Lunar surface aluminum and iron concentration from Galileo solid state imaging data, and the mixing of mare and highland materials

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Abstract. Apollo X ray spectrometer data provide chemical information for 9% of the lunar surface. Galileo solid state imaging system (SSI) multispectral data for the Moon are employed to reexamine the long-accepted positive correlation between lunar surface reflectance (or albedo) and aluminum concentration, derived from Apollo X ray spectrometer data. The overall goal of the analysis is to quantify the relationship between reflectance and aluminum, and to take advantage of the extensive spatial coverage of the SSI data (~75% of the lunar surface) to calculate aluminum concentration from SSI reflectance for the majority of the lunar surface. After removing nonmafic highlands from the analysis, it is found that the relationship between lunar surface reflectance and X ray spectrometer-derived aluminum concentration is described by two diffuse endmembers, representing highland and mare materials, and an apparent mixing line suggestive of mixtures of mare and highland materials. Regression analysis is utilized to show that whereas the correlation between reflectance and aluminum for the entire lunar soil system is fairly good, the correlations for mare soils alone and for highland soils alone are extremely low. The low precision of the X-ray data may at least in part be responsible for the observed poor correlations. Although the low correlation for the individual soil types precludes the precise calculation of aluminum concentration from reflectance, approximate aluminum contents can be determined. The excellent inverse correlation between aluminum and iron concentration for returned lunar soils allows an estimation of iron content to be made as well. An extensive zone of mixtures of mare and highland soils exists in the vicinity of mare-filled impact basins, and around smaller craters. This zone occurs in morphologically defined mare and highland units. Physical mixing of more mafic and less mafic material due to vertical and lateral transport by impact and downslope movement can account for the widespread mixing zones.

Introduction

Mineralogical information provided by high spectral resolution visible and near-infrared reflectance spectroscopy, and elemental information provided by X ray and gamma ray spectroscopy are complementary. Elemental information is useful for determining the general chemical makeup of planetary surface materials. Mineralogical data provide a description of how the chemical constituents are arranged, thus providing information concerning the thermal and geologic evolution of the planetary body in question. In the lunar case, high-quality data of both types exist, although with very limited spatial coverage. The Apollo X ray and gamma ray spectrometers, which flew aboard the Apollo 15 and 16 command modules, provided 9% and 19% coverage, respectively, of the lunar surface, primarily in the near-equatorial regions [e.g., Adler et al., 1972, 1973; Arnold et al., 1972; Biehfeld et al., 1976]. Over the past two or more decades, a range of spectroscopic data has been collected for the Moon [e.g., McCord et al., 1972a, 1972b; Adams and McCord, 1973; Basaltic Volcanism Study Project, 1981; Pieters, 1986, 1993]. High spectral resolution spectroscopic analyses have resulted in detailed mineralogical assessments of several localized areas of the Moon [e.g., Pieters et al., 1980, 1985; McCord et al., 1981; Spudis et al., 1984; Lucey et al., 1986].

Whereas most high spectral resolution near-infrared instruments currently in use produce data that are limited in terms of spatial extent, multispectral cameras provide greater synoptic spatial information at higher spatial resolution, albeit with less mineralogical information due to much lower spectral sampling. The Galileo solid state imaging (SSI) system multispectral data in particular are important in that they provide approximately 75% digital multispectral coverage of the lunar surface at spatial resolutions as high as 1.1 km/pixel. See Belton et al. [1992, 1994] for an overview of SSI results from the two Galileo Earth-Moon encounters. When Clementine data are calibrated and mosaicked, they will provide 100% multispectral coverage of the Moon.

This paper describes the results of a combined analysis of Galileo SSI multispectral imagery and Apollo X ray data. The overall objective of this analysis is to capitalize on relationships between the multispectral and chemical data, and to use the extensive spatial coverage of the SSI data to extrapolate the chemical data into regions not covered by the Apollo spectrometer data. This study specifically focuses on testing and refining the long-accepted relationship between visible reflectance and aluminum (Al) concentration, in which the brighter highland materials are more aluminous than the more...
absorbing, less aluminous mare materials [e.g., Andre et al., 1975]. The goal is to calculate aluminum concentration from SSI reflectance data for regions not observed by the X ray spectrometer.

Data

Three principal data sets were used in this study: Apollo X-ray data, SSI multispectral imagery, and laboratory spectroscopic data of lunar soils. The X ray spectrometers that flew aboard the Apollo 15 and 16 command modules provided data for aluminum and magnesium abundances in the upper tens of microns of the lunar surface. Data reduction resulted in an effective spatial resolution of approximately 30 km [Andre et al., 1977]. The spatial extent of this data is 9% of the lunar surface concentrated primarily in the eastern nearside near-equatorial regions. The reduction of Clark and Hawke [1981] and a newly revised calibration provided by P.E. Clark for converting the Al/Si intensity DN (digital number) data to elemental weight percent Al (P.E. Clark, personal communication, 1994) are used here. This calibration is described below.

The SSI imagery used in this analysis is from a portion of the photometrically corrected (20° phase angle) Lunmos7 mosaic [McEwen et al., 1993; Belton et al., 1994] from the second Galileo lunar encounter (December 1992). The specific portion of the mosaic analyzed here consists of the eastern and central nearside near-equatorial regions. This is the region in which most of the X ray data occur. The nominal spatial resolution of the Lunmos7 SSI data is 1.9 km/pixel. For a description of the calibration and multispectral characteristics of the SSI instrument, see Pieters et al. [1993a]. In the analysis presented here, the SSI reflectance and spectral data are normalized to the values for the lunar standard area in Mare Serenitatis, MS2 (18°40'N, 21°25'E).

The Aluminum-Reflectance Relationship

A positive linear correlation between the albedo and aluminum concentration of the lunar surface was recognized during the initial stages of X ray data analysis [e.g., Adler et al., 1972, 1973]. Early studies recognized the expression of the mare/highland dichotomy in the relationship — in which the darker mare regions are less aluminous than the brighter, more aluminous highland regions. It was also discovered that bright, freshly exposed material associated with recent impact events does not fall along the positive correlation characteristic for other soils [Adler et al., 1973]. The linear relationship between aluminum concentration and reflectance in the remote data was attributed to the same mineralogical relationship that controls the aluminum and iron concentration in lunar soils as a whole, namely, the interplay between amount of bright, aluminous, plagioclase-rich material and absorbing, relatively aluminum-poor, ilmenite and pyroxene-rich material [e.g., Adler et al., 1972; Clark et al., 1976]. These early analyses of the aluminum-reflectance relationship relied on telescopic albedo data for the Moon that were characterized by relatively low spatial resolution, were in some cases analog [e.g., Pohn and Wildey, 1970], and in all cases were limited to the lunar nearside. The higher spatial resolution, extensive coverage (including half of the farside), and digital format of the SSI data provide an opportunity for a detailed reexamination of the relationship between reflectance and aluminum, and an opportunity to calculate aluminum concentration for the majority of the lunar surface.

Figure 1a is a SSI mosaic of our study area at 0.76 μm. Superimposed upon the region is an outline of the extent of the X ray coverage in the area. The 0.76-μm data were chosen over the nominal 0.56-μm data because in raw form the 0.76-μm data appear to exhibit a smaller amount of frame-to-frame offset errors than the 0.56-μm data. After normalization to a central "truth" frame, there were no remaining detectable frame-to-frame offsets in the study area. Shown in Figure 1b is aluminum concentration for this region derived from the Apollo X-ray spectrometer data. The photometrically corrected SSI reflectance at 0.76 μm is compared in Figure 2 to elemental weight percent aluminum calculated from the X ray data. As noted above, in the present analysis the 0.76-μm reflectance data are normalized to the reflectance of the lunar spectral standard area, Mare Serenitatis, MS2. (18°40'N, 21°25'E).

Figure 1a. Reflectance image at 0.76 μm of the central and eastern lunar nearside from a portion of the Galileo SSI Lunmos7 mosaic. Major geologic features and the location of the nearside Apollo X-ray spectrometer data are indicated. This image has been photometrically corrected to 20° phase angle [McEwen et al., 1993].

Figure 1b. Lunar nearside aluminum concentration calculated from Apollo X-ray spectrometer data. Elemental weight percent Al is calculated from the X-ray data reduction of Clark and Hawke [1981] using a new calibration for converting Al/Si intensity to weight percent Al (P.E. Clark, personal communication, 1994).
Elemental weight percent aluminum is calculated from the Al/Si intensity data of Clark and Hawke [1981] using the new calibration (P.E. Clark, personal communication, 1994):

$$\text{Al( wt%) = } \left( \frac{\text{DN}_{\text{Al/Si}} \times 0.093}{1} \right) + 2.69$$  \hspace{1cm} (1)$$

assuming constant Si concentration (21 wt%) and where DN_{Al/Si} is the DN value of the Clark and Hawke [1981] Al/Si intensity data. The previous calibration of Clark and Hawke [1981] produced Al wt% values that were considered erroneously high (P.E. Clark, personal communication, 1994). Clark found these high values to be due to slight inaccuracies in the solar correction model. The revised calibration formula shown above incorporates an updated solar correction model and consequently produces chemical results that are more acceptable if it is assumed that the aluminum content of Apollo 16 soils is typical of highland material. A histogram of the weight percent Al for the nearside X ray data using the revised calibration is shown in Figure 3. For these data, the highland mode is close to anorthositic gabbro, which is commonly assumed to be average highland composition [e.g., Davis and Spudis, 1987]. The previous calibration resulted in a highland mode at more aluminous compositions, between gabbroic anorthosite and anorthosite.

The overall focus of the analysis presented here is to quantify the relationship between SSI reflectance and X ray aluminum in order to calculate aluminum concentration from the spatially extensive SSI reflectance data. However, as noted above, freshly exposed materials do not fall along the positive aluminum-reflectance correlation that is characteristic for other soils. This results from the fact that optical properties (such as reflectance) of lunar soils are a function not only of composition, but also of degree of exposure to the lunar surface (see below). Therefore, in order to accurately quantify the aluminum-reflectance relationship, only soils that have been exposed at the lunar surface for similar amounts of time must be included in the analysis. Our approach here is to isolate mature soils for analysis.

**Identification of Mature Materials**

Optical properties of lunar soils (such as reflectance) are altered as a result of exposure to space weathering processes at the lunar surface. The optical properties of a soil change systematically with increasing exposure until, after a given cumulative length of exposure, the soil reaches a state called "mature." At this point, the optical properties of the soil no longer change with increasing exposure [Adams and McCord, 1973; Charette et al., 1976; Fischer and Pieters, 1994]. Thus the spectral properties of lunar soils are a function both of composition and of degree of exposure at the lunar surface. For example, two soils of identical lithologic origin will be spectroscopically similar if both have been exposed for equal lengths of time. This accounts for the optical similarity of some mature soils from the same Apollo landing site [Adams and McCord, 1973; Charette et al., 1976; Fischer and Pieters, 1994]. However, if one soil has a significantly shorter cumulative exposure age than the other, the two soils will have different spectral characteristics.

The reflectance of a lunar soil decreases with increasing exposure. Therefore, in order to accurately assess the aluminum-reflectance relationship, it is important to compare only soils that have been exposed to space weathering processes for similar amounts of time. Mature soils can be compared because their optical properties have been altered to the same degree. (For further discussion of the alteration of optical properties, see Fischer and Pieters [1994], Pieters et al. [1993b], Charette et al. [1976], Hapke et al. [1975], Adams and McCord [1971a, 1971b], and other papers by the same authors.)

A method for identifying and isolating soils characterized by similar degrees of exposure is discussed by Fischer and Pieters [1993, 1994]. Mature and nonmature highland soils can be discriminated using a 0.76-μm/0.99-μm reflectance ra-
tio, which is related both to the slope of the continuum and to the strength of the ferrous iron absorption at 1 μm. In this method, lunar sample analyses are used to derive a 0.76-μm/0.99-μm value, below which soils are considered mature. This test can then be applied to remotely acquired data to identify nonmature soils and eliminate them from the analysis. It should be noted that the 0.76-μm/0.99-μm method cannot be used for the basaltic mare soils because the large and widely varying amount of opaque minerals in mare soils complicates the relationship between optical properties and degree of exposure.

Using laboratory spectra of a suite of lunar soils, Fischer and Pieters [1994] determined that a 0.76-μm/0.99-μm value of 0.91 distinguishes between mature and nonmature highland soil bidirectional reflectance data for an incidence angle of 30° and an emergence angle of 0°. Because the SSI data in this analysis are relative to MS2 at a phase angle of 20°, it was necessary to correct the soil bidirectional data to be relative to MS2 at 20° phase angle. This involved a simple multiplicative factor that can be derived from telescopic data. Using the recalibrated soil data, an appropriate cutoff ratio value was determined as per Fischer and Pieters [1994] to be 0.96 (0.76 μm/0.99 μm for MS2=1.0). Highland soils with ratios less than 0.96 are considered mature. This maturity criterion was applied to all materials in the study area with reflectances greater than 1.2 times the reflectance of MS2. This value of relative reflectance was found to accurately distinguish between mare soils and other materials (see next section). Mature soils exhibiting reflectances greater than 1.2 times the reflectance of MS2 will hereafter be referred to as "nonmare soils." A visual examination of craters and their associated ejecta in the 0.76-μm/0.99-μm ratio image for the SSI data verifies the appropriateness of the value used to discriminate between mature and nonmature soils. Shown in Figure 4 is the distribution of nonmare soils in our study area determined to be nonmature using this method.

It should be noted that the 0.76-μm/0.99-μm method works very well for identifying nonmature highland material characterized by reflectances greater than 1.4 times MS2, but may result in the mischaracterization of some mature material in the 1.2 to 1.4 reflectance range as nonmature. The reason for this mischaracterization is that mature soils in this reflectance range are mare/highland mixtures (see below). Some of these mixtures have 1-μm absorption bands deep enough to register the soils as nonmature using the 0.76-μm/0.99-μm method [see Fischer and Pieters, 1994]. To be conservative in the identification of mature soils for this analysis, the 0.76-μm/0.99-μm method is applied to materials with reflectances greater than 1.2 times MS2.

Quantitative Analysis of the Aluminum-Reflectance Relationship

In order to accurately evaluate the relationship between aluminum content and SSI reflectance, the data were reprojected to an equal-area projection, and the SSI data were then resampled to the spatial resolution of the X ray data. Shown in Figure 5 is the reprojected SSI mosaic with the nonmature, nonmare soils removed.

For the aluminum-reflectance relationship (shown in Figure 2), a correlation coefficient from regression of all X ray data in the study region is 0.70. A coefficient of 0.71 is found for the relationship when nonmature, nonmare materials are removed. Clark et al. [1976] found a correlation coefficient of 0.78 for a limited area between 0° and 25°N and 15° and 50°E. Using SSI reflectance data, we calculate a coefficient of 0.84 for this same region. The higher correlation calculated in this study relative to that found by Clark et al. [1976] may result from smaller errors in the SSI data relative to the albedo data of Pohn and Wildey [1970], used by Clark and others.

Although the overall nature of the relationship illustrated in Figure 2 is that of a positive correlation, the general linear trend is dominated by two diffuse endmember clouds (one with reflectances less than 1.2 times MS2 and one with reflectances greater than 1.4 times MS2) and an apparent mixing zone between the endmember clouds. The spatial distribution of all material with reflectances less than 1.2 times the value of MS2 corresponds exclusively to mare regions (Figure 6a), whereas the distribution of all material characterized by reflectances greater than 1.4 times MS2 corresponds exclusively to highland regions (Figure 6b). Soils exhibiting reflectances between 1.2 and 1.4 times MS2 occur at mare/highland boundaries, in areas of apparently thin basaltic units, and in mare areas which are obviously overlain by highland material (Figure 6c). It should also be noted that materials associated with ac-

![Figure 4](image-url)  
Figure 4. Nonmare materials determined to be nonmature on the basis of the 0.76-μm/0.99-μm method are shown in black [Fischer and Pieters, 1993, 1994]. The 0.76-μm/0.99-μm maturity criterion was applied to materials exhibiting reflectances greater than 1.2 times the reflectance of MS2. Note that even very small, fresh highland impact craters are correctly identified in this manner.

![Figure 5](image-url)  
Figure 5. The study area reprojected to an equal-area format and resampled to the spatial resolution of the X ray spectrometer data. Nonmare regions indicated in black are determined to be nonmature on the basis of the 0.76-μm/0.99-μm method.
highland materials. Therefore, to a first order, mare soils can be defined as those materials exhibiting reflectances less than 1.2 times the reflectance of MS2, highland soils can be defined as those with reflectances greater that 1.4 times MS2, and mare/highland mixtures as those with reflectances between 1.2 and 1.4 relative to MS2. We will return to a discussion of these mixtures in a later section. Note that 1.2 and 1.4 are rounded figures simplified for discussion; it could be argued that more accurate cutoff values deviate slightly from these figures.

Although the correlation for the entire mare/highland soil system is moderately good (correlation coefficient of 0.71), in order to have confidence in the calculation of Al concentration from SSI reflectance data, not only must the correlation of the entire system be good, but Al and reflectance must be highly correlated for mare soils alone and for highland soils alone as well. To test the correlation for the individual soil types, linear regression analysis was performed separately on the mare, highland, and mare/highland mixture zones. These soil types were defined on the basis of reflectance, as discussed in the previous paragraph. The correlation coefficients resulting from linear regression analysis are shown in Table 1. Whereas the correlation coefficient for all data is moderately good, the coefficients for the individual soil types are all less than 0.4. These results indicate that neither mare nor highland soils alone exhibit a systematic linear relationship between reflectance and X ray spectrometer-derived aluminum. The same is true for the group of soils that are mare/highland mixtures. We are left to conclude that the long-accepted linear relationship between aluminum and reflectance is due at least in part to a mixing line between two diffuse endmembers, broadly defined by mare and highland materials. The low precision of the X ray data may, however, artificially lower the correlation coefficients (see below). Although the poor correlations preclude the simple precise calculation of aluminum concentration from reflectance, the relationship nevertheless (1) allows an approximate calculation of aluminum concentration to be made for the three major soil types, i.e., mare, highland, and mare/highland mixtures, (2) suggests a somewhat more complicated relationship than expected between highland soil optical and compositional properties, and (3) yields information concerning large scale mixing of mare and highland materials. These are discussed below.

<table>
<thead>
<tr>
<th>Data Used</th>
<th>Linear Regression Coefficient</th>
</tr>
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<tbody>
<tr>
<td>All lunar nearside X ray data</td>
<td>0.70</td>
</tr>
<tr>
<td>Mare + mature highland and mixtures (all &lt;1.2xMS2 + mature &gt;1.2xMS2)</td>
<td>0.71</td>
</tr>
<tr>
<td>All mare (all &lt;1.2xMS2)</td>
<td>0.27</td>
</tr>
<tr>
<td>Mature highland (mature &gt;1.4xMS2)</td>
<td>0.26</td>
</tr>
<tr>
<td>Mature mixtures (mature 1.2-1.4xMS2)</td>
<td>0.10</td>
</tr>
<tr>
<td>Mature highland and mixtures (mature &gt;1.2xMS2)</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Figure 6. Three major lunar soil types defined on the basis of reflectance. (a) Soils characterized by reflectances less than 1.2 times the reflectance of MS2 correspond exclusively to mare regions; (b) soils characterized by reflectances greater than 1.4 times MS2 correspond exclusively to highland regions; and (c) soils exhibiting reflectances between 1.2 and 1.4 times MS2 occur at mare/highland boundaries, in areas of apparently thin basaltic units and in mare areas overlain by highland material.
Uncertainties and Sources of Error

In the above regression analyses, the uncertainties of the data were assumed to be negligible. This is certainly not the case for the X-ray data. SSI data (particularly monochromatic imagery) are characterized by much higher precision than the X-ray data, and thus we will focus our attention solely on the errors in the X-ray data. See McEwen et al. [1993] for a discussion of errors in the SSI data.

Clark and Hawke [1981] found the average deviation for the Al/Si intensity data due to spurious interorbital variation to be approximately ±5%. This figure can be considered to provide an estimate of instrumental precision. Assuming an average Al/Si intensity ratio of 1.06 and converting intensity data to weight percent using equation (1) we find the average deviation for aluminum concentration to be ±0.65 wt%. This deviation is illustrated in Figure 2.

Additional possible error is introduced into the calculation of aluminum concentration from X-ray data by assuming a constant Si content across the lunar surface. For a wide range of lunar materials, silicon content can vary 2 wt% or more about the mean 21 wt% [cf. Taylor, 1982]. This alone yields a ±1.25 wt% uncertainty to the Al data. For highland materials only, however, silicon variation is much lower, resulting in a ±0.5 wt% Al uncertainty for highlands.

Clearly, the low precision that characterizes the X-ray measurements of Al significantly reduces the correlation coefficient between Al and reflectance. For example, as shown in Figure 2, the range of observed aluminum content in highland materials alone is approximately 4 to 5 wt%. Because the uncertainties in the X-ray measurements constitute a large fraction of the observed range of highland aluminum values, for example, a stronger correlation between aluminum and reflectance for highlands may be masked by the low precision of the X-ray data. Thus the potential to calculate aluminum content from reflectance may in fact be somewhat better than the current X-ray data suggest. The resolution of this issue awaits more precise X-ray measurements to be made.

Calculation of Al and Fe and Implications for Lunar Soils

Although based upon the results of the combined SSI/Apollo X-ray analyses, the precise determination of Al concentration from reflectance is not possible, the moderately high correlation between Al and reflectance for the entire soil system allows a general calculation of aluminum concentration. The equation determined by linear regression of all mare and mature nonmare soils in the study area is

$$\text{Al}(\text{wt}%) = \left( R_{0.76/\text{MS}2} \times 7.39 \right) + 1.65$$

where $R_{0.76/\text{MS}2}$ is the reflectance at 0.76 μm relative to the reflectance of MS2 (at 20° phase angle). To convert weight percent aluminum to oxide (Al$_2$O$_3$) concentration, multiply by 1.89. The sum of squares of the regression yields an uncertainty of ±2.08 wt% Al (one standard deviation).

Mare soils. The spatial distribution of soils in Figure 6a illustrates quite well that soils with reflectances less than 1.2 times the reflectance of MS2 correspond exclusively to non-contaminated mare regions. The correlation coefficient for linear regression between reflectance and aluminum for these materials alone is a very low 0.27. The lack of a systematic relationship between aluminum and reflectance for mare soils is not surprising. There is a large and widely varying abundance of opaque minerals (mostly ilmenite) in mare soils. This opaque component significantly complicates the theoretically simple mineralogical relationship that controls both brightness and aluminum concentration, i.e., the interplay between the abundance of bright, aluminous, plagioclase-rich material and more absorbing, aluminum-poor, mafic-rich material [e.g., Clark et al., 1976]. Although the optical behavior of mare soils thus does not lend itself to the precise prediction of aluminum concentration, the positive correlation of all data suggests that all soils with reflectances less than 1.2 times MS2 are characterized by aluminum concentrations less than 10.5 element weight percent. Comparing soils in this reflectance range to the X-ray aluminum data, it is found that 82% of the pixels characterized by reflectances less than 1.2 times the reflectance of MS2 do indeed contain less than 10.5 wt% aluminum. This indicates a fairly high (~80%) confidence level for the determination of Al content for soils in this manner. The average Al content for mare soils in the X-ray coverage portion of the study area is 9.1 ±1.9 (one standard deviation) wt%.

Highland soils. Highland soils can be roughly distinguished from other lunar materials as mature soils characterized by reflectances greater than 1.4 times the reflectance of MS2 (see Figure 6b). The low aluminum-reflectance correlation coefficient of 0.26 for the mature highland soils is somewhat unexpected. Highland soils are not typically characterized by large amounts of opaque minerals. Possible sources of scatter in the aluminum-reflectance relationship are the effects of other iron-rich phases, and the fact that the total mineralogical variation of highland soils on the Moon is certain to be more extensive than that in the returned lunar samples [cf. Davis and Spudis, 1985; Hawke et al., 1985]. Finally, as for all soil types, errors in the data may contribute to the scatter.

It is instructive to note that both the Cayley and Descartes materials sampled at the Apollo 16 site plot as outliers in reflectance-aluminum space (Figure 2). Because soil returned from the Apollo 16 site is often considered to be "average" highland material, the fact that the Apollo 16 soils are outliers in reflectance-aluminum space lends credence to the possibility that widely varying highland mineralogy is at least in part responsible for the scattered aluminum-reflectance relationship. This also suggests that the highland soils at the Apollo 16 landing site perhaps should not be referred to as "typical highland materials," as they are often described.

As is the case for the mare soils, although the scattered aluminum-reflectance relationship for highland materials precludes the precise calculation of aluminum concentration from reflectance, it can be calculated that mature soils with reflectances greater than 1.4 times the reflectance of MS2 have aluminum concentrations greater than 12.0 element weight percent. Comparing soils in this reflectance range to the X-ray aluminum data, it is found that 82% of the pixels characterized by reflectances greater than 1.4 times the reflectance of MS2 do indeed contain greater than 12.0 wt% aluminum. The average Al content of highland soils in the X-ray coverage portion of the study area is 13.5 ±2.3 wt%.

Mare/highland mixtures. One of the interesting aspects of this analysis is the information provided concerning mixtures of mare and highland materials. Given the apparent mixing line of materials between 1.2 and 1.4 times the reflectance of MS2 (Figure 2), and given that these materials occur at mare/highland boundaries (Figure 6c), mature soils in
this reflectance range can be inferred to be mixtures of mare and highland materials. This is supported by chemical and petrographic analyses of certain soils returned from landing sites at mare/highland boundaries (i.e., the Apollo 15 and 17 sites) that show the soils to be physical mixtures of mare and highland materials [e.g., Basu and McKay, 1979; Walker and Papike, 1981; Papike et al., 1982]. Spectroscopic data for several of the mixture soils studied by Walker and Papike [1981] and others are included in the John Adams lunar soil spectra collection, as described by Adams and McCord [1970, 1971a, 1971b, 1973]. As expected, these returned mixture soils exhibit intermediate aluminum contents as well as intermediate reflectances when laboratory and telescopic data are compared.

Evidence for widespread mare/highland mixing is provided in the form of an extensive reflectance gradient observed in the vicinity of mare/highland borders (Plate 1). This gradient exists around all mare-filled basins and smaller craters, and extends up to hundreds of kilometers from the morphological mare/highland boundary. This gradual increase of reflectance into the highlands and decrease into the mare is consistent with the mixing of darker, more mafic and brighter, less mafic material. An example of a profile of reflectance and aluminum data across the mare/highland boundary in the eastern portion of the Serenitatis basin is shown in Figure 7.

The overall positive correlation illustrated in Figure 2 suggests that mature soils with reflectances between 1.2 and 1.4 times the reflectance of MS2 contain between 9.2 and 14.4 wt% Al. It is found by comparison with the X ray data that 68% of soils in this reflectance range are actually characterized by aluminum concentrations between 9.2 and 14.4 wt%. The more scattered nature of this portion of the relationship results in large part from nonmature mare soils included in the analysis and from the abnormally bright, aluminum-poor Apennine Bench Formation, which exhibits reflectances in this range. The average Al content for these soils in the X ray coverage portion of the study area is 11.8 ±2.6 wt% Al.

Iron concentration. Returned lunar soils exhibit an excellent inverse correlation between aluminum and iron concentrations (Figure 8) [e.g., Miller et al., 1974]. Although there is a break in slope for this relationship between the mare and highland soil fields (or at least between the mare soil and Apollo 16 soil fields), the relationship exhibits a correlation of 0.98. The correlation for mature soils alone is also 0.98. One caveat should be mentioned, however. The correlation will likely only hold for soils whose Fe/Mg ratios are fairly constant. Thus the extrapolation of this correlation to regions distant from landing sites should be viewed with some caution.

This caveat aside, the reflectance of surface materials allows a general estimation of iron content as well as aluminum concentration. Mare soils (defined on the basis of reflectance) are calculated to contain greater than 7.1 wt% Fe. Highland soils contain less than 5.8 wt% Fe. Mare/highland mixture soils contain between 4.0 and 8.6 wt% Fe. To express these abundances as oxide (FeO) concentrations, multiply by 1.29.

Summary. Summarized in Figure 9 at the nominal resolution of the SSI mosaic are the calculated Al and Fe concentrations within the study area. As suggested by the confidence levels noted in the above sections, the overall agreement between the aluminum concentration calculated from reflectance and that observed by the X ray spectrometer is quite good (compare to Figure 1b). Major deviations from consonance between the observed and calculated aluminum concentrations include the Apennine Bench Formation, and the Cayley and
Descartes materials in the vicinity of the Apollo 16 landing site, all of which are characterized by lower aluminum values (from X-ray measurements) than are implied by reflectance. The low precision of the X-ray data may be the limiting factor in this approach.

**Origins and Implications of Mare/Highland Mixtures**

As discussed in the previous sections, the combined X-ray/SSI analysis suggests the presence of mare/highland mixtures in the vicinity of morphologic highland boundaries. Petrographic and chemical measurements of returned lunar samples have also documented physical mixing of mare and highland material in the vicinity of the mare/highland mor-phologic border [e.g., Basu and McKay, 1979; Walker and Papike, 1981; Papike et al., 1982; Simon et al., 1990]. These sample analyses favor mixing by impact cratering, small-scale gardening of the regolith and downslope movement, but argue that the mixing of local material with material derived from more than 10 km or so distant is extremely limited [e.g., Rhodes, 1977; Hörz, 1978; Laboska et al., 1980; Laut and Papike, 1980; Farrand, 1988; Simon et al., 1990]. Vertical mixing by impact is cited as the preferred mechanism. The zone of mixing suggested by the present analysis, however, is of the order of several tens of kilometers wide (see Plate 1 and Figure 7). Clearly, the scale of mixing suggested by the combined X-ray/SSI analysis and that suggested by previous sample analyses must be reconciled.

**Observational Limitations**

Can the low spatial resolution of the X-ray spectrometer and stray light in both the spectrometer and the SSI camera produce spurious "mare/highland mixing zones?" The effective spatial resolution of the X-ray spectrometer is approximately 30 km [Clark and Hawke, 1981], whereas the SSI data exhibit reflectance gradients on the scale of 100 km at 1.9 km/pixel. Therefore, although the observed width of the apparent chemical mixing zone may be explained in part by the low spatial resolution of the X-ray data, the extremely wide reflectance gradient still must be accounted for.

Stray light has been recognized as a significant component of the SSI data [McEwen et al., 1993; Gaddis et al., 1995]. Stray light may, for example, result in small mare units surrounded by highlands appearing brighter than they actually are. The reflectance gradients from mare to highlands observed in the SSI data, however, can be observed in all previously acquired data (e.g., Lunar Orbiter imagery and Apollo Metric photography). Thus, whereas the width of the mare-highland mixture region may be slightly affected by stray light in the SSI system, the existence of a broad reflectance gradient cannot be doubted.
Physical Mixing by Impact Cratering

The arguments against extensive lateral mixing of material [cf. Rhodes, 1977; Hörz, 1978; Labotka et al., 1980; Farrand, 1988] are based upon three major lines of evidence. First, early theoretical impact calculations suggest that the lateral transport of target material is very inefficient; second, geochemical boundaries between mare and highland units have previously been reported by some as very sharp; and third, mare soils obtained from more than several kilometers from highland massifs have very little highland component.

The early theoretical impact calculations normally cited to refute the efficacy of lateral mixing include Gault et al. [1974] and Arvidson et al. [1975], among others. These excellent analyses of the impact process, however, have several limitations in the current context of lateral mixing. For example, these analyses do not take into account the contributions of the secondary cratering process to lateral transport of primary material. Later work by Schultz and Gault [1985], for instance, shows that secondary impactors transport significant amounts of primary ejecta laterally and that the ratio of transported target material to locally excavated material can be quite high in the secondary cratering process. The evolution of thought regarding cratering calculations since the first discussion of lateral mixing (i.e., from the early ejecta blanket concepts of McGetchin et al. [1973] to the modeling of secondary impactors by Oberbeck [1975] and others) has resulted in the recognition that primary material can be transported to greater distances than previously modeled. It is interesting to note, however, that even though Arvidson et al. relied on a modification of the McGetchin et al. [1973] model, they nevertheless clearly state that soil properties can be strongly affected by components derived from more than 10 km away. These revised conclusions along with the spectroscopic detection of significant amounts of target material in crater rays [e.g., Saunders et al., 1976; Pieters et al., 1985] suggest that lateral transport of target material may be somewhat more efficient than assumed in some previous work.

Most authors cite Adler et al. [1974] to argue that the mare/highland boundary is geochemically sharp. In fact, Adler et al. recognize the evidence for lateral mixing. They simply conclude that lateral mixing has not occurred to the extent that the chemical differences between mare and highland regions have been obliterated. In other words, a boundary will continue to be observed until the soils are fully homogenized at the scale of the observations.

Petrographic data suggesting the highland component in mare soils decreases extremely rapidly away from mare/highland morphologic boundaries provide evidence against extensive mixing of local mare material with material derived from more than several kilometers away [e.g., Labotka et al., 1980; Laul and Papike, 1980; Simon et al., 1990]. Nevertheless, the existence of a significant feldspathic component in Apollo 11 soils in addition to the presence of primary ejecta from the Theophilus impact in the vicinity of the Apollo 11 site emphasize the importance of at least local events in the transport of primary material. Indeed, most mare...
soils are lower in FeO and TiO2 and higher in Al2O3 than local mare basalts [i.e., Haskin and Warren, 1991], indicating a highland component in the soils. Some form of physical mixing is required to account for this component.

Additional evidence for large scale mixing of mare and highland material is revealed by multispectral studies of the Tranquilitatis and Orientale basins and of western Oceanus Procellarum. Using mixing analyses of Galileo SSI data, Head et al. [1993] demonstrated the mixing of feldspathic Orientale ejecta with pre-Orientale mare deposits in the Schiller-Schickard region beyond the continuous ejecta facies. Also employing mixing analyses of SSI data, Mustard et al. [1994] identified extensive evidence for both lateral and vertical mixing of mare and highland materials along the western shores of Oceanus Procellarum. Finally, Staid et al. [1994] demonstrated the existence of physical mixing of highland and mare materials throughout the Tranquilitatis basin, but particularly enhanced in the vicinity of mare/highland morphologic boundaries.

As in the multispectral studies mentioned above, some form of vertical and lateral mixing is necessary to explain the broad (several tens to hundreds of kilometers) mixing zone observed in the X ray and SSI data in the current analysis (Plate 1 and Figure 7). Although lateral mixing may be a somewhat more efficient process than many previous analyses suggest, a large amount of postmare lateral mixing may in fact not be required to account for the observed mixing zone into the highlands. For example, the mixing zone often occurs in highland regions containing units mapped as smooth plains deposits or Fra Mauro Formation [cf. Morris and Wilhelms, 1967; Scott and Pohn, 1972; Wilhelms and El-Baz, 1977]. The abundance of these units usually decreases away from mare/highland boundaries. If some of these plains deposits are, in fact, mare units covered by a thin coating of regionally derived highland ejecta ("cryptomare"), as argued by many authors [e.g., Hartmann and Wood, 1971; Hawke and Spudis, 1980; Hawke et al., 1985; Head and Wilson, 1992], then vertical mixing of the mare and highland material along with lateral mixing of the order of only 10 km or so could account for the chemical and reflectance gradient. Alternately, if the smooth plains are basin-scale impact-derived ejecta derived from deep crustal sources mixed with locally derived material, such as has been suggested for the Cayley plains [e.g., Oberbeck, 1975; Wilhelms, 1987], then the mixing zone might be ascribed to mafic primary basin ejecta mixed with locally derived highland material. A third possibility for the source of the observed mixing zone is impact excavation and mixing of mafic intrusions such as dikes that have been emplaced in the highlands near the mare/highland border [Head and Wilson, 1992]. The abundance of such near-surface intrusions would be expected to decrease away from the mare/highland border.

Red Basalts

An additional implication of the discussion of mare/highland mixing concerns the origin of certain "red" basalt spectral properties. Pieters [1978] identified two types of mare materials which are characterized by spectral signatures that are relatively red in the visible part of the spectrum and which are also relatively bright: "LBG" basalts, which exhibit intermediate 1-15μm absorption band strengths, and LBSP basalts, which exhibit strong absorption bands. The stronger 1-μm absorption band and sharper color boundaries of the "LBSP" basalts likely indicate an inherently distinct basalt type. The location of the LBG material in the SSI mosaic analyzed here, however, corresponds extremely well to that of material in the 1.2 to 1.4 times MS2 mare/highland mixing zone, for example, Lacus Somniorum and northern portions of Mare Crisium. The spectral properties of the LBG basalts are suggestive of mixing of a significant highland component with a mare basalt component. In the case of Lacus Somniorum, if it assumed that the highland component in the region is typified by Montes Taurus material and that the premixing basalt component resembled basalts of eastern Mare Serenitatis, preliminary estimates from SSI multispectral data suggest that at least 30 wt% highland material is required to account for the reflectance and multispectral properties of the LBG material.

Summary

A wide range of evidence indicates extensive zones of mixing of more mafic and less mafic (e.g., mare and highland) material in the vicinity of mare/highland morphologic boundaries. These zones can be accounted for by lateral and/or vertical physical mixing of more mafic and less mafic material. The mixing zones appear to occur at all morphologic mare/highland boundaries and therefore imply a pervasive mechanism of formation.

Conclusion

Quantitative compositional information has been derived using the spatially extensive Galileo SSI data. Specifically, SSI and Apollo X ray spectrometer data were combined to calculate the general concentration of aluminum in lunar soils from SSI reflectance measurements. Analysis of the long-accepted relationship between aluminum concentration and reflectance of the lunar surface confirms the overall positive correlation for lunar soils as a whole. However, detailed examination of the aluminum and reflectance values with the Apollo X ray and Galileo SSI data for mare and highland soils alone reveals no systematic relationship between reflectance and X ray spectrometer-derived aluminum concentration. The relatively low instrumental precision of the present X ray data may be responsible for the observed poor correlations. In reality, aluminum and reflectance may be more directly related. The positive correlation of the system as a whole (including mare and highlands together) is found to be at least in part to mixing of mare and highland material.

The overall character of the aluminum-reflectance relationship allows calculation of approximate aluminum content to be made for the three soil types: mare, highland, and mare/highland mixtures. The excellent inverse correlation between aluminum and iron concentrations of returned lunar soils allows an estimation of iron content to be made from reflectance as well. Mare soils observed remotely are shown to contain elemental aluminum concentrations less than 10.5 wt% and greater than 7.1 wt% Fe. Highland soils contain greater than 12.0 wt% Al and less than 5.8 wt% Fe. Mare/highland mixtures contain between approximately 9.2 and 14.4 wt% Al and between 4.0 and 8.6 wt% Fe.

Soils of intermediate brightness, exhibiting reflectances between 1.2 and 1.4 times that of MS2, correspond to soils in the vicinity of morphologic mare/highland boundaries, basaltic soils clearly overlain by highland material, soils in regions of known cryptomare (i.e., the Schiller-Schickard region) and soils in the returned lunar sample collection that have been shown to be mixtures of mare and highland material.
The SSI data reveal a distinct reflectance gradient across mare/highland boundaries, where reflectance decreases up to hundreds of kilometers into the highlands. In some cases, the reflectance gradient extends upward. The widespread occurrence of the gradients at mare/highland borders implies a pervasive mechanism of formation. Physical mixing (both vertical and lateral) by basin- and non-basin-scale impact can account for the observed mare/highland mixing in the study area. Finally, the observed spectral properties of at least some "red" basalts, specifically the LBG basalts [Pieters, 1978], are suggested to result from the mixing of a significant highland component with basaltic mare material.

Higher spatial resolution Clementine multispectral data may be useful in evaluating the details of the reflectance gradient into the highlands and perhaps in clarifying its origin. Certainly, the global nature of the Clementine data should reaf-

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