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Lunar mare volcanism in the eastern nearside region derived from Clementine UV/VIS data

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Abstract-Clementine UV/VIS multi-spectral data were used to map mare deposits in the eastern lunar nearside region (Mare Tranquillitatis, Mare Fecunditatis, Mare Serenitatis, Mare Crisium, Mare Nectaris) to understand the volcanic history of this region. An array of Clementine and Clementine-derived data were used to classify mare basalts; these include: 750 nm albedo, UV/VIS ratio, 1 μ m absorption signatures, and Clementine derived FeO and TiO₂ contents. We have successfully identified several new geological units and have determined their spectral characteristics. For example, the relatively younger low-Ti basalts were recognized in the eastern part of Mare Tranquillitatis. The central low-Ti basalts in Mare Serenitatis, which had been classed as mISP, were divided into 2 groups. In Mare Nectaris, 2 types of mare basalts were identified, while only 1 group was recognized in the previous study. The stratigraphy constructed from the spectral analysis indicates that the mare deposits tend to become younger in the northern maria, including Serenitatis and Crisium, and older in the southern maria, including Tranquillitatis, Fecunditatis, and Nectaris. According to the relationship between the titanium contents of the mare units and their stratigraphy, the titanium content decreases with time in the early stage but increases toward the end of volcanism in the Serenitatis and Crisium region, while it increases with time but finally decreases in the Tranquillitatis and Fecunditatis region. In connection with the distribution of mare basalts, a large amount of high-Ti mare basalts are found in Mare Tranquillitatis, especially in the western part, while other maria are covered by low-Ti basalts. The iron contents show a similar distribution to that of titanium.

INTRODUCTION

The lunar mare basalts cover about 17% of the lunar surface and occupy about 1% of the total volume of the lunar crust (Head 1976). In spite of the limited distribution, their chemical composition and stratigraphy are important to our understanding of the chemical distribution of the lunar interior and its evolution. From the analyses of lunar mare samples, some say that no correlation exists between their titanium content and their ages (BVSP 1981). However, large variation in the composition of mare basalts has been reported from the spectral observations with Earth-based telescopes (e.g., McCord et al. 1976; Pieters and McCord 1976). Pieters (1978) characterized mare deposits of the lunar nearside with Earth-based telescopic spectral data and suggested that only one-third of the surface basalt types are represented in the returned samples. The recent global distribution maps of TiO₂ derived from remote sensing data (e.g., Giguere et al. 2000;

Elphic et al. 2002) exhibit a biased distribution of the TiO_2 content in the mare surface.

The compositional heterogeneity of the mare surface hints at a compositional diversity of the lunar upper mantle, which is the source region of the mare basalts, and suggests that the basin-scale mare volcanism evolved independently of neighboring regions (Pieters 1993). Therefore, we must know the chemical properties of mare basalts, together with their detailed distribution and stratigraphy in each region, and understand how the mare volcanism evolved compositionally and spatially in a basin. For these purposes, we are currently mapping the mare basalts on the lunar surface using high spatial resolution multi-spectral images obtained by the Clementine UV/VIS camera (Nozette et al. 1994). In this paper, we present the chemical distribution and stratigraphy of mare basalts and temporal changes of the mare volcanism on the eastern nearside of the Moon.

The study area includes Mare Tranquillitatis, Mare

Fecunditatis, Mare Serenitatis, Lacus Somniorum, Mare Crisium, Mare Nectaris, and Sinus Asperitatis. The locations and profiles of the mare basins are shown in Fig. 1a and Table 1. In our analysis, boundaries of mare units were mapped on the basis of their compositional differences, and their spectral and chemical properties were obtained for each unit from the Clementine data set. Then the stratigraphic relationship of mare units was constructed, and the relationship between the stratigraphy of mare units and their chemical and spectral properties was examined in each basin and among the basins.

DATA

The lunar Digital Image Model (DIM) produced from Clementine UV/VIS data by the U. S. Geological Survey (Eliason et al. 1999; Isbell et al. 1999) was used in this study. This DIM consists of 5 spectral bands (415–1000 nm) and is radiometrically and photometrically corrected (McEwen 1996; McEwen et al. 1998). The images are geometrically controlled at a spatial resolution of 100 m/pixel in sinusoidal equal-area projection.

A false color image was generated from the data set with a spatial resolution of 500 m/pixel (Fig. 2) in which the 415/ 750 nm ratio is assigned to red, the 750/950 nm ratio to green. and the 750/415 nm ratio to blue. Similar color ratio assignments were used in the previous studies (e.g., Belton et al. 1993; Pieters et al. 1994). The 415/750 nm and 750/ 415 nm ratios are sensitive to the content of titanium, which is predominantly found in ilmenite (FeTiO₃). Titanium-rich basalts have higher values of the 415/750 nm ratio than titanium-poor basalts. The 750/950 nm ratio is sensitive to iron-rich minerals such as pyroxenes and soil maturity. It becomes higher as the iron content increases, while it becomes lower as the soils become mature due to space weathering (Hapke 2001; Morris 1978). In the false color image, a mature low-Ti basalt or mature highland materials would appear red, while a mature high-Ti mare basalt would appear blue. A green, cvan, or vellow color would indicate freshly exposed basalt. Fresh highland materials, such as crater ejecta from highlands, also appear blue.

FeO and TiO_2 content maps were produced using the algorithms of Lucey et al. (2000). In these maps, the effects of



Fig. 1. a) The eastern nearside of the Moon as seen in a Clementine 750 nm USGS global mosaic; b) telescopic classication map of mare basalt (from Pieters [1978]) relevant to this study.

Table 1	l. Pi	roperties	of	major	mare	basins	anal	vzed	in	this	study	v.
								J				

Basin name	Center (lat., long.)	Basin D (km)	Mare D (km)	Basin age				
Serenitatis	27°N, 19°E	740	600	Nectarian				
Crisium	17.5°N, 58.5°E	1060	420	Nectarian				
Nectaris	16°S, 34°E	860	300	Nectarian				
Fecunditatis	4°S, 52°E	690	600	Pre-Nectarian				
Tranquillitatis	7°N, 40°E	775	600	Pre-Nectarian				

^aData are from Wilhelms (1987).



Fig. 2. False color image of major mare basins in the study area, assigning 750/415 nm ratio to red, 750/950 nm ratio to green, and 415/750 nm ratio to blue: a) Mare Tranquillitatis; b) Mare Fecunditatis.



Fig. 2. False color image of major mare basins in the study area, assigning 750/415 nm ratio to red, 750/950 nm ratio to green, and 415/750 nm ratio to blue: c) Mare Serenitatis; d) Mare Crisium; e) Mare Nectaris.

maturity are removed and the differences due to the compositional variations are isolated. This technique allows us to estimate the FeO and TiO_2 contents to accuracies of 1 wt% (Lucey et al. 2000). The abundance of these elements

can also provide a convenient method of mapping and classifying the geologic units. The FeO map is useful for distinguishing between iron-poor highland materials and mare basalts. Mare units can be categorized based on their TiO₂ content as follows: very low-Ti (<1 wt%), low-Ti (1– 5 wt%), medium-Ti (5–9 wt%), and high-Ti (>9 wt%) (e.g., Neal and Taylor 1992; Papike and Vaniman 1978).

The chemical composition of ejecta deposits and the floors of small craters, tectonic features such as rilles and ridges, and the detailed structure of unit boundaries are important for determining the stratigraphic relationship among mare units. To recognize these small features, we generated another set of images at a spatial resolution of 100 m/pixel.

METHOD

In this study, the boundaries of mare units were mapped using false color images (Fig. 2) and FeO and TiO₂ content maps. In the false color image, we distinguished mare units by their color difference, which correlates with the compositional difference between them (see previous section). The mapped units were classified into stratigraphic units by comparing their chemical and spectral parameters. They were divided mainly based on their chemical compositions. Mare units, which have a similar composition but different spectral characteristics, were further divided into subgroups. The spectral characteristics of the mare basalts are governed by their albedo, UV/VIS ratio, and absorption near 1 µm and 2 µm (e.g., Pieters and McCord 1976; Pieters 1978). Table 2 shows the spectral parameters used in Pieters (1978). The UV/VIS ratio is sensitive to the content of ilmenite, while the absorption bands near 1 μ m and 2 μ m occur due to the presence of pyroxenes. Clementine provides these spectral measurements except for wavelengths near the absorption band around 2 μ m. The albedo can be represented by the 750 nm reflectance, while the UV/VIS ratio is approximated by the 415/750 nm ratio. The 1 μ m absorption band is expressed by the 950/750 nm and 1000/750 nm ratios. We derived these parameters by averaging a continuous area of 50,000 to 100,000 pixels from the Clementine images at 100 m/pixel spatial resolution for each unit (summarized in Table 3).

Since the ejecta of a crater penetrating a surface mare unit contain materials of the underlying unit, the spectral parameters would be affected if these materials are included in the sampled area and their chemical composition is different from that of the surface unit. These materials can be distinguished from the surface basalts in the FeO and TiO_2 maps and the false color images. We carefully eliminated such craters and their ejecta from the sampled area to avoid contamination by these materials. In addition to these parameters, we obtained 5-band spectra of mare soils by averaging a 3×3 pixel area for each unit at 100 m/pixel spatial resolution (Fig. 3). The locations of areas for spectra are shown in the 750 nm reflectane images of each mare region (Figs. 4a, 6a, 9a, 10a, 11a, and 13a).

The stratigraphy of mare units can be defined by studying the spatial distribution, superposition, and chemistry of their crater materials. A crater penetrating a surface mare unit would excavate underlying material, thereby showing a different chemical composition from the surface unit if the underlying materials have a different composition. In addition to the relative stratigraphic relationship, the radioactive ages of lunar samples were used to establish the stratigraphic relationship among the mare basins. The absolute ages determined by the previous chronologic studies using the crater counting or crater degradation model (e.g., Boyce 1976; Hiesinger et al. 2000) were also used to evaluate the stratigraphic relationship among the mare units or to define the ages of several mare units.

RESULTS AND DISCUSSION

Mare Tranquillitatis

Geologic Setting

The Tranquillitatis basin with the center at 7°N, 40°E (Fig. 1a) (775 km diameter), was formed during the pre-Nectarian age and is the oldest basin in the study area (Wilhelms 1987). The mare basalt covers a large fraction of the basin (600 km in diameter) and has a non-circular shape (Fig. 4a). The Apollo 11 astronauts collected high-Ti mare samples (>9 wt% TiO₂) from the southern part of Mare Tranquillitatis, the radioactive ages of which range from 3.59 to 3.85 Ga (Jerde et al. 1994). In Pieters (1978), mare basalts are classed into 3 types (Fig. 1b). Most of the mare is classified into HDWA- and hDWA-type basalts (see Table 2 for definition). Mare basalts of mIG-type are deposited on the southwestern and the northeastern part of the mare. Staid et al. (1996) divided the mare basalts in Mare Tranquillitatis into four groups (T_{vh-A}, T_{vh-B}, T_h, and T_l) using Galileo SSI multispectral images. In their map, the T_{vh-A} unit, which contains the highest contents of TiO₂ (8-10 wt%), is exposed in the western part of the basin, including the Apollo 11 landing site. The T_{vh-} _B basalt (5–8 wt% TiO₂) is extensive in the north, south, and central eastern portions of the basin. The T_h units (3–5 wt%) TiO_2) are seen as small patches within the 2 T_{vh} units. The T₁ unit, which has the lowest TiO₂ content (<3 wt%), occurs in the

Table 2. The parameters used by Pieters (1978) to characterize mare basalt types from telescopic spectral reflectance.

Values	UV/VIS ratio ^a	Albedo	1 μm band	2 µm band
High	H: high (≥1.05) h: med. high (1.02–1.05) m: medium (0.99–1.02)	B: bright (≥9.5%) I: intermediate (8–9.5%) D: dark (≤8%)	S: strong G: general W: weak	P: present A: absent
Low	L: low (≤0.99)			

^aUV/VIS ratio values are compared to those of MS2.

Table 3. The chemical comp	position and spectral	parameters derived	from Clementine	UV/VIS data
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		1	1	ł			Pieters (1978)	Other previous
Unit	Albedo (%)	FeO (wt%)	TiO_2 (wt%)	415/750 nm	950/750 nm	1000/750 nm	classication	works
Trancuillitatis								
Tr1	11.8	15.1 ± 0.6	3.5 ± 0.6	0.599	1.054	1.086	mIG, hDWA	Tl ^a
Tr2	9.4	18.0 ± 0.3	9.0 ± 0.9	0.635	1.051	1.080	HDWA	Th ^a
Tr3	8.7	19.0 ± 0.3	12.6 ± 0.8	0.662	1.053	1.081	HDWA	Tvh-B ^a
Tr4	8.5	19.1 ± 0.4	13.7 ± 0.7	0.680	1.051	1.078	HDWA	Tvh-A ^a
Tr5	10.4	16.9 ± 0.2	5.2 ± 0.7	0.603	1.047	10.76	mIG	Tl ^a
Fecund	itatis							
Fc1	11.7	15.3 ± 0.8	3.3 ± 0.5	0.594	1.047	1.077	mIG	Im1, Im2 ^b
Fc2	12.8	14.3 ± 0.4	2.4 ± 0.5	0.591	1.043	1.077	mBG	Im1, Im2 ^b
Fc3	9.7	17.7 ± 0.3	8.5 ± 0.6	0.636	1.051	1.075	hDWA	Im3 ^b
Fc4	10.4	17.0 ± 0.5	5.6 ± 0.7	0.609	1.043	1.070	mIG	Im3 ^b
Serenit	atis							
Sr1	9.3	18.3 ± 0.2	8.6 ± 0.7	0.628	1.042	1.075	HDWA, hDWA	Group II ^c
Sr2	9.0	18.7 ± 0.2	11.0 ± 0.9	0.651	1.040	1.070	HDWA	Group II ^c
Sr3A	10.7	17.1 ± 0.2	4.2 ± 0.6	0.592	1.023	1.054	mISP	Group III ^c
Sr3B	10.8	16.5 ± 0.5	3.8 ± 0.6	0.589	1.043	1.079	LIG	Group III ^c
Sr4	11.1	16.4 ± 0.2	2.7 ± 0.4	0.575	1.029	1.067	mISP, mottled	Group III ^c /Em ^d
Sr5	9.7	17.9 ± 0.2	6.3 ± 0.6	0.607	1.036	1.067	hDWA	Group II ^c /Em ^d
DMM	9.2	18.0 ± 0.8	6.9 ± 1.1	0.604	1.078	1.119	DMM	CId, Emp ^c
Somnic	orum							
Sm1	13.3	13.7 ± 0.5	1.1 ± 0.2	0.560	1.044	1.085	LBG	Im ^d
Sm2	13.1	13.7 ± 0.7	1.8 ± 0.4	0.581	1.051	1.092	LBG	Im ^d
Crisiun	1							
Cr1	95	178 ± 08	65+11	0.605	1.063	1 099	hDWA	Group Ie
Cr2	12.2	14.7 ± 0.8	2.4 ± 0.3	0.581	1.003	1.088	LBG	Group IIB ^e
Cr3	13.0	13.0 ± 0.6	2.0 ± 0.3	0.580	1.070	1.108	Undivided	Unknown
Cr4	12.1	15.4 ± 0.6	3.1 ± 0.4	0.596	1.033	1.063	LISP	Group IIA ^e
Cr5A	10.4	17.1 ± 0.3	5.4 ± 0.6	0.608	1.034	1.062	mIG	Group III ^e
Cr5B	10.3	17.0 ± 0.2	5.4 ± 0.5	0.605	1.048	1.079	mIG, hDWA	Group III ^e
Nectari	s						-	1
Nc1	124	14.1 ± 0.6	26 ± 0.6	0 590	1.060	1 092	mBG	Imd
Nc2	12.4	14.7 ± 0.0 14.7 ± 0.4	3.4 ± 0.4	0.605	1.045	1.074	mBG	Im ^d
A		=						
Asperit		127.07	20105	0 (11	1.000	1.009	D.C	Lad
ASI	13.3	12.7 ± 0.7	3.0 ± 0.5	0.611	1.068	1.098	mBG	Im ^a
As2	11.8	14.7 ± 0.8	5.2 ± 0.6	0.630	1.061	1.089	mBG	Imd

^aStaid et al. (1996).

^bWilhelms (1987).

^cSolomon and Head (1979).

^dWilhelms and McCauley (1971).

^eHead et al. (1978).

northeastern and southeastern corners of the mare. According to the stratigraphy of Staid et al. (1996), the titanium abundance increases with time. The T_1 basalts are the oldest, followed by T_h and T_{vh-B} , and the youngest is the T_{vh-A} . Hiesinger et al. (2000) defined ages of mare units by using a crater size-frequency distribution method with high spatial resolution photographs taken by the Apollo and Lunar Orbiter and reported results that were inconsistent with those of Staid et al. (1996). In their stratigraphy, some high-Ti units ($T_{vh-A, B}$) in the western part of the basin were older than the lower-Ti basalt group (T_h , T_l).

Characteristics and Distribution of Mare Deposits

Fig. 4b shows the geologic map of Mare Tranquillitatis produced from the Clementine data. We classified the mare basalts into 5 groups in this region, while earlier studies have divided them into 4 groups or less. The 5-band spectra of mare soils for each unit are shown in Fig. 3a, and the spectral properties and chemical composition are summarized in Table 3. The high-Ti mare basalts classed as HDWA by Pieters (1978) were divided into 3 groups (Tr2, Tr3, Tr4). Tr4 basalts, distributed in the western and southwestern part of the basin (including the Apollo 11 landing site; Fig. 4b), show the



Fig. 3. Five-band Clementine spectra of mare soils for each mare region obtained by averaging a 3×3 pixel box: a) Mare Tranquillitatis; b) Mare Fecunditatis; c) Mare Serenitatis; d) Lacus Somniorum; e) Mare Crisium; f) Mare Nectaris and Sinus Asperitatis. All spectra are scaled at 750 nm. The locations of areas for spectra are provided in the 750 nm reflectance images (Figs. 4a, 6a, 9a, 10a, 11a, and 13a). The average standard deviation for mare soils is 0.004.



Fig. 4. a) Clementine 750 nm mosaic image of Mare Tranquillitatis. The area outlined in white is the location of the images in Fig. 5. The + symbols in white indicate the locations of spectra for mare soils shown in Fig. 3a. The + symbol in black provides the position of a small crater in the Tr3 unit, the spectrum of which is shown in Fig. 15; b) geologic map of Mare Tranquillitatis.

darkest and bluest characteristics in the Tranquillitatis region (Table 3). Tr3, which also appears blue (Fig. 3a), is the dominant basalt on the surface of Mare Tranquillitatis. These basalts extend from the northwestern part of the basin to the south and central eastern portions. These high-Ti materials are also observed at deposits of the large craters Maclear and Ross in the western part of the basin (20 km and 25 km in diameter; Fig. 4b). A Tr2 unit, which occurs as a small patch within the Tr3 units also consists of high-Ti basalts (9 wt% TiO₂) having a relatively low UV/VIS value relative to other high-Ti basalt groups (Fig. 3a). This unit is also seen in deposits of the Arago crater (21 km diameter; Fig. 4b).

The distribution of high-Ti basalts (Tr2, Tr3, and Tr4) is consistent with the map of Staid et al. (1996). The Tr4 unit here corresponds to T_{vh-A}, which contains the highest fraction of blue mare end member; the Tr3 unit corresponds to T_{vh-B} , in which the fraction of blue mare component is less abundant than T_{vh-A}, and the Tr2 unit corresponds to Th having the lowest fraction of blue mare end member. However, although the distribution of these units is consistent with the previous study, the concentration of TiO₂ disagrees. The TiO₂ content of these basalts estimated using the method of Lucey et al. (2000) exceeds 12 wt% in Tr3 and Tr4, while Staid et al. (1996) estimated them at less than 10 wt%. The high-Ti basalt samples returned by Apollo 11 contain 10-12.1 wt% of TiO₂ (BVSP 1981). This suggests that the method of Lucey et al. (2000) overestimates the TiO_2 contents by 2-3 wt% in the high-Ti areas. The TiO₂ content map produced by Gillis et al. (2003) displays 8-12 wt% of TiO₂ in this region, which is closer to the sample data.

While the distribution of high-Ti basalts is consistent with previous work, that for the low-Ti basalts is different. Our spectral analysis divided low-Ti basalts in the north and southeastern part of the basin into 2 groups, while Staid et al. (1996) and Pieters (1978) identified only 1 group of mare basalts (T₁ and mIG). A Tr1 unit has the highest albedo in the basin and shows a weak 1 µm absorption signature (Table 3). These basalts contain 3.5 wt% of TiO₂, display a redder signature in Fig. 3a, and are exposed at the margins of the mare (Fig. 4b). A Tr1 composition is also observed on the floor of the Dawes and Jansen-B craters (3-5 wt% TiO₂; Fig. 4b), where materials appear to be colored yellow in the composite image (Fig. 2a). On the other hand, a Tr5 unit is darker than a Tr1 unit and shows a stronger 1 µm absorption signature (Table 3), as it is composed of higher-Ti basalts (5.2 wt% TiO₂). Tr5 units appear at the northeastern part between Tr3 and Tr1 units and in the central eastern and

southeastern parts of the basin. Some of these units overlay Tr3 units (Fig. 4b). Also, the ejecta of a small crater (<2 km diameter) in the Tr5 unit show a higher concentration of titanium (>8 wt% TiO₂; Fig. 5). Recognizing these small craters and their deposits in the earlier low spatial resolution data is difficult.

The stratigraphy of the high-Ti basalt groups (Tr2, Tr3, and Tr4) is based on the results of Staid et al. (1996). The distribution of the Tr2 unit, observed at heavily cratered topographic highs (Morris and Wilhelms 1967), suggests that they are stratigraphically lower than the Tr3 and Tr4 basalts. The Tr4 unit is only interrupted by crater ejecta and topographic highs, indicating that the Tr4 unit is younger than Tr3. Higher-Ti crater deposits within the Tr5 unit indicate the existence of higher-Ti basalts that may represent Tr3 underlying the Tr5. The Tr1 units exposed at the mare highland border and at the floor of large impact craters such as Dawes and Jansen-B (Fig. 4b) is assumed to be the oldest mare unit in the basin. Since the Tr4 and Tr5 have no direct contacts, the stratigraphic relationship between them was not defined.

The stratigraphy of mare units constructed in this study reveals the temporal change in chemical composition of mare basalts. The content of titanium in mare basalt increases with time in the western part of the basin, while the youngest mare unit in the eastern region consists of lower-Ti basalts. In the western part of the basin, high-Ti materials occurring at large craters indicate that a significant amount of high-Ti mare basalts were deposited in this region (Bell and Hawke 1995). However, in the eastern part of the basin, deposits at relatively small craters within the mare units (e.g., the Cauchy crater, 11 km diameter) display a highland composition (<12 wt% FeO). Also, these units include highland materials as topographic kipukas, indicating that mare basalts in this region are thinner than those in the western region (Staid et al. 1996).



Fig. 5. Images of the northeastern part of Mare Tranquillitatis: a) titanium content map; b) geologic map. The titanium-rich materials appear bright in the titanium content map. The crater deposits within the Tr5 unit exhibit higher titanium content than Tr5.

Mare Fecunditatis

Geologic Setting

The Fecunditatis basin is located to the southeast of Tranquillitatis (centered at 4°S, 52°E) (Fig. 1a) and is a pre-Nectarian basin with a diameter of 990 km (Wilhelms 1987). Mare basalts occupy a large fraction of the northern Fecunditatis basin (600 km in diameter) and a small fraction to the south (250 km in diameter) as shown in Fig. 6a. Most of the samples collected by Luna 16, which landed in the northern part of the basin, are feldspathic and indicate an Al-rich composition (Kurat et al. 1976) with radioactive ages ranging from 3.35 to 3.41 Ga (e.g., Huneke et al. 1972). Few precise geologic maps exist due to the lack of high spatial and spectral resolution images before Clementine. Pieters (1978) classified mare basalts in Fecunditatis into 3 types (Fig. 1b). Most mare basalts are classified as mIG. A small unit classed as hDWA is exposed at the northeastern margin of the mare. The south mare is covered by mare basalts classed as mBG. The stratigraphy of mare units in the Fecunditatis region was denied by Boyce (1976) and Wilhelms (1987). According to Boyce (1976), mare units in the northeastern part (mIG) and southern margin (mBG) of the basin are older than the others. In Wilhelms (1987), a Ti-rich unit classed as hDWA in the northern part of the basin is the youngest (Im3), and a central mare unit classed as mIG is defined as an older unit (Im1 and Im2).

Characteristics and Distribution of Mare Deposits

In the Fecunditatis region, mare basalts were classed into 4 groups (Fig. 6b). A large part of the central mare is dominated by medium-Ti content basalts (5.6 wt% TiO₂) designated as Fc4. A relatively dark and blue mare unit in the northern part of the basin (classed as hDWA in Pieters [1978]) was designated as Fc3. These basalts have a higher UV/VIS ratio than the Fc4 (Fig. 3b) and are clearly distinct from the surrounding units (Fig. 2b). This unit consists of high-Ti basalt, which contains 8.5 wt% TiO₂. An Fc3 unit is also distributed as a small patch within an Fc4 unit in the central mare region and western edge of the basin and was not identified in previous works due to the lower spatial resolution.

In the northeastern part of the basin, where mIG mare basalt can be recognized in the Pieters' map, bright and less blue basalts were identified and designated as Fc1 (Table 3). The Fc1 unit is also observed in the northwestern part of the basin near the Taruntius crater, along the south edge of the north mare, and in Mare Spumans (northeast of Mare Fecunditatis; Fig. 6b). Fc1 basalts contain a smaller amount of titanium and iron (3.3 wt% TiO₂, 15.3 wt% FeO) than the central mare basalts such as Fc3 and Fc4. An Fc2 unit, which extends from the southern part of the north mare to the south extensional mare, is characterized by the highest albedo and low UV/VIS ratio (Table 3). This shows the lowest abundance



Fig. 6. (a) Clementine 750 nm mosaic image of Mare Fecunditatis. The solid line indicates the area of the iron content map in Fig. 7. The dashed line indicates the area of images in Fig. 8. The + symbols provide the locations of spectra for mare soils shown in Fig. 3b; b) geologic map of Mare Fecunditatis. The dashed line indicates an uncertain border.

of iron and titanium in the Fecunditatis basin (2.4 wt% TiO_2 , 14.3 wt% FeO).

The boundary between the Fc2 and Fc1 units is unclear due to contamination from Langrenus (Eratosthenian-aged by Wilhelms [1987]) (Fig. 6b). In Fig. 6a, many crater rays from Langrenus and a number of other craters within the highlands are observed across the mare surface. These rays display a relatively low abundance of iron, which becomes lower toward the Langrenus crater (Fig. 7). However, materials excavated from a small crater (2 km diameter) near Langrenus have higher iron concentration than the surrounding materials (e.g., Al-Marrakushi in Fig. 7), indicating that Fe-rich mare basalts are buried below low-iron Langrenus crater ejecta. These observations suggest that the mare surface in the Fecunditatis region was contaminated at sometime by a large amount of highland materials. This would result in a lower estimation of iron content in the mare basalts and would have made it difficult to map mare basalt using previous low spatial resolution data.

Within the central medium- to high-Ti mare units (Fc3 and Fc4), crater materials indicate low-Ti concentration. On the other hand, craters of any size within a low-Ti mare unit, which appears near mare edges, do not eject high-Ti materials, suggesting that low-Ti basalts similar to Fc1 underlie medium- to high-Ti basalts. This relationship is consistent with Boyce (1976), in which the central mare basalts are younger than those in the northeastern part of the basin. The stratigraphic relationship between Fc3 and Fc4 is not, however, consistent with Wilhelms (1987), who defined the northern hDWA unit (corresponding to Fc3) to be younger than the central (mIG) mare basalts (Fc4). In our study, Fc3 units were also found in the central mare region, and were interrupted by Fc4 basalts, suggesting that the Fc3 unit is stratigraphically older than the Fc4 unit. Since the deposits of the Langrenus crater obscure the boundary between the Fc1 and Fc2 units, and as the spectral properties of Fc1 are close to those of Fc2, the stratigraphic relationship between Fc1 and Fc2 was not defined.

The chemical and spectral properties of the Fc1 units in the northwestern part of the Fecunditatis basin are similar to those of the Tr1 unit in the eastern part of the Tranquillitatis basin (both of which are classed as mIG in Pieters [1978]). In addition, they are located in close proximity (Figs. 4b, 6b, and 8). A small crater (9 km in diameter) on the rim of Taruntius, which is a young Copernican crater (Wilhelms 1987), excavated Fe-rich, low-Ti materials (2–3 wt% TiO₂, 15–17 wt% FeO) that probably represent mare materials (Fig. 8), suggesting that mare basalts with the same composition as Fc1/Tr1 were distributed in this area before Taruntius formed. We, therefore, conclude that the Fc1 and Tr1 units were at sometime connected and are stratigraphically at the same position.

According to the stratigraphy of mare units established in this study, the content of titanium in mare basalts becomes higher as time goes but decreases slightly with the last stage

 Langrenus

 Al-Marrakushi
 100km

 Fig. 7. Iron content map of the western part of Mare Fecunditatis.

 Iron-rich materials appear bright, while iron-poor materials appear

dark. The ejecta of the Al-Marrakushi crater show a higher iron

(Fc4). The low-Ti materials of a relatively small crater (about 3 km in diameter) within the younger medium- to high-Ti units (Fc3 and Fc4) suggest that these higher-Ti units are thinner (<300 m by applying the crater depth-diameter scaling relationship; e.g., Croft 1980) than the older low-Ti mare unit (Fc1), which had not been penetrated by large craters (about 10 km in diameter, corresponding to the depth of 1000 m) in the central to western part of the basin. Thus, the younger titanium-rich basalt is assumed to be volumetrically smaller than the older low-Ti mare basalt (Fc1).

Mare Serenitatis

content.

Geologic Setting

The Serenitatis basin, located at 27°N, 19°E with a 740 km diameter, is the youngest impact basin in the study area (Fig. 1a; Wilhelms 1987). A large part of the basin is filled with mare basalts (Fig. 9a and Table 1). Most of mare basalt samples returned by Apollo 17 indicate Ti-rich composition, and their radioactive ages range from 3.56 to 3.79 Ga (e.g., Schaeffer and Schaeffer 1977; Tera et al. 1974). Wilhelms (1987) adopted an age of 3.72 Ga by averaging ages





Fig. 8. Images centered on the Taruntius crater: a) Clementine 750 nm image; b) iron content map; c) geologic map. In the iron content map, iron-rich materials appear bright, while iron-poor materials dark. A small crater on the rim of the Taruntius crater (arrow) excavates relatively iron-rich materials.

that have an error range within 0.1 Ga. Pieters (1978) classified Serenitatis deposits into 5 groups: HDWA, hDWA, mISP, LIG, and a dark mantle material (DMM) (Fig. 1b). The majority of Serenitatis deposits distributed at the center of the mare are classified as mISP. Dark and blue materials classed as HDWA and hDWA are distributed along the southern margin, and LIG basalt is a minor component in this area. A DMM is exposed at the southwest and southeast margins.

The stratigraphy of Mare Serenitatis has been well-studied by many researchers (e.g., Carr 1966; Howard et al. 1973). According to their results, mare basalts in the center of the basin tend to be younger than the marginal blue mare basalts. However, Wilhelms and McCauley (1971) and Boyce (1976) reported that several patches of mare basalts around the edge of the basin were younger than the central mISP basalts. Lacus Somniorum, located to northeast of Serenitatis (Figs. 1a and 10a), is occupied by a single type of mare basalt (LBG). Staid and Pieters (2000) reported that mare basalts in Somniorum are thin because materials excavated from several small craters (3– 5 km diameter) show the highland composition.

Characteristics and Distribution of Mare Deposits

In Mare Serenitatis, 6 groups of mare deposits (including dark mantle materials, DMM) were identified based on spectral analysis (Fig. 9b). A blue mare unit, which is designated as Sr1 and consists of high-Ti basalts (8.6 wt%)



Fig. 9. a) Clementine 750 nm mosaic image of Mare Serenitatis. The white line indicates an area of Fig. 10. The + symbols provide the locations of spectra for mare soils shown in Fig. 3c; b) geologic map of Mare Serenitatis.

 TiO_2), is exposed in the northwestern area, along the southwestern edge, and near the southeastern edge close to the Apollo 17 landing site. An Sr2 unit (11 wt% TiO₂), which is bluer than Sr1 (Fig. 3c), is distributed near the boundary between Serenitatis and Tranquillitatis. These units are assigned to HDWA or hDWA in Pieters' classification (Fig. 1b) and were designated as the same geologic class (Group II) in Solomon and Head (1979). Sr5 basalts, which have a relatively high UV/VIS value (Table 3), consist of medium-Ti basalt (6.3 wt% TiO₂) and are distributed to the west and along the eastern edge of Mare Serenitatis, where hDWA basalts are distributed in the map by Pieters (1978).

The majority of the central Mare Serenitatis region is dominated by the low-Ti basalts (2.8-4.2 wt% TiO₂), as indicated in earlier studies (e.g., Melendrez et al. 1994; Bell and Hawke 1995). These basalts were classified into 2 groups (Sr3 and Sr4), and the Sr3 was further divided into 2 subunits, Sr3A and Sr3B. The Sr4 basalts distributed in the center to northern part of the mare were newly distinguished in this study, while they had been grouped as a part of Sr3 basalts (Sr3A; classed into mISP) in Pieters (1978). In our analysis, this group shows a lower UV/VIS ratio than the Sr3 group (Table 3; Fig. 3c), and is redder in the color composite image (Fig. 2c). Although the Sr3A and Sr3B have a similar chemical composition and UV/VIS ratio (Table 3), they display different characteristics in 1 μ band strength. The Sr3A basalts distributed around the center of the mare, including the Serenitatis standard site (MS2) where they are

classed as mISP, show the strongest 1 μ m absorption in the Serenitatis region (Table 3). On the other hand, the Sr3B in the western part of the basin, which continues over into Mare Imbrium (classified as LIG in Pieters' map), shows a weaker 1 μ m absorption than the Sr3A (Fig. 3c). The DMM unit is distinguished from other mare deposits by using the characteristics of the 1 μ m feature. They display a weaker 1 μ m absorption than any other mare deposits (Fig. 3c). In Mare Serenitatis, most of the DMM units are distributed at the boundary between highland and mare regions (Fig. 9b) and have a large variation in UV/VIS ratio (0.59–0.63).

As mentioned above, the stratigraphy of Serenitatis basalts has been well-studied by many researchers. Some have suggested that the central low-Ti mare basalts of the Serenitatis basin are younger than the high-Ti basalts in the Tranquillitatis basin based on the stratigraphic relationship and existence of tectonic features such as a graben within the Tranquillitatis units (e.g., Howard et al. 1973; Solomon and Head 1979). In addition, the deposits of Bessel crater were reported to have high UV/VIS values (also recognized in Fig. 2c), indicating that high-Ti basalts underlie the central low-Ti basalts (Sr3 and Sr4) (Bell and Hawke 1995; Staid and Pieters 2000). In Fig. 9b, the Sr3A unit interrupts the Sr1 and Sr2 units near the southeast margin of the mare, suggesting that the Sr3A is stratigraphically younger than these high-Ti units. Though the Sr2 unit overlies the Tranquillitatis, the Sr1 basalts that lie along the mare margin might be older than the Tranquillitatis basalts. From the distribution, DMM units are

stratigraphically older than the other surrounding mare units. Hiesinger et al. (2000) similarly mapped these units as being older than surrounding mare units.

The distribution of the Sr4 units indicates that the Sr4 flowed from the northern part into the central downwarped region, suggesting a younger age for the Sr4 unit than that of the Sr3A. Among the Sr3 subgroups, the Sr3B unit in the Serenitatis/Imbrium border is thought to have flowed from the Imbrium region into the Serenitatis region and to have covered a part of the Sr3A unit. The Sr5 unit includes crater deposits with lower titanium content. This fact indicates the existence of low-Ti mare basalts under the Sr5 and that the Sr5 basalts are younger than the central low-Ti basalts of Sr3 and Sr4. This interpretation is consistent with Wilhelms and McCauley (1971) who considered the marginal mare unit to be younger than the central mare unit.

The distribution and chemical properties of mare basalts indicate that the titanium content of mare basalt tends to be higher in the southern part of the mare and lower in the northern part. However, the higher-Ti crater materials within the central low-Ti mare unit and the occurrence of a high-Ti mare unit in the northwestern part of the basin suggest that a large amount of high-Ti mare basalt was emplaced around the mare, including the north region, although its thickness is unknown. According to the stratigraphy of mare basalts constructed in this study, the northern mare units are relatively younger than the southern mare units. The titanium content of mare basalt becomes lower with time but, finally, becomes higher again.

Somniorum basalts are brighter and redder than Serenitatis basalts and the 1 μ m absorption is also weak (Table 3). These characteristics result in the low abundance of iron and titanium (<2 wt% TiO₂, <14 wt% FeO). Most of the Somniroum surface is covered by a considerably redder mare unit designated as Sm1 (Table 3), which consists of low-Ti basalts (1.1 wt% TiO₂). Relatively bluer low-Ti basalts designated as Sm2 are exposed in a small area of the northwestern region (Figs. 3d and 10b). This bluer characteristic of Sm2 is not observed in any other area or crater deposit, suggesting that the emplacement of Sm2 lava is localized in the northwestern region.

Mare Crisium

Geologic Setting

The Crisium basin, formed in the Nectarian period, is centered on 17.5°N, 58.5°E and has a diameter of 1,060 km (Fig. 1a; Wilhelms 1987). In the Crisium region, mare basalts cover only the innermost region of the basin (Fig. 11a and Table 1). Several mare patches are distributed around Mare Crisium at high elevation (Head et al. 1978; Zisk 1978). Luna 24 samples are characterized by Ti-poor (<1.5 wt% TiO₂), Ferich composition and are highly feldspathic (Papike and Vaniman 1978). They have relatively younger radioactive ages than those from other landing sites in the study area (e.g., 3.30 Ga by Lunatic Asylum [1978]). Head et al. (1978) examined mare basalts in Mare Crisium using Earth-based telescopic data and geophysical data obtained from the Apollo and Luna missions and divided them into 3 groups: 1) Group I unit (classed as hDWA in Fig. 1b), which is the oldest mare unit deposit at the eastern part and the southeastern margin of the mare; 2) Group IIb basalts (LBG), which are exposed along the northern margin and eastern part of the mare. A Group IIa unit (LISP), younger than Group IIb, is extending from the central to the northern part of the mare; 3) central-southern mare basalts (Group III; mIG), which were defined as the youngest unit in this region.

Characteristics and Distribution of Mare Deposits

Fig. 11b shows a geologic map of Mare Crisium produced from the Clementine data used in this study. Several mare units were newly defined additions to the map of Head et al. (1978). A mare unit designated as Cr1 in the eastern part of the mare, classed into Group I (hDWA) in Head et al. (1978), shows a dark and blue signature and has the weakest 1 μ m absorption in the Crisium region (Table 3). The concentration of TiO₂ was estimated to be 6.5 wt% and FeO to be 17.8 wt% for Cr1. In this study, a Cr2 unit, which is redder than Cr1 (Fig. 3e), was newly identified at the southwest margin that was not mapped in Head et al. (1978). The spectral properties of mare units in Mare Anguis and in the southwest of the Cleomedes region (designated as Cr3 in



Fig. 10. a) Clementine 750 nm mosaic image of Lacus Somniorum. The + symbols indicate the locations of spectra for mare soils shown in Fig. 3d; b) geologic map of Lacus Somniorum.



Fig. 11. a) Clementine 750 nm mosaic image of Mare Crisium. The + symbols in white indicate the locations of spectra for mare soils shown in Fig. 3e. The + symbols in black provide the positions of small craters the spectra of which are shown in Fig. 12; b) geologic map of Mare Crisium. The dashed lines indicate uncertain borders.

this study) were not defined clearly in Head et al. (1978) due to the lack of spectral data. Our analysis revealed that these units are composed of low-Ti basalts (2 wt% TiO₂), which have a higher albedo and lower iron contents than Cr2 (Table 3). Although the composition of the surface soils of the Cr2 and Cr3 units are different, they are thought to have originally had the same composition because the fresh spectra averaged over a 3×3 pixel box on the small craters (Fig. 11a) exhibit similar characteristics, as shown in Fig. 12. The lower iron content of Cr3 than Cr2 (Table 3) is due to the highland contamination because the Cr3 unit lies outside of the basin (Fig. 11b).

Mare basalts, which cover the northwestern to northern part of the mare and were originally classed into LISP, have been designated as Cr4 here. These basalts are as bright as the Cr2 basalts (Table 3) but show a higher UV/VIS ratio and stronger 1 μ m absorption (Fig. 3e). The TiO₂ content of this group was estimated at 3.1 wt%. The Cr4 unit is also exposed at the southern part of the basin, which includes the Luna 24 landing site (Fig. 11b), while the titanium concentration of this unit disagrees with that of the mare samples, which contain less than 1 wt% of TiO₂ (BVSP 1981).

The Cr5 unit of the central mare appears bluer than the other units (Fig. 3e) and has TiO_2 contents of 5.4 wt%. Its distribution is consistent with Head et al. (1978). We further divided these basalts into 2 subgroups (Cr5A and Cr5B; Fig. 11b). Both of these subgroups have the same chemical composition (Table 3), but they display different 1 μ m band



Fig. 12. Five-band Clementine spectra scaled at 750 nm obtained by averaging a 3×3 pixel area on small craters in the Cr2 (C2) and Cr3 (C3) units. The locations of the craters are shown in Fig. 11a. The spectral properties of the C3 are similar to those of the C2. The average standard deviation is 0.003.

signatures. Cr5A basalts, which extend from the south of the Picard crater to the northeastern region, through the center of the mare, show 1 μ m absorption levels as strong as Cr4 (Fig. 3e). On the other hand, Cr5B basalts distributed in the central east (west of Cr2) and along the southern margin of the mare show a weaker 1 μ m absorption.

The stratigraphy of the mare units has been refined through spectral and spatial interpretation in addition to the topographic interpretation of Head et al. (1978). The deposits of the Picard and Peirce craters appear blue in the color image (Fig. 2d) and have similar UV/VIS ratios and TiO₂ contents (0.61-0.62 UV/VIS ratio, 6.2-7.4 wt% TiO₂) to those of Cr1. These affinities suggest that Cr1 is the oldest unit in this region and that the Cr1 basalts deposited in the large part of the basin. Cr2 units appear along the northern to northeastern mare margin, which is topographically higher than the central area (Zisk 1978), indicating that the Cr2 units are stratigraphically older than the central mare units. The presence of an additional Cr2 unit in the southwestern region supports this relationship and suggests that Cr2 previously had covered most of the area of Mare Crisium. The Cr4 unit is interpreted to be older than Cr5 because small craters (less than 2.5 km in diameter) within Cr5 excavate lower-Ti materials (which appear yellow in Fig. 2d) and because a patch of Cr4 basalts are enclosed by the Cr5 unit (Fig. 11b). Among the subgroups of Cr5, Cr5A is lower than Cr5B, which includes a small patch of Cr5A. Although the stratigraphic position of the Cr3 group is difficult to define because of its scanty contact with the other units, the similarity in composition and geographical closeness to the Cr2 unit in the northern margin (Fig. 11) hints that Cr2 and Cr3 erupted at roughly the same age.

According to the stratigraphy of mare basalts, the titanium content of the mare basalts is higher in the oldest and youngest units (Cr1 and Cr5) in the Crisium basin. The distribution of the oldest deposits (the Cr1 unit and ejecta of Picard and Peirce) indicates that, earlier, they covered a large part of the mare. The younger medium-Ti units also cover the central to southern part of the basin. However, they are thought to be thin because small craters (1.5–2 km in diameter corresponding to 150–200 m depth) located within their midst excavated lower titanium materials (3–4 wt% TiO₂).

Mare Nectaris

Geologic Setting

The Nectaris basin is located at 16°S, 34°E, south of the Tranquillitatis basin (Fig. 1a). Only the innermost region of the Nectaris basin is occupied by mare basalts (Table 1). In this respect, it is similar to Mare Crisium (Wilhelms and McCauley 1971; Wilhelms 1987). Sinus Asperitatis is also filled with mare basalts, which extend to the south of Tranquillitatis and the northwest of Nectaris (Figs. 1a and 13a). Although no sampling sites exist in Mare Nectaris, Delano (1975) reported that some Ti-rich mare fragments of Apollo 16 samples might be ejecta from Mare Nectaris, one of which is dated at 3.79 Ga by Schaeffer and Husain (1974). However, mare basalts in Mare Nectaris are classified as mBG-type by Pieters (1978), that is, not Ti-rich. The TiO₂ content map of Lucey et al. (1998) also shows a low value (<5 wt%) at the surface of the mare.

Characteristics and Distribution of Mare Deposits

In Mare Nectaris, we have divided the mare basalts into 2 groups (Nc1 and Nc2), while Pieters (1978) defined only a single type. Both of these units are bright (Table 3), but Nc2 basalts, which cover most of mare surface in the Nectaris basin, have a higher UV/VIS ratio and display a stronger 1 μ m absorption than Nc1 basalts (Fig. 3f). The latter occurs as a patch in the northern and southeastern parts of the basin (Fig. 13b). In the color ratio image shown in Fig. 2e, the Nc2 unit appears blue to purple, while a Nc1 unit appears yellow to orange. The Nc1 characteristic is also observed in crater deposits within Nc2 (Fig. 2e), indicating that Nc1 basalts are stratigraphically older than and underlie the Nc2 basalts.

The mare basalts on the surface of Mare Nectaris are thought to be contaminated by a significant amount of highland deposits because many crater rays from Theophilus, Madler, and other craters on the highlands observed across the surface of the Nectaris appear to be low in iron abundance (<15 wt% FeO; Figs. 13 and 14), while a small crater (about 1 km diameter) within the mare excavates more iron-rich material (16–17 wt% FeO). Therefore, we suggest that the original Nectaris basalt could contain more iron than estimated in this study. This highland contamination could be a cause for the spectral difference between Nc1 and Nc2



Fig. 13. a) Clementine 750 nm mosaic image of Mare Nectaris. The area outlined in white is the locaion of iron and titanium content maps in Fig. 16. The + symbols in white indicate the locations of spectra for mare soils shown in Fig. 3f, while the + symbols in black indicate the locations of small craters the spectra of which are shown in Fig. 15; b) geologic map of Mare Nectaris. The dashed line indicates an uncertain border.



Fig. 14. Iron content map of Mare Nectaris. Iron-rich materials appear bright, while iron-poor materials appear dark.

(Fig. 3f; Table 3). However, we concluded that Nc1 and Nc2 are different units because the spectra of fresh materials on the small craters (Fig. 15), which would be less contaminated by highland materials, display different characteristics, namely, Nc2 exhibits a stronger 1 μ m absorption than Nc1.

In contrast, As1 and Nc2 are thought to be the same unit because they have a similar characteristics of 1 μ m band in

the fresh spectra (Fig. 15), though the chemical compositions of the surface soils are different (Table 3). Moreover, they are geographically connected (Fig. 13b). The difference in chemical and spectral properties of the surface units could be explained by the different amounts of highland contamination. As1 is thought to be more contaminated by highland materials than Nc2 because it lies closer to the Theophilus crater than Nectaris.

The As2 unit distributed between Tranquillitatis high-Ti basalts and the southern As1 displays higher concentrations of titanium than As1 but lower concentrations than the northern high-Ti basalts (Table 3). Many small craters within the As2 unit (0.4-1 km in diameter) excavate high-Ti materials (>7 wt% TiO₂) and show similar spectral characteristics to Tranquillitatis high-Ti basalt (Fig. 15), implying that the As2 unit is thin (<40 m) and that high-Ti mare basalts underlie the As2. Since the Theophilus rays in the southern Tranquillitatis region also exhibit a relatively low-Fe and medium-Ti composition, like As2 (Figs. 13 and 16), we suggest that the material present in As2 is a mixture of large amounts of highland deposit from the Theophilus crater together with underlying high-Ti mare basalt. Our interpretation is supported by the larger fraction of highland component and the numerous Theophilus rays located near the Tranquillitatis/Asperitatis border in the analysis of Staid et al. (1996).



Fig. 15. Five-band Clementine spectra scaled at 750 nm obtained by averaging a 3×3 pixel area on small craters in the Nectaris region. The spectrum of Tranquillitatis high-Ti basalt (T3) is also provided. The locations of the craters are shown in Figs. 4a and 13a. The spectral properties of N1 are different from those of N2. On the other hand, A1 displays the similar spectral properties to N2. The spectrum of A2, which displays the bluer characteristics (high UV/VIS ratio) is similar to that of T3. The average standard deviation is 0.011.

Determining the stratigraphic relationship between the As1 and Tranquillitatis basalts (including As2) is difficult because of the uncertainty of the As1/As2 boundary. Material from the Torricelli crater near the border between As1 and As2 does not include Ti-rich components, but it does contain highland and low-Ti mare components (Fig. 16). If the Tranquillitatis high-Ti basalts lay at depth, the ejecta of Torricelli should have exhibited a higher titanium composition than those of the Torricelli-B crater did (Fig. 16b). This indicates that a low-Ti mare unit lies at depth near Torricelli. In addition, craters in the As1 unit near the As1/As2 border do not excavate high-Ti component. Therefore, we suggest that the As1 unit is older than Tranquillitatis high-Ti basalts (Tr3), although further investigation is required to confirm this relationship.

In Mare Nectaris, both of 2 mare basalts covered a large part of the mare. In particular, the Nc2 basalts had been extended to the Asperitatis region (designated as As1). The younger units (Nc2 and As1) contain higher titanium content than the older unit (Nc1), though the titanium content of these basalts is generally low (<3.4 wt% TiO₂). The surfaces of Nectaris and Asperitatis are heavily contaminated by the Theophilus and Madler ejecta, and, thus, deriving the correct chemical composition of the Nectaris basalt is difficult. This may have resulted in lower iron abundance for the Nectaris and Asperitatis basalts.



Fig. 16. a) Iron content map; b) titanium content map of Sinus Asperitatis.

CHARACTERISTICS OF MARE VOLCANISM IN THE EASTERN NEARSIDE

Temporal Changes

Spatial Distribution

In the previous section, the stratigraphy of mare basalts for each mare (except for Mare Crisium) was compared with that of Mare Tranquillitatis. The spectral and chemical similarities between the oldest mare units in the Fecunditatis basin (Fc1) and the Tranquillitatis basin (Tr1), considered together with the fact that they are geographically adjacent, suggest that they have the same stratigraphic position. Most of the mare basalts in Serenitatis appear to be stratigraphically younger than those of Tranquillitatis (Solomon and Head 1979; Wilhelms 1987). From the analysis of Asperitatis basalts, the Nectaris basalts are known to be of the same age or older than the Tranquillitatis high-Ti basalts (Tr3).

In addition to these relative stratigraphies, the chemical compositions and ages of lunar samples also allow us to evaluate the absolute stratigraphic relations of the mare units. Table 4 shows the inferred assignments of the mare units defined in our spectral analysis to the mare samples. Each group of mare samples was assigned to the mare unit deposited near the sampling site and shows a closer abundance of titanium contents to the sample (asterisks in Figs. 4b, 6b, 9b, and 11b). In Tranquillitatis, mare samples from the Apollo 11 site were classed into 3 groups (e.g., A, B3-B1, B2-D; Jerde et al. 1994). Although the titanium concentration of mare units is higher than that of mare samples in Tranquillitatis, we assigned the mare units to these samples by correlating the stratigraphy of these samples to that of mare units: the youngest Tr4 unit, which includes the Apollo 11 site (Fig. 4b), can be assigned to the youngest high-K group A basalt (>0.2 wt% K; Neal and Taylor 1992), which has the age of 3.59 Ga. The low-K group B3-B1

Table 4. Assignments of observed units to mare basalt types.

basalts (<0.2 wt% K), with an older age than the group A (3.67-3.71 Ga), are thought to represent the Tr3 basalts. The Tr2 unit may be associated with the oldest low-K group B2 and D basalts (3.85 Ga).

The Luna 16 landing site is located near the boundary between the Fc1 and Fc3 units in Mare Fecunditatis (Fig. 6b), and the titanium content of its sample is close to that of Fc3. The Sr2 basalts distributed near the Apollo 17 landing site (Fig. 9b) show consistent titanium content with the Apollo samples. In Mare Crisium, the Luna 24 landing site is located within the Cr4 unit (Fig. 11b), though the titanium content of the Cr4 disagrees with that of the mare sample (see the subsection on Characteristics and Distribution of Mare Deposits of Mare Crisium). Delano (1975) suggested that a Ti-rich fragment of mare basalt in a breccia of the Apollo 16 sample was thought to be ejected from Mare Nectaris. However, the high-Ti basalt was not found in any previous TiO₂ map (i.e., Lucey et al. 1998) or in our analysis using high spatial resolution data. Thus, we did not assign an absolute age to Mare Nectaris.

Fig. 17 summarizes the relationship between the stratigraphy of mare units for major basins in the study area and their geographical position. In this figure, the mare volcanism in the Fecunditatis basin, which is located to the east of Tranquillitatis basin, displays the same or longer longevity as Tranquillitatis. These basins are older than the other maria, and include the oldest mare basalts in the study area. Mare Crisium is younger than Mare Nectaris, although both have roughly the same basin formation age (Wilhelms 1987). This relationship suggests that no correlation exists between basin forming events and mare emplacement. According to Boyce (1976) and Hiesinger et al. (2000), the age of the central Serenitatis low-Ti basalts ranges from 3.3 Ga to 3.5 Ga, and younger mare basalts (Eratosthenian age) are observed in this region. In our analysis, the eastern Sr5 unit (Fig. 9b) is grouped as the youngest in both our

Unit	TiO ₂ of unit (wt%)	TiO_2 of sample (wt%) ^a	Age of sample (Ga)	Comments
Tranquillitatis				
Tr2	9.0	8.6	3.85 ^b	Low-K, B2-D group
Tr3	12.6	10.3	3.67-3.71 ^b	Low-K, B1-B3 group
Tr4	13.7	11.3-12.1	3.59 ^b	High-K, A group
Fecunditatis	o z	40.51	2.416	Faldanathia
FC3	8.3	4.9-5.1	3.41	Feldspathic
Serenitatis Sr2	11.0	10.8–13	3.72 ^d	Low-K
Crisium	2.1	-1	2 De	MT
UI4	5.1	<1	3.32	VLI

 $^aBVSP\,(1981)$ and Taylor et al. (1991).

^bJerde et al. (1994).

^cHuneke et al. (1972).

^dAn average value (Welhelms 1987).

eLunatic Asylum (1978).



Fig. 17. Relationship between the ages of mare units for major basins in the study area and their geographical position along (a) east and west and (b) north and south transects. Tr is Tranquillitatis, Fc is Fecunditatis, Sr is Serenitatis, Cr is Crisium, and Nc is Nectaris. The numbers in the circle or square correspond to the classication system used in the text. The square indicates that the age of the mare unit is calibrated with a mare sample or with the result of previous works (see the text), while the circle indicates an uncalibrated unit. The error bars show the possible range of units without absolute ages. Mare units included in a box with dots have the same stratigraphic position.

stratigraphic sequence and that of Boyce (1976) (2.6–3.0 Ga). These younger ages indicate that the mare volcanism in Serenitatis lasted longer than in the other basins.

Based on the crater morphology method, Boyce (1976) suggested a tendency for the eastern mare units to be older than the western mare units on the nearside of the Moon. Hiesinger et al. (2000) evaluated the mare ages using the crater size-frequency distribution method, and concluded that this east-west trend could be applied only to Tranquillitatis, Serenitatis, and Imbrium. In our study, the stratigraphic relationship between Serenitatis and Tranquillitatis is consistent with Hiesinger et al. (2000) and agrees with the proposed east-west trend (Fig. 17a). However, several mare units in the Crisium basin, located in the easternmost part of the study area (Table 2), are stratigraphically younger than those of the Tranquillitatis (Fig. 17a). In addition, the younger age (2.93 Ga) for the Luna 24 sample reported by Burgess and Turner (1998) supports our interpretation. These younger ages for the eastern mare contradict the previously proposed trend. On the other hand, a clear trend in mare ages exists between the northern and southern maria. Mare units in northern maria such as Serenitatis and Crisium are generally younger than those of southern maria such as Tranquillitatis, Fecunditatis, and Nectaris (Fig. 17b). In addition, more locally, mare units in the northern part of the Serenitatis basin tend to be younger than the southern Serenitatis mare unit. These north-south trends suggest that the mare volcanism lasted longer in the northern part of the study area.

Chemical Composition

Fig. 18 shows the temporal change in the titanium content for 5 mare basins derived by combining the stratigraphy and chemical composition of mare units. Soderblom et al. (1977) combined variations in the age, chemistry, and magnetism of lunar nearside maria. They found that the eastern oldest and western youngest maria have high-Ti concentrations. Although we have not yet analyzed the western maria, our analysis so far indicates that the older mare units tend to have high-Ti concentrations (Fig. 18). However, evidence exists that the low-Ti basalts erupted earlier than the high-Ti basalts in the study area. In Mare Tranquillitatis, where the old high-Ti mare basalts were sampled, the oldest mare basalts display a low-Ti composition (Fig. 18). In Fig. 18, we found that 2 types of compositional change occur in mare basalts. One type includes 2 older southern maria, the Tranquillitatis and Fecunditatis, where the titanium content increases with time but finally decreases, except for the western part of Mare Tranquillitatis. The other type includes 2 younger northern maria, the Serenitatis and Crisium. In contrast to the former older maria, the titanium content here decreases with time but shows a slight increase in the latter stages.

Compositional Diversities

Mare basalts were produced by the melting of olivine and pyroxene in the lunar mantle so that they provide chemical information about their source regions if the melting process



Fig. 18. Relationship between the titanium contents of mare units and their stratigraphy for five mare basins. The symbols indicate the mare units whose ages are determined by the mare samples or by the crater studies (e.g., Hiesinger et al. 2000). The lines show the inferred temporal changes in the titanium content for the mare basins, including mare units without absolute ages. The Tr5, Fc2, and Cr3 units are excluded, because their stratigraphic positions are uncertain.

involved chemical equilibrium between the melted and unmelted portions.

Titanium Contents

Since a titanium component tends to be included in materials which solidified during the last stage of the lunar magma ocean (Taylor and Jakes 1974), the abundance of this component plays an important role in our understanding of the structure of the lunar upper mantle. According to the distribution derived from the Clementine data used in this study, the content of titanium in the eastern nearside is highest in the western part of Mare Tranquillitatis and reduces with distance from Mare Tranquillitatis. For instance, the surface of the Fecuditatis region is covered by medium-Ti basalts $(5.6 \text{ wt}\% \text{ TiO}_2)$ in the north and low-Ti basalts $(2.4 \text{ wt}\% \text{ TiO}_2)$ in the south. A large part of Mare Serenitatis is covered by low-Ti mare basalts (2.8-4.2 wt% TiO₂). In Mare Crisium, low to medium-Ti mare basalts (2.4-5.4 wt% TiO₂) are dominant, while mare basalts on the surface of Mare Nectaris have a lower concentration of TiO₂ (3.4 wt%). In addition, Lacus Somniorum, the furthest region from Tranquillitatis, exhibits the lowest titanium content of all (1.1 wt% TiO₂). The sequence of titanium content in these maria is summarized below:

TiO_2 content: Tr > Fc > Sr > Cr > Nc > Sm

where *Tr* is Tranquillitatis, *Sr* is Serenitatis, *Fc* is Fecunditatis, *Cr* is Crisium, *Nc* is Nectaris, and *Sm* is Somniorum.

The sequence of TiO_2 content is consistent with the titanium distribution maps derived from Galileo SSI data and Lunar Prospector (LP) data (e.g., Giguere et al. 2000; Elphic et al. 2002). However, the ranges of the titanium concentration are different from these studies. In Mare Tranquillitatis, Giguere et al. (2000) estimated the TiO₂ content of high-Ti basalts at about 10 wt% from the Galileo data, while our

estimation, using the method of Lucey et al. (2000), exceeds 12 wt% of TiO₂ in Tr3 and Tr4 (Table 3). The LP data shows much lower abundance values compared to our result in this region (<9 wt% TiO₂ in Elphic et al. [2002]). The central low-Ti basalts of the Serenitatis display 1-3 wt% of TiO₂ in Giguere et al. (2000) and less than 1.5 wt% of TiO₂ in Elphic et al. (2002), while our study estimated 2.8-4.2 wt% of TiO₂. Through the study area, the concentrations of TiO₂, derived from the equations of Lucey et al. (2000), are higher than those derived from Galileo SSI and LP data by 1-5 wt%. The comparison of titanium content between the lunar samples and the mare units defined in this study suggests the overestimation of titanium content derived by using the algorithm of Lucey et al. (2000) (Table 4). Since the algorithm of Gillis et al. (2003) can resolve this problem, it may be used for more accurate calculation of titanium contents from Clementine data.

In the study area, as mentioned above, the titanium content of the mare basalts displays a large variation, that is, rich in the Tranquillitatis region and poor in the other regions distant from Tranquillitatis. This suggests a lateral diversity of mantle compositions on a basin scale, although other possible causes may exist, such as complex mantle dynamics and specific physical conditions for lava emplacement, including variation in crustal thickness. However, the Serenitatis and Fecunditatis regions also contain considerable quantities of high-Ti mare basalts (nearly 9 wt% of TiO₂). In these maria, most of the high-Ti basalts are overlain by younger mare basalts that contain low abundances of titanium. The high-Ti component can sometimes be exposed in patches at surfaces near mare edges and/or in crater ejecta excavated from the units beneath. Mare Crisium also shows a relatively higher titanium content (reaching to 6.5 wt% TiO_2) both at the surface and in crater ejecta. The existence of these buried high-Ti basalts would affect the estimation of volume and fraction of high-Ti basalts, which reflect the compositional distribution of their source region. Further investigation is required to evaluate the volume and fraction of each mare basalt group accurately.

Iron Contents

The abundance of FeO contents for each mare estimated by the method of Lucey et al. (2000) is summarized in Table 3. According to their distribution, the Tranquillitatis basalts on the surface have higher iron contents (18–19.1 wt% FeO). The Fecunditatis displays 15.3–17 wt% of FeO in the northern part and 14.3 wt% in the south. The central Serenitatis basalts, which dominate the most of the mare surface, contain 16.5–17.1 wt% of FeO. In Mare Crisium, the FeO abundance in mare basalts ranges from 14.7 to 17.1 wt%. The basalts in the Nectaris and Somniorum region have lower iron contents (<15 wt% FeO). These are summarized as:

FeO content (Lucey et al.): Tr > Sr > Cr > Fc > Nc > Sm

On the other hand, the relative iron content of mare basalts can also be estimated based on a mineralogic interpretation (Staid and Pieters 2000). The strength of the 1 μ m band absorption is correlated with the abundance of iron-rich minerals such as pyroxenes (Adams 1974). A scatter plot of 950/750 nm versus 1000/750 nm for mare basalts in the study area is shown in Fig. 19. Any unit showing stronger 1 μ m absorption tends to be plotted in the lower left of this figure. Most mare units of Serenitatis are distributed in the lower left, while those of Tranquillitatis are plotted in the upper right. This fact indicates that the Serenitatis basalts include more Fe-rich minerals than those of the Tranquillitatis basalts. Several units in the Fecunditatis and Crisium regions also show stronger 1 μ m absorption. The relative iron contents in the eastern nearside maria inferred from Fig. 19 can be summarized as:

FeO content (mineralogy): Sr > Cr > Fc > Sm > Tr, Nc

Staid and Pieters (2000) predicted the relative iron content of the basalts to be Sr > Sm > Tr. Our results reveal that the mare basalts in the Crisium and Fecunditatis regions contain higher iron contents than those in the Tranquillitatis region, which supplements to the result of Staid and Pieters (2000).

The results derived from the mineralogic interpretation are inconsistent with the results derived from the method of Lucey et al. (2000), especially in Mare Tranquillitatis, where high-Ti mare basalt is the dominant component. The distribution of iron content derived from Lunar Prospector gamma-ray spectrometer data (LP-GRS) (Lawrence et al. 2001) is consistent with that from the method of Lucey et al. (2000) rather than that from the mineralogic interpretation. The LP-GRS-derived iron abundance in Lawrence et al. (2001) shows that the mare basalts of the Tranquillitatis region contain higher Fe content (15-17 wt%) than those of the other maria (approximately 15 wt% Fe or less) in the study area. The iron abundance in this area from the LP-GRS data is summarized as Tr > Sr > Fc, Cr > Nc, Sm. The high-Ti basalts contain much ilmenite, which also includes ferrous iron as a component (FeTiO₃) and tends to subdue the absorption features in the 1 μ m band due to pyroxenes. Thus, the iron content of Mare Tranquillitatis predicted on a mineralogical basis may be lower than the real value. One must consider the content of iron-rich minerals, including glasses, for the exact estimation of iron content with the latter method to become reliable. For these reasons, we conclude that the iron content derived from the method of Lucey et al. (2000) is more realistic for this area.

SUMMARY AND CONCLUSIONS

We have used Clementine UV/VIS data to map spectrally distinct mare basalts in the eastern nearside of the Moon. These multi-spectral images of high spatial resolution allow detailed mapping of the mare basalts. In addition to spectral parameters that have been used in previous works, the iron and titanium contents in mare basalts were used to



Fig. 19. Scatterplot of 950/750 nm ratio against 1000/750 nm ratio for mare units in the study area.

characterize and classify mare units. Overall, our analysis not only shows consistency with the results of earlier works but also newly identifies several mare units. In the study area, 8 geologic units were newly recognized, and their spectral characteristics were determined. Most of the units newly recognized in this study are found on a small spatial scale or exhibit complicated boundaries with other units so that mapping them from low spatial resolution data taken by Earth-based telescopes becomes difficult.

The stratigraphy of mare units constructed from our spectral analysis reveals the temporal change in their spatial distribution and chemical composition for the eastern nearside maria. According to our stratigraphy, Mare Crisium shows a younger age than Mare Tranquillitatis, which lies southwest of Crisium, contradicting the global trend proposed by Boyce (1976) in which eastern basalts are generally older than western basalts. Instead, a north-south trend was discovered for this region. Mare basalts tend to be younger in the northern maria such as Serenitatis and Crisium and become older in the southern maria of Tranquillitatis, Fecunditatis, and Nectaris. On a more local scale, the northern mare units are stratigraphically younger than the southern mare units in the Serenitatis basin. These north-south trends indicate that mare volcanism lasted longer in the northern region of the eastern nearside of the Moon.

Although the titanium concentration tends to be higher in the older units and lower in the younger units, as indicated by Soderblom et al. (1977), the older and lower-Ti units were recognized in the Tranquillitatis basin. The titanium content decreases with time in the early stage but increases toward the end of volcanism in the Serenitatis and Crisium region, while it increases with time but finally decreases in the Tranquillitatis and Fecunditatis region. According to the distribution of mare basalts, a large amount of high-Ti mare basalts were emplaced in Mare Tranquillitatis, especially in the west. This lateral heterogeneity of mare basalts is probably associated with lateral heterogeneity in their source region in the lunar mantle. However, the existence of medium- to highTi basalts covered by the low-Ti basalts in other maria suggests that further investigation is required to evaluate the distribution of titanium contents accurately. Distributions derived from the method of Lucey et al. (2000) indicate that Mare Tranquillitatis has a higher iron concentration than other maria, though mineralogical assessments suggest that Serenitatis should contain the highest abundance of iron.

We are currently extending the spectral analysis to other maria of the Moon to identify the temporal changes in space and composition of mare volcanism on the Moon. These analyses will contribute to modeling the structure of the lunar upper mantle and the thermal evolution of the Moon. In 2005, the SELENE mission is scheduled to be launched and is expected to acquire various new data sets (Mizutani et al. 2002), which should lead to further examination and refinement of the results obtained in our study and, in turn, a better understanding about the history of the Moon.

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