Goldschmidt crater and the Moon’s north polar region: Results from the Moon Mineralogy Mapper (M$^3$)


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Soils within the impact crater Goldschmidt have been identified as spectrally distinct from the local highland material. High spatial and spectral resolution data from the Moon Mineralogy Mapper (M$^3$) on the Chandrayaan-1 orbiter are used to examine the character of Goldschmidt crater in detail. Spectral parameters applied to a north polar mosaic of M$^3$ data are used to discern large-scale compositional trends at the northern high latitudes, and spectra from three widely separated regions are compared to spectra from Goldschmidt. The results highlight the compositional diversity of the lunar nearside, in particular, where feldspathic soils with a low–Ca pyroxene component are pervasive, but exclusively feldspathic regions and small areas of basaltic composition are also observed. Additionally, we find that the relative strengths of the diagnostic OH/H$_2$O absorption feature near 3000 nm are correlated with the mineralogy of the host material. On both global and local scales, the strongest hydrous absorptions occur on the more feldspathic surfaces. Thus, M$^3$ data suggest that while the feldspathic soils within Goldschmidt crater are enhanced in OH/H$_2$O compared to the relatively mafic nearside polar highlands, their hydration signatures are similar to those observed in the feldspathic highlands on the farside.


1. Introduction

[2] Recent findings from the Moon Mineralogy Mapper (M$^3$) [Pieters et al., 2009], Visual and Infrared Mapping Spectrometer (VIMS) [Clark, 2009], and the Deep Impact High-Resolution Instrument–IR spectrometer (HRI-IR) [Sunshine et al., 2009] have identified absorption features near 2800–3000 nm attributed to OH and/or H$_2$O on the lunar surface. High spatial resolution data from M$^3$ onboard Chandrayaan-1 show that these absorptions exhibit marked variability in their local distribution. In particular, soils within and immediately surrounding the impact crater Goldschmidt (73.2°N, 3.8°W), shown in Figure 1a, display strong hydration absorptions relative to surrounding material, as illustrated by the bright tones in Figure 1b [see Pieters et al., 2009]. This is in contrast with measurements from the Lunar Prospector Neutron Spectrometer (LPNS), which indicate a relatively low concentration of hydrogen at Goldschmidt [e.g., Johnson et al., 2002; Maurice et al., 2004; Lawrence et al., 2006]. Although M$^3$ and the LPNS measure materials at different depths below the surface (~1 mm and ~1 m, respectively), the identification of Goldschmidt as a local anomaly in both data sets suggests that it holds unique information about the character of the local crust, and may help constrain the compositional and/or surface maturity controls on the distribution of surficial OH/H$_2$O. In the present work, we examine M$^3$ data of the Goldschmidt region in the context of the overall compositional variability in the northern high latitudes.

[3] Goldschmidt is a 113 km pre-Imbrium-aged crater on the northern nearside (Figures 1a and 2a) [Lucchitta, 1978; Wilhelms et al., 1987]. Much of the plains material in its interior is covered by ejecta from the 51 km Copernican-aged crater Anaxagoras on its western rim (73.4°N, 10.1°W) [Wilhelms et al., 1987], including impact melt deposits at the eastern rim of Anaxagoras [Hawke and Head, 1977]. Telescopic analyses have identified spectra lacking a 1000 nm absorption in the floor of Goldschmidt, suggesting that pure crystalline anorthosite may have been excavated by the Anaxagoras impact [Hawke et al., 2003]. Similarly, recent analyses of Clementine 5-band UV–VIS data have indicated that...
while the surface unit in this region north of Imbrium has a mafic (low-Ca pyroxene) component, it is underlain by an anorthositic layer [Isaacson and Pieters, 2009]. However, the Isaacson and Pieters [2009] analysis detected mafic absorptions in the central peaks of Anaxagoras, suggesting that the Anaxagoras impact did not penetrate to the feldspathic material.

In this contribution, parameterizations of M3 near-IR spectra are applied to a north polar mosaic of individual M3 data strips. We then examine in detail spectra from Goldschmidt and Anaxagoras in comparison to three other areas at similar latitudes, which should exhibit similar surface temperatures. Since the stability of highly volatile OH and H₂O molecules is largely dependent on temperature, comparing areas that are at similar latitudes is necessary for consideration of other factors (such as composition) that may control the distribution of adsorbed hydrous species. The locations of these three additional areas are shown in Figure 2a: Baillaud crater (74.6°N, 37.5°E), Thiessen crater (75.4°N, 169.0°W), and Karpinskiy crater (73.3°N, 166.3°E). All are relatively large, degraded craters at latitudes similar to Goldschmidt, but represent widespread locations longitudinally, including both the nearside and farside.

2. Data and Methods

[5] The Moon Mineralogy Mapper (M3) is an imaging spectrometer that collected reflectance spectra in 85 spectral bands, from ~430 nm to 3000 nm at 20–40 nm spectral resolution (in its global coverage mode, that used reduced spectral and spatial resolution) (R. O. Green et al., The Moon Mineralogy Mapper (M3) imaging spectrometer for lunar science: Instrument, calibration, and on-orbit measurement performance, submitted to Journal of Geophysical Research, 2011). Most of the data presented here were acquired during part C of the instrument’s second optical period (OP2c), when spectra were collected at a spatial resolution of ~280 m/pixel and the spacecraft was at an altitude of ~200 km. Data from the first optical period (OP1b) were obtained at a spatial resolution of ~140 m/pixel when the spacecraft was at ~100 km altitude. Initial spacecraft pointing was poorly known for OP2c data, often resulting in inaccurate spatial location on the surface, and orbit-to-orbit offsets in preliminary M3 data projections. Corrections are underway for data delivery to the Planetary Data System (PDS), and a detailed discussion of the M3 and relevant Chandrayaan–1 operations and data acquisition strategies is provided by J. W. Boardman et al. (Measuring moonlight: An overview of the spatial properties, lunar coverage, selenolocation and related level 1b products of the Moon Mineralogy Mapper, submitted to Journal of Geophysical Research, 2011). Science analyses of M3 spectral properties that are discussed here, however, do not depend on these corrections, and all crater locations were referenced from the IAU Gazetteer of Planetary Nomenclature (http://planetarynames.wr.usgs.gov/).

[6] In order to compare the spectral character of Goldschmidt to other high-latitude areas on a global scale, we have examined a low spatial resolution (10 × 10 pixel binned) north polar mosaic of individual M3 strips that was prepared for data validation (J. W. Boardman et al., submitted manuscript, 2011). For a more detailed analysis of the variability...
within the Goldschmidt/Anaxagoras region, spectra have been evaluated from an individual full-resolution data strip obtained during OP2c that covers this location. A comparable strip acquired during OP1b is also analyzed to confirm the persistence of spectral characteristics with differences in lighting conditions. Three additional M^3 data strips from widespread locations across the Moon are analyzed in order to characterize at high spatial resolution the overall spectral variability observed at approximately 70–75°N.

The data are presented in "apparent reflectance," which is calculated by multiplying radiance by pi, and dividing by both the cosine of the incidence angle and a solar spectrum that has been corrected for the Sun-Moon distance. Spectra are calibrated to the M^3 version K (R. O. Green et al., submitted manuscript, 2011), and multiplied by a single corrective spectrum (internally known as “KRC1”) for reduction of systematic, high-frequency calibration residuals in the spectra. The KRC1 spectrum is calculated as the inverse of a mean spectrum averaged from a suite of featureless M^3 spectra, from which a straight-line continuum and residual curvature have been removed. Values for the KRC1 spectrum are defined as unity at wavelengths longer 2700 nm, so application of this correction factor should not alter the shape of the hydrous absorption feature. The data presented here have not been corrected for thermal emission [Clark, 1979], although at high latitudes thermal emission is relatively weak and has only a minor effect, if any, on spectral properties such as hydrous absorption band depths (R. N. Clark et al., Thermal removal from near-infrared imaging spectroscopy data of the moon, submitted to Journal of Geophysical Research, 2011).

The most common mafic minerals found on the lunar surface have diagnostic absorption features near 1000 nm (olivine and pyroxene) and 2000 nm (pyroxene) due to electronic transitions of ferrous iron in specific distorted crystallographic sites [e.g., Burns, 1993]. The strengths and positions of these absorption features depend on the mineral compositions and modal abundances in the host rock [e.g., Adams, 1974; Hazen et al., 1978; Cloutis et al., 1986; Cloutis and Gaffey, 1991]. For example, low-Ca pyroxene, the principal mafic component in norites, exhibits shorter-wavelength (~900 and ~1900 nm) absorption bands than high-Ca pyroxene (~1050 and ~2350 nm), which is abundant in basalts. Plagioclase also exhibits a weak mafic absorption, located at ~1250 nm, due to trace amounts of ferrous iron [e.g., Bell and Mao, 1973; Adams and Goulaud, 1978]. However, this plagioclase feature is lost when the mineral is subjected to moderate shock pressures [e.g., Adams et al., 1979], and spectra of feldspathic lunar rocks and soils are, therefore, generally featureless, unless they contain some amount of strongly absorbing pyroxene. Spectra with short-wavelength pyroxene absorptions are referred to in this analysis as “noritic,” since they are interpreted to represent materials containing plagioclase and low-Ca pyroxene. The term noritic is used as an adjective signifying the relative strength of the short-wavelength pyroxene band. Stronger bands are assumed to represent greater abundances of pyroxene when comparing surfaces of similar maturities (space weathering processes are also known to affect spectral contrast) [see Pieters et al., 2000; Hapke, 2001; Noble et al., 2001, 2007].

Spectra of immature surfaces (small craters and steeply sloping crater walls), which preserve the strongest mafic absorptions, are compared for each of the areas studied here. The mafic character of the materials is discussed in relation to the ~2000 nm band in particular, since no olivine absorptions are detected. Soil spectra (multipixel averages) are also examined to allow comparison of the abundance of adsorbed hydrous species on materials of variable mineralogy and maturity.

In the analyses of both the mosaic and individual data strips, parameterizations of M^3 spectra were used to map the spatial distribution of spectral features that are indicative of surface mineralogy. In addition to decreasing the spectral contrast of mafic absorption bands, space weathering processes increase the continuum slope of near-IR spectra of lunar surface materials. A ratio of a long-wavelength spectral band to a short-wavelength band selected from parts of the spectrum not affected by mafic minerals is a first-order approximation of the continuum slope, and can therefore be used as a measure of relative surface maturity. Measuring the absorption strength of materials on the lunar surface requires that the continuum slope first be removed from the spectrum by division [Clark and Roush, 1984]. Following continuum removal, an integrated measure of the local mafic mineral band strength is made by summing reflectance values over the expected wavelength range of the absorption feature.

The four parameters used here are defined in Table 1. The integrated band depth (IBD) is calculated for both the ~1000 and ~2000 nm wavelength regions, although discussions of the mafic character of individual spectra focus only on the ~2000 nm region. The 3000 nm band ratio is sensitive to the slope between 2616 nm and 2856 nm, and therefore may be controlled by the stretching vibration of OH near 2800 nm, the larger superimposed ~3000 nm OH/H2O absorption, or both. Since the ratio does not distinguish between these possibilities, it is referred to generally as the ‘hydrous absorption’ in the text. Interpretations of the 3000 nm band ratio must be considered cautiously, because thermal emission can increase I/F (irradiance divided by solar flux) at 2856 nm relative to 2616 nm. Consequently, the sensitivity of the hydration band decreases with local surface temperature, resulting in an underestimate of the spatial extent and strength of the absorption at 2856 nm, especially on well-illuminated slopes.

3. Analysis of North Polar Mosaic

Results for the spatial distributions of the spectral parameterizations used here are shown in Figures 2a–2e (altimetry from the Lunar Orbiter Laser Altimeter is shown in Figure 2f for context). In each representation, the nearside appears to be much more heterogeneous than the farside as expected, and the Anaxagoras ejecta deposit within Goldschmidt, in particular, can be distinguished from the surrounding material. The variation in the NIR continuum ratio is given in Figure 2b, showing the relatively immature Anaxagoras ejecta covering much of Goldschmidt’s floor. The 1000 nm and 2000 nm IBD parameters are mapped in Figures 2c and 2d, respectively. The Anaxagoras ejecta deposit has relatively weak mafic absorptions, consistent with previous observations that the Anaxagoras impact excavated material that is more feldspathic than local soils [Isaacson and Pieters, 2009]. Also apparent in the 1000 and 2000 nm IBD parameters are the numerous small, mafic
craters across the northern nearside. As expected, the strengths of mafic absorptions on the farside are relatively weak. Materials with strong hydrous absorptions, which are attributed to enhanced abundances of OH/H$_2$O, are indicated by bright areas in Figure 2e. The Anaxagoras ejecta deposit is enhanced in OH/H$_2$O relative to surrounding soils, confirming initial observations based on data from Optical Period 1b (Figure 1b) [see also Pieters et al., 2009]. Additionally, the greater coverage of the Optical Period 2c data in Figure 2e shows that these hydrous absorptions are perhaps comparable in strength to typical farside highland soils. The preservation of crater topography in Figure 2e suggests a contribution from thermal emission to the signal, although this effect is less prominent above $\sim$70°N.

Table 1. Definitions of Spectral Parameterizations$^a$

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Estimates</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIR (2000 nm)</td>
<td>Relative maturity (continuum slope)</td>
<td>$(R_{2576} + R_{2616} + R_{2656})/(R_{1578} + R_{1618} + R_{1658})$</td>
</tr>
<tr>
<td>1000 nm IBD</td>
<td>Fe mineralogy (1000 nm band strength)</td>
<td>$\sum_{n=0}^{26} 1 - \frac{R_{789 + 20\delta}}{R_{c}(789 + 20\delta)}$ Sum of band depths between 789 nm and 1308 nm relative to local continuum with anchor points at 699 nm and 1578 nm.</td>
</tr>
<tr>
<td>2000 nm IBD</td>
<td>Fe mineralogy (2000 nm band strength)</td>
<td>$\sum_{n=0}^{21} 1 - \frac{R_{1658 + 40\delta}}{R_{c}(1658 + 40\delta)}$ Sum of band depths between 1658 nm and 2498 nm relative to local continuum with anchor points at 1578 nm and 2538 nm.</td>
</tr>
<tr>
<td>3000 nm Band Ratio</td>
<td>Hydrous absorption strength</td>
<td>$R_{2616}/R_{2856}$</td>
</tr>
</tbody>
</table>

$^a$In the parameter formulations, R2616 (for example) refers to the reflectance value at the 2616 nm wavelength.

Figure 3. Standard M$^3$ color composite illustrating general mineralogic variation at the north pole. Coverage extends to 60°N. R, integrated band depth (IBD) at 1000 nm (Figure 2c), G, integrated band depth at 2000 nm (Figure 2d), B, reflectance at 1489 nm. Yellow, green, and orange tones represent variations in composition and maturity of mafic lithologies. Blues and purples represent materials that have relatively weaker ferrous absorptions resulting from a greater feldspathic component and/or a large extent of weathering.
Variations in albedo and the strengths of mafic absorptions are combined in the M$^3$ standard color composite (Figure 3). The basaltic soils in Mare Frigoris (yellow tones in Figure 3), and the feldspathic region associated with the Anaxagoras ejecta deposit within Goldschmidt (blue and purple tones in Figure 3), are both clearly distinguished. The surface materials across the nearside, including prevalent small, mafic craters (yellow and green tones in Figure 3), are generally weakly mafic in character but show significant compositional heterogeneity. By contrast, the farside soils are largely feldspathic and much less variable.

From these parameter maps, we have chosen three locations at $\sim$74°N that represent a variety of soil characteristics to compare in detail with the Goldschmidt/Anaxagoras region: Baillaud crater, Thiessen crater, and Karpinskiy crater. Investigating areas at similar latitudes allows comparison of surfaces with comparable temperatures, which is a major control on abundance of OH/H$_2$O [e.g., Pieters et al., 2009; Sunshine et al., 2009]. Baillaud is a 90 km Lower Imbrium–aged crater, filled with smooth light plains material [Boyce et al., 1974; Lucchitta, 1978]. It is located approximately 40 degrees east of Goldschmidt, and its greater distance from the Imbrium basin suggests that it may be less influenced by that major event [e.g., Housen et al., 1983; Haskin et al., 2003]. The presence of mare deposits immediately south of Baillaud in the $\sim$30 km crater Arnold E Table 2. Individual Full Resolution M$^3$ Data Strips$^a$

<table>
<thead>
<tr>
<th>Data Strip File Name</th>
<th>Region Covered</th>
<th>Date</th>
<th>Optical Period$^a$</th>
<th>Orbit altitude (km)</th>
<th>Phase angle range (deg)</th>
<th>Figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3G20090609T060742</td>
<td>Goldschmidt/Anaxagoras</td>
<td>9 Jun 2009</td>
<td>2c</td>
<td>200</td>
<td>70–78</td>
<td>4, 5, 14</td>
</tr>
<tr>
<td>M3G20090206T065053</td>
<td>Goldschmidt crater</td>
<td>9 Feb 2009</td>
<td>1b</td>
<td>100</td>
<td>68–89</td>
<td>6, 7</td>
</tr>
<tr>
<td>M3G20090605T212253</td>
<td>Baillaud crater</td>
<td>5 Jun 2009</td>
<td>2c</td>
<td>200</td>
<td>69–79</td>
<td>8, 9, 14</td>
</tr>
<tr>
<td>M3G20090718T101402</td>
<td>Thiessen crater</td>
<td>18 Jul 2009</td>
<td>2c</td>
<td>200</td>
<td>68–86</td>
<td>10, 11, 14</td>
</tr>
<tr>
<td>M3G20090623T012541</td>
<td>Karpinskiy crater</td>
<td>23 Jun 2009</td>
<td>2c</td>
<td>200</td>
<td>67–77</td>
<td>12, 13, 14</td>
</tr>
</tbody>
</table>

$^a$See full discussion from Boardman et al. (submitted manuscript, 2011). Data have not been corrected for topography, thermal emission, or photometry.

Figure 4. Individual strip of M$^3$ data covering Anaxagoras and Goldschmidt craters acquired during Optical Period 2c. Locations of numbered spectra shown in Figure 5 are indicated. North is up, and the strip is 80 km wide. Shadows have been masked and appear black. (a) Apparent reflectance at 2936 nm. (b) Standard M$^3$ color composite as defined for Figure 3. (c) LOLA gridded topography data for the same area. The file name of this M$^3$ observation is M3G20090609T060742.
(pre-Imbrium-aged) [Lucchitta, 1978; Wilhelms et al., 1987], as well as the distinctly flat floor of Baillaud itself, could indicate that the plains material in its interior is covering mare fill (e.g., a cryptomare deposit [Head and Wilson, 1992]). On the basis of multispectral data from the Galileo mission [Greeley et al., 1993; Pieters et al., 1993] and Earth-based telescopic data [Hawke et al., 1993], some evidence exists for cryptomare in the broader region.

4. Analysis of Individual Data Strips

[15] The four north polar regions are examined in detail using individual high spatial resolution strips of M3 data. Information about each strip, such as the acquisition date, orbit altitude, and phase angles are given in Table 2. The strips are evaluated using the same parameters identified above and in Table 1, and spectra were extracted from various surfaces in each image.

4.1. Goldschmidt and Anaxagoras Craters

[16] As discussed in section 3, the soils within Goldschmidt crater appear to be covered by an Anaxagoras ejecta deposit, which is relatively immature, feldspathic, and displays a strong hydrous absorption feature. The full-resolution strip (~280 m/pixel) of M3 data used to evaluate this region includes coverage of Anaxagoras and the western quarter of Goldschmidt (Figure 4). Reflectance at 2936 nm (Figure 4a) illustrates the degraded nature of Goldschmidt’s rim, in addition to the central peaks and relatively steep walls of the younger Anaxagoras. As in Figure 3, the M3 standard color composite applied to this data strip (Figure 4b) distinguishes mafic lithologies (green, yellow, and orange tones) from more feldspathic materials (blue tones). Locations covered by Anaxagoras ejecta, particularly within Goldschmidt crater, are distinctly more feldspathic than the nonejecta material to the north or south.

[17] The strong, short-wavelength (indicating low-Ca pyroxene compositions) 2000 nm absorptions of small craters south of Anaxagoras demonstrate the noritic character of the local highlands (e.g., Figures 5a–5b, spectrum 1). However, spectra from both small craters (Figures 5a–5b, spectrum 2) and mature soils (Figures 5a–5b, spectrum 3) within the Anaxagoras ejecta deposit are all typically featureless, indicating a feldspathic composition. However, a localized area within Goldschmidt does show a weak

Figure 5. Representative spectra extracted from the corresponding numbered locations in the M3 strip shown in Figure 4. The KRC1 correction has been applied, but the data have not been corrected for thermal emission. Goldschmidt spectra are shown in blue, Anaxagoras spectra are in red. A spectrum from a small noritic crater in the highlands around Goldschmidt and Anaxagoras is shown in black. Solid lines are small craters, dashed lines are crater walls, and dotted lines are soils. The number of adjacent pixels averaged to give each spectrum is indicated in the legend. (a) Apparent reflectance with the KRC1 correction applied. (b) Spectra in Figure 5a divided by a linear continuum anchored at 1619 nm and 2537 nm. (c) Spectra from Figure 5a scaled to unity at 2616 nm.
2000 nm absorption, indicating greater abundances of low-Ca pyroxene than the surrounding soil (e.g., Figures 5a–5b, spectrum 4). It is unclear if this material simply escaped being overlain by Anaxagoras ejecta, or if it is has since been excavated from beneath the ejecta by a crater such as the one shown in Figure 4. Shadows have been masked and appear black. The eastern rim of Anaxagoras (in shadow) is visible on the left. The file name of this M3 observation is M3G0090206T065053.

This diversity within Goldschmidt is confirmed by repeat measurements of the area. An additional strip of M3 data (Figure 6) obtained during OP1b was analyzed, and spectra were collected from representative locations similar to those presented for the OP2c data strip. The lack of a 2000 nm absorption in spectra of the wall and floor of Goldschmidt (Figures 7a–7b, spectra 1–2) are consistent with the predominately feldspathic compositions observed

Figure 6. M3 data strip (shown in apparent reflectance at 2936 nm) acquired during Optical Period 1b covering the western half of Goldschmidt crater. Locations of numbered spectra shown in Figure 7 are indicated. North is up, and the strip is 40 km wide (half the width of the strips in Figure 4). Shadows have been masked and appear black. The eastern rim of Anaxagoras (in shadow) is visible on the left. The file name of this M3 observation is M3G0090206T065053.

[18] This diversity within Goldschmidt is confirmed by repeat measurements of the area. An additional strip of M3 data (Figure 6) obtained during OP1b was analyzed, and spectra were collected from representative locations similar to those presented for the OP2c data strip. The lack of a 2000 nm absorption in spectra of the wall and floor of Goldschmidt (Figures 7a–7b, spectra 1–2) are consistent with the predominately feldspathic compositions observed

Figure 7. Representative spectra extracted from the corresponding numbered locations in the Optical Period 1b M3 strip shown in Figure 6. The KRC1 correction has been applied, but the data have not been corrected for thermal emission. The spectra shown here are from locations analogous to those from which the Optical Period 2c spectra in Figure 4 were collected (spectra 2 and 3 in Figure 7 are from the same locations as spectra 3 and 4 in Figure 4). Solid lines are small craters, dashed lines are Goldschmidt wall, and dotted lines are soil. The number of adjacent pixels averaged to give each spectrum is indicated in the legend. (a) Apparent reflectance with the KRC1 correction applied. (b) Spectra in Figure 7a divided by a linear continuum anchored at 1619 nm and 2537 nm. (c) Spectra from Figure 7a scaled to unity at 2616 nm.
Like Goldschmidt, Anaxagoras crater contains both feldspathic and weakly mafic surfaces, but the heterogeneity is on a larger scale. Spectra from the western wall and central peaks have a slight noritic character, as shown by the weak short-wavelength ferrous absorptions near 2000 nm in the continuum-removed spectrum (Figure 5b, spectrum 5). The north and eastern walls, however, are much more

\[\text{Figure 8. Individual M}^3\text{ data strip acquired during Optical Period 2c covering Baillaud crater (the large flat-floored crater in the northern half of the image). Locations of numbered spectra shown in Figure 9 are indicated. North is up, and the strip is 80 km wide. Shadows have been masked and appear black. (a) Apparent reflectance at 2936 nm. (b) The IBD at 2000 nm, showing the two mare basalt flows just south of Baillaud (the southernmost flow is within the interior of Arnold E). The file name of this M}^3\text{ observation is M3G20090605T212253.}\]
feldspathic, as their spectra are essentially featureless (e.g., Figures 5a–5b, spectrum 6).

[20] All spectra collected within Goldschmidt and Anaxagoras have stronger hydrous absorption features than the noritic crater south of Anaxagoras (Figure 5c, spectrum 1).

The strongest absorptions occur in the feldspathic Anaxagoras ejecta deposit within Goldschmidt (Figure 5c, spectrum 3), and in the walls of Anaxagoras crater (Figure 5c, spectra 5 and 6). The absorption in the feldspathic eastern wall of Anaxagoras is somewhat stronger than in the mafic western wall. The two small craters within Goldschmidt both have weak hydrous absorptions of comparable strength, even though crater 2 occurs in more mafic soils. The difference in the hydrous absorption strength between the soils (stronger absorptions) and craters (weaker absorptions) within the Anaxagoras ejecta deposit suggests that maturity of a surface could be a factor in controlling the apparent abundance of OH/H$_2$O, although the observation may simply be a function of strong illumination at the craters (discussed in section 5).

4.2. Select North Polar Locations

[21] Baillaud crater is a flat-floored crater on the lunar nearside that is similar in morphology and latitude to Goldschmidt. The distribution of relatively immature Anaxagoras rays (dark tones in Figure 2b) illustrates that Baillaud has not been affected by Anaxagoras ejecta, and therefore may serve as a useful comparison to Goldschmidt. The two small mare basalt flows just south of Baillaud [Lucchitta, 1978] illustrate the compositional diversity of this region of the northern highlands. The M$^3$ strip used to evaluate this area is shown in Figure 8. Reflectance at 2936 nm (Figure 8a) illustrates the flat-floored morphology of Baillaud. The 2000 nm IBD in Figure 8b shows that the mineralogy is relatively homogenous in and around Baillaud, with the exception of the mare deposits that exhibit stronger mafic absorptions.

[22] Small fresh craters within Baillaud exhibit spectra with short-wavelength 2000 nm absorptions (e.g., Figures 9a–9b, spectrum 2), suggestive of noritic (low-Ca pyroxene) compositions. Spectra of soils within Baillaud (e.g., Figures 9a–9b, spectrum 1) have much weaker mafic absorptions than the spectra of craters, which is expected for more highly weathered surfaces. However, these soils do have relatively stronger hydrous absorptions than the small craters (Figure 9c). Spectra of small craters in the crater Arnold E (e.g., Figures 9a–9b, spectrum 3) display longer-wavelength 2000 nm absorptions than small craters in Baillaud. This suggests that Arnold E consists of basaltic (high-Ca pyroxene) compositions. The mafic absorptions in mare soils within Arnold E (e.g., Figures 9a–9b, spectrum 4) are weaker than those exhibited by the small craters, presumably due to soil maturation processes and contamination from surrounding nonmare material. However, the mafic absorptions of Arnold E soils are stronger than the mafic absorptions of Baillaud soils. The mare soils in Arnold E also show much weaker 3000 nm absorptions than the soils in Baillaud (Figure 9c).

[23] The two farside craters investigated here, Thiessen (Figures 10–11) and Karpinskij, (Figures 12–13) are located in relatively homogeneous feldspathic highland material, as indicated by the low values for mafic absorption strength in Figures 2c–2d, and by the blue/purple tones in Figure 3. Spectra from the soils, walls, and small craters within Thiessen (spectra 1, 2, and 3, respectively, in Figure 11a) are all relatively homogeneous in composition, and lack strong mafic absorptions. All spectra exhibit hydrous absorptions (Figure 11b), the strongest of which are typically associated...
Representative spectra extracted from the corresponding numbered locations in the M$^3$ strip shown in Figure 10. The KRC1 correction has been applied, but the data have not been corrected for thermal emission. Solid lines are small crater, dashed lines are Thiessen wall, and dotted lines are soil. The number of adjacent pixels averaged to give each spectrum is indicated in the legend. (a) Apparent reflectance with the KRC1 correction applied. (b) Scaled to unity at 2616 nm.

Figure 11. Representative spectra extracted from the corresponding numbered locations in the M$^3$ strip shown in Figure 10. The KRC1 correction has been applied, but the data have not been corrected for thermal emission. Solid lines are small crater, dashed lines are Thiessen wall, and dotted lines are soil. The number of adjacent pixels averaged to give each spectrum is indicated in the legend. (a) Apparent reflectance with the KRC1 correction applied. (b) Scaled to unity at 2616 nm.

with soils (Figure 11b, spectrum 1) rather than small craters (Figure 11b, spectrum 3) or sun-facing wall slopes (Figure 11b, spectrum 2).

Karginsky’s central peaks and floor fractures are visible in the long-wavelength image in Figure 12a. Spectra collected from the floor, walls, small craters, and floor fractures in Karginsky all lack strong mafic absorptions (Figure 13a), which is consistent with a feldspathic highland composition. Spectra collected from each of these surfaces all exhibit hydrous absorptions, although there is a strong enhancement north of the largest fracture (Figures 12b and 13b, spectra 2, 4, and 5). This enhancement of the 3000 nm absorption at Karginsky is apparent in the low-resolution polar images discussed above (appears bright in Figure 2e). Topography data from the Lunar Orbiter Laser Altimeter (LOLA) (Figure 12c) indicate that the strong hydration bands correlate with a topographic low just north of the largest fracture. Possible interpretations of the relationship between topography and the hydrous enhancement are discussed in section 5.

4.3. Distribution of the 3000 nm Absorption Feature

To compare the relative strengths of the hydrous absorption features in the four high-latitude locations studied here, the spectrum from each area (Figures 5c, 9c, 11b, and 13b) exhibiting the strongest 3000 nm absorption is plotted in Figure 14. The comparison is made using spectra that are not continuum removed, since the removal of different continua will affect the band ratio near 3000 nm. This illustrates that Anaxagoras and its ejecta deposit within Goldschmidt exhibit stronger hydrous absorptions than the other nearside location, Baillaud crater. These nearside absorptions, however, are weaker than those seen at either of the two farside locations. Karginsky, in particular, has the strongest hydrous absorption feature of any of the regions investigated here, and possible interpretations of this observation are discussed in section 5.

5. Discussion

The north polar mosaics in Figures 2 and 3 show the nearside to be more heterogeneous in mineralogy than the farside, and this is confirmed by analyses of individual M$^3$ data strips. We interpret this dichotomy to be associated largely with the Imbrium basin. A recent analysis of Clementine multispectral data has shown that a compositional anomaly is expressed on the nearside in nonmare regions north of Imbrium. The relatively mafic character of this highland region was interpreted as resulting from lower crustal material being excavated by the Imbrium and possibly South Pole-Aitken basin-forming events [Isaacson and Pieters, 2009]. The present study confirms the noritic character of the surface soils of the northern Imbrium region, and shows that these mafic compositions extend northward of Goldschmidt and Anaxagoras craters, and at least as far east as Baillaud. We have also confirmed the presence of mare basalt flows near Baillaud, which is additional evidence for nearside compositional diversity at high latitudes. However, the present analysis suggests that noritic, rather than basaltic, lithologies comprise the plains material filling this large, flat-floored crater. Therefore, if the smooth morphology of Baillaud is due to a buried mare basalt unit (cryptomaria) that predates the mare basalt exposed at the surface in Arnold E, then this buried unit must be highly obscured by contributions from noritic ejecta deposits and/or mildly noritic local highland material.

Clementine 5-band spectra have indicated that the central peak of Anaxagoras is noritic in composition, implying that the Anaxagoras impact did not penetrate the regional mafic surface unit [Melosh, 1989; Isaacson and Pieters, 2009]. The M$^3$ data confirm the noritic character of much of the Anaxagoras interior, including the central peak and western wall. However, the present analysis finds that the northern wall, eastern wall, and ejecta are notably feldspathic. The compositional diversity within Anaxagoras itself, and the exclusively feldspathic nature of its ejecta, may require that the target material of this region was highly heterogeneous, and perhaps, more feldspathic, than suggested by the Isaacson and Pieters [2009] analysis.

The present research confirms that the Anaxagoras ejecta deposit within Goldschmidt crater exhibits a strong
local enhancement of OH/H₂O, as observed in initial M₃ results [Pieters et al., 2009]. By contrast, hydrogen measurements made by the Lunar Prospector Neutron Spectrometer (LPNS) found the same region to be relatively low in hydrogen [e.g., Johnson et al., 2002; Maurice et al., 2004; Lawrence et al., 2006]. The discrepancy between these two data sets is likely due to differences in sampling depth, since the LPNS measured hydrogen present in the upper ~1 m of regolith, whereas M₃ detected surficial OH/H₂O in just the upper ~1 mm [Pieters, 1983]. Thus, the processes controlling the distribution of buried hydrogen at the poles may be entirely different than those controlling the distribution of surficial hydrogen. It is likely that much of the OH/H₂O detected by M₃ is adsorbed onto grain surfaces, based partly on observations that the strengths of the NIR hydrous absorption features are correlated with temperature and illumination conditions [Pieters et al., 2009; Sunshine et al., 2009]. In this discussion, we have mainly assumed that variations in hydrous absorption strength are attributable to adsorption onto surfaces of varying mineralogy and age. However, the presence of some amount of structural hydration is also a possibility [e.g., Clark, 2009].

Our observations demonstrate that mineralogy of the host material may be a significant factor controlling the
distribution of OH/H$_2$O, for surfaces with similar surface temperatures and maturities (i.e., comparing soils to other soils at similar latitudes). For example, the feldspathic Anaxagoras ejecta deposit has stronger hydrous absorptions than the surrounding weakly mafic soils. On a smaller scale, the relatively feldspathic eastern wall of Anaxagoras has a stronger hydrous absorption than the mafic exposures in its western wall. For all locations studied here, strong mafic absorptions correspond to only weak hydrous absorptions. This apparent correlation of OH/H$_2$O concentration with feldspathic materials could be due to a number of physical and/or chemical properties of the mineral plagioclase. For example, a greater number of surface defects produced on plagioclase grains relative to pyroxene or olivine grains would enhance adsorption on feldspathic surfaces. Additionally, if plagioclase grains mechanically break down more quickly than mafic minerals during surface maturation [e.g., Cintala and Hörz, 1992; Taylor et al., 2001], their smaller grain sizes may provide more surface area for adsorption. It should also be noted that high-albedo materials are generally cooler, and therefore at least some of the variations in band strength may be due to some aspect of relatively low-temperature thermal emission that is not well characterized. Further, if some amount of the detected OH/H$_2$O is bound within the mineral structure (rather than adsorbed onto the surface), some component of the absorption strength may be attributed to the relatively high optical path length of plagioclase as compared to mafic minerals [Isaacson et al., 2011].

[30] In addition to being more feldspathic than surrounding soils, Anaxagoras ejecta are also relatively immature. Surface maturity is likely to play a role in controlling the amount of adsorbed OH/H$_2$O at the lunar surface, although the nature of the effect is not yet well understood. In contrast to what is observed at Anaxagoras (which may be principally controlled by the compositional trend discussed above), the spectra of mature soils in this study tend to have stronger hydrous absorptions than the spectra of small (presumably fresh) craters. This would suggest that in the regions studied, the space weathering process increases the concentration of adsorbed OH/H$_2$O, perhaps due to a greater number of defects at crystal surfaces produced by solar wind and micrometeorite bombardment over time. This is consistent with the neutron spectroscopy results of Johnson et al. [2002], who found low hydrogen abundances at relatively fresh lunar craters. However, our result may
also be influenced by the effects of illumination conditions, since spectra for small craters are typically taken from strongly illuminated (warm) northern slopes which may be expected to have low OH/H$_2$O concentrations at the time of measurement. Pieters et al. [2009] found that the ejecta of small craters north of Orientale have stronger hydrous absorptions than local soils, suggesting that younger surfaces may favor adsorption, due to a greater number of freshly broken bonds at the crystal surface. Thus, the role of maturity on the distribution of adsorbed OH/H$_2$O is not yet well understood, but future studies using M$^3$ data, using analyses of maturity parameters, such as continuum slope, should be informative in this regard. Indeed, a number of factors, such as mineral chemistry and surface texture (e.g., grain size, porosity), which cannot be directly evaluated with the techniques of the current analysis, may also influence the adsorption of OH/H$_2$O on lunar regolith. Additional laboratory work is necessary to constrain the various parameters controlling adsorption, and to investigate the expression of these factors in the spectra of lunar materials [see Dyar et al., 2010; T. B. McCord et al., Sources and physical processes responsible for OH/H$_2$O in the lunar soil discovered by the Moon Mineralogy Mapper (M3): Possible space dew?, submitted to Journal of Geophysical Research, 2011].

[31] Finally, the local hydrous enhancement in the floor of Karpinskiy crater appears to be unrelated to either composition or maturity. The spatial association of the strong hydration band with the floor fracture suggests that there may be a genetic relationship between the fracture and the local enhancement. If the fracture was produced by intrusion of a magmatic body beneath Karpinskiy [e.g., Schultz, 1976], the enhanced OH/H$_2$O signature may be a result of degassing from the intruded magma. Since even the most recent lunar magmatism appears to have ceased ~1 billion years ago [e.g., Schultz and Spudis, 1983], retention of the OH/H$_2$O signal until the present would require a mechanism to preserve the hydration over long time scales, unless the intrusion was very recent [Schultz et al., 2006]. Another interpretation is that this enhancement is a result of local topography. LOLA data (Figure 12c) show that the crater floor south of the fracture has been uplifted, perhaps during the intrusion of magma [e.g., Schultz, 1976]. The area to the north of the fracture, however, remains at particularly low elevation, and may, therefore, be somewhat shielded from strong direct illumination and be relatively cold. Solar wind hydrogen implanted on the adjacent sun-facing slope may then migrate through the regolith at some depth toward colder temperatures [Grieve et al., 2010], which in this case includes the near-surface soils of the area north of the fracture. This requires that the materials north of the fracture have sufficient surface defects, perhaps produced before the formation of the uplift, to accommodate an OH/H$_2$O enhancement, despite being somewhat shielded from irradiation by solar wind.

6. Conclusions

[32] Analysis of M$^3$ data collected from the Moon’s north polar region reveals that there is considerable mineralogical variability at high latitudes on the nearside, whereas the farside is more homogeneously feldspathic. In particular, the nearside is largely noritic in character, but mare basalts are identified in places. The Anaxagoras impact excavated relatively typical feldspathic highland material from beneath the more mafic surface units, and deposited this material across the floor of Goldschmidt crater. As a result, the spectral character of Goldschmidt is distinct from the surrounding nearside soils, but is generally similar to the feldspathic regions of the lunar farside. Additionally, we find that the distribution of the hydrous species in the north polar region is correlated with the abundance of feldspathic material. Anaxagoras ejecta have stronger hydrous absorptions than the mafic soils dominating the northern nearside, but this enhancement is similar to the signature observed across the feldspathic highlands of the lunar farside.

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References


