reported to expose anorthosite in their inner rings based on telescopic and Clementine data [Spudis et al., 1989; Hawke et al., 1991; Bussey and Spudis, 2000]. Such anorthosite identifications are confirmed by the more recent Kaguya and M^3 data [Ohtake et al., 2009; Donaldson Hanna et al., 2012; Yamamoto et al., 2012; Donaldson Hanna et al., in review, 2013].

5.2. Implications for the Lunar Magma Ocean

[33] Determining the abundance of plagioclase in the Moon’s anorthositic crust is an important goal in lunar science because of the implications for magma ocean composition and crystallization history. In most LMO models, the anorthositic crust is generally thought to have formed by flotation and accumulation of plagioclase crystals from a dense, high-FeO residual liquid after ~80% solidification [e.g., Snyder et al., 1992; Elkins-Tanton et al., 2011]. However, the details of this process remain somewhat unclear in terms of predictions of the actual modal abundance of plagioclase in the resultant crust. Feldspathic lunar meteorites, which likely represent averages over large areas of the Moon’s crust, tend to be significantly more mafic than the anorthosites discussed here for Orientale, ranging from 76 to 89 vol% normative plagioclase [Korotev et al., 2003]. However, the most reliably pristine ferroan anorthosite samples, which are more analogous to the materials exposed at Orientale, average 93.7 ± 6.7 vol% plagioclase [Warren, 1990]. The range of plagioclase modes for these pristine anorthosite samples is large and includes compositions that are too mafic to be considered anorthosites, in a strict sense. Other examples in this ferroan anorthosite suite, however, clearly range up to plagioclase abundances similar to those reported here for Orientale and for other areas across the Moon measured by the MI and SP spectrometers on board Kaguya [Ohtake et al., 2009; Yamamoto et al., 2012].

[34] A key difference between lunar sample data and the new remote sensing measurements is spatial scale. Although study of lunar samples can provide detailed information on the composition and textures of lunar anorthosites, limitations in either geographic extent sampled (e.g., Apollo and Luna samples) or available geographic context (e.g., feldspathic lunar meteorites) make it difficult to obtain a comprehensive view of magma ocean crystallization history solely from the currently available samples. As demonstrated in Figure 7 of this paper, high-spectral-resolution NIR data are sensitive to percent-level changes in the abundance of the mafic component of plagioclase-dominated rocks, and this level of detail can be now measured at outcrop scale. At Orientale, these new observations of crystalline anorthosite require that magma ocean crystallization must produce vast contiguous regions of anorthosite that contain no more than a few percent pyroxene in the upper crust. These pure, crystalline anorthosites are well exposed at the IRR in particular, with remnants presumably also currently below the surrounding megaregolith.

[35] The mechanism by which plagioclase is accumulated in terrestrial anorthosites is poorly understood, even when detailed stratigraphic context and cumulus textures are preserved [e.g., Irvine, 1980; Raedeke and McCallum, 1980;
ashwal, 1993; namur et al., 2011]. indeed, study of cumulus rocks in layered mafic intrusions has shown that perfect adcumulus, monomineralic rocks are more rare than troctolites and norites, suggesting that crystal-crystal and/or crystal-liquid separation processes are commonly inefficient [e.g., raedeke and mccallum, 1980; snyder et al., 1992]. in general, the low density of plagioclase compared to the residual liquid and coexisting mafic minerals [e.g., elkins-tanton et al., 2011; suckale et al., 2012] is thought to have facilitated the formation of a relatively pure plagioclase flotation crust at the top of the lmo [e.g., herbert et al., 1977]. during the last stages of solidification, the plagioclase-dominated crust may have been further purified by the extraction of residual liquids via compaction and diffusion processes [morse, 1982; parmentier and liang, 2010]. at orientale, we have shown that these processes together must produce a massive and coherent zone of at least ~95% plagioclase over several hundred kilometers.

6. conclusions

[36] abundant exposures of crystalline anorthosite are identified and mapped across the orientale basin based on the presence of the highly diagnostic plagioclase absorption feature in m^3 spectra. the anorthosite is concentrated overwhelmingly in the inner rook ring, in agreement with previous data that indicated an abundance of mafic-poor materials in the region. the advantage of the high-spectral-resolution nir data analyzed here, however, is that the presence of the diagnostic plagioclase absorption feature permits unambiguous identification of crystalline anorthosite as well as estimation of anorthosite purity at outcrop scale over the full basin extent. the irr anorthosite is exceedingly mafic-poor: most spectra from the inner ring either lack any discernable mafic mineral absorptions or have a mafic mineral absorption that is subequal in strength to the ~1250 nm plagioclase feature. comparison with nonlinear mixing calculations confirm that the plagioclase abundances in these anorthosites are very high, resembling modeled spectra containing >95%, and commonly ≥99%, plagioclase. these new near-infrared spectroscopic data provide direct compositional observations of the lunar crust and therefore provide constraints on models of magma ocean crystallization:

[37] 1. the primary crystallization sequence early in lunar history must produce regions of the crust that are composed entirely of anorthosite that is nearly free of mafic minerals.

[38] 2. the overall stratigraphy of the crust and processes of multiring basin formation must result in this crustal anorthositic zone being exposed predominantly across the irr of the orientale basin during the impact event.

[39] 3. the areal extent of this anorthosite must be large enough to include the entire zone of crust sampled by the irr during the orientale impact. similar spectroscopic analyses at other lunar basins will determine the extent to which this process is repeated across the moon.

appendix a: additional considerations for mineral abundance estimates

[40] an important component of this work is constraining the range of plagioclase abundances that are consistent with each of the major spectral classes found in the orientale region. because the approach relies on estimating the relative band strengths in both calculated mixtures and in m^3 spectra, it is important to consider what factors, besides mineral abundance, might affect absorption strength. although there are a number of parameters, such as space weathering, photometry, local topographic effects, particle size, spatial (linear) mixing, and mineral composition, that are known to affect absorption strengths in minerals, only those factors that could lead to substantial differences in the relative strengths of the plagioclase and pyroxene absorptions are likely to influence the classification used here. these effects are discussed below.

a1. pyroxene composition

[41] mineral composition is perhaps one of the most important considerations in predicting relative absorption band strengths. for plagioclases, feo content is the most significant chemical control on absorption strength [e.g., bell and mao, 1973; adams and gouliaud, 1978]. fortunately, the feo concentrations in plagioclase from most sampled lunar anorthosites are remarkably consistent, typically ~0.05~0.2 wt% [e.g., papike et al., 1991; mcgee, 1993]. this gives us confidence that the plagioclase end-member used in the mixing calculation (containing 0.1% feo) is representative of the absorption strength of highland plagioclase that is observed at orientale (plagioclases in mare basalts, however, often contain >0.3 wt% feo [isaacson et al., 2011]). the compositions of pyroxenes found in lunar anorthosites are more variable. we focus on low-calcium pyroxenes here, which are the most common mafic mineral found in lunar anorthosites [e.g., mcgee, 1993]. low-calcium pyroxenes typically have short-wavelength absorption features below ~950 nm [e.g., klima et al., 2007, 2011], similar to those observed at orientale. because of the low calcium content in pyroxenes
found in lunar anorthosites, typically <5 wt % CaO [McGee, 1993], the major control on absorption strength for the ~1000 nm pyroxene absorption is the relative magnesium and iron contents of the sample. Relative FeO contents of low-calcium pyroxenes are approximated by comparing their Mg′ (Mg′ = molar Mg/[Mg + Fe]). Analyses in the literature suggest that compositions of low-calcium pyroxenes in anorthosites vary substantially, ranging from ~Mg40 to ~Mg70 [e.g., Ryder and Norman, 1978; Warren and Wasson, 1980; James et al., 1989; McGee, 1993; Warren, 1993].

[42] To demonstrate the effect that different Mg′ values for low-calcium pyroxene could have on the estimates of plagioclase abundance illustrated in Figure 7, we produced similar nonlinear mixing models using four different pyroxene compositions from Klima et al. [2007, 2011] that span the range of low-calcium pyroxenes found in lunar anorthosites. The four pyroxene end-members are shown in Figure A1, and the modeled mixtures use the same lunar plagioclase end-member as in Figure 7. The modeled mixture spectra for these four pyroxenes are shown in Figure A2. Pyroxene compositions are referred to by En′ rather than Mg′ to accommodate the small amount of calcium in one of the samples. Figure A2 illustrates that the same general pattern is observed for all pyroxene compositions. For three of the pyroxenes (En50Fs50, En35Fs65, and En30Fs59Wo5), variation in relative absorption strengths between calculated mixtures containing the same modal proportions are on the order of only ~1% variation in pyroxene abundance. The models produced with the En70Fs30 pyroxene, however, show ~1000 nm absorptions that are notably weaker than for the other pyroxene samples, requiring higher abundances of pyroxene for detection in the bulk calculated material. Although these synthetic pyroxenes are useful for demonstrating trends of absorption strength over a given compositional range, it is difficult to directly compare their absorption strengths to lunar samples (partly due to particle size effects).

[43] Shown in Figure A3 are modeled spectra produced using a lunar Mg-Suite low-calcium pyroxene from norite 78235, 9002A (En76Fs17Wo6). Here it is apparent that even a pyroxene end-member with very low FeO (relative to the range expected for sampled lunar anorthositic pyroxenes) would not change the plagioclase abundance estimate for either Class A or Class B by more than ~1%. Thus, it does

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**Figure A2.** Nonlinear mixture models for various pyroxene compositions produced using the approach described in section 3. The input plagioclase spectrum for all models is a separate from highland soil 62241 (the same as that used for the modeled spectra shown in Figure 7). The pyroxene end-members correspond to the four synthetic pyroxenes shown in Figure A1. The plagioclase abundances that were assigned to the Class A spectra of Figure 7 are shown in red. The plagioclase abundances that were assigned to the Class B spectra in Figure 7 are shown in orange with symbols. The plagioclase abundances that were assigned to the Class C spectra in Figure 7 are shown in grey. The only pyroxene end-member that remains undetectable at the 1% level is the highest-Mg sample. Arrows are positioned at 950 and 1250 nm.
not appear that pyroxene composition will substantially affect the plagioclase abundance estimates for Orientale that are described in Table 2.

A2. Particle Size Variations

Particle size can have a strong effect on absorption strength. The mixing calculations described in section 3 have been carried out assuming, for simplicity, that both the plagioclase and pyroxene end-members are equal in particle size. Petrography of lunar anorthosites in the sample collection has shown that plagioclase crystals commonly form millimeter-sized laths, whereas pyroxenes are only tens of microns in diameter [e.g., McGee, 1993]. All other constraints being equal, the optical path length would thus on average be shorter for the pyroxene, and this difference would result in a weaker pyroxene absorption than if grains were equal in size. This effect would produce a slight overestimate of the plagioclase abundance associated with each spectral class. If, however, as expected, the exposed surfaces contain particulate material derived from small-scale impact gardening, the size discrepancy should diminish as pyroxene by comminution [Cintala and Hörz, 1992]. Thus, it is not possible to reliably estimate the relative grain sizes of plagioclase and pyroxene represented by the Orientale spectra, and the assumption of comparable grain size is compatible with most regolith evolution models. However, it is clear that systematic grain size variations over even a relatively large interval would not result in Class A or Class B areas containing less than anorthositic proportions of plagioclase.

A3. Linear Versus Nonlinear Mixing

The physical scale of mixing, here assumed to be on the order of millimeters, can affect the relative absorption strengths of plagioclase and pyroxene in a bulk spectrum. For example, in a strictly intimate mixing scenario, the contribution of pyroxene to the bulk spectrum will be the most highly nonlinear. However, if any mafic component exists concentrated in large-scale heterogeneities such as discrete pyroxene-rich boulders, the mixing behavior would be more linear and the measured regional spectrum could exhibit a relatively weaker pyroxene absorption than in the intimate mixing scenario described above. Petrography of returned lunar anorthosites suggests that the assumption of an intimate mixture, in which light interacts with a number of grains before being absorbed or returned to the sensor, is appropriate for these applications [e.g., Pieters, 1983]. For instance, the largest grains in anorthosites, typically plagioclases, are usually only a few millimeters in length and occur in a matrix of smaller (<1 mm) mafic mineral grains [e.g., McGee, 1993]. Further, although our analysis of several NAC images in this region did not suggest that discrete pyroxene-dominated blocks are common on IRR massifs, additional analyses would be useful to address the importance of areal mixing on the scale of an M³ pixel as well as regolith mixing issues. We note, however, that even under a strictly linear mixing scenario, calculations using the same lunar end-members as described above (Table 3) result in Class A spectra that correspond to 92–100 vol% plagioclase. Thus, even in the most extreme case (e.g., very pure plagioclase areas distinct from large blocks of pyroxene within an M³ pixel), Class A spectra, which dominate the mineral exposures in the IRR, are representative of anorthosite, in a strict sense.

A4. M³ Data Considerations

The data used in this analysis were Level 2 as delivered to the Planetary Data System. We evaluated whether the “ground-truth” correction described by Isaacson et al. [2013] affects the result. Although this correction is now recommended for M³ data, we found that it did not significantly alter the spectral characteristics of the crystalline nonmare material in the Orientale region that is the focus of this analysis. A subset of ~100 Class A spectra were examined with and without ground truth applied, and the level of the correction was found to be well below that of varying plagioclase abundance.

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References


Figure A3. Calculated mixture spectra using a lunar pyroxene end-member that is more Mg-rich (En76Fs17Wo6) than the end-member in Figure 7 (the plagioclase end-member is the same). The pyroxene end-member is a spectrum of an orthopyroxene separate from norite 78235, 9002A (0–250 μm). The plagioclase abundances that were assigned to the Class A spectra of Figure 7 are shown in red. The plagioclase abundances that were assigned to the Class B spectra in Figure 7 are shown in orange with symbols. The plagioclase abundances that were assigned to the Class C spectra, up to 15% pyroxene, in Figure 7 are shown in grey. Arrows are positioned at 950 and 1250 nm.