C. M. PIETERS1, J. W. HEAD1, J. M. SUNSHINE1, E. M. FISCHER1, S. L. MURCHIE1, 2, M. BELTON3, A. MCEWEN4, L. GADDIS4, R. GREELEY5, G. NEUKUM6, R. JAUMANN6, AND H. HOFFMANN6

The multispectral images of the lunar limb and farside obtained by the solid state imaging (SSI) system on board the Galileo spacecraft provide the first new pulse of compositional data of the Moon by a spacecraft in well over a decade. The wavelength range covered by SSI filters (0.4-1.0 \( \mu \)m) is particularly sensitive to the composition of mare basalts, the abundance of mafic (ferrous) minerals, and the maturity of the regolith. To a first order, the limb and farside material is consistent with previous characterization of nearside lunar spectral types for mare and highland soils and craters. Most basalts are of an intermediate TiO\(_2\) composition and most of the highland crust is feldspathic with local variations in mafic content identified principally at impact craters. Dark mantling material on the farside can be interpreted in terms of known properties of lunar pyroclastic glass. Regions of cryptomare are shown to have spectral properties intermediate between those of highland and mare soils, as would be expected from a mixture of the two. There are several important exceptions and surprises, however. Unlike the basalt types identified on the nearside, limb and farside basalts exhibit an exceptionally weak 1 \[xrn ferrous absorption band. This may indicate a compositionally distinct lunar basalt group that, for example, is more Mg-rich than most basalts on the nearside. Some of the most notable compositional anomalies are associated with South Pole-Aitken Basin. This large region has a much lower albedo than surrounding highlands. The inner, darkest, portion of the basin exhibits optical properties indistinguishable from low-Ti basalts. Deposits to the south exhibit unique properties with a strong and broad ferrous absorption band. These unusual compositions associated with South Pole-Aitken and their spatial extent suggests the impact creating this huge lunar basin excavated mafic-rich lower crust or perhaps mantle material.

1. INTRODUCTION

The extraterrestrial samples returned by the U.S. Apollo program and the Soviet automated Luna missions changed forever our perspective of the Earth-Moon system and our understanding of how planetary bodies evolved during the first billion years of solar system history. Since the Apollo-Luna era, lunar science has progressed significantly through increasingly sophisticated analyses of lunar samples and through the use of an evolving suite of instruments on Earth-based telescopes. Two decades after Apollo, the Galileo spacecraft passed through the Earth-Moon system on its way to Jupiter and provided our first multispectral imaging view of the western lunar limb and neighboring farside. Discussed here are the compositional implications of this relatively small, but highly significant, pulse of new data for the Moon as acquired by the solid state imaging (SSI) system. An overview of the SSI system can be found in Belton et al. [1992a].

Even with the first samples from Apollo 11 it was recognized that a global differentiation event occurred early in lunar evolution which resulted in an anorthosite-enriched primordial crust and a mafic mantle that later was to become the source region of basalts [Wood et al., 1970; Wood, 1986]. The variety of processes proposed for early evolution of the lunar crust are summarized in schematic form in Figure 1 [see Taylor, 1982; Heiken et al., 1991]. Extensive early melting is hypothesized as a "magma ocean" which, with reasonable assumptions of starting composition, is believed to account for the enrichment of plagioclase feldspar (anorthosite) into the crust and the accumulation of mafic mineral cumulates forming the lunar mantle. It was also recognized from detailed analysis of "pristine" lunar samples (fragments which have escaped much of the subsequent reworking) that early crustal evolution also required smaller, more localized differentiation events, or plutons, to account for additional, but distinct, compositional components of crustal material [e.g., Warren, 1985].

In addition to the development of a primordial crust and mantle, physical processes reworked the surface to an unknown depth to form a variety of rock types. A few hundred million years after the formation of the Moon when the crust was sufficiently developed and rigid, major impact events produced basins hundreds of kilometers in diameter, excavating material to a depth proportional to their size. Some may have been large enough to excavate to the mantle, but this has not been confirmed. These high energy events altered, mixed, and redistributed material across the Moon. As space debris continued to bombard the early Moon, the upper kilometer or two of crust was heavily brecciated and locally well mixed by impact craters. This zone is referred to as the "megaregolith" or broken and brecciated zone of the lunar crust [e.g., Heiken et al., 1991]. On a smaller scale, the well developed fine-grained regolith which we see today with remote sensors is only a few meters thick and represents the uppermost zone which has interacted with small scale processes (solar wind, micrometeorite bombardment, etc.).

Copyright 1993 by the American Geophysical Union.

Paper number 93JE01221.
0148-0227/93/93JE-01221$05.00
The structure and compositional diversity of the crust, however, is not well documented. Apollo seismic measurements estimated the nearside anorthositic crust to be on the order of 60 km thick [Toksoz et al., 1974]. The 10-20% of the surface measured by the Apollo x-ray and gamma-ray experiments aboard the orbiting Apollo 15 and 16 Command and Service Modules showed the highlands to be generally Al-rich and the maria to be Fe- and Mg-rich on a regional scale. This suggests that the mare and highland compositions sampled at the nine sites on the eastern equatorial nearside are representative of principal lunar lithologies with the highlands being feldspathic and the maria being basaltic. The limited Apollo orbital experiments, however, also identified several anomalies beyond the sampled sites, some of the most notable being the distinct concentrations of radiogenic elements associated with localized regions such as the Aristarchus plateau [Metzger et al., 1983] and a modest, but regional increase in Fe- and radiogenic elements when the Apollo 15 module passed over the south central far side [Metzger et al., 1974; Arnold et al., 1977; Davis, 1980].

The scale and nature of crustal diversity has been addressed in more detail with measurements of the nearside lunar surface using spectroscopic instruments on Earth-based telescopes [e.g., see reviews by Pieters, 1978, 1986, 1993]. Mare basalts on the nearside exhibit a great range of compositions and age, two thirds of which are distinctly different from the compositions sampled. The bulk of the nearside feldspathic highland crust is notably noritic (plagioclase-rich, containing low-Ca pyroxenes) in character although gabbroic components (containing high-Ca pyroxene) appear to increase toward the west. On a local and regional scale spectroscopic studies of basin massifs and craters large enough to excavate material from beneath the megaregolith (~upper 2 km) have shown there to be a great diversity of highland rock types including crystalline noritic anorthosite, anorthosites, gabbroic anorthosite, and troctolite (trending to dunite), highly suggestive of plutons [Lucey et al., 1986; Pieters, 1986, 1991; Lucey and Hawke, 1988].

The Galileo encounter with the Earth-Moon system in December of 1990 provided the first new compositional data for the lunar limb and farside in well over a decade. Science highlights of the Galileo SSI lunar encounter are discussed in Belton et al. [1992b]. Compositional analyses of SSI data are presented in more detail in the following three sections. The first summarizes previous spectroscopic analyses applicable to this extended visible part of the spectrum. The second describes the spectral calibration procedures using lunar samples. The third, most extensive section presents and discusses the compositional diversity observed by SSI for different terrains and how they do or do not fit within our current perspective of lunar crustal evolution.

2. BACKGROUND: COMPOSITIONAL INFORMATION DERIVED FROM THE EXTENDED VISIBLE

At visible and near-infrared wavelengths, measured radiation from the Moon is entirely reflected solar radiation. Since several highly diagnostic mineral absorption features occur in this part of the spectrum [Burns, 1970; Adams, 1974, 1975; Gaffey et al., 1993], the reflectance of the surface measured as a function of wavelength can often be used to identify compositional properties of material present. For lunar samples, the type and abundance of mafic minerals (olivine and pyroxene of various compositions) are particularly important for identifying the variety of distinct rock types comprising the lunar crust (recent review of the compositional implications of lunar spectral properties can be found in Pieters [1993]). The SSI camera contained filters...
covering the spectral range from 0.4 to 1.0 μm and the discussion below will focus on the compositional information that can be derived using multispectral imaging in this extended visible part of the spectrum.

2.1. Properties of Lunar Materials: Ground Truth

Shown in Figure 2 are visible to near-infrared laboratory reflectance spectra of representative lunar rock and soil samples. Sample 67455 is a noritic breccia from Apollo 16 and 12063 is a basalt from Apollo 12. These two particulate samples exhibit typical spectral properties of unaltered highland and mare rocks, respectively. The prominent absorption bands near 1 and 2 μm are due to Fe$^{+2}$ and are indicative of the mafic mineral pyroxene. The shorter wavelengths of band centers for 67455 identify the pyroxene composition as a low-Ca pyroxene [Adams, 1974; Hazen et al., 1978], whereas the longer wavelengths of the bands for 12063 indicate a high-Ca pyroxene, as would be expected for basaltic material. The higher reflectance of 67455 and proportionately higher abundance of pyroxene bands result from the lower abundance of pyroxene and higher abundance of feldspar, respectively, which are characteristics typical of highland noritic breccias. Another common lunar mafic mineral, olivine, exhibits a diagnostic absorption band at somewhat longer wavelengths, near 1.05 μm. This absorption, not evident in these samples, exhibits a ferrous band that is much broader than that observed for pyroxene.

The remaining spectra in Figure 2, shown with dashed lines, are for representative well developed soils from Apollos 12 and 16 landing sites. The characteristic continuum of lunar soils has been approximated as a tangent to the spectrum (near 0.73 and 1.6 μm) and removed to allow the character of subtle absorptions to be discerned. Mature soils are darker than particulate rock samples from the same site and exhibit similar but very subdued absorption bands. Both characteristics are due to the accumulation of weathering products that result from exposure to the space environment (cosmic ray and solar wind irradiation, micrometeorite bombardment, etc.). All mature lunar soils exhibit an overall "red" continuum that increases in reflectance towards longer wavelengths. Bright, freshly exposed feldspathic (highland) material such as 67455 generally has a much flatter continuum than compositionally comparable mature soil from the same site (e.g., 62231).

Shown in Figure 3 superimposed on extended visible lunar spectra are effective band passes for five of the filters for the Galileo SSI system (two additional SSI narrow methane filters were not included in this analysis due to calibration difficulties). Images of the Moon obtained in all filters were individually co-registered, allowing five point spectra for surface elements to be evaluated and compared. These are discussed in section 4. Several diagnostic properties of the 1 μm ferrous absorption band, for instance the width and wavelength of band center, cannot be measured with five filters in this part of the spectrum. Nevertheless, the SSI filters can provide a measure of the strength of the overall mafic mineral absorption features near 1 μm and the smooth spectral variations across the visible region. Using the "ground truth" properties of the returned lunar samples as a basis for comparison and confident interpretation, even these relatively simple spectral properties provide compositional information of immense value for unexplored lunar regions.

2.2. Properties of Lunar Materials: Lunar Spectral Types From Telescopic Measurements

The spectral properties of various terrains on the lunar near side were measured from 0.32 to 1.1 μm with photoelectric detectors in the late 1960's and 1970's. During that period, spectra were obtained relative to a standard area in Mare Serenitatis (MS2, located at 18ø 40' N, 21ø 25' E). Such "relative reflectance" spectra not only allowed instrumental and atmospheric effects to be removed, but they also emphasized the small variations in color between lunar regions. Several hundred spectra of the lunar near side obtained with Earth-based telescopes show that mare, highland, and fresh impact crater lithologies can be readily distinguished. Lunar spectral types were first summarized by McLeod et al. [1972a, b] and later expanded upon by Pieters and McCord [1976] and Pieters [1977]. The McLeod et al. summary of lunar spectral types based on relative reflectance spectra are shown in Figure 4. These early surveys of the near side are important to the Galileo
As can be seen in Figure 4, spectra of fresh mare impact craters are quite different from those of mature mare soils. (The spectral properties of mare soils are discussed extensively in the next section.) The most prominent distinction between soils and craters is that the pyroxene absorption near 1 μm is much stronger in spectra for fresh mare craters. Although not evident in Figure 4 (because the spectra have been scaled to unity at 0.56 μm), fresh craters are also always brighter than surrounding mare. This distinction in albedo and strength of combined Fe$^{2+}$ absorptions in mafic mineral is comparable to the differences between rock powders and mature soils observed in the laboratory (Figures 2 and 3).

Highland craters and mature soils exhibit a similar distinction in albedo; freshly exposed material at highland craters is the brightest material on the surface of the Moon [Pohn and Widley, 1970]. Unlike the diversity seen for mature mare soils, however, most mature highland soils are observed to have somewhat similar spectral characteristics. Although minor variations occur between 0.5 and 0.7 μm, the feldspathic highland soils tend to have a somewhat steeper continuum than many mare regions (including MS2) and thus are relatively "red" in the visible part of the spectrum with increasing reflectance toward longer wavelengths. Reflectance spectra of highland soils relative to a mare soil, such as those relative to MS2 in Figure 4, exhibit a positive bump in the spectrum near 1 μm because the pyroxene absorption bands are weaker in highland soils (mirroring the low abundance of mafic minerals). As will be discussed below, this normally weak 1 μm absorption is an important mappable property of feldspathic highland soils.

As a group, highland impact craters exhibit more diversity in the extended visible part of the spectrum than do mare craters [see Pieters, 1977]. The cause of this diversity is a complex coupling of feldspar and mafic mineral abundance, as well as degree of shock alteration and length of exposure to the lunar environment. Felspathic materials exposed at fresh craters tend to have continua that are less steep ("flatter") than surrounding mature soils (similar to the difference in continuum between Apollo 16 feldspathic breccia 67455 and Apollo 16 mature soil in Figure 2). This is the principal cause of the blue-sloped trend in the reflectance spectra of highland craters (decrease toward longer wavelengths) shown in Figure 4 relative to MS2. Mafic minerals present at a highland crater produce an absorption near 1 μm superimposed on the distinct immature feldspathic "blue" continuum. Most of the common lunar lithologies identified spectriscopically are distinguished by variations in the abundances of plagioclase and pyroxene (the principal mafic mineral). As seen in Figures 2 and 3, ferrous pyroxene absorption bands are centered between 0.9 and 1.0 μm and the spectra peak near 0.75 μm. The subtle inflections that occur near 0.76 μm in the relative reflectance spectra are thus an important indicator of compositional variations associated with abundance of this common mafic mineral. As can be seen from the examples in Figure 4, the strength of mafic mineral absorptions vary from crater to crater. Felspathic material also exhibits a distinct inflection near 0.40 μm (see 67455), which creates a peak at that wavelength in reflectance spectra relative to mare soil [Adams and McCord, 1971b]. The wavelength of the turn-down toward the blue can be affected by other components present as well as the shock history [e.g., Pieters, 1977; Pieters and Taylor, 1989].

2.3. Composition of Mare Soils From UV/VIS Measurements

Perhaps the most frequently measured spectral property of the Moon is the color variation among mature mare soils between the ultraviolet (UV) and the visible (VIS), typically measured as a UV/VIS ratio. The attention given to this spectral parameter merits special discussion. The strengths and limits to using this spectral parameter in mapping mare composition is discussed in detail below. The spectral variability from the ultraviolet to about 0.73 μm for different mare soils is apparent in the examples of spectra in Figure 4. Furthermore, differences among these spectral properties are spatially coherent on the scale of the remote measurements (1-2 km) and define extensive and relatively uniform flows or deposits within the maria.

The basaltic samples from different lunar sites exhibit a range of compositions [Papike et al., 1976] that could account for observed spectral variations of surface units. Returned basalt samples also exhibit a range of textures, grain sizes, glass content, etc., and these petrographic properties are equally important for interpretation of spectroscopic measurements. Although the bulk properties of a basalt unit may be uniform, localized variability exists, particularly on the scale of individual samples. Soil formation processes (repeated cycles of comminution forming fine grained particulates, exposure to solar wind, bombardment by micrometeorites, formation of glass and recrystallized components, accumulation of single domain reduced Fe) tend to homogenize surface material on a regional scale. Over billions of years a regolith several meters thick is developed, but the time scale for the uppermost soils to reach steady state maturation is short relative to the age of mare basalts [e.g., Adams and McCord, 1971b, 1973; Pieters et al., 1985].
Fig. 4. Lunar spectra obtained using Earth-based telescopes for representative mare, mare craters, highland, and highland craters [after McCord et al., 1972a]. All spectra are relative to the standard region in Mare Serenitatis, MS2, and scaled to unity at 0.56 μm.
Because the process, however complex, is the same everywhere, regional spectral variations thus reflect inherent differences of the basalt lithology and allow mare basalt types to be mapped in a regional extent based on the spectral properties of mature soils.

Excluding areas near fresh craters, regional mare units have been successfully mapped with multispectral images that span the ultraviolet to visible part of the spectrum [Whitaker, 1972; McCord et al., 1976, 1979; Johnson et al., 1977a, b; 1991a, b]. The distinct variation between mare in a UV/VIS ratio has been empirically linked to the TiO$_2$ content of the soils [Charette et al., 1974; Pieters et al., 1973]. The quantitative use of this relationship, however, has been substantially modified as additional laboratory and telescopic data have been analyzed [Head et al., 1978a; Pieters et al., 1979; Pieters, 1978, 1993]. The relation between the UV/VIS ratio and TiO$_2$ for mare soils is calibrated principally from empirical evidence and, for reasons outlined below, is valid only within certain constraints.

The notable variations in the UV/VIS ratio for mare soils have no single physical explanation. Several compositional properties are known to affect this part of the spectrum: absorptions of Fe- and Ti-bearing glasses, charge transfer mineral absorptions, Ti$^{4+}$ electronic transition absorptions, scattering and absorption by submicroscopic metal particles, shock alteration, recrystallized ilmenite and other opaques, etc. The overall spectral contrast of the bulk sample, which is controlled by many of the above factors, also affects the measured color. Spectra of dark soils (with low spectral contrast) tend to be relatively flat, which for lunar materials results in a relatively blue spectrum. All of these characteristics affect the measured UV/VIS of soils, but for any given soil the relative importance of these competing processes that create the spectral variations observed remotely is poorly known. The cause of the relation between TiO$_2$ and UV/VIS for mature mare surfaces is most certainly coupled to the overall opacity of the soil particles and the effect of these upon spectral contrast, and is thus dependent on the abundance of Fe and Ti in the soil. Since all basalts have a high FeO content which varies only slightly, variations in color are thought to be principally correlated to larger variations in TiO$_2$ (see discussion in Pieters [1978, 1993]).

Isolating various optical effects is not easily achieved using returned soils, due to the complexity of soil particles and the $10^5$ difference in scale between the remote measurements and laboratory samples. Because lunar soils are multi-component and complex, one frequently used procedure for quantifying compositional information extracted from spectra is to derive an empirical relation between composition and spectral properties [e.g., Charette et al., 1974; Jaumann, 1991]. Using Earth-based color difference photography (two filters with matched positive and negative film characteristics) it was recognized early in the Apollo program that the regions around landing sites from which Ti-rich basalts were returned appeared relatively blue compared to other mare sites [Whitaker, 1972]. It was the lunar samples, coupled to the telescopic measurements that substantiated this relationship. In the early Charette et al. [1974] analysis, the TiO$_2$ content of soils measured in the laboratory was compared to the slope of the reflectance spectrum between 0.40 and 0.56 $\mu$m (measured as the ratio of 0.40/0.56 $\mu$m). Ti-rich soils of Apollo 11 and 17 did indeed exhibit a "bluer" (higher 0.40/0.56 $\mu$m) spectrum than lower Ti soils, provided that only accurately measured mature mare soil spectra were used in the analysis. Rock powders and immature soils, soils of mixed heritage, or soils that have not otherwise reached equilibrium with lunar alteration processes, did not follow this relationship. Similarly, in a comparison of 0.40/0.56 $\mu$m measurements of telescopic spectra for the landing sites with the TiO$_2$ of returned soils, the bluer soils were shown to be Ti-rich. Later analyses using the entire data base of lunar soil spectra obtained by J. B. Adams in the early 1970's showed there to be much scatter when several soils from the same site were used [Johnson et al., 1991a, b; H. Hoffmann et al., personal communication, 1991]. This scatter is likely due to a combination of laboratory measurement variations and the small number of truly representative and mature soils in the collection.

The preferred method of establishing an empirical relation between UV/VIS color and TiO$_2$ content for mare surfaces is to use a measurement of the UV/VIS obtained remotely for each sampled site in comparison with the TiO$_2$ of mature soils from that site. As discussed above, the scale of remote measurements provides a good measure of the regional bulk properties and is relatively insensitive to variations of a smaller scale.

After additional telescopic and laboratory spectra were obtained, a more complete TiO$_2$ versus UV/VIS relationship was presented in Pieters [1978]. This analysis incorporated a range of measured TiO$_2$ (since there was no good reason to favor one mature soil sample over another to represent bulk regional properties) and a range of measured UV/VIS for each landing site (due to observational variations). UV/VIS for one site is measured relative to that for the standard lunar mare area, MS2. The resulting TiO$_2$ versus UV/VIS relationship still shows that dark, relatively blue mare surfaces are TiO$_2$-rich, but includes a range of uncertainty for TiO$_2$ values estimated from UV/VIS measurements, with increasing uncertainty for lower values of TiO$_2$.

When using soil TiO$_2$ estimates, recall that although mature mare soils directly reflect the composition of underlying basalts, they are not identical to it. Crystalline Ti-rich basalts from Apollo 11 and 17, for example, are typically several percent higher in TiO$_2$ than local soil. We have used the calibration and estimates of TiO$_2$ from Pieters [1978] for the current SSI analyses of mare soils, but have expanded the UV/VIS categories somewhat to accommodate variations observed within SSI data (dominated by large spectral contrasts in Oceanus Procellarum). The nomenclature and estimated range of UV/VIS used here are summarized in Table 1 and Figure 5.

For high-TiO$_2$ soils the empirical evidence suggests a direct relationship between UV/VIS ratio measured remotely and $\%$ TiO$_2$, with the bluest basalts (high UV/VIS) being the most Ti-rich. Inversely, low-Ti soils have low UV/VIS values (relatively red). It is the intermediate range of measured UV/VIS values that has the most uncertainty associated with TiO$_2$ compositions. Mare soils with intermediate values of UV/VIS (medium 0.40/0.56 $\mu$m ratio: 0.97-1.02) have nonunique predictions for TiO$_2$ (see Figure 5). Despite these uncertainties in actual TiO$_2$ percentages, basalts in the medium and medium-high categories can be readily distinguished by variations in the UV/VIS ratio and therefore mapped as separate units with multispectral images. In this case, distinguishing and mapping distinct basalt units using UV/VIS measurements is more accurate than an estimation of $\%$ TiO$_2$ for these basalt soils.
Table 1. Empirical Relation Between UV/VIS Ratio and TiO$_2$ Content of Mature Mare Soils [After Pieters, 1978]

<table>
<thead>
<tr>
<th>Terminology</th>
<th>SSI Measured</th>
<th>Mare Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.40/0.56 µm*</td>
<td>Est. wt% TiO$_2$</td>
</tr>
<tr>
<td>High-Ti (HT)</td>
<td>&gt; 1.07</td>
<td>&gt; 6</td>
</tr>
<tr>
<td>Med. High (MH)</td>
<td>1.02-1.07</td>
<td>3-7</td>
</tr>
<tr>
<td>Median (M)</td>
<td>0.97-1.02</td>
<td>&lt;4</td>
</tr>
<tr>
<td>Low-Ti (LT)</td>
<td>&lt; 0.97</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>

*Relative to standard area MS2 and scaled to unity at 0.56 µm.

3. SPECTRAL CALIBRATION OF SSI IMAGES

A transparent dust cover (removed September 5, 1991) was still in place for the December 1990 lunar measurements. An in-flight SSI calibration sequence was not available for this optical arrangement, but adequate gain and offset calibrations were derived and tested using pre-flight calibrations and several empirical corrections. In addition to standard flat field and dark current corrections, more complicated corrections were required in order to account for out of focus dust rings ("dust doughnuts") and an apparent low magnitude image reflection(s) [McEwen et al., this issue]. Calibration of spectral properties utilizes relative reflectance spectra of areas on the nearside obtained previously with earth-based telescopes and reflectance spectra of mature lunar soils measured in the laboratory. These procedures are summarized below. Photometric calibrations for changes in viewing geometry are discussed more thoroughly by McEwen et al. [this issue] and P. Helfenstein et al. [manuscript in preparation, 1993].

Coregistered mosaics of SSI data, photometrically corrected to a uniform 20° phase angle prepared by McEwen et al. [this issue], are the principal form of SSI multispectral data used in the compositional analyses presented here. Multispectral analysis using band ratios and other techniques applied to these mosaics provide an excellent synoptic perspective on the location and spatial extent of distinct surface units for the western half of the Moon (centered on the limb). Specific lunar areas a few pixels in diameter were chosen for more detailed spectral analysis and comparison. The locations of these areas are identified by numbers superimposed on the Galileo SSI mosaic in Figure 6. Table 3 provides coordinates for each area.

Fig. 5. Empirical relation between %TiO$_2$ content of returned mature mare soils and the remotely measured 0.40/0.56 µm color ratio for Apollo and Luna landing sites [after Pieters, 1978]. The four classifications of mare soil composition used in this discussion based on 0.40/0.56 µm ratios (Table 1) are outlined with heavy solid lines. Under this scheme, the LT and HT groups are readily distinguished, while greater uncertainty and overlap exist in the intermediate categories (M and MH, see text).

The geometry of the Galileo Earth-Moon encounter provided a favorable opportunity for spectral calibration. Half of the lunar near side was illuminated and measured by Galileo. These near side SSI data allowed consistency checks to be performed with well-calibrated Earth-based telescopic data of the lunar nearside. The near side telescopic data for Apollo and Luna sampling sites also allowed direct spectral calibration with returned lunar soils, which are thought to be representative of the sampled site as a whole [e.g., Adams and McCord, 1970; McCord and Adams, 1973]. Neither of the standard lunar areas normally used for calibration, the Apollo 16 site in the central highlands [e.g., Pieters, 1986] nor MS2 in Mare Serenitatis [e.g., McCord et al., 1972a], were illuminated during the Galileo flyby. Instead, a secondary standard area in Mare Humorum (MHO) was used for the SSI data. The spectral properties of MHO (99 in Figure 6) have been previously measured relative to MS2 and Apollo 16 and are well known.

Several additional spectral calibration steps were applied to the Galileo SSI data presented in this paper. To calibrate to previous data, SSI mosaics for each spectral channel were scaled to the value for MHO in that channel. MHO thus has an average value of 1.0 in all spectral channels after this procedure. In this form, a five point relative reflectance spectrum can be obtained for each location in the SSI mosaic. Such relative reflectance spectra (spot/MHO) are shown in Figure 7a for several additional areas on the near side. These data show both the color variations relative to the standard mare area MHO as well as differences in albedo between areas.

The spectral character of these Galileo SSI relative reflectance spectra are essentially equivalent to independent data obtained with Earth-based telescopes [Belton et al., 1992b], providing confidence in the overall accuracy of SSI data.

For ease of comparison with the wealth of previously published lunar relative reflectance spectra [i.e., McCord et al., 1972a; Pieters and McCord, 1976; Pieters 1977], Galileo SSI spectra have been converted to spectra relative to the standard area in Mare Serenitatis, MS2, using telescopically measured MHO/MS2 values. Examples of reflectance spectra are shown in Figure 7b, relative to the common lunar standard MS2 and scaled to unity at 0.56 µm. For the Galileo SSI data, the principal spectral variations occur in four filters (1) in the ratio of the blue to the visible (0.40/0.56 µm), (2) in continuum slope across the visible (0.56/0.76 µm), and (3) in strength of the 1 µm mafic mineral absorption (0.76/0.99 µm).

Derivation of "absolute" spectra, or reflectance/Sun ($R(\lambda)$), requires a few minor assumptions combining telescopic and laboratory data for the Moon. Although accurate laboratory bidirectional reflectance measurements of Apollo 16 soil have been measured at the full range of viewing geometries encountered by Galileo [Pieters et al., 1991], previously obtained telescopic measurements of MHO/Apollo 16 are scaled to unity at 0.56 µm and thus do not directly contain albedo information. The following expression summarizes the steps used to derive reflectance/Sun for lunar area x:

$$R(\lambda) = \left(\frac{\text{SSI}}{\text{MHO}}\right)_{\text{Apollo16}} \times \left(\frac{\text{Apollo16}}{\text{Sun}}\right)_{\text{Lab}}$$

To obtain reflectance values for SSI data the SSI/MHO data are multiplied by telescopic values of MHO/Apollo 16 (scaled to
Fig. 6. Map of Galileo SSI images (0.6 μm filter) obtained during the first flyby of the Moon in December 1990. Superimposed on the image are the six grids of specific areas for which SSI spectra were analyzed. The coordinates for these areas are provided in Table 3.
0.56 μm), next by the laboratory measurement of Apollo 16 soil (obtained at 20° phase angle), then by a scaling factor to account for the albedo difference between Apollo 16 and MHO. This is estimated to be a factor of two based on Pohn and Widley [1970], but given the differences in scale and viewing geometry, the actual albedo ratio could differ as much as 20%. Resulting reflectance spectra/sun of the areas in Figures 7a and 7b that maintain relative albedo information are shown in Figure 7c.

The regions in Figure 7 were chosen to represent a variety of surface lithologies with known spectral properties [Pieters et al., 1975, 1980]. The three mare soils include an intermediate "blue" (medium-high 0.40/0.56 μm) basalt (MHO), a dark, relatively "blue" (high-0.40/0.56 μm) high-Ti basalt in the Flamsteed ring (Surv), and one of the medium basalt soils (MH203) in Mare Humorum (with a relatively low 0.40/0.56 μm). These albedo and color properties are readily seen in the relative spectra in Figures 7a and 7b. The highland soil (MH40) is much brighter, somewhat "redder" (low 0.40/0.56 μm), and exhibits little if any mafic mineral absorption near 1 μm (a relatively low 0.76/0.99 μm ratio in the relative reflectance spectra; positive absorption feature), indicative of its low mafic character. On the other hand, a fresh crater in the mare (MH45) has exposed basaltic material with a prominent mafic mineral (pyroxene) absorption near 1 μm (very high 0.76/0.99 μm ratio).

Two additional aspects of this lunar flyby SSI data calibration should be kept in mind when the first lunar encounter SSI data are used in science analyses. First, the exposure times for the SSI filters coupled with the presence of the dust cover resulted in relatively low DN (data number) values in the raw data. Typical values in Mare Humorum, for example, were 30 DN. Although the instrument performed superbly, the low DN values limit the overall accuracy for individual pixels as the data are quantized into a small DN range. For this reason, the spectral analyses discussed here use areas several pixels in diameter (see Table 1). The error bars shown in Figure 7a are the standard deviation of the statistical average of the several pixels involved and show that the pixel to pixel variance due to low DN values is typically on the order of 3%. For some regions near the terminator and limb additional sources of error may arise from poorly corrected scattered light [see McEwen et al., this issue]. We have avoided these regions, except where noted. Second, the "absolute" lunar spectra of Figure 7c could not have been created without the ground truth provided by lunar samples. The preflight radiometric calibration data produced spectra that were unrealistic for lunar materials and showed a broad variance in spectral character of up to 40% compared to those described above derived using the lunar soils. This inaccuracy is believed to be due largely to the lack of in-flight calibration prior to the first Earth-Moon encounter and the fact that the transparent dust cover was still in place during these lunar measurements [Belton et al., 1992b].

<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>MHO/MS2</th>
<th>MHO/Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>411</td>
<td>1.046</td>
<td>0.058</td>
</tr>
<tr>
<td>563</td>
<td>1.001</td>
<td>0.072</td>
</tr>
<tr>
<td>660</td>
<td>0.988</td>
<td>0.081</td>
</tr>
<tr>
<td>756</td>
<td>0.983</td>
<td>0.088</td>
</tr>
<tr>
<td>990</td>
<td>0.970</td>
<td>0.091</td>
</tr>
</tbody>
</table>
The principal form of SSI data used in the discussion below are the SSI/Sun reflectance spectra and the SSI/MS2 relative reflectance spectra. For reference, values for MHO/MS2 and MHO/Sun spectra at Galileo SSI effective wavelengths are provided in Table 2.

4. COMPOSITIONAL IMPLICATIONS OF SSI DATA

Albedo data and multispectral images provide information that can be used to define, or map, the spatial extent of distinct surface units, while reflectance spectra or combinations of channels of spectral data known to be sensitive to specific compositional parameters can be used to partially characterize the type of material on the surface [Head et al., 1978]. Although mineral identification requires high spectral resolution visible and near-infrared spectra, both of these approaches have been important in the science analysis of Galileo SSI multispectral images.

A histogram of albedo of the SSI mosaics (brightness values at 20° phase angle) relative to MHO for the 0.56 μm filter SSI mosaic is shown in Figure 8. The relative reflectance scale on this figure, as well as for Figure 7a, can be converted to albedo directly by multiplying the reflectance value for MHO (normal albedo of approximately 7%) [e.g., Pohn and Widley, 1970]. The two principal lunar soil lithologies, low albedo mare basalts and higher albedo feldspathic highlands, form the two prominent peaks in the histogram, roughly in proportion to their surface extent. There is additional non-random structure in the albedo data of Figure 8 which becomes apparent when the spatial distribution of albedo units are examined.

Shown in Plate 1 is a color representation that combines aspects of SSI albedo and color ratio data to define some of the most prominent units in the lunar highlands and mare observed by Galileo SSI. Several important highland lithologies on the western lunar limb and far side are readily distinguished by albedo, or brightness variations. In Plate 1, these range from the very dark interior of the South Pole-Aitken basin region (black), to the brighter highlands (shades of purple), to the very bright, relatively immature fresh feldspathic craters and ejecta (white). The asymmetric distribution of materials surrounding Mare Orientale is readily apparent, as is the spatial extent of the unusual materials of South Pole-Aitken basin and areas of ancient mare, or cryptomare such as in the Schiller-Schickard area [see Head et al., 1993; Belton et al., 1992b]. This first-order distinction of highland units by albedo is petrographically reasonable, given the generally feldspathic character of highland soils, where small variations in bulk composition result in detectable variations in brightness. Mature highland soils measured by the Apollo x-ray spectrometer, for example, show a correlation between brightness and Al/Si that should extend to other areas of the highlands [Adler et al., 1972, 1973; Clark et al., 1976, 1978; Fischer et al., 1992]. On the other hand, distinctions between the feldspathic highland soils and the much brighter immature surfaces, such as at craters, require analysis of the actual spectra and are discussed in more detail below.

The maria are low albedo and are as dark or darker than the central South Pole-Aitken region (the darkest category of Figure 8 and Plate 1). Variations in the mare are more readily mapped by spectral parameters other than albedo. In Plate 1, the mare units are distinguished by their UV/VIS (0.40/0.56 μm) properties. The color assignments used here (red, yellow, green, blue) approximate the UV/VIS groupings of Pieters [1978] and range from relatively red (low UV/VIS) to the relatively blue, Ti-rich soils found in Oceanus Procellarum [see Greeley et al., this issue; Sunshine et al., 1992; Pieters, 1978].

Compositional interpretation of units identified and defined spatially with multispectral images requires a more quantitative analysis of their spectral properties. Representative SSI spectra for mare and highland areas within the Galileo SSI mosaic are shown in Figure 9. Each spectrum is identified by a number, which corresponds to the general locations in Figure 6 and specific coordinates in Table 3. The spectral characteristics of these SSI spectra are similar to Earth-based spectra shown in Figure 4 and allow broad compositional comparisons with materials sampled on the lunar nearside. As discussed below, there are also several important differences that distinguish many of the limb and far side materials from those on the near side.

4.1. Mare Soils

Spectra for a variety of basaltic soils are shown in Figure 9 (left): northern Oceanus Procellarum (solid symbols), limb basalts in Grimaldi (open symbols), Orientale basalts (plusses and crosses), and a small region of Schickard basalt (square with cross). For comparison, spectra are shown of basaltic soils within Oceanus Procellarum. The Procellarum basalts exhibit some of the largest variations in UV/VIS color observed on the Moon (~15%) and illustrate the diversity of basalts filling this vast region. The relatively "blue" basalt (65) of northern Procellarum is in the same spectral group as the young high-Ti basalts filling the Flamsheed ring in southern Oceanus Procellarum (82 Surv in Figure 7b) and in Mare Imbrium [Pieters et al., 1980; Pieters and McCord, 1976].

With the exception of a small region in southeast Mare
Orientale (12), the limb and far side basalts have medium to medium-high UV/VIS values (Figure 9, left), indicating an intermediate TiO$_2$ composition (see Table 1). One of the most notable characteristics of the limb and far side basalts, however, is their distinctly weak mafic mineral absorption near 1 μm (relatively low 0.76/0.99 μm) relative to other basalts. Although a generally weak 1 μm band has been observed for some of the eastern near side basalts (e.g., the Ti-rich basalts at Apollo 11, Mare Tranquillitatis; see Figure 4), the weakness of mafic mineral absorptions observed for limb and far side basalts is uncommon for near side basaltic materials [Pieters and McCord, 1976], even for basaltic material significantly contaminated with highland feldspathic material such as in the Schiller-Schickard region (see discussion below). This unusual property of limb and far side basalts can be readily seen in the 0.76/0.99 μm ratio image shown in Figure 10 (dark in the figure indicates low 0.76/0.99 μm). In this figure the limb and far side basalts, although much lower than the highlands in albedo at visible wavelengths, are indistinguishable in terms of 1 μm absorption band strength from the surrounding low-mafic feldspathic highland soils. An accurate estimation of the strength of this mafic absorption is difficult because the band is superimposed on a generally red sloped continuum and thus derivation of an accurate reference continuum requires data on both sides of the band (see Figure 1). Even when the continuum is estimated using data from 0.56 to 0.76 μm and extrapolated to 0.99 μm (see example in Head et al., [1993]), the 1 μm band strength of limb and far side basalts is relatively weak. Figure 10 reveals additional regions of basalt with this unusual property, some of the more extensive areas that merit further study occur east of Mare Humorum in western Mare Nubium and in Palus Epidemiarum to the south. As discussed further in Sunshine et al. [1992] the Marius Hills region also exhibits a relatively weak mafic absorption band, with this property often correlated with specific features.

Detailed compositional interpretation of the exceptionally weak 1 μm absorption observed for limb and far side basalts requires high spectral resolution near-infrared data, because it is
Fig. 9. Representative reflectance spectra for Galileo SSI mare and highland areas (see Figure 6 and Table 3 for locations; for convenience, short abbreviations are associated with each numbered area). Wavelength is in nanometers (1000 nm = 1 μm). All reflectance spectra/Sun values are on the same scale and plots are placed to maintain the albedo information measured by Galileo SSI (see text) (0.15 reflectance is marked on all plots for reference). All relative reflectance spectra/MS2 are scaled to unity at 0.56 μm to allow comparison of principal spectral features. The scale remains the same for all data.
TABLE 3. Lunar Coordinates of Areas for Which SSI Spectra are Presented and Discussed in the Text

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Upper Left</th>
<th>Lower Right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lat.</td>
<td>Long.</td>
</tr>
<tr>
<td>7</td>
<td>MGR</td>
<td>-5.250</td>
<td>67.375</td>
</tr>
<tr>
<td>12</td>
<td>MOR</td>
<td>-23.000</td>
<td>93.250</td>
</tr>
<tr>
<td>15</td>
<td>MOR</td>
<td>-20.500</td>
<td>98.125</td>
</tr>
<tr>
<td>17</td>
<td>MAU</td>
<td>-25.625</td>
<td>91.750</td>
</tr>
<tr>
<td>20</td>
<td>BEV</td>
<td>-1.000</td>
<td>82.500</td>
</tr>
<tr>
<td>24</td>
<td>Cra</td>
<td>12.125</td>
<td>93.625</td>
</tr>
<tr>
<td>27</td>
<td>Cra</td>
<td>-10.500</td>
<td>107.750</td>
</tr>
<tr>
<td>28</td>
<td>SSH</td>
<td>-47.250</td>
<td>40.375</td>
</tr>
<tr>
<td>29</td>
<td>SSH</td>
<td>-45.000</td>
<td>48.875</td>
</tr>
<tr>
<td>30</td>
<td>SSH</td>
<td>-45.125</td>
<td>46.000</td>
</tr>
<tr>
<td>31</td>
<td>MSSH</td>
<td>-42.250</td>
<td>56.750</td>
</tr>
<tr>
<td>32</td>
<td>SSH</td>
<td>-55.000</td>
<td>44.375</td>
</tr>
<tr>
<td>33</td>
<td>SPA</td>
<td>-37.750</td>
<td>143.250</td>
</tr>
<tr>
<td>34</td>
<td>SPA</td>
<td>-45.375</td>
<td>154.750</td>
</tr>
<tr>
<td>35</td>
<td>SPA</td>
<td>-54.750</td>
<td>142.500</td>
</tr>
<tr>
<td>36</td>
<td>SPA</td>
<td>-55.125</td>
<td>132.875</td>
</tr>
<tr>
<td>39</td>
<td>SPA</td>
<td>-62.500</td>
<td>134.000</td>
</tr>
<tr>
<td>40</td>
<td>SPA</td>
<td>-73.500</td>
<td>136.000</td>
</tr>
<tr>
<td>41</td>
<td>SPA</td>
<td>-67.000</td>
<td>144.000</td>
</tr>
<tr>
<td>42</td>
<td>AM</td>
<td>-20.500</td>
<td>87.000</td>
</tr>
<tr>
<td>43</td>
<td>Lenz</td>
<td>3.375</td>
<td>100.500</td>
</tr>
<tr>
<td>45</td>
<td>Cra</td>
<td>-1.000</td>
<td>109.500</td>
</tr>
<tr>
<td>56</td>
<td>MRK</td>
<td>-31.375</td>
<td>92.250</td>
</tr>
<tr>
<td>58</td>
<td>MAU</td>
<td>-24.875</td>
<td>96.625</td>
</tr>
<tr>
<td>61</td>
<td>HNM</td>
<td>0.625</td>
<td>107.250</td>
</tr>
<tr>
<td>62</td>
<td>MDRa</td>
<td>48.750</td>
<td>58.750</td>
</tr>
<tr>
<td>65</td>
<td>MBLb</td>
<td>21.000</td>
<td>62.750</td>
</tr>
<tr>
<td>69</td>
<td>CP</td>
<td>33.500</td>
<td>61.750</td>
</tr>
<tr>
<td>70</td>
<td>CRA</td>
<td>38.750</td>
<td>57.375</td>
</tr>
<tr>
<td>73</td>
<td>SSP</td>
<td>-43.500</td>
<td>33.875</td>
</tr>
<tr>
<td>74</td>
<td>SSH</td>
<td>-51.125</td>
<td>56.500</td>
</tr>
<tr>
<td>75</td>
<td>CRA</td>
<td>-23.875</td>
<td>40.750</td>
</tr>
<tr>
<td>78</td>
<td>Ais</td>
<td>24.125</td>
<td>47.625</td>
</tr>
<tr>
<td>77</td>
<td>Byr</td>
<td>-24.375</td>
<td>64.125</td>
</tr>
<tr>
<td>79</td>
<td>MH40</td>
<td>-19.750</td>
<td>44.875</td>
</tr>
<tr>
<td>86</td>
<td>MHO3</td>
<td>-24.625</td>
<td>45.250</td>
</tr>
<tr>
<td>88</td>
<td>SURV</td>
<td>-2.125</td>
<td>43.750</td>
</tr>
<tr>
<td>84</td>
<td>SPA</td>
<td>-29.500</td>
<td>144.125</td>
</tr>
<tr>
<td>87</td>
<td>MGR</td>
<td>-6.125</td>
<td>67.625</td>
</tr>
<tr>
<td>89</td>
<td>ARI</td>
<td>29.750</td>
<td>51.875</td>
</tr>
<tr>
<td>92</td>
<td>CR</td>
<td>-27.625</td>
<td>97.875</td>
</tr>
<tr>
<td>94</td>
<td>SAE</td>
<td>-5.625</td>
<td>14.625</td>
</tr>
<tr>
<td>99</td>
<td>MHO</td>
<td>-20.250</td>
<td>37.750</td>
</tr>
</tbody>
</table>

The latitude and longitude coordinates are provided for the upper left and lower right corners of a data rectangle. The box size and upper left sample and line number for the Galileo SSI mosaic [see McEwen et al., this issue] are also provided.

...the energy and shape of the absorption that are diagnostic markers of mineralogy. Using the low spectral resolution SSI data there are a number of general interpretations of the weak absorption which involve either masking or diluting the ferrous absorptions of presumably basaltic material. A weaker 1 μm band typically indicates a lower abundance of ferrous pyroxene in the soils. This accounts for the classic difference between mare and highland soils (Figures 4, 7). A principal difficulty when comparing mare soils, however, is that there is no apparent correlation of the band strength with either albedo nor with UV/VIS. All mare basalt samples are pyroxene-rich [Papike et al., 1976]. If the variations in band strength were due to basaltic soils being diluted with low-Fe feldspathic material, there should be an inverse correlation of albedo with band strength. Similarly, if variations in opaque components and their subsequent effect on spectral contrast are the principal cause of variations in 1 μm band strength, there should be a direct correlation of albedo and band strength. Neither appears to be the case for limb and farside basalts. Our current working hypothesis is that as a group these limb and farside basalts have an inherently different form of mafic mineralogy than that normally found on the nearside. This could mean different olivine/pyroxene proportions, exceptionally fine-grained textures (scattering light before it acquires absorption features), or that some of these materials have a bulk composition quite different from what has been sampled. They could be more Mg-rich (less Fe-rich), for example, but contain sufficient opaques to give them the albedo of mare.

4.2. Mare Craters

Material freshly excavated by an impact in the maria is relatively unweathered by the lunar environment and exhibits a
strong absorption near 1 μm due to the abundance of clinopyroxene in basalts and the lack of weathering. These areas of freshly exposed basalt have high 0.76/0.99 μm ratios and appear as bright small localized areas randomly dispersed across the mare in Figure 10. Spectra of representative mare craters 5-15 km in diameter are shown in Figure 9, center left. Although they are brighter than surrounding mare soils, fresh mare craters rarely exceed the albedo of typical highland soils (compare with Figure 9, center right). The strong mafic mineral absorption associated with mare craters is readily apparent in Figure 10. For mare craters the 0.40/0.56 μm ratio is variable (see also MH45 in Figure 7). Although the continuum slope between 0.56 and 0.76 μm is sometimes relatively blue (flatter spectrum), there is a distinct inflection downward at 0.76 μm into the strong mafic absorption. This is due to the high concentration of pyroxene in mare basalts. At the spatial and spectral resolution of Galileo SSI, mare craters are distinct from their surroundings, but all exhibit generally similar spectral properties.

4.3. Highland Soils

Several representative spectra for highland soils on the limb and farside are shown in Figure 9, center right (two from the Hevelius Formation (circles), two from the Maunder Formation (diamonds), two from the Montes Rook Formation (triangles), and an Apollo 16 soil measured in the laboratory for reference (crosses)). The relative albedo measurements of SSI data are internally accurate (derived relative to MHO). These limb and farside highland soils share several common characteristics with Apollo 16 soil that indicate a common feldspathic composition; they are all about twice as bright as the mare (e.g., MH0; see Figure 8), have little if any mafic mineral absorption (low 0.76/0.99 μm in Figure 10), and are relatively red in the UV/VIS.

Although these highland soils to a first order appear similar to one another, there are small, but consistent differences between them that appear to be spatially, and hence geologically, related [see Head et al., this issue; Murchie et al., 1992]. As shown in Figure 9, for example, the brighter highland soils of the limb and far side tend to exhibit a flatter (bluer) continuum between 0.56 and 0.76 μm compared to darker soils. Although the albedo variations of highland soils were not originally recognized as an indicator of composition, a correlation between albedo and Al/Si was noted from Apollo x-ray data [Adler et al., 1972, 1973]. This correlation is almost certainly associated with the abundance of the bright Al-rich mineral plagioclase and its alteration products. The correlation between albedo and Al/Si, however, breaks down for immature materials such as those associated with fresh highland impact craters [Fischer et al., 1992]. Nevertheless, if immature regions are identified (see discussion below) and removed from consideration, the regionally extensive and brighter mature highland soils of the limb and farside can be interpreted to be relatively Al-rich soils (see Fischer et al., 1992 for calibration). Most areas shown in pink in Plate 1 are thus predicted to have high Al/Si values while dark purple and black areas should have low values. Examples of two areas interpreted to contain regionally extensive Al-rich
anorthositic soils are NNW Orientale from the inner Rook Mountains to the Cordillera Mountains and the region west and south of the crater Bailly near the southwestern nearside limb.

4.4. Highland Craters and Steep Mountains

Fresh impact craters that are located in the highlands exhibit the highest albedo of all lunar materials. Representative spectra showing the diversity of highland craters (and steep-sided massifs unable to develop a mature soil) are shown in Figure 9 right. The distinctly high albedo coupled with a flat continuum between 0.56 and 0.76 μm distinguishes these immature highland regions from more mature highland soils and the more mafic immature mare crater material. Albedo is particularly important. The high albedo slice of Galileo SSI data shown in Plate 1 (white) readily separates the freshest (most immature) highland lithologies. Both the high albedo and the flatter continuum are directly linked to the high abundance of the mineral plagioclase. Although only a few experiments have addressed shock effects on minerals, it has been shown that high shock pressures, characteristic of major impact events, alters the optical properties (including the continuum) of plagioclase, but not of the more mafic minerals [Adams et al., 1979]. The abundance of mafic minerals present in limb and far side craters and mountains, however, can be quite variable and is estimated by the strength of the 1 μm band strength. Two extremes characterized prior to Galileo are included in Figure 9 right: pure anorthosite represented by 42 AM, a massif of the Inner Rook Mountains (<5% mafic minerals, identified by Spudis et al. [1984] and by Hawke et al. [1991]), and an anorthositic gabbro represented by 76 Aristarchus (~ 30% mafic minerals, identified by Lucey et al. [1986]). SSI spectra of previously unexplored limb and far side highland craters also reveal there is a great deal of diversity in mafic mineral content on a small spatial scale. Two neighboring craters northwest of Mare Orientale, for example, have excavated distinctly different lithologies: anorthosite at 45 Cra and noritic (or gabbroic) anorthosite at 27 Cra.

Distinct spectral characteristics of fresh feldspathic material can also be recognized in the scaled relative reflectance spectra of Figure 9 right. The flatter continuum slope seen between 0.56 and 0.76 μm often extends to shorter wavelengths causing fresh craters to appear "blue" in UV/VIS color ratio images. The presence of mafic minerals in immature anorthositic material is not sufficient to confuse feldspathic highland lithologies with the more gabbroic lithologies such as mare basalts. For example, in addition to the major albedo differences between these immature feldspathic highland areas and mare crater material (see Plate 1), a downward inflection toward longer wavelengths at 0.76 μm, common to mare crater reflectance spectra relative to MS2, is not observed for highland crater material, even at Aristarchus, one of the most gabbroic highland lithologies. Most feldspathic lithologies exhibit a positive inflection at 0.76 μm in such relative reflectance spectra, indicative of their generally lower mafic mineral content.

4.5. Dark Mantling Material

Three types of areally extensive regions of dark mantling deposits (DMD) are recognized in Galileo SSI coverage, two on the nearside (areas near Sinus Aestuum and on the Aristarchus Plateau) and one along the southern edge of the Outer Rook Mountains of the Orientale Basin. In addition, several smaller localized deposits are also within SSI coverage (Coombs et al. [1992]; see discussion in Greeley et al. [this issue]). SSI spectra for the areally extensive DMD are shown in Figure 11a. From Apollo experience, dark mantling material has been recognized and identified as deposits of fine-grained pyroclastic glass beads [Pieters et al., 1974; Adams et al., 1974; Heiken et al., 1974; Gaddis et al., 1985]. Based on their physical and spectral properties, many of the large nearside deposits are interpreted to be similar to the "black spheres" of Apollo 17 such as sample 74001 [Adams et al., 1974]. The SSI spectrum for Galileo area 98 SAE has all the properties of other regions of "black spheres" and agrees well with earthbased spectra [Pieters et al., 1973]. The relatively weak 1 μm band is due to the crystallization of this Fe- and Ti-rich glass into relatively opaque ilmenite-rich ("barred") spheres. The spectral minimum that occurs between 0.56 and 0.76 μm, however, is due to the semitranslucence of a few squares (ilmenite interfingered with a silicate matrix) and the spectral properties of ilmenite [Adams et al., 1974]. The deposits on the Aristarchus Plateau (89 Aris) are more akin to the uncrystallized homogeneous orange glass of Apollo 17, such as sample 74220. A prominent 1 μm ferrous glass band has been unambiguously identified for this near side mantling material with high spectral resolution near-infrared spectra [Lucey et al., 1986]. The SSI spectra are consistent with the Earth-based data: the deposits are relatively red (low UV/VIS) and exhibit a mafic band comparable in strength to most nearside basalts. These characteristics distinguish these homogeneous (quenched) glass deposits from their crystallized black glass cousin.

The Orientale dark mantling material (92 OR) shares some but not all of these characteristics. It is somewhat brighter than nearside mantling deposits, has a very weak 1 μm band (weaker than most highlands), and has a relatively high UV/VIS ratio, but not as high as that observed for nearside "black spheres" deposits. Although the albedo suggests contamination with highland material [see Greeley et al., this issue], the high UV/VIS ratio may not be consistent with a large amount of highland material and may indicate that much of the spectral properties of the mantling deposit itself dominates the measured characteristics.

Two possible compositional interpretations of the Orientale DMD spectra are consistent with these overall characteristics. First, if significant highland material is in the deposits, then, because highland soils are relatively red, the spectral properties of the pyroclastic component must have a higher UV/VIS ratio than the measured value. The character of DMD material would tend toward those of the ilmenite-rich near side dark deposits (e.g., 98 SAE) of material similar to the black glass spheres found at Apollo 17.

Alternatively, if contamination is minor, then the measured spectral properties reflect the inherent properties of the deposits. The weak 1 μm band suggests that the deposits are in the crystallized form rather than homogeneous glass. The spectrum of Orientale DMD is very similar to that of the black spheres deposits observed elsewhere, except the UV/VIS ratio is lower. Assuming ilmenite is the principal opaque phase present that accounts for the darkness of the Orientale deposits, then ilmenite is either less abundant than for the crystallized black glass of the near side or the physical form of this opaque is less translucent. There is no reason to suggest, however, that the physical form of crystallized glass forming regional deposits on the far side should be different from the many areas
of black glass deposits observed on the nearside. A lower abundance of ilmenite would be more likely to account for the lower UV/VIS and would also be consistent with the albedo. With less ilmenite, the Orientale dark mantle may be the crystallized equivalent of the local medium-TiO₂ basalts.

4.6. Cryptomare: Schiller-Schickard

Schiller-Schickard is an extremely interesting region that has been suspected to contain ancient basalts that have been masked by subsequent highland ejecta [Hawke and Bell, 1981; Schultz and Spudis, 1983; Bell and Hawke, 1984]. Preliminary analysis of Galileo SSI data [Belton et al., 1992b] suggested the presence of an extensive cryptomare, and the geologic context of the Schiller-Schickard region and the relation of surface materials to basin ejecta and mixing of lithologic units are discussed in further detail in Head et al. [this issue] and Mustard et al. [1992]. Representative spectra from the Schiller-Schickard region are shown in Figure 11b, and the compositional implications of these spectra are discussed here as they pertain to other lunar lithologies. Schiller-Schickard areas 28, 29, 30, and 32 are local soils or intercrater plains, whereas areas 73 and 74 are local fresh craters (see Figure 6).

The intercrater soils are darker than most highland soils, as is evident both from the spectra as well as the colored albedo slices of Plate 1. Compared to typical highland soils (Figures 4 and 10), Schiller-Schickard soils also have a slightly stronger 1 μm mafic absorption, most easily seen comparing the relative reflectance spectra of Figure 11b and Figure 9, center right. This lower albedo and stronger mafic absorption for the soils at Schiller-Schickard strongly suggests the
presence of a low albedo mafic component, such as a basalt. The two craters evaluated in the area have quite different spectra, each of which can be readily interpreted. SSI spectrum 73 in Figure 11b has all the properties of a classic highland feldspathic crater, including the inflection upward towards longer wavelengths at 0.76 \( \mu m \). SSI spectrum 74, however, has a much stronger ferrous absorption at 1 \( \mu m \). Although it is brighter than many mare craters, its spectral properties, and strength of the 1 \( \mu m \) band in particular, appear to be associated with freshly exposed basalt (this association should be tested with higher spectral resolution near-infrared data). Analysis of the spatial distribution of mafic soils in the Schiller-Schickard region and the mixing relationships between highland and mare lithologies presented by Head et al. [this issue] and Mustard et al. [1992] provide convincing evidence that this region is indeed an ancient pre-Orientale "cryptomare." Thus, both the geologic and compositional evidence support the existence of an extensive ancient mare deposit whose optical properties have been subsequently altered by the addition of an extensive highland feldspathic component.

4.7. South Pole-Aitken

The optical properties of the South Pole-Aitken basin are unique. Small patches of low albedo material, presumably basalt, occur throughout the basin [e.g., see Wilhelms, 1987], but as seen in Plate 1 this far side low albedo anomaly is expansive and appears to encompass much of the entire basin. In addition, an unusually strong mafic absorption associated with this region was an important discovery during initial SSI analyses [Belton et al., 1992b].

It is well known that the Apollo 15 gamma-ray experiment detected an increase in iron content and in radioactivity as the spacecraft passed across the northern boundary of the basin [Arnold et al., 1977; Davis, 1980]. An increase in bulk Fe is normally thought to create a lower albedo soil [e.g., Adams and McCord, 1971a], which in turn would be coupled to a decrease in Al. Since most of the basin can be delineated on the basis of its low albedo (Plate 1) a general interpretation of high Fe, low Al soils across the basin appears consistent with the observations and can be quantified by extrapolating from the correlation of x-ray Al/Si measurements and albedo [Fischer et al., 1992].

Because of its low albedo and the strong 1 \( \mu m \) absorption, there is little doubt that the huge lunar region recognized as South Pole-Aitken Basin is not typical feldspathic highland crust; it is clearly more mafic. The principal compositional issue is the type and abundance of mafic lithologies present. Furthermore, the unusual properties of South Pole-Aitken material occur over an extensive region and have survived continuous bombardment since the formation of this ancient basin very early in lunar history. Within the resolution of SSI images, it is also important to note that no bright craters are observed in the basin implying that these optical, and hence compositional, characteristics are pervasive and not just surficial. Since the current surface has certainly been subjected to the same weathering environment as the rest of the Moon, the compositional information must be extracted largely from well developed soils that represent the underlying regolith lithologies.

Representative SSI spectra for several areas in and around the South Pole-Aitken region are shown in Figure 11c. Three types of material are shown. First, the lowest albedo areas (areas 33, 34, 35, 36 shown with solid symbols and dashed lines) that are in the central part of the basin are redder than most highland soils but exhibit a mafic absorption band as strong as many mare. Second, the strongest mafic mineral absorptions are not associated with the darkest material, but with areas that are somewhat brighter and occur in the southern part of the region (areas 39, 40, and 41, shown with solid lines). The spectra of these regions relative to MS2 peak in the green (0.56 \( \mu m \)): they are relatively red (low UV/VIS) and have a relatively broad and strong 1 \( \mu m \) absorption band. (These areas are near the limb, but the relative absorptions would actually be stronger than what is observed if the measurements contain residual scattered light since the data obtained in the green filter exhibit the least scattered light [see McEwen et al., this issue].) Third, the areas shown with open symbols and dotted lines (53, 54, 84) lie just exterior to the northeastern basin massif and could be ejecta from Apollo Basin (see locations in Figure 6). These latter regions exhibit properties more comparable to common mature and immature highland soils (less red than South Pole-Aitken interior and lower 0.76/0.99 \( \mu m \) with a positive inflection at 0.76 \( \mu m \)) and imply a sharp boundary exists between these and the principal South Pole-Aitken lithologies.

Although a high-Fe, low-Al description of the interior South Pole-Aitken is accurate in a general sense, it does not characterize the mineralogy and the important distinctions between the darker inner and the brighter outer portions of the basin. The interior basin is as dark as many mare basalts and these soils exhibit a mafic mineral band equal in strength and character to low-Ti basalt soils on the nearside. Because the SSI data are of low spatial and spectral resolution, however, they cannot distinguish between mare and mare-like optical properties. Viable hypotheses describing the low albedo inner portion of South Pole-Aitken basin include (1) the presence of numerous small patches of postbasin formation mare basalt, (2) a cryptomare extensively reworked into the regolith by impact bombardment, (3) soil formed on lower crust mafic-rich lithology (compositionally similar to mare basalt) excavated by basin formation, (4) soil developed on Fe-rich impact melt that dominates the optical properties when mixed with crustal feldspathic lithologies. The optical properties of inner South Pole-Aitken basin are unusual and indicate a mafic lineage, but there is insufficient information to determine which of the above (or combination) are more likely.

The unusual but consistent properties of intermediate albedo areas 39, 40, 41 (solid lines in Figure 11) present an enigma. These areas all peak in the green (near 0.56 \( \mu m \)) relative to MS2, implying the presence of a broader mafic absorption than that which occurs for pyroxene alone. Based on spectroscopic analysis of lunar and terrestrial materials in the laboratory, several types of materials can be identified which exhibit these unique spectral properties associated with portions of the South Pole-Aitken basin region: (1) Mafic minerals such as pyroxene with a ferrie component often exhibit overlapping near-infrared absorptions with a reflectance peak near 0.6 \( \mu m \) [e.g., Adams, 1975]. Such features are common in terrestrial materials. (2) High iron, low titanium homogeneous glass (quenched, without crystalline components) has a broad 1 \( \mu m \) glass band and a reflectance peak in the green [Adams et al., 1974; Bell et al., 1976]. The "green glass" of Apollo 15 is the most common example with this property. For comparison, two examples of Apollo 15
"green" glass are shown with Apollo 17 orange and black glass in Figure 12. (3) Olivine of some compositions (usually Mg-rich) exhibit overlapping ferrous bands that extend toward shorter wavelengths causing a reflectance peak near 0.6 μm. Several olivine spectra [from Sunshine and Pieters, 1990] are shown in Figure 13. (4) Alternatively, because the natural system is often extraordinarily complex, an unknown process or unsuspected lithology could be responsible for the unusual spectral properties at South Pole-Aitken. For the lunar case, option 1 is unlikely and 4 is undeterminable, leaving options 2 and 3 as reasonable working hypotheses. Thus, either an abundance of olivine and/or of Fe-rich, Ti-poor quenched glass could account for the unusual properties observed in the southern South Pole-Aitken basin. Both imply an enhanced mafic concentration. It should be noted that the SSI data do not preclude the presence of pyroxene, but they require the presence of an additional component that causes these subtle but distinct variations from the norm.

There is no compelling spectroscopic reason to favor either of the above two interpretations for the southern part of South Pole-Aitken, but, for the reasons summarized below, experience with lunar materials would tend to favor an enhanced concentration of olivine rather than homogeneous glass. Although Fe-bearing glass exhibits distinct absorption bands [Adams, 1975; Bell et al., 1976], it can be detected as a species only if the glass is homogeneous (quenched, not crystalized) and if it occurs in high concentration. The few areas on the lunar nearside for which Fe-bearing glass has been detected with confidence are in the vicinity of several regional pyroclastic deposits [Gaddis et al., 1985] and in local regions of impact melt accumulation such as at a few sites in Copernicus, Tycho and Aristillus [Smrekar and Pieters, 1985]. Although a basin-forming event would certainly form a large amount of melt, the lunar sample evidence suggests the most common product is a variety of polymict breccias (composed of a diversity of lithic fragments), and impact melt glass is rarely homogeneous quench glass. In spite of the identification of

![Graph](image)

Fig. 12. Reflectance spectra of lunar glasses. Samples 74220 and 74001 are of the same composition (Fe- and Ti-rich), but different mineralogy. Sample 74220 is the homogeneous quenched "orange" glass from Apollo 17; 74001 is the black glass crystallized equivalent containing very fine laths of ilmenite interfingered with silicate minerals or glass. Sample 15401 (two samples shown with textured line spectra) is the "green" glass of Apollo 15 (high-Fe, low-Ti). It is a homogeneous quenched glass, but of distinctly different composition from that of Apollo 17. Data are from J. B. Adams' collection of lunar sample spectra.

5. SUMMARY AND CONCLUSIONS

The new Galileo data for the lunar limb and far side greatly expands our knowledge about the diversity of lunar materials and their implications for evolution of the Moon. The following points reiterate several highlights of the compositional analyses of the SSI data.

1. Most highland soils on the limb and far side are of a feldspathic character generally similar to those sampled during the Apollo and Luna missions. Feldspathic highland crust exposed at fresh craters exhibits diverse compositions ranging from anorthosite to noritic (or gabbroic) anorthosite. Regions of ancient mare (cryptomare) within the highlands diverge from these properties and can be identified on the basis of spectral properties of both soil and craters.

2. Observed mare basalts on the limb and far side exhibit a more narrow range of compositions than basalts of the near side. Most limb and farside basalts are of a intermediate TiO$_2$ content, but because of their weak 1 μm mafic mineral absorption they do not readily fall into basalt classifications developed for the nearside. The dark mantling material at Orientale appears to be either a crystallized equivalent of these low to intermediate TiO$_2$ basalts or a deposit similar to the black glass of Apollo 17 that is mixed with a significant component of highland material.

![Graph](image)

Figure 13. Reflectance spectra of a suite of olivines of different composition [after Sunshine and Pieters, 1990]. Fo values indicate Mg/(Mg + Fe) composition.
3. The huge mafic-rich anomaly associated with South Pole-Aitken Basin dominates the southern far side crust. Soils developed in the dark central portion cannot be distinguished from low-Ti basalts. The southern part of the basin contains regionally unique lithologies that appear to be enriched in olivine, or possibly (Fe-rich, Ti-poor) quenched glass.

These compositional data allow several general conclusions to be drawn about the geologic evolution of the lunar crust. Both the similarities and the differences with the near side are significant. First, the predominance of feldspathic lithologies across areas of the limb and far side highland crust reconfirms the concept of a generally anorthositic crust and the need for a mechanism (such as the hypothesized magma ocean) to concentrate large amounts of plagioclase into the crust early in lunar evolution. Second, the survival of varied lithologies ranging from almost pure anorthosite to noritic (or gabbroic) anorthosite at localized fresh craters or massifs indicates that local heterogeneities persist in the crust in spite of the impact record. (Due to the limited nature of the data, it is not known whether these small-scale heterogeneities are indicative of plutonic activity or simply indicate remnant variations of a primordial crust.)

Furthermore, the persistence of the South Pole-Aitken compositional anomaly through time suggests that not only is the region compositionally distinct throughout the megaregolith, but that lateral mixing with surrounding highlands since South Pole-Aitken Basin formation has been minor. The inner, darker portion of the basin is consistent with the presence of extensive cryptomare, massive (gabbroic) impact melt or breccias, and/or postbasin basaltic volcanism. It is difficult to distinguish which of these, or a combination, is more probable. On the other hand, one of the most obvious and important implications of the South Pole-Aitken mafic anomaly is that the extensive exposures of olivine or mafic glass observed in the southern part of the basin most likely represent deep-seated material excavated by the basin forming event. Although the precise dimensions of South Pole-Aitken are not well determined, potential depths of excavation [Spudis and Davis, 1985] are estimated to range from 88-167 (assuming a 2500 km diameter). These mafic materials along the southern portion of the basin could thus very well be derived from lower crust depths. They could also represent materials with a significant mantle component.

6. SCIENCE AND EXPLORATION IMPLICATIONS

Even with the small pulse of new data over this limited spectral range, the Galileo SSI multispectral images of the lunar limb and far side have provided a wealth of information about the compositional character of unexplored lunar regions. As frequently occurs for exploration missions, the SSI results raise more questions than they answer. What, for example, is the significance of the unusual limb and far side basaltus in terms of volcanic evolution of the Moon? If the South Pole-Aitken impact tapped lower crust or mantle material, what is its composition and how does that affect estimates of the bulk composition of the Moon? Hypotheses are testable with more complete data and global coverage. Additional multispectral images, such as those to be acquired by the Clementine mission (DSPSE) [Shoemaker and Nozette, 1993; Lucey, 1993], may provide a valuable base map of general surface units which will allow their distribution to be analyzed in geologic context. Fundamental lunar science questions, however, await resolution with additional global compositional information on mineral and elemental abundances [Lunar Exploration Science Working Group, 1992]. This primary information about the Moon is now well within our grasp with the suite of instruments such as those on the proposed Lunar Scout missions. These include gamma-ray and x-ray spectrometers for elemental abundance measurements and a visible to near-infrared imaging spectrometer (MinMap) for accurate high spectral and spatial resolution mapping of mineralogy [Head et al., 1993; D. Morrison, personal communication, 1992].

The uniformity of the distinctive western limb and far side basalt properties suggests an inherent difference in the type of magma that reaches the surface on this part of the Moon. These basalts, nondistinct in TiO₂ content, all exhibit a weaker 1 μm ferrous iron absorption than their well studied near side cousins. Assuming the weak absorption is due to a compositional rather than a physical property, an intriguing hypothesis is that these basalts are Mg-rich, and relatively Fe-poor, perhaps the extrusive equivalent to the proposed intrusive Mg-rich plutons. Since the limb and farside are presumed to have thicker crust, characterizing the composition of their possible Mg-rich lavas would provide lunar petrologists with concrete compositional constraints with which to model volcanic evolution (e.g., degree of partial melting, assimilation, magma buoyancy, emplacement) for such crustal regions.

Two important measurements are needed to confirm and then interpret the significance of these unusual basalts. The first is to directly measure the Fe and Mg abundance of these materials. From a 100 km orbit, the effective field of view for a gamma-ray spectrometer is about 100 km and resolution for an x-ray spectrometer is ≥ 15 km. Given the size of the Mare Orientale deposits (~200 km in diameter), there should be no difficulty obtaining accurate elemental data with the proposed gamma-ray and x-ray spectrometers [Moss et al., 1993; Clark et al., 1993]. The second critical piece of compositional information is characterization of the basalt mafic mineralogy using high spectral resolution measurements across diagnostic mineral absorption bands in the near-infrared. The spatial (~200 m) and spectral (~11 nm) resolution and continuous spectral coverage from 0.35 to 2.4 μm of the proposed orbital imaging spectrometer [Pieters et al., 1993] is well-suited to such mineral characterization objectives. Mg-rich pyroxenes and/or olivine can be readily identified and distinguished from their Fe-rich counterparts based on the energy and shape of observed absorptions [Adams, 1974; Burns, 1970]. Identification of mineral combinations is determined through deconvolution of multiple absorption bands superimposed on a lunar continuum [Sunshine and Pieters, 1990, 1993a]. The high spectral resolution of the imaging spectrometer will allow the subtle variations between maria to be evaluated in terms of compositional variations in geologic context. The high spatial resolution compositional information allows genetic relations between basalt compositions to be ascertained.

The unusual mafic deposits associated with South Pole-Aitken Basin provide perhaps the most unique opportunity to document the composition of the lunar crust with depth. The SSI results have highlighted the compositional anomaly at SPA, but only hint at its extent and character. A more complete determination of the elemental and mineral composition of SPA deposits, in their geologic context and relation to each other, can provide the first direct compositional measurement of crustal stratigraphy for any planet to such depths (> 50 km).
How is the composition of the lower crust distinguished from the upper mantle? Do stratigraphic zones rich in incompatible elements (such as KREEP) exist within the crust as a magma ocean residual? What is the relation of the low albedo interior to the exterior deposits of SPA? Again, information on both the elemental and mineral abundance is fundamental to such science issues. The low albedo interior of SPA and the southern SPA deposits of possibly olivine-rich material identified by Galileo SSI data are spatially large enough to allow gamma-ray measurements of Fe, Ti, and radiogenic elements (essential to assess the KREEP component). Mineralogy will be assessed at higher spatial resolution with the visible to near-infrared imaging spectrometer, allowing sharp boundaries and gradational mixing of lithologies to be characterized and mapped throughout the deposits. Confirmation of the presence of olivine and its distribution requires high spectral resolution near-infrared spectra and deconvolution of diagnostic olivine absorptions from those of other mafic minerals such as pyroxene. With such data it is anticipated that the composition of the olivine, a principal marker for magmatic evolution, can be discerned for those regions of high concentration [e.g., *Sunshine and Pieters*, 1993b]. Equally important for reconstructing crustal stratigraphy will be characterization of the pyroxene composition of various lithologies and the mixing relations of olivine/pyroxene throughout the deposits, challenges readily addressed with available advanced computational capabilities.

One very important lesson from the Galileo first Earth-Moon encounter is that the Moon continues to hold surprises. Before the encounter, it was expected that the deposits around the Orientale Basin would exhibit notable variations, and many investigators were somewhat disappointed when the data indicated a predominantly feldspathic composition. On the other hand, few (perhaps no one) expected South Pole-Aitken to be so prominent and dramatic. Having 382 kg of lunar samples for study in Earth-bound laboratories for the last 20 years has laid the foundation for further exploration, but has also limited our expectations. We did not expect to see such obvious evidence for extensive deposits of mafic material derived from the lower crust or mantle. Until the global assessment of the mineral and elemental composition of the Moon is completed, we will always be limited in what we think we know about the character and evolution of Earth’s nearest neighbor.

**Acknowledgments.** We gratefully acknowledge the Galileo Team at JPL for their efforts leading to a successful Earth-Moon encounter. Part of this research was supported by NASA grants NAGW-28 and NAG9-184 (C.M.P.). We are most thankful for the assistance of Joel Plutchak in computer programming and analyses.

**REFERENCES**


Farr T.G., B.A. Bates, R.L. Ralph, and J.B. Adams, Effects of


Pieters, C.M., Mare basalt types on the front side of the Moon:


M. Belton, Kitt Peak National Observatory, National Optical Astronomy Observatories, Tucson, AZ 85726-6732.

E.M. Fischer, J.W. Head, C.M. Pieters, and J.M. Sunshine, Department of Geological Sciences, Brown University, Providence, RI 02912.


R. Greeley, Arizona State University, Tempe, AZ 85287-1404.

H. Hoffmann, R. Jaumann, and G. Neukum, DLR, Institute for Planetary Exploration, 12484 Berlin and 82230 Oberschleissheim, Germany.

S.L. Marchie, Lunar and Planetary Institute, Houston, TX 77058.

(Received September 9, 1992; revised May 6, 1993; accepted May 6, 1993.)