Mare Tranquillitatis: Basalt emplacement history and relation to lunar samples

Matthew I. Staid, Carlé M. Pieters, and James W. Head III
Department of Geological Sciences, Brown University, Providence, Rhode Island

Abstract. Galileo and Clementine multispectral data of the Mare Tranquillitatis region have been analyzed to investigate the stratigraphy of basaltic units and the effects of lateral and vertical mixing processes within the mare. The distribution of compositionally distinct mare units is observed to be correlated with previous UV/VIS ratio images, although estimates of soil titanium contents are low in some areas as a result of mixing of local basalts with nonmare feldspathic materials. Basalt units identified by their spectral properties and spectral mixture analysis are compared with groups of Apollo 11 samples defined by previous workers on the basis of age and chemistry. Spectral studies presented here indicate that the Apollo 11 site lies at the edge of a localized western mare unit which includes the youngest and most titanium-rich basalts in Tranquillitatis (Apollo 11 high-K, high-Ti samples). In southern Tranquillitatis, these basalts have been contaminated by a large degree of mixing with nonmare feldspathic materials. Nonmare materials near the Apollo 11 site are attributed largely to crater rays from Theophilus (100 km in diameter), which is located approximately 300 km to the south. A more extensive and stratigraphically older unit exposed near Apollo 11 is related to the low-K, high-Ti Apollo 11 samples and appears to extend as a coherent surface unit as far north as the Apollo 17 site in southern Serenitatis. The distribution of this spectrally identified basalt unit supports petrologic and geochemical evidence for the grouping of the high-Ti, low-K Apollo 11 and 17 basalt samples into the same regional volcanic events. Multispectral analysis of Tranquillitatis deposits also identify low-titanium basalts in the northeastern and southeastern portions of the basin that are older than the high-Ti basalts and are believed to be unsampled by Apollo 11. Several lines of evidence suggest that the Cayley Formation along the western Tranquillitatis margin may indeed lie on top of an ancient mare deposit buried by Imbrium basin ejecta (e.g., a cryptomare deposit). The distribution of vertically excavated feldspathic premare material within the mare provides information on the depth of the mare units and the proximity of the underlying basin topography. Compositional stratigraphy observed in both sets of multispectral data supports an asymmetric pre-mare-fill basin topography containing thicker basalts in the northwestern portion of the basin than previously predicted by crater flooding data.

1. Introduction

Understanding the emplacement history of mare basalts and their relation to returned lunar samples is an important step in interpreting the igneous and thermal history of the Moon. Since lunar samples were collected from a limited number of sites, much of the existing knowledge about the diversity and distribution of lunar basalts has relied on remote studies of unsampled regions. Remote analysis of the lunar mare includes photogeologic observations, Apollo X-ray and γ ray data and broader studies relating the spectral character of lunar soils to remotely acquired imagery [Adams et al., 1981]. Earth-based telescopic studies have provided important information on the compositional diversity of lunar basalts through classification of mare units based on albedo and visible to near-infrared absorption features [Pieters and McCord, 1976; Johnson et al., 1977a, b; Matson et al., 1977; Pieters, 1978, 1993]. Such Earth-based observations also provide information about the abundance and distribution of resources within the lunar maria, such as titanium-rich ilmenite [Hawke, 1989; Johnson et al., 1991; Melendrez et al., 1994]. Most recently, classification and analysis of lunar maria have been extended to limb and farside basalts through studies of Mariner 10 multispectral images [Robinson et al., 1992] and the interpretation of Galileo solid-state imaging (SSI) multispectral data [Greeley et al., 1993; Pieters et al., 1993]. The spectral diversity of unsampled mare units suggests that the lunar basalts, and potentially their source regions, are more heterogeneous than returned samples imply. Lunar volcanism appears to have been complex and multiphased with basin-scale magmatism evolving independently within neighboring regions [Pieters, 1993].

The mare deposits of the Tranquillitatis and Serenitatis basins are of unique importance to studies of lunar basalts, as they display a compositionally complex sequence of regional volcanism with distinct stratigraphic relationships and significant spectral variation. These volcanics also include the only two Apollo sites which sampled high-titanium basalts, Apollo 11 and 17. Though unsampled by other lunar missions, high-titanium basalts appear to be relatively common in other areas of the Moon [Pieters, 1978; Metzger and
Parker, 1979; Pieters et al., 1980] and provide important constraints on the nature of lunar volcanism and the composition of the lunar mantle. Galileo SSI multispectral imagery of Mare Tranquillitatis acquired during a lunar flyby in 1992 is examined here using quantitative techniques to separate bulk reflectance properties into distinct spectral components [Adams et al., 1993]. In order to interpret the distribution and stratigraphy of emplaced mare units at the basin scale, geological and geochemical units are separated from the effects of lateral and vertical impact mixing of mare and highland materials. Higher resolution Clementine multispectral data acquired during lunar mapping in 1994 are then analyzed to confirm stratigraphic and mixing relationships for key sites within the Galileo regional analysis. Together the two data sets provide insight into the stratigraphy of mare units, lateral and vertical mixing processes within and across the mare, and the underlying structure of the Tranquillitatis basin.

Mare Tranquillitatis is a nonmascon basin [Muller and Sjogren, 1968] on the eastern limb of the Moon extending about 800 km in diameter at its longest dimension from east to west. The Imbrian-age basalts in the southwestern portion of this basin were the site of the first manned landing, Apollo 11's Tranquility Base. Extensive areas of mare within other parts of the basin are similar to the region sampled by Apollo 11 in both spectral character [Pieters, 1978; Johnson et al., 1991; Melendrez et al., 1994] and crater age [Boyce, 1976]. The northernmost occurrence of such spectrally characterized basalts lie within the southern border of Serenitatis, adjacent to the last Apollo landing site in the Taurus-Littrow valley, Apollo 17. The relation of Mare Tranquillitatis to surrounding mare regions and Apollo landing sites is shown in a Galileo SSI image of the basin in Figure 1. Together, the samples returned by Apollo 11 and 17 include the oldest and highest titanium basalts collected directly by any lunar mission [Papike et al., 1976; Beatty and Albee, 1978; Nyquist and Shih, 1992]. Similar age dates and compositions for some basalt samples from the Apollo 11 and the Apollo 17 sites may be evidence that the older Ti-rich Serenitatis basalts resulted from the same period of early high-titanium volcanism as in Tranquillitatis [Wilhelms, 1987; Jerde et al., 1994; Snyder et al., 1994]. However, the voluminous younger volcanics which fill most of the Serenitatis basin exhibit spectral properties indicative of a very different low titanium composition. These low-titanium flows appear to have buried the older high-titanium basalts north of Tranquillitatis [Carr, 1966; Pieters, 1978; Wilhelms, 1987], and as a result, the extent of the older titanium-rich basalts within Serenitatis is unknown.

Telescopic studies have characterized the mare units within Tranquillitatis as some of the darkest and "bluest" basalts on the Moon [Pieters, 1978]. These spectral properties are thought to be a direct result of a high abundance of TiO₂ which has been empirically related to the ultraviolet to visible

**Figure 1.** Galileo SSI 660-nm image of the Tranquillitatis study region (LUNMOS06 S0165042100). The locations of image end-members used in the spectral mixing analysis are shown by the labeled boxes.
2. Regional Analysis of Mare Tranquillitatis: Galileo EM2 Data

Galileo's lunar flybys in 1990 and 1992 produced multispectral images of the Moon over a wide range of viewing and lighting conditions with the SSI system [Belton et al., 1992, 1994]. A small phase angle (~25°) image sequence taken during Galileo's second Earth-Moon encounter (EM2) was selected for the analysis of the Tranquillitatis region. The spatial extent of the image sequence used in this study is shown in Figure 1. The study area encompasses all of Mare Tranquillitatis and its neighboring regions; including the Apollo 11 landing site in southwestern Tranquillitatis and the Apollo 17 landing site and MS2 telescopic standard [McCord et al., 1972] in southern Serenitatis. The image sequence used includes six of the SSI filters (0.4 - 1.0 μm) sensitive to compositional and maturity variations within the lunar maria. The bandpasses of these filters are centered at 0.41, 0.56, 0.66, 0.76, 0.89, and 0.99 μm. When these image data are co-registered, a low spectral resolution image cube is formed in which there are two dimensions of spatial information and one dimension of spectral information. The spatial resolution of the SSI data is comparable to Earth-based telescopic data (1.5-2 km/pixel), but the Galileo measurements do not experience the atmospheric complications of spectral measurements. Additionally, the large size of the SSI CCD array (800 x 800 pixels) allows for regional-scale studies within a single image cube, minimizing the optical effects of lighting and viewing geometry. An overview of the SSI observations and calibrations can be found in the work by Belton et al. [1992].

A set of compositionally sensitive ratio images were created from the visible to near-infrared channels of the SSI detector and adopted for a first-order characterization of surface units within Tranquillitatis. These ratios have been used in previous Galileo analyses [Belton et al., 1992] and consist of UV/VIS ratio (0.41/0.76 μm) and a 0.76/0.99 μm ratio. Both ratios are sensitive to the composition and freshness of the lunar surface materials [Pieters et al., 1993]. While such compositionally sensitive ratio images are fairly homogeneous across central Mare Serenitatis (excluding craters), Mare Tranquillitatis shows significant spectral variations within the basin. This heterogeneity has also been documented in high spatial resolution Earth-based mapping of mare UV/VIS ratios in Tranquillitatis [Johnson et al., 1991; Melendrez et al., 1994]. As discussed below, these measured variations result from the combination of compositionally distinct units as well as the mixing of different highland and mare lithologies.

2.1. Spectral Mixing Analysis: Data and Procedure

In the present study, a linear spectral mixing analysis [Adams et al., 1993] has been applied to provide a more quantitative assessment of albedo and color information in terms of mixtures of discrete spectral components. In this approach, a group of end-members with distinct spectral properties is identified, and the reflectance signal of each pixel within the image is decomposed into fractions of the individual end-member components. A number of fraction images equal to the number of end-members in the analysis is created from the least squares solution to this mixing problem. Each fraction image displays the relative abundance of one end-member for each pixel in the image scene [Adams et al., 1993]. Preprocessing of the data was utilized to simplify the mixing problem by eliminating areas of relatively pure highland materials from the study. Mature highlands were masked by eliminating bright pixels that did not exhibit a strong 1-μm feature indicative of mafic (mare) materials, while immature highlands were masked based on their high albedo. This masking procedure removed only portions of the image previously mapped as highlands on the basis of morphology [Carr, 1966; Morris and Wilhelms, 1967; Wilhelms, 1972] except for a small portion of the image along the western border of Tranquillitatis, which has previously been mapped as Imbrium Cayley Formation deposits [Wilhelms, 1987] and may include cryptomare [Head and Wilson, 1992; Head et al., 1993]. Sources of spectral variation within the mare, such as bright mare crater and mixtures of highland materials within the basin, were preserved in the preprocessed image.

End-member selection. Initial end-members for the Galileo mixing analysis were selected from within the study image after a detailed analysis of the spectral characteristics of the mare and surrounding regions. The goal of this selection was to find the fewest number of spectral components (end-members) which could be mixed linearly to explain all of the observed heterogeneity within the mare while maintaining spatial coherence as meaningful geologic materials and units. The number of end-members that can be used in a mixing analysis of an image is primarily a function of the signal-to-noise characteristics of the data and the number and appropriateness of filters used to characterize spectral diversity [e.g., Sabol et al., 1992]. The positions of the six Galileo SSI instrument bandpasses used in the Tranquillitatis mixing analysis are very good for spectral characterization of lunar surface materials [Belton et al., 1994]. The SSI data also have extremely good signal-to-noise due to the instrument design and lack of atmospheric interference [Belton et al., 1994].

The most appropriate solution to the spectral mixture analysis required the use of four end-members: a very blue (high-titanium) mare basalt, a relatively red (low-titanium) basalt, mature highland, and material rich in freshly exposed iron-bearing minerals associated with a bright and relatively young mare crater. These image end-members are discussed in more detail in the subsequent section. The maria and crater end-members were selected directly from the image guided by multispectral data. Selection of an appropriate highland end-member to represent mare-highland mixtures was complicated by the significant spectral variations observed within the basin.
highlands surrounding Tranquillitatis. An inverse modeling technique [Tompkins et al., 1996] was applied to the preprocessed image (pure highlands removed) to optimize the highland end-member representing nonmare feldspathic materials within mare soils. This model solved for the best set of spectral end-members which describe contaminated mare soils by allowing the highland end-member to vary and keeping the mare and fresh crater end-members constrained in iterative mixing analyses. The optical properties of the best highland end-member solution obtained from the inverse modeling was then compared to the spectral properties of the highlands around Tranquillitatis in the Galileo data, and a comparable highland image end-member was chosen as the end-member used in the Galileo mixing analysis.

The average root-mean-square (RMS) error of the fit for the four image end-members used was 0.8 data number (DN) (<1% of the image mean). Uniformly low values and a lack of structure in the RMS image area criteria used to indicate a good fit to the data. The largest errors in the RMS image center inside several mare craters and may result from the large range of optical maturity of these materials and the inability of the mixing model to treat optical maturity (a process) as a linear combination of end-members. Attempts to use greater than four end-members resulted in poor spatial coherence of end-member fractions, indicating that the mixing analysis has begun to model noise in its fraction images. On the other hand, removal of any one of the four end-members increased the error of the fit significantly (to >5% RMS error of the image mean) and produced residual errors that have spatial coherence and geologic significance. Although the use of a "shade" end-member is important in many terrestrial applications [Adams et al., 1993], this end-member was not necessary in the high-Sun lunar imagery used here because of the lack of shading and textural information within the image. Topographic slopes within the mare study region are extremely small. Shading effects are thus only expected to be important for small areas along crater walls, but such areas are not included in the interpretation of the Galileo data.

Galileo image end-members. The locations of the four image end-members are indicated with boxes in Figure 1, and their reflectance spectra are shown in Figure 2. The blue mare end-member was selected from the spectrally darkest and bluest soils from the center of the Tranquillitatis basin where Earth-based UV/VIS maps indicate the highest soil Ti concentrations [Melendrez et al., 1994; Johnson et al., 1991]. This image end-member is thought to represent the purest and most titanium-rich basaltic soils within Tranquillitatis resolvable at the Galileo SSI resolution. The redder mare end-member was selected to be the MS2 telescopic standard [McCord et al., 1972] within the low-titanium basalts of Serenitatis [Carr, 1966]. Since the entire image cube is calibrated to this telescopic standard, the red mare end-member is spectrally flat relative to MS2. An area in the bright mare crater Dawes (26.5°E, 27°N) interpreted to be Copernican in age [Wilhelms and McCauley, 1971] was selected to represent freshly exposed (unweathered) mare basalt. The fresh material from within this crater exhibits the high albedo and strong 1-μm absorption characteristic of fresh mare soils, and telescopic studies indicate that no feldspathic component has been excavated at this site [Bell and Hawke, 1992]. The last end-member, a mature highland area south of the Tranquillitatis basin, maps variations of nonmare feldspathic contamination within the mare resulting from impact excavation and deposition of highland lithologies.

Fraction images, which indicate the abundance and distribution of the four end-members resulting from the mixing analysis, are shown in Figure 3. The spatial variations of the two mare end-members reflect compositional differences in the emplaced basaltic units. The remaining two end-members, highland and fresh mare crater, account for feldspathic contamination and optical effects resulting from differences in soil maturity within and around impact craters. Discrete mixtures of these four endmembers describe the spectral variations within the mare in terms of physically meaningful components which can be used to provide a regional geologic framework.

2.2. Mare Basalt Units

The Galileo mixing analysis identifies four spectrally distinct mare types within Tranquillitatis based on the fractional abundances of the red and blue mare end-members shown in Figures 3a and 3b. The regional distributions of these spectrally distinct basalt units (Tvh-A, Tvh-B, Th, T1) are illustrated in Figure 4a and are the units characterized below.

The first basalt unit, an area in the western-most portion of Tranquillitatis contains the highest fractional abundances of the blue mare end-member and a corresponding lack of the red mare end-member. These basalts extend continuously from the northwestern part of Tranquillitatis around the western side of the Lamont feature and as far south as the Apollo 11 landing site in southwestern Tranquillitatis. This unit is interpreted to contain the highest abundances of titanium and is designated as the Tvh-A (very high titanium - A) unit. A more extensive basalt unit in the north, south, and central-eastern portions of the basin also contains large, but slightly lower, fractions of the blue mare end-member. This more extensive spectrally blue unit is designated as the Tvh-B (very high titanium - B) unit. Both Tvh units appear to be spatially continuous and are only interrupted by patches of less blue basalts and impact crater ejecta.

A less blue mare unit (Tbh in Figure 4a) is mapped by intermediate fractions of the red and blue mare end-members and occurs as small patches within the two bluer units. These dis-
Figure 3. Fraction images for each end-member as derived from the spectral mixing analysis. These images show the spatial distribution and relative abundance of each end-member component. Derived end-member abundances within the Tranquillitatis basin are scaled such that black equals a lack of the end-member and white equals the maximum percent abundance for the range listed.

Continuous less blue basalts are interpreted to have lower (but still relatively high) titanium abundance and are designated as the $T_h$ (high titanium) unit. The fourth basalt unit defined in this study coincides with areas exhibiting large fractions of the red mare end-member. These basalts, which occur in the northeastern and southeastern corner of Tranquillitatis, are the spectrally redest basalts within the basin and are interpreted to have low-titanium contents. They are referred to as the $T_l$ (low-titanium) basalts. These $T_l$ basalts are spectrally similar to the low-titanium Serenitatis basalts (MS2) but are much more heterogeneous. It is thought that these basalts are older and predate the high-titanium basalts within Tranquillitatis (as discussed in subsequent sections).

Representative Galileo relative reflectance spectra of the units defined above are shown in Figure 4b, and the locations are indicated by boxes on Figure 4a. The distinctive characteristics of the six-band spectra for these selected areas within Tranquillitatis are fully consistent with the unit distinctions derived from the spectral mixing analysis described above. The Galileo relative reflectance spectra document a characteristic UV/VIS slope which is diagnostic of each unit at different locations within the mare where the basalts are exposed. Where units are uncontaminated by nonmare feldspathic materials there is an anticorrelation between albedo and UV/VIS slope. Mare units display higher albedos toward lower titanium compositions along with a decrease in UV/VIS slope. Within a given unit, however, a higher albedo is observed where nonmare feldspathic contamination has lightened the mare surface, as is the case for the brightest four spectra shown in Figure 4b. Despite their higher albedo, these materials still display diagnostic spectral features which are consistent with their primary units.

The Tranquillitatis units defined here by mixing analyses are consistent with trends observed in telescopically derived...
Figure 4a. Schematic distributions of basalt units. Tranquillitatis units (T, Tv, Th, Tvh-A, Tvh-B) have been distinguished on the basis of the relative abundance and spatial distributions of "red" and "blue" mare end-members. The locations of the representative Galileo SSI spectra of these units presented in Figure 4b are indicated by black boxes. Additional units in this region include Cayley plains material (Cf) and the Serenitatis border basalts (Sb). The deposits of Ritter and Sabine are labeled separately (R, S). Pyroclastic deposits (Py) are not analyzed here.

soil titanium maps [Melendrez et al., 1994; Johnson et al., 1991] for regions where contamination has not occurred (as indicated by no significant highland or fresh crater component). Estimated bulk soil titanium abundances (wt % TiO2) obtained from these comparisons for uncontaminated areas of the mare are as follows: Tv-B = 8-10%, Tvh-B = 5-8%, Th = 3-5%, T1 = <3%. These telescopically derived estimates of wt % TiO2 for bulk soils would be expected to be lower than actual values measured for the individual basalt fragments of flows from which these soils are derived because all lunar soils contain a fraction of foreign materials [Laul and Papike, 1980] which contributes to the bulk analyses.

Stratigraphy of mare units. The spatial distribution of each end-member has been registered to low illumination angle telescopic images [Kuiper et al., 1967] and geologic maps [Wilhelms, 1972; Morris and Wilhelms, 1967; Carr, 1966] for comparison of end-member abundance with geologic features. Low illumination angle photographs allow evaluation of morphologic features which are not easily observed in the Galileo images which were acquired at higher Sun. These combined data allow end-member abundance and spectral variance to be placed in the general context of the regional topography of the basin. The locations of topographic features and craters discussed in the text are shown on the low illumination angle photograph of Figure 5 [Kuiper et al., 1967]. A color composite overlay is shown in Plate 1 in which three of the fraction images are superimposed on the telescopic mosaic (red is red mare 0-100%, blue is blue mare 0-100%, green is highlands 0-50%). Lunar Orbiter and Apollo images, as well as topographic maps derived from Apollo data were also extensively utilized in this study. Of particular interest in the discussion below are relationships between end-member materials and geologic features such as mare-highland contacts, craters, wrinkle ridges, and potential mare source regions such as domes.

Comparison of the distribution of mare units from the Galileo analysis with previously prepared geologic maps and with large-scale topography demonstrates that the spectrally mapped basalt units are more well-defined, but generally consistent with previous data. Geologic maps of western Tranquillitatis are based primarily on albedo, stratigraphic relationships, and crater frequency [Morris and Wilhelms, 1967], and maps of eastern Tranquillitatis include relative color information as well [Wilhelms, 1972]. The low-titanium Th unit corresponds with the oldest and most heavily cratered mare within Tranquillitatis predating adjacent regions containing the Tvh-B basalts [Wilhelms, 1972]. The location of Tb basalts corresponds directly to the brightest and most heavily cratered mare unit in western Tranquillitatis [Morris and Wilhelms, 1967; unit Ipm 1] and the relationship of this unit to other mapped units suggests that it is stratigraphically younger than the T1 unit in eastern Tranquillitatis. The Tvh units corresponds with darker, less cratered and stratigraphically younger units of western Tranquillitatis [Morris and Wilhelms, 1967; Ipm 2 and 3 units]. In many areas of the basin the younger Tvh flows have flooded low areas but not covered topographic highs which coincide with either the older and spectrally redder Th mare unit or highland kipukas within the basin. Such relationships between basaltic units and morphologic features can be observed in Plate 1.

The stratigraphy for the spectrally mapped basalt units appears to be consistent on the basin scale: younger titanium-rich Tvh units overlying the older less titanium-rich Tb and T1 units. This stratigraphy of deposits is also generally consis-
Figure 5. Low illumination angle telescopic photographic mosaic showing major morphologic features within the Tranquillitatis basin (images from Kuiper et al. [1967]).

Potential sources of observed mare units. Lunar dome and rille features represent potential sources for basaltic flows, and the locations of these features within Tranquillitatis have been compared to distribution of spectrally mapped basalt units. The locations of mare domes and the Cauchy Rille as mapped by Morris and Wilhelms [1967] and Wilhelms [1972] have been overlain onto the mapped basaltic units in Figure 6a. Almost all the domes are located within or along the border of the two youngest and most titanium-rich T\textsubscript{vh-A} and T\textsubscript{vh-B} units.

Potential sources for the T\textsubscript{vh-B} unit include abundant domes occurring in topographically high regions along the northeastern mare-highland boundary and in the central eastern portion of the basin near the Cauchy rilles [Wilhelms, 1972, 1987]. Several of these domes lie at the ends of fingers of the T\textsubscript{vh-B} unit near the stratigraphically older and elevated T\textsubscript{I} units and appear to be sources for younger basalts. The Rima Cauchy rille and nearby domes also lie within a narrow topographically high region of T\textsubscript{vh-B} basalts. The distribution of the T\textsubscript{vh-B} basalts widens in topographically lower regions to the west, suggesting that the Cauchy region may be another source region for the T\textsubscript{vh-B} unit. The Rima Cauchy rilles within this region lie radial to Imbrium [Wilhelms, 1987] and thus may be purely tectonic features. On the other hand, Head and Wilson [1994] have suggested that some linear lunar rilles may result from dikes stalled just below the surface rather than from a purely tectonic origin. If the large linear rilles in eastern Tranquillitatis were formed in this manner, then other (earlier or contemporaneous) dike events may have reached the surface in this area, providing another source for the topographically lower and more extensive deposits of T\textsubscript{vh-B} basalts to the west.

Potential sources for the less extensive T\textsubscript{vh-A} basalts include a string of three small domes in the western portion of the basin between the craters Arago and Maclear. These features have been associated with the highest titanium soils in Tranquillitatis [Melendrez et al., 1994]. Sources for the older T\textsubscript{I} and T\textsubscript{I} units are not readily apparent and may be largely buried. Galileo mixing analysis and Clementine imagery are consistent with previous telescopic measurements [Melendrez et al., 1994] which indicate that a large dome (21°30'E,
Plate 1. Color composite of mare and highland fraction images superimposed on low illumination angle telescopic photograph mosaic (blue mare end-member is blue; red mare end-member is red; and highland end-member is green). Spectrally distinct units within and around mare craters may result from the vertical excavation of underlying units and embayment by subsequent flows. The lateral transport of nonmare feldspathics along crater rays is especially prominent in the southwestern portion of the basin, as indicated by an abundance of the highland end-member in this region.

Figure 6b. Distribution of Theophilus rays as observed in the highland fraction image. Black lines indicate an abundance of the highland end-member occurring along rays radial to the Eratosthenian crater Theophilus (100 km diameter, located just southwest of the study region). Mare craters within Tranquillitatis and the large highland crater Taruntius are also located on this sketch map.

7°40′N north of the crater Arago is slightly spectrally redder than surrounding Tvh-A basalts in Tranquillitatis. This large dome may be a source related to the slightly redder Tvh-B or Th basalts which has been subsequently embayed by the high-titanium Tvh-A unit.

2.3. Mare-Highland Mixing

Contamination of the lunar maria by nonmare feldspathic materials can result from both vertical mixing from below [Hörz, 1978; Rhodes, 1977; Farrand, 1988] and lateral transport of materials along crater rays and ejecta blankets [e.g., Oberbeck, 1975; Pieters et al., 1985]. Depending on location in the mare, impact craters have resulted in the vertical excavation of underlying basalts and/or highland basement and deposition of these units onto overlying surface units. Lateral mixing of adjacent highland materials onto the mare basalts has also occurred along crater rays and near mare-highland boundaries. Although the distributions of the three principal mare units mapped in this Galileo analysis are highly correlated with telescopically derived soil titanium maps [Melendrez et al., 1994; Johnson et al., 1991] and geologically mapped units [Morris and Wilhelms, 1967], the boundaries and distribution of the high-titanium units differ significantly where a highland component has affected the optical properties. Specifically, as discussed below, the mixing of nonmare feldspathic materials with Tvh-A basalts can mimic some of the characteristics of the lower titanium Tvh-B and Th basalts units.

Vertical excavation and impact mixing. Impact events have excavated materials from various depths within the mare depending upon the size of the crater. As a result, impact craters can be used as probes into the basalt stratigraphy by applying an approximate relationship of excavation depth of
Hawke, 1995] which have detected feldspathic materials within Plinius' central peaks. A highland component within end-member occurs within and directly around the large either Serenitatis basin deposits or the feldspathic basement. The presence of the highland components allows evaluation of the penetration of the mare cover into the underlying feldspathic basement or an ancient feldspathic ejecta layer. The distribution of highland materials or T h basalts. The lack of highland or low-titanium basalts associated with Ross suggests the superposition of the Tvh-A and Tvh-B units in this region of the basin resulted in basaltic deposits which are more than 2.5 km thick.

On the other hand, the presence of highland end-member materials within some large mare craters indicates that the crater penetrated the mare cover into the underlying feldspathic basement or an ancient feldspathic ejecta layer. The distribution of such highland components allows evaluation of the depth of the mare units and the proximity of the underlying basin highland topography. The presence of the highland end-member observed within Plinius (Figure 3d) is consistent with high spectral resolution telescopic spectra [Bell and Hawke, 1995] which have detected feldspathic materials within Plinius' central peaks. A highland component within the crater Plinius (43 km diameter) suggests the excavation of either Serenitatis basin deposits or the feldspathic basement. In central Tranquillitatis, an increased abundance of the highland end-member occurs within and directly around the large crater Arago (26 km) and the crater Jansen B (18 km). The highland end-member is also abundant along protruding peaks of highland kipukas in the Jansen B region, indicating regionally thin basalts in the center of Tranquillitatis along the central ridges. Highland kipukas also occur in the southern and eastern portions of the basin and suggest that the basalts are also very thin in these areas. Furthermore, highland materials have been excavated by small craters (e.g., the 11-km Cauchy and Tauruntillus F craters) along these mare-highland boundaries, implying mare thickness of less than 1 km. Excavation of nonmare feldspathic materials also occurs near the southwestern edge of Tranquillitatis by the small crater Moltke (6 km) and is discussed further with Clementine imagery in a subsequent section.

The unusual crater pair Ritter and Sabine (29 and 30 km) also occurs along a Tranquillitatis basin boundary in southwestern Tranquillitatis. On the basis of surface morphology of the crater rim and floor, De Hon [1971] originally interpreted Sabine and Ritter to be volcanic calderas. More recent work [Head and Wilson, 1992, 1994] suggests that shallow magma reservoirs, and thus large calderas and large shield volcanoes, should be very rare on the Moon because of the density trap at the base of the anorthositic crust and the difficulty of stalling abundant dikes in one place in the shallow lunar crust. Our multispectral analysis of Sabine and Ritter shows a significant highland component along the rim and interior (Figure 3d and Plate 1), which strongly suggests that these structures are impact craters penetrating through shallow mare material at the southwestern edge of Mare Tranquillitatis, and not endogenic volcanic craters.

Vertical excavation of submare feldspathic materials observed at the craters Arago (26 km), Maskelyne (22 km), and Jansen B (18 km) and lack of similar deposits at Ross (25 km) or Dawes (18 km) indicates that basalts may be thickest, more than 2 km, in the northwestern portion of the basin (Tvh-A unit). These estimates of basalts thickness are considerably greater than those made by extrapolation of contours through the very limited crater flooding data within this region: De Hon [1974] predicted that the basalts were 750 m to 1 km thick, and Hörz [1978] predicted a thickness of about 400-500 m based on a reinterpretation of De Hon's data.

**Lateral mixing of nonmare materials.** Rays of the highland end-member stretch across much of the basin but are most significant in the southwestern portion of Tranquillitatis. The radial distribution of these rays with respect to the highland crater Theophilus (100 km in diameter) is sketched in Figure 6b. The prominent rays of this crater observed with Earth-based telescopes led to early estimates of a Copernican age for Theophilus [Wilhelms and McCauley, 1971]. More detailed considerations of crater densities, however, have led to the assignment of an older, Eratosthenian age for the Theophilus event [Wilhelms, 1987]. Theophilus rays are distinguishable in the highland fraction image (Figure 3d) as far as northern Tranquillitatis (as much as 600 km from Theophilus), which is comparable to the extent of the more prominent Copernicus rays observed in small phase angle telescopic imagery [e.g., Kuiper et al., 1967]. On the basis of our analysis, portions of Theophilus' rays clearly contain a significant component of primary feldspathic material. This interpretation for the Theophilus rays is very similar to spectral studies of Copernican rays, which showed that the rays' higher albedo results from a component of bright primary material.
The rays of Theophilus are a likely source for much of the nonmare material near the Apollo 11 landing site. Ray cluster craters within a few kilometers of the Apollo 11 site have been identified through telescopic mapping and have been interpreted to result from the Theophilus event [Grolim, 1970; Wilhelms, 1987]. Some of the rays observed in the Galileo imagery pass very close to the landing site and are examined in more detail below with higher resolution Clementine imagery.

Nonmare feldspathic mixing has significantly affected the spectral character of mare soils in the southwestern portion of the basin. When mixing is not taken into account, interpretations of telescopic UV/VIS data of the southwestern mare suggest a compositional gradient between higher and lower titanium mare units [Johnson et al., 1991]. Similarly, albedo-based geologic maps [Morris and Wilhelms, 1967] assign the Apollo 11 region to a slightly brighter Ipm 2 unit rather than the darkest Ipm 3 unit with an "uncertain" contact. However, mixing analyses of the Galileo data demonstrate that this region instead contains an extension of the stratigraphically youngest and very high titanium T vh A basalts, similar to those in northwestern Tranquilitatis. These T vh A basaltic soils in the Apollo 11 area appear to have been spectrally reddened by mixing of feldspathic materials. We interpret the feldspathic component to be associated with lateral transport by crater rays and possibly with vertical excavation of sub-mare highland materials by smaller craters like Moltke near the mare-highland border (Figure 3d, Plate 1).

The western boundary of Tranquilitatis also contains a significant amount of the highland end-member which does not occur as discrete rays radial to Theophilus and is not directly associated with craters Ritter and Sabine. By comparison, the eastern margin of the Tranquilitatis basin exhibits a much sharper mare-highland contact where basalts directly embay against highlands. The relationships between mare units and mare-highland contacts can be easily seen in Figure 3d and Plate 1. The youngest western basalts (T h basalts) embay light plains on the western edge of Mare Tranquilitatis that have been mapped as the Imbrium Cayley Formation [Wilhelms, 1987]. The extent of Cayley plains included in the Galileo analyses is shown in Figure 4a.

The Galileo mixing analysis suggests these Cayley plains are a mixture of abundant highland and basaltic materials. One possible explanation for this high degree of mare-highland mixing is that the Cayley plains in this region may result from the emplacement of Imbrium basin ejecta onto early Tranquilitatis basalts. This is supported by the proximity of these plains along the western edge of Tranquilitatis to the Imbrium basin, by the presence in the Apollo 11 mare basalt suite of samples that predate the Imbrium basin event, and by the subsequent impact excavation of sub-Cayley basalts. The excavation of basalts from beneath the Cayley plains in this region is suggested by the dark rays of the crater Dionysius [Schultz, 1976].

A small component of highland material is also sometimes observed associated with older T h basalts in areas across the central part of the basin where the T h unit was embayed but not covered by younger basalts. It is possible that the emplacement of some of the Tranquilitatis T h basalts predate and were contaminated by the Imbrium event before being partially covered by younger more titanium-rich T vh flows. This scenario would explain the significant amounts of highland materials and lack of uncontaminated T h basalts associated with impact craters in western Tranquilitatis (e.g., Arago, Ritter, and Sabine). Perhaps some of the large western craters which exhibit a nonmare feldspathic component excavated Imbrium ejecta and underlying basalts rather than highland basement.

In summary, there is evidence that the Cayley Formation along the western margin may indeed lie on top of an ancient mare deposit buried by Imbrium basin ejecta (e.g., cryptomare [Head and Wilson, 1992]), and that portions of central Tranquilitatis might have similar characteristics. This adds further evidence to an increasingly widespread documentation of cryptomaria on the Moon [Head et al., 1993; Greeley et al., 1993; Antonenko et al., 1995; Mustard and Head, 1996].

3. A Closer Look With High-Resolution Clementine UVVIS Data

High spatial resolution Clementine multispectral data have been analyzed to assess stratigraphic and mixing relationships for key areas identified in the Galileo synoptic analyses. Clementine multispectral cameras include an ultraviolet-visible imaging system (UVVIS) with five filters between 0.4 and 1.0 μm [Nozette et al., 1994] coinciding with the spectral range of the Galileo SSI camera. These higher resolution data have spatial resolutions of about 150-300 m/pixel compared to 1.5-2 km/pixel in the Galileo EM2 data. Initial calibration and mosaicking procedures for the application of this data are discussed by Pieters et al. [1994, 1995]. The higher spatial resolution of these data provides a means to clarify lateral and vertical mixing processes. Sites chosen for examination with Clementine UVVIS data include mosaics of the mare crater Arago (in central Tranquilitatis) as well as the Apollo 11 landing site and the nearby crater Moltke (see Figure 5 for locations). Clementine data of these sites confirm the stratigraphic relations between the T vh and T h basaltic units and help place the Apollo 11 basalt samples within the context of these units.

3.1. Central Tranquilitatis and Arago Crater

The central western portion of Tranquilitatis is one of the most spectrally heterogeneous areas in the entire basin. The Galileo mixing analysis attributes this spectral complexity to the surface expression of both of the younger bluer T vh units as well as islands of the older redder T h unit. Additionally, highland mixing appears to have occurred associated with material excavated by the crater Arago (26 km in diameter) and material transported laterally along rays of Theophilus.

Previous telescopic studies of the central Tranquilitatis/Lamont region have noted that the soils within and surrounding the Eratosthenian crater Arago are spectrally redder than adjacent mare soils [Melendrez et al., 1994]. Clementine imagery centered on Arago (Figures 7a and 7b) also indicates regionally redder deposits around Arago with lower UV/VIS ratio values. A small impact crater that occurs within these deposits can be seen in Figure 7a. This crater exhibits a distinct dark halo (arrows in Figure 7) similar in albedo to the T vh basalts in the northern portion of the image beyond the Arago anomaly. This small crater indicates that the spectral anomaly around Arago is only a thin surface veneer corre-
Figure 7a. Clementine 750-nm image mosaic centered on the mare crater Arago.

Figure 7b. Clementine 415/750-nm UV/VIS ratio image for the same region. Note the spectrally blue (high 415/750 nm) dark haloed crater just above the north rim (arrow). This crater indicates exposure from beneath Arago ejecta deposits and subsequent maturation of material that is comparable to the relatively blue unit to the north (Tvh-A basalts).

The excavation of the Tvh unit by the small crater also demonstrates that the Arago event could not have been older than the emplacement of Tvh mare. This new evidence argues against the interpretation of an embayment relationship between the younger bluer mare against Arago's raised rim as suggested by Melendrez et al. [1994]. Continuing studies of Clementine imagery of the mare crater Dawes [Staid et al., 1995; Staid and Pieters, 1996] in the northernmost region of Tranquillitatis suggest a similar stratigraphy for Dawes, an optically fresh mare crater, namely, that a lower titanium unit has been excavated from beneath spectrally bluer surface units. Such a relation was initially hypothesized at Dawes based on lower resolution telescopic data [Melendrez et al., 1994].

High-albedo floor hummocks within Arago can be seen in Figure 7a and exhibit spectral properties characteristic of nonmare feldspathic materials. The occurrence of the high-albedo floor hummocks within Arago is consistent with the excavation of highland materials as predicted in the Galileo spectral mixture analysis of this crater. If the nonmare feldspathic materials define the base of the mare basalts, then excavation-depth-to-diameter relationships predict that the basalts within this region are less than 2.5 km thick.

3.2. Southwestern Tranquillitatis: Apollo 11 Landing Site

The Galileo analyses of basalt units discussed above indicate that the Apollo 11 site lies within the darkest and bluest basalts within Tranquillitatis (Tvh-A unit), but soils have been contaminated by significant mixing of bright nonmare feldspathic material that is spectrally red. A mosaic of Clementine data over the Apollo 11 landing site was prepared from imagery taken at high Sun (close to zero phase angle) and is shown in Figure 8a. This low phase angle lighting condition enhances the optical contrasts between surface materials of different albedos and allows a more detailed examination of the sources of nonmare feldspathic contamination within this region.

Bright crater rays from Theophilus extend from the south to the north and are easily identified in Figure 8a. One ray visibly passes within a kilometer or two of the Apollo 11 landing site. The spectral characteristics of the ray materials (e.g., the strength of the 1 µm absorption band approximated by a 0.95/0.75-µm ratio in Clementine imagery) indicate that the rays are no different from surroundings and are thus optically mature. A large zone of relatively low-albedo materials is apparent around the nearby 6-km crater Moltke out to 8 crater radii. The southernmost portions of the Theophilus rays, south of the Apollo 11 landing site, disappear within this dark area.
High-albedo materials are also observed in and directly around the crater Moltke (6 km in diameter). Subsequent small impacts into the bright Moltke ejecta, however, have formed small dark halo craters (Figure 8a). The bright Moltke ejecta deposits (1 to 2 crater radii) appear to be optically mature based on the superimposed dark halo craters, the low albedo of which indicates significant maturation and darkening of these younger deposits. The relatively high albedo of Moltke ejecta is thus a compositional distinction and indicates Moltke has excavated nonmare feldspathic material.

The Galileo observation of a significant amount of nonmare feldspathic surface contamination of the basalts emplaced within the proximity of the Apollo 11 landing site is consistent with the nature of the Apollo 11 soil samples which contain a large feldspathic component, ~14% of soils [Rhodes, 1977] and 20% of breccias [Wood et al., 1970; Laul and Papike, 1980]. A lateral mixing mechanism, rather than vertical migration from below [e.g., Hörz, 1978], seems the likely mechanism of nonmare feldspathic contamination in this region because the inherent properties of the local basalts are optically much darker than the uppermost veneer of contaminated material. Much of this mixing appears to have occurred laterally along the rays which lie radial to the Theophilus (100 km) impact crater. The spectrally mature nature of these rays is consistent with this crater’s Eratosthenian age. The close proximity of these rays to the Apollo 11 site and the nonmare feldspathic material excavated by nearby Moltke provide likely sources for feldspathic contamination in the Apollo 11 soil samples.

A schematic cross section through the crater Moltke presented in Figure 8b describes the interpreted sequence of feldspathic contamination across the Apollo 11 and Moltke region. High-titanium basalts (Tvh_A) were emplaced over a feldspathic crust and Imbrium basin ejecta. The feldspathic rays from Theophilus deposited a thin high-albedo veneer onto the surface of the very low-albedo surface Tvh_A basalts in this region. Subsequently, the Moltke event is interpreted to have excavated underlying nonmare feldspathic materials from beneath the low-albedo basalts producing the bright deposits around this crater to ~2 radii. More recently, small impacts into Moltke ejecta deposits produced dark haloed craters by exposing the Tvh_A surface unit from below the veneer of Moltke ejecta that contains nonmare feldspathic materials.

The excavation of highlands materials by Moltke (6 km) and estimates of the depth of excavation suggest that the low-albedo basalts in this region, about 30 km to the south of the Apollo 11, are likely to be less than 600 m thick. On the other hand, the approximate diameter (1 km) of the dark haloed craters in Moltke ejecta indicates a minimum basalt thickness of 100 m. The larger circular dark zone around Moltke to the north (8 crater radii) has no obvious cause. One hypothesis is that this dark zone with no Theophilus rays might result from the disturbance of surface materials associated with the Moltke impact event. Within this zone, the thin veneer of high-albedo surface materials may have been mixed more extensively with the darker underlying Tvh_A soils, diluting the feldspathic component and erasing the Theophilus rays in this area.

The spectral analyses presented above distinguishes the character and distributions of basaltic units emplaced in Mare Tranquillitatis by considering the optical effects of mixing processes within the mare. The resulting information about basalt types and stratigraphy across Mare Tranquillitatis allows associations to be made to the returned Apollo samples. Recent geochemical studies by Jerde et al. [1994] have assigned the five Apollo 11 basalt types observed in returned samples [Papike et al., 1976] to three principal magmatic groups: A, B3-B1, and B2-D. In this interpretation, the earliest volcanic activity sampled at the Apollo 11 site produced the low-K Group B2 and D basalts (TiO2 content 8.4-8.9 wt %) at about 3.85 Ga. The activity producing the B3-B1 basalts took place ~150 m.y. later and display a continuum of compositions consistent with the fractionation of a magma of Group B3 composition. These basalts have an average TiO2 content of 10.2 wt %. The youngest volcanic activity sampled at the Apollo 11 site was the eruption of the higher-K group A basalts with an average TiO2 wt % of 11.0. There is a remarkably good correspondence between the remote observations and the sample studies. Provided in Table 1 are the inferred
assignments of the basalt units derived from spectral analyses to these volcanic events identified at Apollo 11 with returned samples. The abundant younger high-titanium basalts at Apollo 11 are associated with the two $T_{vh}$ units. The less abundant lower titanium basalts ($B_{2-D}$) may be associated with the $T_b$ unit.

4. Overview of the Tranquillitatis Region

4.1. Tranquillitatis: An Asymmetric Structure

Estimates of crater excavation depths for craters interpreted to have excavated nonmare feldspathic materials provide constraints on the depth of the mare units and the proximity of the underlying basin topography. The spectral studies of crater deposits presented above indicate that the Tranquillitatis' basalt fill (and thus the premare basin topography) may be much more asymmetric than initially suggested by crater flooding data [De Hon, 1974]. Evidence for thick basalts in the northwest includes the lack of nonmare feldspathic excavation at Ross (25 km) or Dawes (18 km) leading to estimates of basalt thickness in excess of 2 km for this portion of the basin. Thinner predictions of basalt thickness by De Hon [1974] are likely to be the result of a lack of available flooded craters in the regions north and west of the central ridge system. The original estimates of shallow deposits may thus be an artifact of contouring the very sparse data in these areas. It is instead suggested that the lack of flooded craters in these regions results from the complete burial of most features by relatively thick basalts, the youngest of which are $T_{vh-A}$ basalt flows. On the other hand, vertical excavation of highland material at the mare craters Arago (26 km) and Jensen B (16 km) indicates that the basalts are less thick in the Lamont region and central portions of the basin than in the north and northwest portions of the basin.

A west to east topographic rise is apparent in the Clementine LIDAR data of Mare Tranquillitatis [Zuber et al., 1994] and is shown in Figure 9. A corresponding gravity anomaly is seen only in the west [Zuber et al., 1994]. This change in topography occurs primarily across the numerous mare wrinkle ridges which extend from the southwestern to the northeastern mare-highland boundary, as can be seen in Figure 5. The combined spectral and geophysical data suggest that instead of being a circular basin, Tranquillitatis may be part of a larger asymmetric structure associated with early impact and tectonic events with the thickest deposits of basalts located in the northwestern portion of the basin. A strongly asymmetric model for the basin structure is consistent with interpretations of a Procellarum ring through central Tranquillitatis [Whitaker, 1981] but does not exclude other structural interpretations of the basin and its ridges [Dvorak and Phillips, 1979; Spudis, 1993].

4.2. The Emplacement and Evolution of Mare Basalts in Tranquillitatis

These analyses of Clementine and Galileo imagery identify at least four basalt types in Mare Tranquillitatis and provide concrete examples of basalt stratigraphy for the $T_{vb}$, $T_{vh}$, and $T_1$ units defined in Galileo mixing analysis. Excavation and embayment relationships in the north (e.g., Dawes, Plinius), central (e.g., Arago), and southern (Maskelyne) regions of the basin indicate that the $T_b$ unit is stratigraphically older than the overlying $T_{vh}$ basalts. Similarly, embayment relationships and crater frequency estimates in eastern Tranquillitatis [Wilhelms, 1972; Morris and Wilhelms, 1967] indicate that the lowest titanium $T_1$ basalts also underlie the $T_{vh}$ units. The overall stratigraphic sequence appears to be (oldest to youngest) $T_p$, $T_b$, $T_{vh-B}$, $T_{vh-A}$.

---

Table 1. Assignments of Observed Spectral Units to Apollo 11 Basalt Types

<table>
<thead>
<tr>
<th>Event</th>
<th>Age, Ga</th>
<th>$\sim$TiO$_2$ wt %</th>
<th>Mare Samples%</th>
<th>Spectral Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.59</td>
<td>11.0</td>
<td>60</td>
<td>$T_{vh-A}$</td>
</tr>
<tr>
<td>B1-B3</td>
<td>3.67-3.71</td>
<td>10.3</td>
<td>30</td>
<td>$T_{vh-B}$</td>
</tr>
<tr>
<td>B2-D</td>
<td>3.85</td>
<td>8.6</td>
<td>10</td>
<td>$T_b$ or laterally mixed material</td>
</tr>
</tbody>
</table>

* Jerde et al. [1994].
Spectral analyses of mare basalts and comparison with the ages and compositions of returned samples suggest that the Apollo 11 site is dominated by the youngest $T_{vhA}$ unit, whose bulk soil properties have been affected by laterally mixed feldspathic materials. These spectral analyses associate the stratigraphically youngest $T_{vhA}$ spectral unit in western Tranquillitatis with the Apollo 11 sample group A [Jerde et al., 1994]. The distribution of these high-Ti, high-K flows is mapped across the western basin. The slightly less titanium-rich and more extensive $T_{vhB}$ basalts occur abundantly in topographic lows throughout the central portion of the basin and appear to have been buried only by the youngest $T_{vhA}$ in the western portion of the basin. Stratigraphically older $T_{vhB}$ basalts are exposed just north of the Apollo 11 site (Figure 4a) and occur throughout the central portions of the basin and as far north as southern Serenitatis. This basin unit is associated with the older B1-B3 [Jerde et al., 1994] low-potassium, high-titanium volcanics sampled at Apollo 11. The spectrally redder and stratigraphically earlier $T_h$ unit may be related to the older B2-D event [Jerde et al., 1994], but it is not clear whether this unit was sampled at the Apollo 11 site. The stratigraphy of the three high-Ti spectral units, from the stratigraphically older $T_h$ basalts to the younger $T_{vhB}$ and youngest $T_{vhA}$ unit, agrees with the relative ages and stratigraphic origin of the associated basalt samples.

Spectral mapping of the $T_{vhA}$ unit thought to be associated with the bulk of the Apollo 11 basalt samples (Group A: high-Ti, high-K) indicates that this unit is contiguous at the basin scale, extending throughout topographically low areas of the basin as far north as Plinius. The $T_{vhB}$ basalts are exposed just north of the Apollo 11 site and extend as a spatially contiguous units as far north as southern Serenitatis near the Apollo 17 site and in the central-eastern portion of Tranquillitatis. These basalts are thought to be sampled by the B1-B3 Apollo 11 basalts fragments (high-Ti, low-K), perhaps excavated by West crater (30 m deep [Wilhelms, 1987]). The spatial continuity and stratigraphic consistency of the $T_{vhB}$ unit suggest that the mare unit observed in northern Tranquillitatis and adjacent to the Apollo 17 site is the same or a very similar unit from which the Apollo 11 high-titanium, low-potassium Group B basalts are derived. The proximity of this unit to the Apollo 17 site suggests that it may also have been sampled by the high-Ti, low-K basalts collected from the edge of Serenitatis. This spectral link between the Apollo 11...
and 17 sites supports petrologic evidence that the Apollo 11 and 17 sites sampled the same early period of high-Ti basalt extrusion [Wilhelms, 1987]. The low-K, high-titanium basalts from Apollo 17 share similar age ranges (3.69-3.75) as the low-K, high-Ti Apollo 11 basalts (3.67-3.71). Recent trace element studies by Snyder et al. [1992, 1994] support the petrologic link between the high-Ti, low-K basalts at both Apollo sites.

As the common high-titanium Tₖ-B textures are interrupted by islands of lower titaniferous Tₐ basalt portions of Mare Tranquillitatis, it is likely that the spatial extent of the Tₖ-B textures results from both source location and the topography of the basin when they were extruded. The eastern region of the basin currently lies significantly higher than the western portion, as can be seen in topographic data of the basin in Figure 9. The Tₖ-B units are spatially continuous and appear to derive from sources in the northeastern topographically high portions of the basin. These flows have filled in much of the lower lying areas to the west reaching both the Apollo 11 and Apollo 17 landing sites. The stratigraphically younger Tₖ-B basalts (sampled only at Apollo 11) may then have continued to fill the topographically low westernmost portions of Tranquillitatis, producing an accumulation of lower titanium deposits in the northwestern corner of the basin.

The volcanic deposits within Mare Tranquillitatis and Serenitatis clearly shared several common elements during their early history of basin emplacement. An evaluation of the extent of the older Tₐ units beneath the voluminous low-titanium basalts of Mare Serenitatis has yet to be undertaken, but would help to further define the nature of early high-titanium volcanism within the two basins. Additionally, it would be worthwhile to investigate whether the older and possibly pre-Imbrium deposits of lower titanium basalts occur beneath the high-titanium border basalts of Tranquillitatis in order to define the extent of a common stratigraphy within these two neighboring basins.

Acknowledgments. NASA support for this research is gratefully acknowledged by CMP under NASA grant NAGW-28. JWH gratefully acknowledges Contract NASW-8512 for the Galileo Solid State Imaging Team from the National Aeronautics and Space Administration. Jet Propulsion Laboratory. We thank B. Ray Hawke and Paul Johnson for thoughtful and helpful reviews of the original manuscript.

References


Schultz, P.H., Moon Morphology, 626 pp., Univ. of Texas Press, Austin, 1976.


Staid, M.I., and C.M. Pieters, Craters as indicators of basalt stratigraphy in Mare Tranquilitatis and Serenitatis, Lunar Planet. Sci., XVII, 1259-1260, 1996.


J.W. Head III, C.M. Pieters, and M.I. Staid, Department of Geological Sciences, Box 1846, Brown University, Providence, RI 02912.

(e-mail: pieters@pds.geo.brown.edu)

(Received July 17, 1995; revised July 22, 1996; accepted July 31, 1996.)