Buried stratigraphic relationships along the southwestern shores of Oceanus Procellarum: Implications for early lunar volcanism

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Abstract. The composition of mare-highland boundaries is investigated in the region of southwestern Oceanus Procellarum using multispectral images from the Galileo solid-state imaging system. The data are analyzed using a linear image-based spectral mixture model to map the distribution and abundance of spectral end-members representing mare basalt, mature highland soils, and fresh crater materials. The fraction images that result from the mixture modeling are then integrated into a geographic information system database to analyze the relationship between the compositional gradients and regional geologic and geomorphic units. Within this framework, three basic types of mixing gradients are recognized: narrow mixing zones, broad mixing zones, and complex mixing zones. The narrow zones appear to be the result of simple postformation lateral mass transport of surface materials due to the time averaged effects of impact cratering and regolith gardening. The broad or moderate mixing zones exhibit evidence for significant incorporation of basalt into the distal basin ejecta of Orientale, and thus are interpreted to indicate that pre-Orientale volcanism and volcanic deposits were widespread in the Procellarum region. This is further corroborated by the mare-rich ejecta blanket observed for the 100-km-diameter impact crater Leatone. The complex mixing zones show evidence for extensive pre-Orientale, and perhaps pre-Imbrium cryptomare, as well as some volcanism extending into the late Imbrian period. These results indicate that mare-highland boundaries frequently contain a convolved geologic record that allows insight into the geologic events prior to the final one apparently recorded by surface deposits. For this region of the Moon, we now recognize that volcanism was well established and widespread in early Imbrian time but had become more focused to a few major volcanic regions (Humorum, Procellarum) by the late Imbrian.

Introduction

Crustal formation processes have been classified as primary (derived from energy associated with accretion and bombardment) and secondary (derived from partial melting of the mantle) [Taylor, 1989]. The lunar maria are secondary crustal materials superposed on a global primary crust, exposed as the lunar highlands, and represent a wide range of basalt compositions derived from partial melting of the lunar mantle. Because of the small volume of the lunar maria (about 10^7 km³, less than 1% of the total volume of the primary crust [Head, 1976]), the Moon offers an excellent opportunity to study the transition from primary to secondary crust, and to learn about the initial stages of emplacement of a secondary crust [Head and Wilson, 1992].

Thus an important goal is the determination of the history of emplacement of lunar maria. Initially, the sharp contrast between the high-albedo highland crust and the low-albedo maria, coupled with obvious onlap relationships of the mare and distinctive crater size-frequency distributions, led to the hypothesis that mare emplacement began soon after the end of heavy bombardment, specifically following the formation of the last major impact basins (see discussions by Wilhelms [1987]). More recently, however, evidence for the presence of prebasin mare deposits has mounted (mare clasts in basin ejecta breccias, dark-halo craters exposing buried maria deposits, etc. [Ryder and Taylor, 1976; Schultz and Spudis, 1979]. Conclusive evidence for the presence of buried mara deposits (named cryptomaria [Head and Wilson, 1992]) has been found in several areas of the Moon (e.g., Hawke and Spudis, 1980; Hawke and Bell, 1981; Bell and Hawke, 1984; Hawke et al., 1991; Head et al., 1993; Mustard et al., 1992; Williams et al., 1995; Blewitt et al., 1995), and it is now clear that the emplacement of mare deposits overlapped the period of heavy bombardment and basin formation.

The cumulative destructive, blanketting, and mixing aspects of impact cratering processes, however, make it progressively more difficult to trace volcanism back into the earlier phases of lunar history. Nevertheless, evidence for early volcanism is convolved within the geologic record, and it should be possible to establish criteria by which the presence and extent of early volcanism may be recognized. In this analysis we have focused on the region of the youngest of the major impact basins, Orientale. In principle, the well-exposed deposits of the 900-km-diameter Orientale basin are sufficiently well-preserved and unmodified by subsequent large cratering events that they represent one of the best possible regions to study the interaction of basin ejecta emplacement with pre-basin maria.

A general strategy for the detection of cryptomaria has been established [Antonenko et al., 1995]. Recognition criteria include defining evidence which indicates the likely presence of
an obscured basalt (e.g., dark-halo craters, regional spectral, and geochemical anomalies) and supporting evidence that corroborate defining evidence (e.g., association with light plains deposits, location within basins or near known mare). Within the regions influenced by the Orientale event, cryptomaria will be difficult to detect in the proximal parts of the ejecta deposit (near the basin rim) because of the great thickness of primary ejecta. In medial parts of the ejecta deposits, primary ejecta is less abundant, excavated local material (including any pre-event maria) is more abundant, and the aggregate thickness of the ejecta deposit is thinner, although still generally continuous. Here cryptomaria are detected by the presence of postbasin dark-halo craters and remote sensing evidence for cryptomare components incorporated into basin ejecta deposits [Mustard et al., 1992; Head et al., 1993; Blewitt et al., 1995]. At still greater radial ranges, Orientale ejecta deposits become thinner and discontinuous, and pre-existing topography and surface morphology become more evident. Cryptomaria that occur in these areas are more readily detected and cataloged.

The location and extent of early lunar volcanism becomes increasingly more difficult to detect in terrains that record the effects of several large-scale events. The southwestern shores of Oceanus Procellarum (Figure 1) is one such area where overlapping basin ejecta from Humorum and Orientale are recognized as well as secondary craters from the Imbrium event, and which has a long record of volcanism subsequent to the formation of these basins [Whitford-Stark and Head, 1980]. In this paper we examine the stratigraphic relationships between the highlands and the mare primarily using Galileo solid-state imaging (SSI) multispectral imaging data from the Earth-Moon 1 encounter. A variety of techniques are used to assess the boundaries between maria and highlands, and to separate the effects of the various events and examine several cryptomare candidates. We show that these cryptomaria considerably enhance the area of known early mare deposits in the southwestern part of the lunar nearside.

**Regional Geology**

The geology of the Orientale-Humorum-Southwest Procellarum region (Figure 1) has been analyzed on a regional scale [Marshall, 1963; McCauley, 1967, 1973; Titley, 1967, Wilhelms and McCauley, 1971; Wilshire, 1973; Scott et al., 1977] and can be subdivided into three main stratigraphic phases from youngest to oldest: (1) lunar maria deposits of...
Imbrian and Eratosthenian age making up the main deposits of Oceanus Procellarum [Whitford-Stark and Head, 1980], Mare Humorum [Pieters et al., 1975], Mare Orientale and Grimaldi [Greeley et al., 1993], and smaller patches distributed between Mare Orientale and Procellarum-Humorum [Gaddis and Head, 1981; Yingst and Head, 1994]; (2) deposits of the Orientale basin including the exterior Hevelius Formation emplaced about 3.8 Ga separating the late and early Imbrian epochs, and adjacent smooth, low-albedo plains of comparable age [McCauley, 1977 and 1987]; (3) pre-Orientale basin deposits include materials of Imbrian age (impact craters such as Letronne; deposits mapped as Fra Mauro Formation, secondary pits and lineations from the Imbrium basin, emplaced at about 3.85 Ga), Nectarian age (crater and basin deposits, including Humorum), and pre-Nectarian age (craters and basins, e.g., Grimaldi basin) [Wilhelms and McCauley, 1971; McCauley, 1977].

**Approach: Data Analysis and Integration**

The principal new data used in this analysis are multispectral images obtained by the Galileo SSI instrument. The specific data used are from the Earth-Moon 1 encounter in 1990. We use a portion of the mosaic discussed in detail by McEwen et al. [1993] that covers the southwestern boundary of the Procellarum basin (Figure 1). These data were reprojected and photometrically corrected to normal albedo [McEwen et al., 1993] and then further normalized to the spectral properties of a reflectance standard area in Mare Humorum (MH0) [Pieters et al., 1993]. Gaddis et al. [1995] have reexamined the calibration of the Earth-Moon 1 SSI data and identified an important component of scattered light. They calculate that this may contribute up to 5% brightening of dark regions next to bright regions for the 990 nm data, but that it decreases to contributions of the order of 1-2% for the other filters. For a typical mare brightness of 30 data number (DN), a 5% brightening corresponds to a change in DN of 1-2. Though very important for accurate measurement of band strength, this does not greatly impact the techniques described below to calculate mare highland mixing ratios.

The important characteristics of the boundary between the highlands and mare that are the focus of this investigation are fundamentally a result of mixing between spectrally distinct end-member lithologies on the lunar surface (mare and highland). Spectral mixture analysis is therefore used to deconvolve the multispectral images into fraction images that summarize the basic mixing characteristics between these end-members. For this analysis we use an image-based, linear spectral mixture model [Adams et al., 1986; Mustard et al., 1994]. In the image-based approach, the end-members are selected from the remote data set rather than from a laboratory or telescopically database. The image-based approach is justified in this application, since we are primarily concerned with large-scale mixing between fundamental compositional end-members which are well represented as approximately pure components on the surface. The dimensionality (five spectral bands) and dynamic range of the SSI data also do not permit the recognition and mapping of more than a small number of surface materials.

Since the components are anticipated to be intimately mixed on the surface, a nonlinear model may be more appropriate [e.g., Pieters et al., 1985; Mustard and Pieters, 1989]. However, accurate applications of nonlinear models require that the data be calibrated to a very high degree of photometric accuracy. In a linear mixture model, the end-member abundances are insensitive to calibration as long as the data are related to true reflectance by a linear gain and offset correction. Given a data set calibrated to absolute reflectance, the primary difference between the results of a nonlinear versus a linear mixture approach is the absolute magnitude of the end-member abundance values. The general spatial associations and systematics will be similar.

This same approach has been used successfully to determine the regional extent of the Schiller-Schickard cryptomare and to investigate mixing relationships between pre-existing mare and Orientale basin ejecta [Mustard et al., 1992; Head et al., 1993]. From these analyses, it was determined that three spectrally distinct and geologically meaningful end members could be resolved and mapped within the constraints imposed by the spectral dimensionality and dynamic range of the SSI instrument. The Procellarum-Highland region shares many of the same spectral units as the previous analyses and thus the same endmembers are used in this analysis. The relative reflectance spectra (relative to the Mare Humorum standard area MH0) are shown in Figure 2 and represent mature mare (Humorum), mature highland (Hevelius Formation), and fresh crater (Byrgius A). Using these end-members, the five-channel Galileo SSI data for the region shown in Figure 1 were deconvolved into the percent spectral contribution of the three end-members using a least squares mixture model. The proportion of each end-member required to minimize the error of the fit, subject to the constraint that the sum of the end-members equals unity, determines the spectral abundance of that end-member. The spectral abundance is to first order equivalent to physical abundance.

Shown in Figure 3 are the fraction images for the three end-members and an image of the rms error of the fit. The average
fitting error was 1.4 DN (or ~0.5% of the 8-bit dynamic range), approximately the noise level of the data. Additional end members result in unrealistic end-member abundances (i.e., \( \gg 1.0 \) or \( \ll 0.0 \)) and spatial distributions that are not meaningful. The fraction images provide a framework for understanding the mixing relationships of the surface components represented by the spectral end members. Although compositional variations within end-member classes (e.g., TiO\(_2\) abundance in the mare) are not distinguished in this analysis, they do not significantly affect the abundance calculations. For the SSI data, ratio images provide the best tool for mapping compositional variations within end member classes [e.g., Greeley et al., 1993; Pieters et al., 1993], though the contributions to the reflectance from scattered light (Gaddis et al., 1995) must be accounted for. Analysis of the rms error across the area indicates that the fitting error is generally low, with large errors generally associated with small fresh craters (which have high spectral variability) and misregistration of the spectral bands.

For the purposes of understanding the significance of the mixture maps, they need to be referenced to existing morphologic and geologic databases. This is accomplished through a geographic information system (GIS) database. For direct comparison to large-scale geomorphic features, the mixture maps are merged with the U.S. Geological Survey (USGS) digital airbrush map of the lunar surface using intensity-hue-saturation (IHS) transforms. For this application, the airbrush map is assigned to intensity, the fraction image is assigned to
Narrow Mixing Gradients. The type area for narrow mixing gradients is the mare-highland contact in the Grimaldi Basin (Figures 1 and 4 and Plate 1). The transition from low to high mare abundance typically occurs over length scales of a few kilometers (Figure 4, profile 1). The geologic contact between mare and highland, as defined by morphologic mapping [e.g., Wilhelms, 1987], is found within the mixing zone and is positioned on the low mare abundance end of the mixing gradient. Detailed topographic characteristics of the lunar surface are not well known in this area. However, the general nature can be inferred from the geomorphology. Typically, the local relief in areas with narrow mixing gradients is relatively high, with the highlands rising significantly above the mare. In addition to the Grimaldi Basin, this type of boundary is found at mare-highland contacts in Crüger, Orientale, along the scarp on the east side of the crater Hevelius, and along the western edge of the Humorum Basin.

Moderate Mixing Gradients. The principal region exhibiting moderate mixing gradients extends from the crater Damoiseau to the crater Sirsalis along the mare-highland boundary southeast of the Grimaldi Basin (Figures 1 and 4 and Plate 1). The mixing zone is relatively uniform in this area and approximately 100 km in width. The geologic contact is found on the high mare abundance side of the mixing gradient, typically where the mare abundance gradient levels off. The topography along the boundary is low and rolling, without uniformly steep characteristics, as seen in the narrow mixing gradient regions. We also observe numerous secondary craters, chains, and sculpture from the emplacement of the Orientale Basin ejecta in the highland terrain that extend up to the mare contact.

Extended and Complex Mixing Gradients. Complex mixing gradients are found principally from crater Sirsalis southeastward to the western side of the Humorum Basin (Figures 1 and 4 and Plate 1). Unlike the relatively simple mare-highland geology of the preceding types, here the geology is complex, with numerous small mare patches, the widespread but enigmatic hilly-furred terrain [Wilhelms, 1987], cryptomare [Head et al., 1993; Hawke et al., 1993], floor fractured craters [Schultz, 1976], and Hansteen a, a spectrally anomalous red spot. The mixing systematics are equally complex, but some general patterns are recognized. The geologic contact (Figure 4, profile 3) occurs on the high mare side of the mixing zone, similar to the moderate mixing gradients. The variability in mare abundance across the zone appears to be correlated to the geology. For example, the number of resolved mare patches observed in Lunar Orbiter images decreases with distance from the Procellarum-highland boundary, and this is tracked in the mare mixing systematics. The cryptomare identified by Hawke et al. [1993] is well expressed. One area that is anomalous is the ejecta blanket of the crater Letronne. Here the mare abundances are uniformly high, typically greater than 60%. The only other areas with such elevated abundances occur in association with mare patches or very close to the mare highland contact.

Specific Features That Modify and Obscure the Boundary Characteristics

The three basic mixing gradients provide a general perspective on the regional characteristics of the mare-highland boundary relationships. However, there are anomalous areas within the general zones where the typical gradient character-

Results

Three Basic Types of Boundaries Defined by Mixing Systematics

Analysis of the GIS database, summarized in Plate 1, reveals several global properties of the mixing systematics across the mare-highland contact in the study area. There is a zone of mixing at every mare-highland contact, including the contacts within the Grimaldi Basin. The width of the mixing zone is greater than the spatial resolution of the SSI data (~4 km/pixel), indicating that the mixing zone is not a result of spatial averaging due to limited spatial resolution. The gradient and width of the mixing zone, however, is not uniform within the study area. Within the variability observed, there are three general types of boundaries identified: narrow, moderate, and complex. A type profile of the mare abundance across each of these boundaries is shown in Figure 4. The principal defining characteristics of each type boundary are discussed in detail below.

![Figure 4. Profiles of mare abundance across the three principal types of mare-highland mixing boundaries. The profile locations are shown in Plate 1 and labeled 1, 2, and 3. The arrowheads on the profiles indicate the location of the geologic boundary as mapped by Scott et al. [1977]. On profile 3, which traverses the complex terrain northwest of Humorum, the letter M indicates where the profile crosses post-Orientale mare patches, and the letter B indicates where the profile crosses the crater Billy.](image-url)

hue (or color), and a saturation of 50% is assigned to all pixels with fractions greater than 20%. This lower bound for the fraction was chosen to minimize high frequency variations in the fraction images at low abundances and emphasize the large-scale mixing gradients. Geologic unit contacts for mare-highland, and facies of the Orientale ejecta (e.g., inner and outer Hevelius, light plains) were digitized from the mapping of Wilhelms and McCauley [1971] and Scott et al. [1977], and coregistered to the airbrush map. Analysis of the integrated database is also supplemented by new observations using Lunar Orbiter IV photographs.
Plate 1. Mare fraction image merged with digital airbrush base map (Figure 1). The principal geologic contact between mare units in Oceanus Procellarum, Humorum, Grimaldi, Crüger, and Orientale, and the highlands is shown by the yellow line, and the outline of light plains units is shown by the blue lines. The mare abundances are represented in color ranging from 100% mare (red) to 25% mare (blue). Areas with mare abundances less than 25% are shown in grey. Analysis of this result in conjunction with Lunar Orbiter IV images reveals three types of mare-highland mixing relationships: narrow (profile 1), moderate (profile 2), and complex (profile 3). Plots of the mare abundance across these zones are shown in Figure 4 and the significance of these relationships is discussed in detail in the text.

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Plates 1-5. Maps of mare fraction derived from Lunar Orbiter IV images. (Note: The plates are not visible in the text provided.)

The characteristics of the mare regions are modified by local processes or are in the vicinity of specific features. Recognition of these anomalies in the mixing gradients, and their causes, is important for assessing the regional extent and importance of the mixing gradients.

Ejecta from fresh craters in highland terrains causes well-characterized decreases in mare abundances. Examples include several craters east of Grimaldi and on the western rim of Humorum. Ejecta from Cavalerius, adjacent to and north of the crater Hevelius, causes a conspicuous anomaly of low mare abundance extending several tens of kilometers into mare beyond the mare-highland geologic contact. The general pattern of the anomaly correlates well with the ejecta patterns, as observed in Lunar Orbiter IV photographs.

Rims of flooded craters and other apparent highland outliers within the mare typically have moderate to high mare abundance (>60%). Two areas, however, exhibit unusually low mare abundances, despite being surrounded by mare. These are Hansteen-a (a red spot) and massifs in the narrow region of mare between Oceanus Procellarum and the Humorum Basin (Figures 1 and Plate 1). The anomalies are highly localized to the geographic footprints of these features and do not appear to affect the surface compositions of surrounding mare.

Both of the above anomalies were negative or low mare anomalies. A notable positive or high mare abundance anomaly occurs northeast of Grimaldi. This anomaly is associated with well-characterized oval craters surrounded by a dark mantle deposit. This dark mantling material was erupted from the volcanic vents [e.g., Head and Wilson, 1979] and has significantly lowered the albedo and made the surface material similar to the mare within the SSI band passes. Near-infrared spectra of this deposit indicate it is composed of volcanic glass with an additional crystalline mineralogic component such as olivine or high calcium pyroxene [Hawke et al., 1989].

Relationship to Dark-Halo Impact Craters

Dark-halo impact craters are important for recognizing the locations of mare deposits covered by obscuring layers of
Origin of Light Plains Units

The origin of the lunar light plains continues to be a subject of active investigation. Many workers believe that at least some of the light plains were formed by highlands volcanism (e.g., Hawke and Head, 1978) or impact melt deposits (Head, 1974; Hawke and Head, 1977). The spatial distribution of light plains in the study region, however, indicates that they are most likely due to processes identified in the two principal competing end-member hypotheses for light plains deposits: (1) ponded basin ejecta (which may include impact melt) or (2) volcanic plains mantled by ejecta of highland composition (cryptomare). The Oberbeck et al. (1975) model for emplacement of basin ejecta predicts that the ejecta should incorporate a significant fraction of local material in the distal reaches of the ejecta deposits. This model is consistent with Orientale light plains deposits in the Schiller-Schickard region that are associated with elevated mare abundances and that map out the regional extent of a cryptomare (Head et al., 1993; Mustard et al., 1997; Antonenko et al., 1995; Blewitt et al., 1995).

Extensive light plains deposits are found within the outer facies of the Hevelius Formation in the 50° arc between the craters Calvysius and Schickard (Plate 1). Through the analysis presented here, we can assess the origins of light plains in this region. Light plains associated with significant mare fractions would indicate the presence of cryptomare, while those without a mare signature would indicate predominantly ponded basin ejecta. Despite the large concentration of light plains units in the distal facies of the Hevelius, few have any definitive signature of mare. Those with the most elevated abundance of mare occur very close to, or at, the Procellarum boundary and are probably simply associated with the mare-highland boundary mixing gradients. Thus the light plains in this region are dominated by the spectral properties of highland material and are likely ponded basin ejecta. Cryptomare may exist in this region, and numerous dark-halo craters are recognized (e.g., Antonenko et al., 1995) that attest to the presence of buried mare. The lack of regional cryptomare signatures may be due to several factors. As discussed by Antonenko et al. (1995), the buried mare in this area may be patchy and small in extent, and/or the greater thickness of Orientale basin ejecta relative to the Schiller-Schickard region may have prevented significant mixing of mare material within the overlying ejecta.

Discussion and Implications

From analysis of the results of the mixture modeling, we identify three distinct types of mare-highland mixing gradients at mare-highland contacts. The purpose of the following discussion is to develop a theoretical framework for understanding origins of the mixing gradients and then to assess the significance of the identified mixing gradients in the context of this framework. The focus of the following discussion is on processes contributing to physical mixing across boundaries. Other processes such as petrologic mixing and compositional zonation in basin ejecta have been assessed by Fischer and Pieters (1995). They conclude that these processes may be important in some specific situations, but are generally not viable for explaining the majority of observed gradients, and the most probable processes are vertical and lateral mixing by basin and non-basin scale impacts. Our analyses differ from their study, in that we examine the nature of mixing relationships in the context of local geologic features and processes, and thus can resolve the relative importance and timing of competing processes.

Physical mixing of materials at, and across, compositional boundaries and geologic contacts is thought to occur through vertical and lateral transport during impact. There is abundant evidence for lateral transport. Continuous ejecta deposits typically extend to 2.5 crater radii from crater rims, while discontinuous deposits, including rays and secondary craters, extend the zone of influence to greater distances (e.g., Moore et al., 1974; Oberbeck et al., 1974; Pieters et al., 1985). The extensive ray systems of relatively recent impact craters such as Tycho, Copernicus, and OIters A can be tracked with ease across thousands of kilometers of mare. Mare soils collected far from highland sources have measurable quantities of highland fragments, typically concentrated in the finest fraction. Soils collected from the Apollo 15 and 17 sites close to highland-mare contacts show evidence for even greater amounts of mare-highland mixing (e.g., Heiken et al., 1973; Heiken and McKay, 1974).

However, lateral transport through the cumulative effects of several eons of impact cratering is generally considered to be an inefficient process. Many workers point to the apparent sharpness of contacts at morpho-geologic and compositional boundaries as enduring testimony to this. Despite the intense interest in the importance of lateral transport, and the apparent contradictions between obvious mechanisms for transport (impacts) and the persistent sharpness of geologic contacts, few analytical models exist that could be used to make specific predictions of local/foreign mixing ratios across the Moon. Arvidson et al. (1975) developed a model for horizontal transport based on McGetchin et al.'s (1973) model for mass distribution in ejecta blankets from impacts, and estimates of cumulative crater productions for relatively young surfaces. This model predicts an accumulation rate of 0.6 mm/m.y. of which ≤1% is derived from sources at distances greater than 10 km. On the basis of this type of analysis and other evidence, Hörz (1978) concluded that vertical mixing should be the dominant process for mare-highland mixing.

The results from Arvidson et al. (1975) can be used to derive a general set of predictions for the width of mixing zones across mare-highland compositional boundaries (Figure 5). The important observational and conceptual aspects of the model for mixing zones are (1) the gradients should be relatively steep, (2) the mixing zones should have horizontal
dimensions not greater than a few tens of kilometers, and (3) the ratio of mare to highland at the contact will be 1:1. The predicted mixing systematics for the simple case where mare and highland are in contact without topography across the boundary or subsurface complications is illustrated in Figure 5a. The gradient is steep and symmetric across the geological contact. If there is a topographic element, as illustrated in Figure 5b, then it is predicted that transport from the higher topography is more efficient, the mixing gradient length will be greater, and the gradient is no longer symmetric across the contact. It is also reasonable to consider a more realistic contact where the mare rests on a basement of highland and the mare thins toward the contact (Figure 5c). Including a component of vertical mixing will cause the width of the mixing gra-
dient to be extended and the geologic contact will be shifted from the center of symmetry (Figure 5c).

These three cases allow us to assess whether the mixing gradients identified in the analysis of Galileo SSI data can be understood as due simply to postformation lateral transport from impact gardening. The situation illustrated in Figure 5a provides a reasonable explanation for the narrow mixing gradients in the Grimaldi Basin. The mixing gradients are narrow, and the geologic contact is shifted from the axis of mixing symmetry toward low mare abundance. It is also possible that additional highland contributions to the mare could be derived from vertical mixing near the edges of the mare if the mare is thin.

The models for simple lateral transport across a compositional contact, no matter how the contact and geologic relationships are configured, fail to explain what is found in the regions with moderate and complex mixing gradients. The important characteristic of these boundaries that cannot be accommodated with lateral mixing, is that the geologic contact is at the high mare abundance side of the mixing gradient and, in fact, is typically where mare abundances have plateaued. The process of vertical mixing alone [e.g., Horz, 1978] is similarly unable to account for the observations. In the region of complex mixing gradients, there is evidence for cryptomare [Hawke et al., 1993] and abundant postbasin mare deposits, which could be contributing to the enriched matic signature of the highland areas. Alternatively, Coombs and Hawke [1992] have noted that dark mantle deposits tend to occur near mare-highland contacts and could also therefore contribute to the observed width of the mixing zones. However, dark mantle deposits tend to have unique spectral properties, associations with vents, and deposits that cross typical units. Thus, for the moderate mixing gradients, features related to these processes are not present, and a different model for formation of the moderate mixing gradients is required.

The ejecta deposits from the crater Leprone (Figure 6) provide an important piece of information for understanding this mixing zone. Leprone is considered to be post-Imbrium/pre-Orientale in age [Wilhelms and McCauley, 1971; Wilhelms, 1987]. Its position at the edge of the Procellarum region indicates that it excavated materials that were present prior to the later stages of volcanism in Procellarum. The ejecta deposits are characterized in the mixing analysis presented here (Plate 1) by a homogeneous and elevated "mare" signature (≈50%). On the basis of high spectral resolution telescopic spot spectral measurements of the ejecta deposits, Peterson et al. [1994] estimate that the ejecta deposits contain 45% mare.

In general, the area mapped as highlands northwest of Humorum exhibits anomalously low depolarized radar returns in 3.8 cm, 7.5 cm data [Thompson, 1978, 1987; Hawke et al., 1993; B.C. Campbell et al., Long-wavelength radar studies of the lunar maria, submitted to Journal of Geophysical Research, 1996]. Typically, highlands exhibit a high radar backscatter, and mare a low radar backscatter. These differences are generally thought to be due to the higher concentration of low dielectric materials in the mare relative to the highlands. The low radar returns are considered anomalous, since this area exhibits highland-like morphology and thus is expected to have a high radar return. These radar signatures can result from a low abundance of blocks with sizes equal to or greater than the radar wavelengths, or from materials that have low radar reflectivity relative to typical highland material. A paucity of blocks is the less likely alternative, given the size of the anomaly and that it is observed in all three radar data sets. Thus it is likely

Figure 5. Schematic profiles illustrating expected mare-highland mixing profiles due to lateral transport from impact processes. The arrow indicates the location of the geologic contact in relation to the mixing profile. (a) Mare and highland have a vertical geologic contact, and the expected mixing profile is narrow and symmetric across the contact. (b) The contact is vertical, but the highland terrain lies topographically above the mare. In this case the profile is also narrow, but the axis of mixing symmetry is displaced toward the mare side of the contact. (c) The geologic contact between mare and highland slopes toward the mare and is more typical of mare-highland contacts.
that this terrain contains material that has a lower average dielectric constant, intermediate between average mare and highland [Hawke et al., 1993]. This is consistent with the spectral observations of elevated mare abundance in the ejecta blanket of Letronne [Peterson et al., 1994].

Taken together, these data indicate that the ejecta deposits of Letronne are enriched in mare. A substantial accumulation of mare therefore existed in the Procellarum region prior to the Letronne impact event. It is possible to estimate the thickness of pre-Letronne mare present from models and observations of crater excavation. However, there is considerable controversy and disagreement among impact cratering investigators concerning estimates of the depth of excavation on the basis of crater diameter. For the purposes of this study, the analysis of Pike [1980] provides an estimate based simply on the morphology of craters. For a crater the size of Letronne, the observations of Pike [1980] suggest that 3.5 km of material may have been excavated. Given the estimated abundance of mare in the ejecta blanket of Letronne (~50%), then a conservative estimate is that approximately 1-2 km of mare may have existed at the site of Letronne prior to impact and excavation by the Letronne event.

The age of Letronne is post-Imbrium but pre-Orientale [Wilhelms and McCauley, 1971; Wilhelms, 1987], and thus there was extensive pre-Orientale volcanism in the southwest Procellarum region. Pre-Orientale volcanism is also recognized in the Schiller-Schickard region [Schultz and Spudis, 1979; Hawke and Bell, 1981; Bell and Hawke, 1984; Head et al., 1993; Blewitt et al., 1995], indicating that widespread, early Imbrian-aged volcanism was present in the southwestern frontside of the Moon. There are no recognized early Imbrian or earlier deposits of mare exposed on the surface [Wilhelms, 1987], although volcanics of this age have been identified in several lunar samples [Taylor, 1982; Taylor et al., 1983].
Such deposits are likely to have been covered by deposits of the Imbrium and Orientale basins, as well as upper Imbrian-aged and later volcanics.

The presence of pre-Orientale mare in the Procellarum region presents a possible explanation for the moderate mixing gradients with the geologic contact toward the high side of the mare abundance. Basin ejecta from the Orientale event impacted into, and mixed with, the proto-Procellarum basalts. This created a mixed mare-highland composition with increasing mare abundance away from Orientale, similar to that observed in the Schiller-Schickard region [Mustard et al., 1992; Head et al., 1993; Blewitt et al., 1995]. Obscured and partially flooded Orientale secondaries can be identified in what is now contiguous Procellarum mare [Wilhelms, 1987]. Continued flooding of basalts embayed the mixed boundary and lateral transport since the end of major volcanism has diffused the sharpness of the contact. However, since the boundary already contained a significant component of mare, the geologic contact would be definitely shifted toward the mare side of the mixture gradient.

Additional evidence to support this hypothesis is found in a detailed examination of mare abundance profiles acquired perpendicular to the boundary from Grimaldi to Sirsalis (Figure 7). Along this zone, the continuous rise in mare abundance is frequently interrupted by an abrupt increase in mare abundance at, or near, the mare-highland geologic contact. This increase typically occurs near 50-70% mare abundance, is 10-15% in magnitude, occurs over 3-5 pixels (12-20 km) and is correlated with the geologic boundary between mare and highland. The increase could occur over a shorter spatial scale, but may not be resolved by the 4 km/pixel resolution of the SSI instrument for these data. This rise is interpreted to be the contact between the latest mare basalts and the mixing boundary.

A similar sequence of events is indicated for the regions with the complex and extended mixture profiles. However, throughout this area there are numerous post-Orientale mare patches extending well into the highland units. A combination of extrusive and intrusive magmatism could contribute to the overall enhanced mare abundances, and continued lateral and vertical post-volcanic mixing could contribute to the extended zone of mare contamination. Many of the important features in this area are not well resolved within the resolution of the Galileo SSI data, and verification of these hypotheses

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**Figure 7.** Five profiles acquired perpendicular to the mare-highland contact in the region with moderate mixing gradients. The top profile crosses the Grimaldi Basin and the last profile is located slightly north of the crater Crüger. Each profile is vertically offset 50% from the next for clarity. Note the 10-15% increase in mare abundance, indicated by the short arrows, that occurs at the geologic contact.

**Figure 8.** Interpretive geologic cross sections for the three type profiles shown in Figure 4. In each section, mare is represented in black, highlands by the plus pattern, and the arrows show typical direction for material transport. See text for discussion.
will require detailed analysis with new data from the Clementine mission.

Geologic interpretations for the three types of mixture gradients are shown in Figure 8. For the narrow mixing gradients (Figure 8, panel 1), postmare emplacement lateral transport and impact gardening are the primary processes responsible for creating the observed systematics in mare abundance. Material from the highlands is preferentially transported toward the mare owing to enhanced relief. This is best illustrated in the Grimaldi Basin, where highland material has contaminated the mare, causing the axis of mixing symmetry to be shifted away from the mare-highlands contact toward the center of the basin. Moderate mixing gradients (Figure 8, panel 2) reveal more complex relationships, and we interpret these boundaries to have formed in three primary stages. In stage 1, volcanic materials are extruded on the surface in the region later to become Oceanus Procellarum. During stage 2, much of this material is buried during the emplacement of the Orientale Basin deposits. However, target materials, including the volcanics, are incorporated into the deposits through processes of ballistic erosion and sedimentation [Oberbeck et al., 1975], and a gradient in mare abundance is created in the basin deposits. Continued volcanism, the full extent of which formed Oceanus Procellarum, emplaced the basin ejecta deposits along the western shores. The complex and extended mixing gradients (Figure 8, panel 3) are believed to form in a similar manner to moderate gradients, but the post-Orientale volcanism did not completely bury the terrain.

Conclusions

The identification of significant mare-highland mixing in the region of southwestern Oceanus Procellarum and the relationship of that mixing to the principal geologic contact between mare and highland units allow new insight into the timing and extent of early lunar volcanism in this region. It is evident that narrow mixing zones between mare and highland, characterized by the relationships in the Grimaldi Basin (Figure 4 and Plate 1), are due to simple postmare emplacement, horizontal transport, and limited vertical mixing from impact and regolith gardening processes. The extended and complex mixing relationships typified by the regions northwest of the Humorum Basin (Figure 4 and Plate 1) cannot be explained by such simple processes. These relationships require processes that significantly enhance the mafic content of the highland materials, which we propose is due primarily to significant pre-Orientale and perhaps pre-Imbrium volcanism. Our study is supported by other investigations of the composition of this region [e.g., Hawke et al., 1993; Peterson et al., 1994], which indicate the presence of cryptomere, as well as basalt in the ejecta deposits of the crater Letronne. The moderate mixing gradients with the geologic contact on the high side of the mare abundance map also cannot be accounted for with simple mare emplacement followed by horizontal and vertical mass transport. These relationships are interpreted to indicate a three-stage sequence of events: (1) pre-Orientale volcanism in the region now exhibiting the gradient in mare abundance, (2) emplacement of Orientale Basin deposits which become mixed with the volcanic deposits, and (3) emplacement of the Procellarum mare.

Integration of these results within a regional stratigraphic framework permits us to consider a new perspective on the sequence and timing of volcanism in southwestern Procellarum and by implication, the surrounding regions (Figure 9). Extensive pre-Orientale volcanism is indicated by the presence of cryptomere from the Schickard region to northwest of Humorum Basin [Head et al., 1993; Hawke et al., 1993; Blewitt et al., 1995] and the extensive mare-rich ejecta blanket of the crater Letronne [Peterson et al., 1994; and this study]. Furthermore, the moderate mare-highland mixing gradients along the western margin of Procellarum suggest widespread volcanic deposits in this region as well. Cryptomere [Hawke et al., 1993; Antonenko et al., 1995] and the widespread elevated mare abundances in the terrains northwest of Humorum indicate that there was also pre-Imbrium volcanism. Therefore it is quite evident that regional volcanism extending from the Schiller-Schickard region, through the Humorum Basin and around Procellarum to at least the region near Grimaldi, was well established by the late Imbrian time.

It appears, however, that the widespread volcanism became localized to a few major regions shortly after the Orientale event. There are only minor mare patches throughout the Schiller-Schickard region in the area extending up to the large concentration of mare in the Humorum Basin, and likewise there are small, patchy post-Orientale volcanic deposits in the region northwest of Humorum. The Humorum [Pieters et al., 1975] and Procellarum [Whitford-Stark and Head, 1980] regions have relatively thick accumulations of volcanics, and the youngest lavas and deposits are Eratosthenian in age.
Further analysis of the mare-highland relationships in this and other regions will lead to a greater understanding of this important period of lunar thermal history as widespread volcanism gave way to more regional, but long-lasting and volumetrically important mare accumulation centers.

One of the principal observations from this analysis is that there exists considerable diversity in compositional gradients across photogeologic contacts in this region of the Moon. Evidence is building from other investigations [e.g., Fischer and Pieters, 1995; Staid et al., 1995] for diversity in compositional gradients elsewhere on the Moon. In regions where the relationship between compositional gradients and geologic contacts is relatively simple, a straightforward sequence of stratigraphic superposition is indicated, with minor preformation and postformation modification. In other regions, complex relationships reveal the effects of important geologic events that mostly predate the final, apparent stratigraphic sequences. Detailed analysis of the nature of the compositional gradients and relationships to local and global stratigraphy using new observations and data will provide important new insights into early volcanic and impact processes on the Moon.

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References

Mustard, J. F., J. W. Head, and I. Antonenko, Mare-highland mixing
relationships along the southwestern shores of Oceanus Procellarum,
Oberbeck, V. R., R. H. Morrison, F. Hörz, W. L. Quaide, and D. E.
Gault, Smooth plain and continuous deposits of craters and basins,
Oberbeck, V. R., F. Hörz, R. H. Morrison, W. L. Quaide, and D. E.
Gault, On the origin of the lunar smooth plains, Moon, 12, 19-54,
1975.
Peterson, C. A., B. R. Hauke, P. G. Lucey, G. J. Taylor, and P. D.
Spudis, The distribution of lithologic units in the western highlands of
Pieters, C. M., J. W. Head, T. R. McCord, J. B. Adams, and S. Zisk,
Geochronological and geological units of Mare Humorum: Definition
Pieters, C. M., J. B. Adams, P. Mougis-Mark, S. H. Zisk, J. W. Head,
T. R. McCord, and M. Smith, The nature of crater rays: The
Coppennius example, J. Geophys. Res., 90, 12,393-12,413, 1985.
Pieters, C. M., et al., Crustal diversity of the Moon: Compositional
analyses of Galileo solid state imaging data, J. Geophys. Res., 98,
17,127-17,148, 1993.
Pike, R. J., Formation of complex impact craters: Evidence from Mars
Ryder, G., and G. J. Taylor, Did mare-type volcanism commence early
Schultz, P. H., and P. D. Spudis, Evidence for ancient mare volcanism,
Scott, D. H., J. F. McCauley, and M. N. West, Geologic map of the west
Staid, M., C. M. Pieters, and J. W. Head, A multispectral view of
stratigraphy in Mare Tranquilitatis (abstract), Lunar Planet. Sci.,
Taylor, L. A., J. W. Shervais, R. H. Hunter, D.-Y. Shih, B. M. Bunsal,
and L. F. Nyquist, Pre-4.2 AE moon basalt volcanism in the lunar
Taylor, S. R., Plutonic Science: A Lunar Perspective, 481 pp., Lunar and

Taylor, S. R., Growth of planetary crusts, Tectonophysics, 161, 147-156,
1989.
Thompson, T. W., High resolution lunar radar map at 7.5 meter
Thompson, T. W., High-resolution lunar radar map at 70-cm
Titly, S. R., Geologic map of the Mare Humorum region of the Moon. 
Whitford-Stark, J. L., and J. W. Head, Stratigraphy of Oceanus
Procellarum basalts: Sources and styles of emplacement, J. Geophys.
Wilhelms, D. E., and J. F. McCauley, Geologic map of the near side of
Williams, D. A., R. Greeley, G. Nenkum, R. Wagner, and S. D. Kadel,
Multispectral studies of western limb and farside maria from Galileo
Earth-Moon encounter 1, J. Geophys. Res., 100, 23,291-23,300,
1995.
Wilshire, H. G., Geologic map of the Byrgius quadrangle of the Moon,
anorthosites and a geophysical model of the Moon, Geochem.
Yin, K. A., and J. W. Head, Lunar mare deposit volumes, composition,
age, and location: Implications for source areas and modes of

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