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Key Points:

- Two types of orthopyroxene-dominated materials in the South Pole-Aitken basin were distinguished
- One, widely distributed from center to edge across the basin, is interpreted as the South Pole-Aitken impact melt
- The other with lower calcium, distributed in some feldspathic regions, is considered the excavated deep-seated material

Supporting Information:

- Supporting Information S1

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Mafic Minerals in the South Pole-Aitken Basin

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Abstract The formation of the South Pole-Aitken (SPA) basin is thought to excavate the deep crust or mantle because of its large size. The pervasive orthopyroxene-dominated materials found across the basin suggest that they either represent the SPA impact melt or the excavated materials from the lower crust and/or upper mantle. This study analyzes the relative content and distribution of mafic minerals in the SPA area based on the spectra from small fresh craters. The orthopyroxene-dominated materials in the nonmare regions are classified into two types based on their distribution and different composition. One is distributed from the center to the edge across the SPA basin and interpreted as the SPA impact melt. The other is Mg richer and generally located in some plagioclase-rich regions (e.g., some large impact craters/basins and the SPA edge), thought to represent materials from the lower crust and/or upper mantle. For the maria in the SPA area, the basaltic materials in the northwest are found to be richer in olivine and/or clinopyroxene than the southern ones.

Plain Language Summary The South Pole-Aitken (SPA) basin is the largest impact structure on the farside of the Moon, which is believed to excavate and melt rocks from deep beneath the lunar surface due to its large size. However, the melted rocks and excavated rocks are difficult to be distinguished because of their similar composition. This study analyzes the composition of fresh materials exposed by small impact craters in the SPA basin, which enhances the diagnostic features of the data acquired by orbital instruments. A geostatistical method is also applied to enhance the variation trend of diagnostic features in different locations. The melted rocks and excavated rocks in the SPA basin are distinguished based on their distribution and relatively different composition. The melted rocks are widely distributed across the basin from the center to the edge. In contrast, the excavated rocks are generally located in some specific regions.

1. Introduction

The South Pole-Aitken (SPA) basin is the largest and oldest recognized impact structure on the lunar surface (Garrick-Bethell & Zuber, 2009; Spudis et al., 1994). Its formation was thought to excavate the deep crust or mantle (e.g., Jolliff et al., 2000; Melosh et al., 2017; Potter et al., 2012; Spudis et al., 1994). Previous remote sensing observations have revealed that the SPA interior is distinct from the remainder of the Moon in terms of topography and compositions (e.g., Jolliff et al., 2000; Lucey et al., 1998; Pieters et al., 2001). Compared with the lunar highlands, the nonmare regions of the SPA basin exhibit a mafic character that is dominated by low-Ca pyroxene and elevated concentrations of Fe and Th (e.g., Lawrence et al., 2000; Lucey et al., 1998; Moriarty & Pieters, 2018; Ohtake et al., 2014; Pieters et al., 2001). These low-Ca pyroxenes are pervasive across the SPA basin, which suggests that they are a result of the SPA formation as either impact melt (e.g., Hurwitz & Kring, 2014; Uemoto et al., 2017; Vaughan & Head, 2014) or excavated materials from the lower crust and/or upper mantle (e.g., Moriarty & Pieters, 2018; Ohtake et al., 2014; Pieters et al., 2001).

However, the spatial distribution difference between the excavated materials and impact melt of the SPA basin remains unclear. Analysis of hyperspectral data offers an opportunity to map their distribution based on compositional differences at the surface. Given that exposed surface materials are subject to space weathering agent (e.g., Hapke, 2001; Pieters et al., 2000) and impact materials redistribution, looking at fresh craters' ejecta offers the opportunity of probing the composition of both the surface and subsurface materials. Optically fresh, "immature" materials are more crystalline in nature resulting in stronger spectral signatures (e.g., Hapke, 2001; Pieters et al., 2000), which aids analysis and characterization. Since some larger craters may expose deep-seated materials from different layers, this study aims to investigate the relative content and distribution of mafic minerals in the SPA area based on the spectra extracted from small fresh craters.

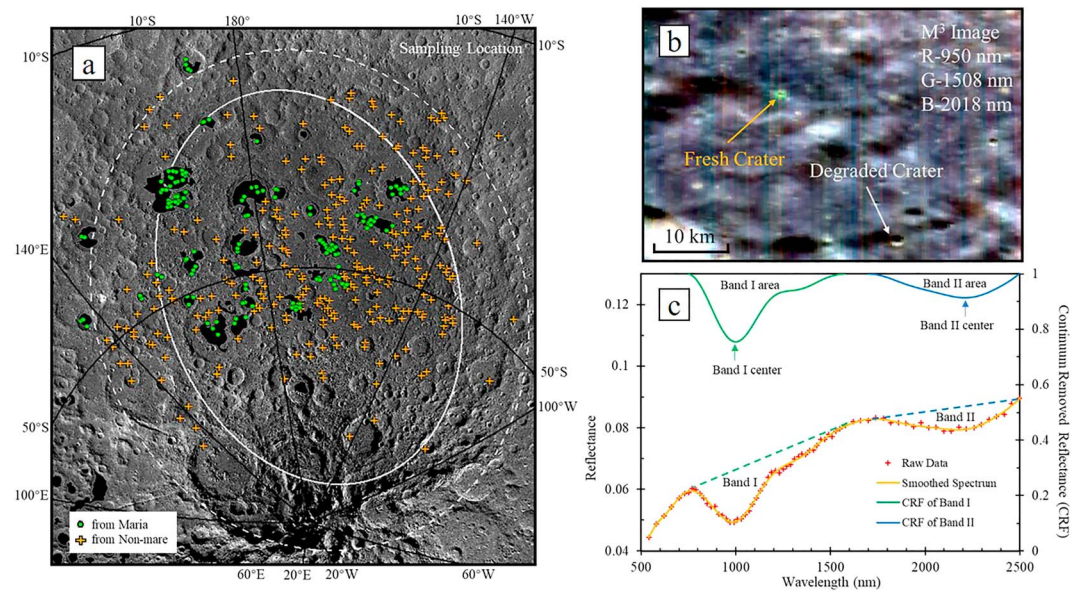


Figure 1. (a) Locations of the extracted spectra, superimposed over a Lunar Reconnaissance Orbiter Camera-Wide Angle Camera mosaic (Robinson et al., 2010). The green spots represent the locations of spectra extracted from the maria, and the yellow crosses lie in nonmare regions. The black areas denote the identified maria (e.g., Nelson et al., 2014; Yingst & Head, 1997), and the white ellipses delineate the inner and outer structures of the South Pole-Aitken basin (Garrick-Bethell & Zuber, 2009). (b) Example of a small fresh crater with strong mafic mineral absorption features (yellow arrow) and a degraded crater (white arrow) in the M³ color composite image (ID: M3G20090623T052831: R-950 nm, G-1,508 nm, and B-2,018 nm) with a linear 2% stretch. (c) Example of the spectral processes (smoothing, continuum removal, and estimations of the band areas and band centers) documented by Zhang, Ouyang, et al. (2016).

2. Background

2.1. The Structure and Composition of the SPA Basin

The 2,500-km diameter SPA basin is considered of pre-Nectarian age, having an elliptical morphology, and occupying a major part of the south central lunar farside (Garrick-Bethell & Zuber, 2009; Spudis et al., 1994). Garrick-Bethell and Zuber (2009) described the SPA basin as two elliptical structures (centered at 53°S, 191°E) with outer topography about 2,400 × 2,050 km (Figure 1a). Since previous studies believe that for basin-scale impacts the depth of melting should exceed the depth of excavation (e.g., Cintala & Grieve, 1998), lots of mantle materials could have melted during the SPA formation (e.g., Hurwitz & Kring, 2014). Maybe some of these melts have been ejected from the basin (e.g., Osinski et al., 2011), but most of them probably formed a central melt sheet within the transient cavity of the SPA basin (Morrison, 1998; Potter et al., 2012; Vaughan & Head, 2014).

The SPA basin floor is dominated by low-Ca pyroxene-bearing (i.e., orthopyroxene and/or pigeonite) noritic materials, high-Ca pyroxene-bearing (i.e., clinopyroxene) gabbroic materials, and basaltic lithologies (Moriarty & Pieters, 2018; Ohtake et al., 2014; Pieters et al., 2001). Although the SPA basin exhibits mare/cryptomare basaltic signatures, the dominant mafic signature is from the orthopyroxene-dominated (Opx) nonmare regions (Moriarty & Pieters, 2015; Pieters et al., 2001; Whitten & Head, 2014). Since many central peaks within the SPA basin exhibit a limited compositional range, it indicates the presence of a thick, homogeneous, Opx-dominated layer (Moriarty et al., 2013; Nakamura et al., 2009; Tompkins & Pieters, 1999). For the nonmare regions, the potentially higher concentration of clinopyroxene (Cpx) was mostly identified in the central and northwestern portions of the SPA basin (e.g., Moriarty & Pieters, 2018; Ohtake et al., 2014). In addition, small exposures of olivine and pure plagioclase in the SPA basin have also been documented (Ohtake et al., 2009; Yamamoto et al., 2012). Based on the distinct composition, Moriarty and Pieters (2018) mapped four concentric zones in the SPA basin: (1) the SPA compositional anomaly (SPACA) exhibiting an elevated Cpx abundance, (2) the Mg-pyroxene annulus dominated by Opx, (3) the heterogeneous annulus dominated by the mixtures of mafic and feldspathic materials, and (4) the SPA exterior dominated by feldspathic materials.

2.2. Spectral Characters of Lunar Mafic Minerals

Pyroxenes are the dominant mafic minerals on the surface of the Moon and are identified by spectral absorption bands around 1,000 nm (Band I) and 2,000 nm (Band II; Adams, 1975; Burns, 1993; Cloutis, 1985). The Band I and Band II centers provide a qualitative way to access the composition of pyroxenes (Klima et al., 2007; Klima et al., 2011; Moriarty & Pieters, 2016). In general, higher Fe^{2+} and Ca^{2+} contents tend to shift all bands of pyroxenes toward longer wavelengths (Burns, 1993; Hazen et al., 1978). According to Klima et al. (2007, 2011), the Band I and Band II centers increase together as Fe and Ca substitute for Mg in the crystal structure. Mg-rich Opx shows a relatively narrow and symmetrical Band I absorption centered near 900 nm and a broad Band II absorption centered near 1,900 nm, which is due to Fe^{2+} occupying the M2 crystallographic site and Mg^{2+} in the M1 crystallographic site (Adams, 1975; Burns, 1993; Klima et al., 2008).

Fe, Ca-rich Cpx is usually classified into two spectral categories (Adams, 1975). “Type-B” Cpx also exhibits a narrow, symmetrical Band I absorption centered near 1,050 nm as well as a broad Band II absorption centered near 2,200 nm, which is due to Fe^{2+} in the M2 site as in Opx (Adams, 1975; Cloutis, 1985; Klima et al., 2007; Klima et al., 2008; Klima et al., 2011). Pyroxene with high Fe^{2+} content usually displays a secondary absorption centered near 1,200 nm because of Fe^{2+} in the M1 site (Klima et al., 2007; Klima et al., 2011). The intensity of this band is a function of both the total Fe^{2+} and Ca^{2+} in composition because the M2 site is occupied by the high concentration of Ca^{2+} that forces Fe^{2+} into the M1 site (Klima et al., 2007; Klima et al., 2011). “Type-A” Cpx, which is generally correlated with high- Ca^{2+} content, shows a complex Band I absorption near 1,000 nm but without Band II absorption (Adams, 1975; Burns, 1993). This Band I absorption is a combination of two or three distinct bands centered near 940, 1,030, and 1,150 nm due to both the M1 and M2 sites occupied by Fe^{2+} (Adams, 1975; Cloutis, 1985; Klima et al., 2007; Klima et al., 2011).

For the spectrum of olivine which is another common mafic mineral of the Moon, it is revealed by a broad and asymmetric Band I absorption but lacks the Band II absorption (Adams, 1975; Burns, 1993; Singer, 1981). The Band I absorption of olivine displays as three overlapping individual absorptions centered near 800, 1,100, and 1,300 nm (Adams, 1975; Burns, 1993; Cloutis, 1985). The “secondary” absorption near 1,300 nm allows it to be detected when admixed with the spectrally “stronger” pyroxene (Singer, 1981).

In case of olivine-pyroxene mixtures, the Band I absorption is dependent on the relative abundance of both olivine and pyroxene, which make the interpretation problematic (Cloutis et al., 1986). The band area ratio (BAR), defined as the ratio between Band II and Band I absorption features, is useful for estimating the relative abundance of olivine and pyroxene (Cloutis et al., 1986; Gaffey et al., 1993). Gaffey et al. (1993) introduced a relationship between the Band I center and BAR to reduce the error caused by the presence of Cpx in the mixture. The BAR is inversely proportional to the olivine abundance but increases linearly with the pyroxene abundance (Cloutis et al., 1986).

3. Materials and methods

3.1. Data

The Moon Mineralogy Mapper (M^3) instrument was an imaging spectrometer onboard the Indian Chandrayaan-1 mission and mapped more than 95% of the Moon in global mode (Boardman et al., 2011), which acquired images with 140 or 280 m per pixel in 85 channels from 430 to 3,000 nm (Green et al., 2011). The M^3 data with wide band coverage and high resolution are ideal data for mineral identification in the SPA basin. These global data have five sets of suboptical periods (OPs): OP1A, OP1B, OP2A, OP2B, and OP2C (Boardman et al., 2011). Because of the broadest coverage, the Level 2 data of OP2C, which offer a spatial resolution of 280 m/pixel and include photometric and thermal corrections (Green et al., 2011), were used in this study.

3.2. Spectra Extraction

This study mainly focused on the optically immature materials exposed by the small impact craters to avoid the detrimental effects of space weathering that lowers albedo, weakens band absorptions, and reddens the spectral slope of lunar minerals (e.g., Hapke, 2001; Pieters et al., 2000). Most spectra were extracted from the small fresh craters about 1 km in diameter with strong absorption features of mafic minerals (Adams, 1975; Burns, 1993; Cloutis, 1985). As Figure 1b shows, the fresh crater with stronger absorption features of mafic

minerals (Adams, 1975; Cloutis, 1985) is distinguished from the degraded crater in the M^3 image. These small fresh craters generally retain bright ray and topographic freshness. Some fresh craters dominated by feldspathic materials with very weak absorption features (Crown & Pieters, 1987) were not included in this study.

The crater candidates were manually selected from the M^3 color composite image, as the example in Figure 1b. For most craters, spectra were extracted from only one pixel to represent the spectral feature of the corresponding crater. It is because that the resolution of the M^3 image is about 280 m/pixel, and more pixels will increase the mixture of soils. The pixel was generally selected according to its highest signal-to-noise ratio and strongest absorption features among all the pixels representing the crater morphology (e.g., rim, wall, and ejecta). To guarantee that the least weathered materials were extracted from the SPA basin, the optical maturity parameter “OMAT” (Lucey, Blewett, Taylor, et al. 2000) of each extracted spectrum was verified. Following the suggestions from Lucey et al. (2014), the OMAT value of 0.25 was set as the threshold to isolate candidate immature materials (the OMAT values of all the spectra is shown in Figure S1 in the supporting information).

For the maria in the SPA area (Figure 1a), which are mapped based on previous studies (e.g., Nelson et al., 2014; Yingst & Head, 1997), 161 small fresh craters were selected including a few within the maria boarding the outer structure of the SPA basin (Garrick-Bethell & Zuber, 2009). Given that the suitable, small, fresh craters are hard to find in some small areas, spectral extraction was not carried out in some small maria. For the nonmare regions, defined by the outer structure of the SPA basin (Garrick-Bethell & Zuber, 2009), 285 small fresh craters were extracted for analysis (Figure 1a), including few craters just outside the outer structure.

3.3. Spectral Parameters Analysis

To calculate the BAR and Band I center of spectrum, several spectral processes (e.g., smoothing, continuum removal, and measurements of the band areas and band centers) were performed using the technique documented in Zhang, Ouyang, et al. (2016). An example of the spectral processing method is presented in Figure 1c. Smoothing is to create an approximate function for acquiring the important pattern of the spectrum and leaving out the noise (e.g., Simonoff, 1996). B-spline smoothing (Eilers & Marx, 1996) was first applied for deriving more precise band centers. Since the thermal component causes the spectrum to steepen at longer wavelengths ($\sim 2,000$ nm), which has a detrimental effect on spectral analysis based on the Band II absorption features (Clark et al., 2011), the M^3 data were truncated at 2,497 nm to minimize this effect. According to Klima et al. (2011), the Band II absorptions of some high-Ca pyroxenes may extend beyond 2,500 nm. Although the BAR values of these materials may be underestimated, it has a limited effect on the analysis of the relative content.

Continuum removal, defined as the ratio of the reflectance value of the spectrum to the continuum value of the corresponding band, is a necessary process to outline the spectral features (Clark & Roush, 1984), producing a relative reflectance named “continuum removed reflectance.” As Figure 1c shows, two straight lines were separately constructed across Band I and Band II, which is tangent to the spectrum on the left and right shoulders of the target absorption band, to remove the continuum individually. Except for the right endpoint of spectrum set by the user, other tangent points are automatically selected by the algorithm. Because the first and last spectral data are the tangent points of the line segment, their values are equal to 1 in the output continuum removed reflectance. For the band center, it is derived by fitting a sixth-order polynomial curve over the predefined wavelength range of the continuum-removed reflectance (850–1,150 nm for Band I and 1,850–2,450 nm for Band II). The wavelength of the lowest value on the polynomial curve is considered as the band center. The band area of each continuum segment is estimated as one minus the value of each band in this range multiplied by the spectral resolution. Detailed information about these spectral processes can be accessed in Zhang, Ouyang, et al. (2016) and Wu et al. (2018).

3.4. Interpolation Method

An interpolation surface was generated to facilitate the analysis of the distribution of spectral parameters in the nonmare regions of the SPA basin (see section 4.2). The purpose of generating an interpolation surface is to enhance the differences of spectral features in a spatial context, not to provide precise data points. Kriging is a geostatistical interpolation technique widely used in mining, geology, and environmental science (e.g.,

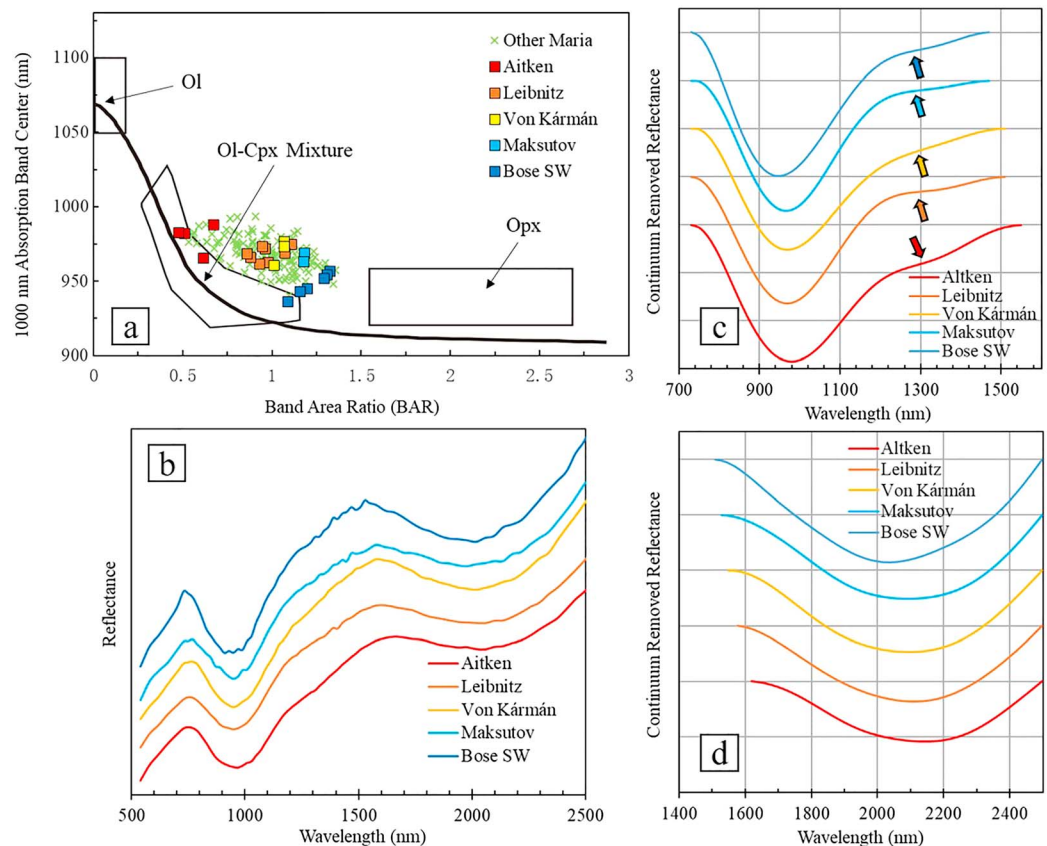


Figure 2. (a) Plot of the band area ratio versus Band I center for the spectra extracted from the maria in the South Pole-Aitken area. The Ol-Opx mixing line from Cloutis et al. (1986) and some compositional groups from Gaffey et al. (1993) are drawn for reference. (b) The averaged raw spectra (without smoothing) of five mare locations (vertically offset for clarity). (c and d) The averaged continuum removed spectra of Band I and Band II (with smoothing) of five mare locations (vertically offset for clarity). The arrows mark the secondary absorption around 1,200–1,300 nm.

Goovaerts, 1997). This method considers both the distance and the degree of variation between known data points when it estimates values in unknown regions. In its original formulation, a kriged estimate at a locality is a weighted linear combination of the known sample values around the point to be estimated (Goovaerts, 1997; Isaaks & Srivastava, 1989). The cokriging method is used to enhance the estimation of primary variable by using secondary variable assuming that the variables are correlated to each other (Isaaks & Srivastava, 1989). For example, the interpolation result of the BAR value can be improved by setting the value of Band I center as the secondary variable. This study generates the interpolation surface in ArcGIS software program by using the simple cokriging method, which assumes that the average of the entire data set is known (Isaaks & Srivastava, 1989). Detailed introduction of kriging methods can be found in some previous studies (e.g., Goovaerts, 1997; Isaaks & Srivastava, 1989).

4. Results

4.1. Mafic Minerals of the Maria

Spectra were extracted from over 24 different locations within the maria areas in the SPA region (Nelson et al., 2014; Yingst & Head, 1997), including a few mapped just outside the outer structure of the SPA basin, see Figure 1a. The spectral parameters of them are shown in the plot of the BAR versus Band I center (Figure 2a). Some compositional groups, which represent different relative abundances of olivine (i.e., Ol) and pyroxene (as defined by Gaffey et al., 1993), are also plotted for comparison. Although these compositional groups are used to investigate asteroidal data (Cloutis et al., 1986; Gaffey et al., 1993), they still provide a useful reference tool for the analysis of the relative abundance of olivine and pyroxene.

Table 1
The Averaged Spectral Parameters of the Five Mare Locations

Mare	Band I center	Band I area	Band II area	BAR
Aitken	979.2	103.3	57.16	0.553
Leibnitz	968.5	78.54	75.13	0.956
Von Kármán	969.2	80.66	84.25	1.044
Maksutov	965.9	74.49	88.33	1.185
Bose SW	947.3	90.83	111.2	1.225

Note. BAR = band area ratio.

As mentioned in section 2.2, olivine displays an asymmetric Band I absorption. For the Opx-olivine mixtures, their Band I absorptions are usually more asymmetric than those of Opx (Horgan et al., 2014), which results in a higher Band I absorption area and a lower BAR value. Generally, most data points of the maria are around the region that represents the mixture of olivine and Cpx (Figure 2a). Notably, the maria materials are the mixtures of multiple minerals (e.g., Isaacson et al., 2011; Moriarty & Pieters, 2016). All the compositional groups discussed in this study are based on the relative component of mafic minerals and do not account for other factors such as the plagioclase or opaque abundance.

The averaged spectra (including raw spectra and continuum removed spectra) of the mare locations analyzed in this study are shown in Figures S1 and S2, and five representative averaged spectra of them are presented in Figures 2b–2d. For the spectra extracted from the maria, they display obvious asymmetric Band I and broad Band II absorption features (Figure 2b), and distinct secondary absorptions around 1,200–1,300 nm are also apparent (Figure 2c), which is consistent with the presence of abundant olivine and/or Cpx in composition. Although plagioclase feldspar and Fe-rich glass also produce a weak absorption near 1,300 nm, the absorption features of plagioclase feldspar are swamped when admixed with mafic minerals (Crown & Pieters, 1987), and Fe-rich glass rarely produces a strong olivine-like absorption in the spectra of fresh basaltic craters (Farr et al., 1980; Staid et al., 2011). Since the spectra were extracted from fresh craters in maria, these minerals can be ruled out here.

Table 1 presents the averaged spectral parameters of the five mare locations, and those of others are shown in Table S1. Generally, the variation of the BAR value is associated with the Band I center. The maria with lower BAR values ($\sim <1.1$) usually have higher values of Band I center (approximately from 968 to 979 nm, for example, the Aitken crater, Leibnitz basin, and Von Kármán crater in Table 1). This could be due to the presence of more olivine and/or Cpx. Moreover, as the BAR value decreases, the Band I absorptions becomes broader and Band II absorptions narrower (see Figures 2c and 2d), which is consistent with less Opx in composition. Notably, Opx usually displays a narrower Band I absorption than Cpx (Klima et al., 2007; Klima et al., 2011) resulting in a higher BAR value. In general, the maria with the lower BAR values suggest the presence of more olivine and/or Cpx in composition.

Figure 3 presents the averaged BAR values of the mare locations in the SPA area. Note that since the limited fresh craters can be sampled in small mare area (see Figure 1a), it is difficult to determine how typical the spectrum represents the corresponding mare location. However, the distribution of the BAR values does not appear to be strongly linked to the size of the individual mare. The maria with the lowest BAR values ($\sim <0.9$, i.e., red hues in Figure 3) mainly occur in the northwestern SPA area, such as the Aitken crater and Ingenii basin, and in the central portion of the Apollo basin, which is the largest impact crater within the SPA basin. In contrast, the maria with the highest BAR values ($\sim >1.2$, i.e., dark blue hues in Figure 3) are generally located in the areas farther south (e.g., Mare Bose SW and the Poincaré basin) and several small regions (e.g., the Davisson crater). The maria in the middle commonly have medium BAR values (~ 0.9 – 1.2 , i.e., orange, yellow, and light blue hues in Figure 3), such as the Leibnitz basin, Von Kármán crater, and Maksutov crater. The distribution of the BAR values for the maria indicates a trend broadly increasing from the north to the south, which suggests that the northern maria in the SPA area contain more olivine and/or Cpx than the southern ones. The reason for this phenomenon is unclear, and it needs further investigation. Particularly, based on Zhang, Wu, et al. (2016), these spectral properties (the BAR values derived from the spectra of fresh craters) are generally compositionally related rather than a latitude-related artifact.

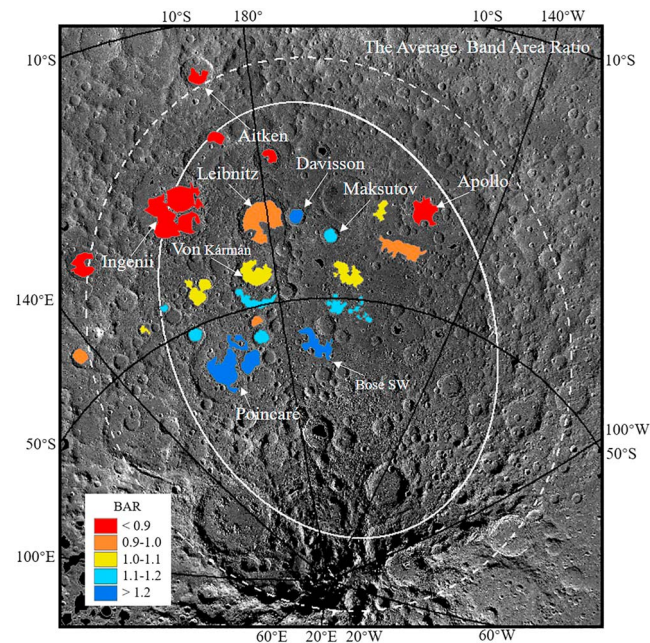


Figure 3. The averaged band area ratio (BAR) values of the mare locations in the South Pole-Aitken area, superimposed on the Lunar Reconnaissance Orbiter Camera Wide Angle Camera mosaic (Robinson et al., 2010). In general, a lower BAR value (redder) indicates a higher content of olivine and/or Cpx. The approximate boundaries of the maria are mapped based on Yingst and Head (1997) and Nelson et al. (2014).

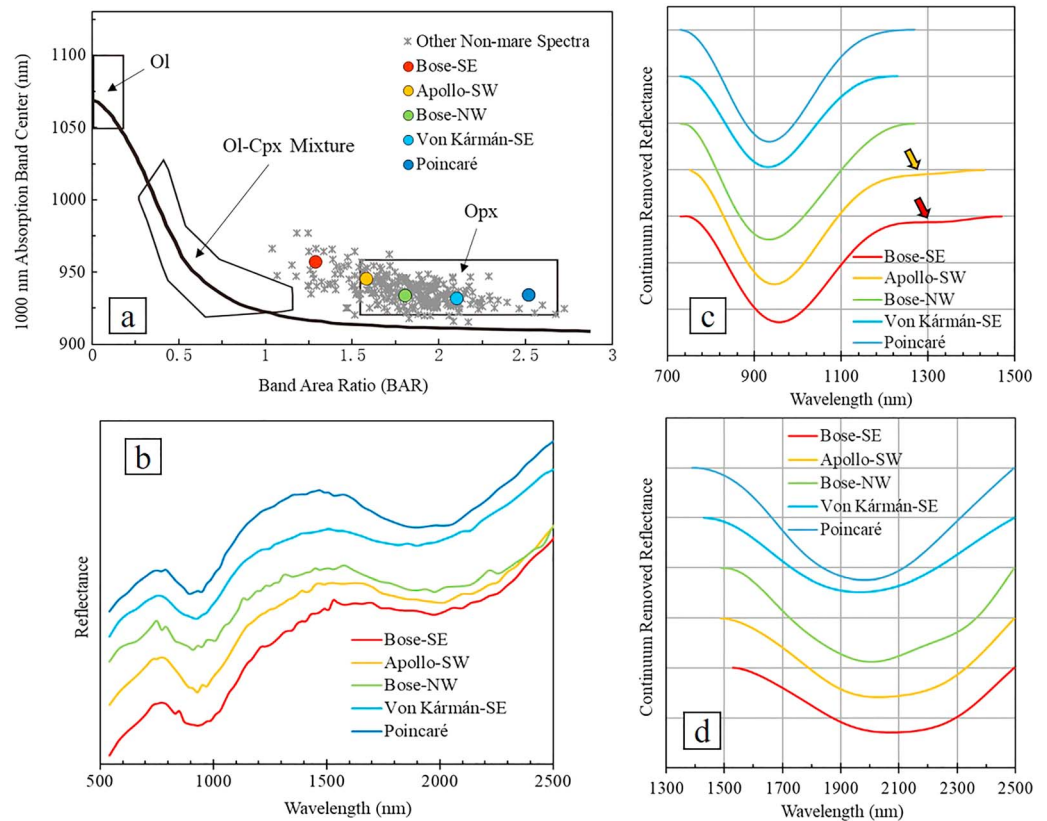


Figure 4. (a) Plot of the band area ratio versus Band I center for the spectra extracted from the nonmare regions in the South Pole-Aitken basin. The Ol-Opx mixing line from Cloutis et al. (1986) and some compositional groups from Gaffey et al. (1993) are drawn as a reference. (b) The raw spectra (without smoothing) of five craters (vertically offset for clarity). (c and d) The continuum removed spectra of Band I and Band II (with smoothing) of five craters (vertically offset for clarity). The arrows mark the secondary absorption around 1,200–1,300 nm.

4.2. Mafic Minerals of the Nonmare Regions

Figure 4a presents the BAR values and Band I centers of the spectra extracted from the nonmare regions in the SPA basin. Most data points of these spectra are mainly around the regions that represent the composition varying from olivine-Cpx mixtures to Opx-dominated materials (Figure 4a). Five representative spectra with different BAR values are shown in Figures 4b–4d (raw spectra and continuum removed spectra), and their sampling locations are presented in Figure 5a. Compared to the maria, the spectra of the nonmare regions also display obvious Band I and Band II absorption features, but Band I appears more symmetric with only a few spectra featuring a weaker secondary absorption around 1,200–1,300 nm (Figures 4b and 4c). This is consistent with much lower olivine and/or Cpx in compositions. More examples of spectra with different BAR values can be acquired in Figures S3 and S4, and their spectral parameters are presented in Table S2.

Table 2 shows the spectral parameters of each of the five spectra. Generally, the Band I centers of the nonmare regions occur at shorter wavelengths (e.g., approximately from 931 to 957 nm in Table 2) than those belonging to maria areas. The spectra with lower BAR values (<1.7 , e.g., samples “Bose-SE” and “Apollo-SW” in Table 2) are obviously distinguished from other nonmare spectra by higher values of Band I center. They usually display relatively broad Band I and narrower Band II absorption features than others (Figures 4c and 4d). These spectral features are consistent with presence of less Opx in composition. For the spectra with medium (~ 1.7 – 2.0) and higher (>2.0) BAR values (e.g., samples “Bose-NE,” “Von Kármán-SE,” and “Poincaré”), they do not display a secondary absorption around 1,300 nm (Figure 4c), which could be due to the presence of abundance Opx. As Table 2 shows, the spectrum of sample “Poincaré” (BAR = 2.5) has a relatively small Band I area but a much larger Band II area than the

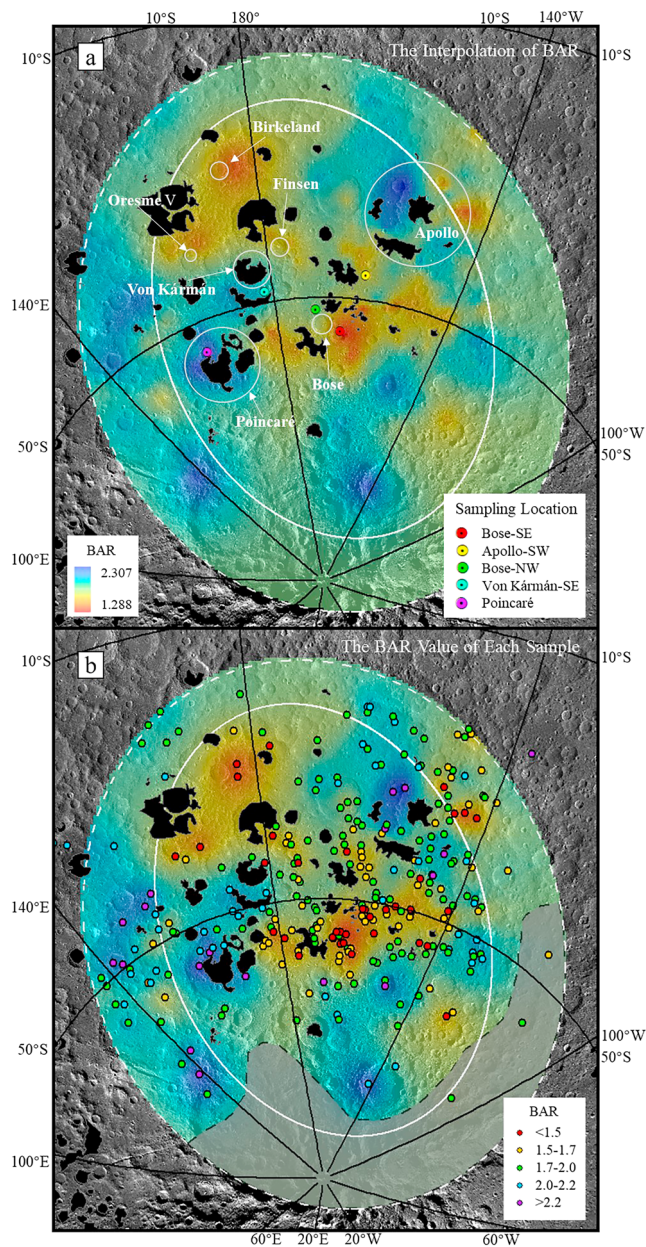


Figure 5. (a) Interpolation map (by simple cokriging method) for the band area ratio (BAR) values of the nonmare regions in the South Pole-Aitken basin (with minimum-maximum stretch), superimposed over an Lunar Reconnaissance Orbiter Camera Wide Angle Camera mosaic (Robinson et al., 2010). In general, a lower BAR value (redder) indicates that the localized mafic material contains less Opx. The small white circle indicates the rim or wall of the crater/basin discussed in this study. The color dots represent the locations of spectra shown in Figure 4. (b) The BAR values of the spectra extracted from the nonmare region. The base map is identical to that for Figure 5a. The gray area presents a region without enough data point.

plagioclase-rich materials (e.g., Ohtake et al., 2014; Pieters et al., 2001). The Opx-H materials mainly occur in the large impact craters/basins, such as the Apollo and Poincaré basins, and the south and edge of the SPA basin (Figure 5a). These regions are roughly consistent with the distribution of the plagioclase-rich materials identified in previous studies (e.g., Ohtake et al., 2014).

spectrum of sample “Bose-NE” (BAR = 1.8), also consistent with the presence of more Opx. Therefore, the spectra of the nonmare regions with the lower BAR values suggest lower concentrations of Opx.

Since some spectra of the nonmare regions are difficult to be distinguished by Band I center (e.g., samples “Bose-NE, Von Kármán-SE, and Poincaré” in Figure 4a and Table 2), the BAR value provides a more sensitive way to analyze the composition of the nonmare materials. An interpolation surface of the BAR values was generated (see Figure 5a) based on the simple cokriging method (the values of Band I center set as the secondary variable). Notably, for the regions with fewer suitable samples, such as those in the south of the SPA basin (marked as a gray area in Figure 5b), the interpolation values in these areas may not represent the most typical local spectral features. The BAR value of each spectrum extracted from the nonmare regions is also plotted in Figure 5b for comparison.

4.2.1. Clinopyroxene

For the spectra with the lower BAR values ($\sim <1.7$, i.e., red and yellow dots in Figure 5b), they are mainly located in the central (around the Bose crater, see Figure 5a) and northwestern (around the Birkeland crater, Finsen crater, and Oresme V crater) portions of the SPA basin, and a few of them distribute in some localized areas (e.g., the northwestern portion of the Apollo basin). Previous studies (e.g., Moriarty & Pieters, 2018; Ohtake et al., 2014; Pieters et al., 2001) usually consider these regions as Cpx-dominated areas. Compared with other nonmare regions, these spectra usually display a weak secondary absorption around 1,200–1,300 nm (Figure 4c), consistent with the presence of Cpx and supporting those interpretations.

For the Cpx-dominated materials around the Bose crater (Figure 5a), named as the SPACA zone by Moriarty and Pieters (2018), previous studies suggest that they are either the materials representing cryptomare or a mixture of old mare/extrusive magma and some low-mafic materials (Moriarty & Pieters, 2018; Ohtake et al., 2014; Pieters et al., 2001; Uemoto et al., 2017; Whitten & Head, 2014) or the differentiated SPA impact melt sheet (Ohtake et al., 2014; Uemoto et al., 2017). For the Cpx-dominated materials in the northwestern SPA basin, they are interpreted as thin ejecta by Ohtake et al. (2014).

4.2.2. Orthopyroxene

For the nonmare regions with medium ($\sim 1.7\text{--}2.0$) and higher ($\sim >2.0$) BAR values (i.e., green, light blue, and dark blue hues in Figure 5a), previous studies used to interpret these areas as an Opx-dominated layer (e.g., Moriarty & Pieters, 2018; Ohtake et al., 2014; Pieters et al., 2001). However, based on the distribution of BAR values, at least two types of Opx-dominated materials can be identified. One type is the Opx-dominated materials with medium BAR values (Opx-M, $\sim 1.7\text{--}2.0$, i.e., green dots in Figure 5b), which are not associated with one region or one size of crater and widely distributed from the center to the edge in the nonmare regions. The other type is the Opx-dominated materials with the higher BAR values (Opx-H, $\sim >2.0$, i.e., blue and purple dots in Figure 5b), which are generally located in the areas associated with

Table 2
The Spectral Parameters of the Five Craters in the Nonmare Regions

Name	Band I center	Band I area	Band II area	BAR
Bose-SE	957.1	59.40	76.53	1.288
Apollo-SW	945.3	60.61	95.94	1.582
Bose-NW	933.5	63.69	115.1	1.807
Von Kármán-SE	931.9	43.10	90.61	2.102
Poincaré	934.0	53.62	135.1	2.519

Note. BAR = band area ratio.

5. Discussion

5.1. Nonmare Opx-Dominated Materials

The numerical simulation results from Melosh et al. (2017) indicate that the SPA impact should have excavated the upper mantle materials and spewed them onto the farside highlands. The SPA edge (i.e., the areas between the inner and outer structures, see Figure 1a), which mostly corresponds to the heterogeneous annulus mapped by Moriarty and Pieters (2018), is described as a mixing zone between crustal materials and the SPA melt and/or ejecta. For the plagioclase-rich areas found within the

SPA inner structure, Ohtake et al. (2014) interpreted them as the residual crust (upper and/or lower crust), which escaped the excavation of the SPA-forming impact and were covered by the SPA ejecta until reexposed by some post-SPA impact events (e.g., the Apollo and Poincaré basins). Some researchers (e.g., Petro & Jolliff, 2013) believe that the formation of the Apollo and Poincaré basins should have excavated into the mantle. Therefore, it is reasonable to consider that the Opx-dominated materials found in these plagioclase-rich areas (i.e., Opx-H materials) are from the mafic lower crust (e.g., Wieczorek et al., 2006) and/or upper mantle. Although not all these areas are with higher BAR values (i.e., light blue and dark blue hues in Figure 5a), it can be argued that some of these regions may have been contaminated by other mafic materials produced by the post-SPA impact events. For example, some Cpx-dominated materials and/or Opx-M materials in the SPACA zone may have been ejected into these areas by some impact cratering.

In contrast, the Opx-M materials around the Bose crater (i.e., green dots in Figure 5) lie within the transient cavity of the SPA impact (e.g., Hurwitz & Kring, 2014) and possibly represent the impact melt of the SPA basin. Lucey et al. (2014) found that the mafic materials on the lunar highlands have higher low-Ca pyroxene/total pyroxene ratios (i.e., higher BAR values) than the typical Opx-dominated materials in the SPA nonmare regions. They suggest that the Opx-dominated materials on the lunar highlands represent the excavated mantle materials from the three largest lunar basins (Serenitatis, Imbrium, and SPA). These results are consistent with our interpretations that the excavated materials from the lower crust and/or upper mantle have higher BAR values (i.e., Mg richer) than the SPA impact melt. Notably, according to the previous studies (e.g., Hurwitz & Kring, 2014), the depth of these excavated materials is generally shallower than the SPA impact melt. The excavated materials discussed in this study refer not only to materials exposed by the SPA formation but also to materials associated with some post-SPA impact events, such as the ejecta and melt of the Apollo basin. Some studies (e.g., Hurwitz & Kring, 2014; Vaughan & Head, 2014) instead interpret the Opx-dominated materials in the SPA basin as a differentiated product of the impact melt sheet because of an assumption that the SPA impact excavated and melted the olivine-rich upper mantle. Although this hypothesis cannot be ruled out, there is no need to invoke such a melt differentiation mechanism if the hypothesis of an Opx-dominated upper mantle is correct (e.g., Lucey et al., 2014; Melosh et al., 2017).

5.2. Immature Materials and Interpolation Surface

Generally, based on the previous studies about space weathering (e.g., Pieters et al., 2000), the difference of some spectral parameters (e.g., the Band I center and BAR) between soils and fresh materials should be limited. However, the weak absorption features of soil spectra can be partially masked by other factors (e.g., spectral noise), as in the M³ data, which possibly affect the output results and make the geologic interpretation challenging. The spectral features of immature materials are more “obvious,” with minor differences between spectra easily observed. For example, as Figures 4c and 4d show, the Opx-M and Opx-H materials have a similar width of Band I absorption, but the Band II absorptions of Opx-H are relatively boarder than Opx-M (more examples are presented in Figure S5). To enhance the variation trend of these spectral features in the study area, a suitable interpolation surface, which helps the geologic interpretation, needs to be applied. Generally, the interpolation surface of the BAR values (Figure 5a) appears “more regular” than the color dots shown in Figure 5b. Although the interpolation surface cannot provide precise point values, it is useful to analyze spatial variation trend of different materials, especially for those with a slight difference in spectral features.

6. Summary and Conclusions

This study analyzed the relative content and distribution of mafic minerals in the SPA basin based on the BAR value and Band I center of the spectra extracted from small fresh craters. For the maria in the SPA

area, the basaltic materials of the northwestern maria are found to contain more olivine and/or Cpx than the southern ones. For the nonmare regions, the Opx-dominated materials can be classified into two types (Opx-M and Opx-H) based on their distribution and different BAR values. One is the Opx-M materials with the medium BAR values, which are widely distributed from the center to the edge of the SPA basin and interpreted as the SPA impact melt. The other is the Opx-H materials with higher BAR values (i.e., Mg richer), which are generally located in some plagioclase-rich regions (e.g., some large impact craters/basins and the SPA edge) and considered to represent materials from the lower crust and/or upper mantle.

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