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Spectral reflectance studies of the Grimaldi region of the moon

C.A. Peterson, B.R. Hawke, P.G. Lucey, C.R. Coombs[1]
Planetary Geosciences, Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, Hawaii

P.D. Spudis
Lunar and Planetary Institute, Houston, Texas

Abstract. Near-infrared reflectance spectra were used to investigate the composition and origin of the various geologic units in the Grimaldi region as well as the stratigraphy of the Grimaldi pre-impact target site. The results of our spectral analysis indicate that the portions of the Hevelius Formation that occur in the Grimaldi region are composed of noritic anorthosite and anorthositic norite. Gabbroic material was excavated from beneath Orientale-related units by small impact craters in three areas in the Grimaldi region. The primary ejecta deposits of the Grimaldi basin as well as the pre-Orientale floor unit are dominated by noritic anorthosite and anorthositic norite. The peak ring of Grimaldi is composed, at least in part, of pure anorthosite. The anorthosites on the inner ring and elsewhere within Grimaldi were derived from a layer of pure anorthosite that exists at depth beneath a more pyroxene-rich unit.

Introduction

This paper reports the results of an analysis of more than 60 spectra obtained for the area in and around the lunar basin Grimaldi. The region we studied extends from Olbers A crater in the north to the crater Darwin in the south and is bounded on the west by the Orientale basin's Montes Cordillera and on the east by Oceanus Procellarum (Figure 1).

The Grimaldi basin is a Pre-Nectarian double-ring impact structure centered at 5°S, 68°W [*Wilhelms*, 1987]. This multi-ringed basin was identified and described by *Hartmann and Kuiper* [1962]. Mare basalt fills much of the basin interior to the 230-km-diameter peak ring and is also present in Lacus Aestatis and in the interior of the craters Riccioli and Crüger. A somewhat more irregular outer ring has a diameter of 430 km [*Wilhelms*, 1987].

Near-infrared spectra were collected and analyzed for a wide variety of geologic units in the Grimaldi region. The purposes of this study are: 1) To determine the composition of geologic units in the region; 2) To investigate the composition of highlands materials exposed by the Grimaldi impact event as well as the stratigraphy of the Grimaldi pre-impact target site; 3) To gain a better understanding of Orientale-related deposits in the region; and 4) To investigate the nature and origin of mare and dark mantling units.

Methods

Near-infrared reflectance spectra were obtained utilizing the University of Hawaii 2.24-m and 60-cm telescopes at the Mauna Kea Observatory (MKO). The Planetary Geosciences indium antimonide spectrometer was used. This instrument successively measured intensity in each of 120 or more wavelengths covering a 0.6-2.5 μm re-gion by rotating a filter with a continuously variable band pass. Because Grimaldi is near the western limb of the Moon, the instrument's aperture collected light from a nearly elliptical area of the lunar surface which ranged from about 4 km to 20 km along the major axis. Differential atmospheric refraction limited high-resolution observations to periods when the Moon was near zenith.

The lunar standard area at the Apollo 16 landing site was frequently observed during the course of each evening, and extinction corrections were made using the methods described by *McCord and Clark* [1979]. These procedures produce spectra representing the reflectance ratio between the observed area and the Apollo 16 site. The photometric precision of lunar spectra obtained with the Planetary Geosciences indium antimonide spectrometer and reduced by the techniques described above was discussed in detail by *McCord et al.* [1981]. Analyses of mafic band positions and shapes, continuum slopes, and uncertainties related to these measurements were made using the methods presented by *McCord et al.* [1981] and *Lucey et al.* [1986]. Mineralogic and petrologic interpretations of spectral measurements were made using the procedures described by previous workers [e.g., *Adams*, 1974; *McCord et al.*, 1981; *Spudis et al.*, 1984, 1989; *Lucey et al.*, 1986; *Pieters*, 1986, 1993]. The classification and nomenclature of lunar highlands rocks used in this paper is that proposed by *Stöffler et al.* [1980]. The locations and lithologic classification of the spectral data appear in Figure 1, and representative continuum-removed spectra are presented in Figure 2.

Results and Discussion

Orientale Exterior Deposits

Much of the Grimaldi region is covered by the Hevelius Formation, a highlands unit that was emplaced as a result of the Orientale impact event [*Scott et al.*, 1977]. The Hevelius Formation occurs outside the prominent Cordillera ring of the Orientale basin and probably contains large amounts of primary ejecta from Orientale.

Numerous spectra were obtained for mature surfaces on the Hevelius Formation as well as young craters that expose fresh Hevelius material. Analyses of these spectra show the presence of plagioclase feldspar and low-Ca pyroxene (Figure 2). Noritic anorthosites dominate the terrain between the Cordillera ring and Crüger crater, but anorthositic norites are more common elsewhere (Figure 1). These results are in agreement with our previous findings [*Hawke et al.*, 1991] as well as the preliminary results of the Galileo SSI experiment [*Head et al.*, 1993]. Olbers A crater, a 43-km-diameter impact structure in the northwestern portion of the Grimaldi region, exposes noritic anorthosite excavated from beneath a slightly more mafic surface unit.

Grimaldi-Related Units

Even though Orientale-related deposits cover and obscure primary Grimaldi material in most areas, some spectra were obtained for fresh craters that expose Grimaldi debris. Both Grimaldi DA (diameter = 7 km) and GA (diameter = 11 km) expose material from the inner or peak ring of Grimaldi basin (Figure 1). An analysis of these spectra indicates that either no "1 μm" absorption features exist or that they are extremely shallow bands (Figure 2a). Only very minor amounts of low-Ca pyroxene are present in the areas for which the spectra were obtained; an anorthosite lithology is indicated. Spectra obtained for previously identified lunar anorthosite deposits are also shown in Figure 2a. At least a portion of the Grimaldi inner ring is composed of pure anorthosite [plagioclase >90%; *Stöffler et al.*, 1980].

Anorthosite has also been identified at Damoiseau D (diameter = 17 km). This crater is located on the rim of Damoiseau A, a 47-km impact crater located largely between the inner and outer rings of Grimaldi, which excavated material from deep beneath the floor deposits of Grimaldi basin (Figure 1). In addition, anorthosite appears to have been exposed by Damoiseau C, a 15-km crater located just outside the Grimaldi outer ring (Figure 1). Grimaldi T crater exposes material from beneath the surface of an

[1] Now at Department of Geology, College of Charleston, Charleston, SC 29424

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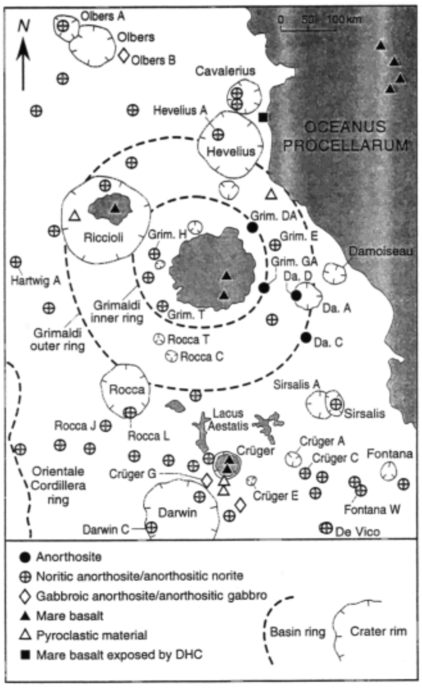


Fig. 1 Sketch map of the Grimaldi region. The symbols indicate the lithology of the areas for which near-infrared reflectance spectra have been obtained and interpreted. DHC means "dark halo crater."

outlier of the Grimaldi inner ring, and the very shallow band depth exhibited by its spectrum (Figure 2c) suggests that at least some pure anorthosite may be present in the area for which the spectrum was obtained. The spectrum of Grimaldi E crater also exhibits a very shallow "1 µm" band (2.3%) and may indicate the presence of major amounts of anorthosite (Figure 2c). Grimaldi E is 13 km in diameter and is located between the inner and outer basin rings (Figure 1).

Grimaldi H is a 9-km impact crater on the western floor of the inner portion of Grimaldi basin (Figure 1). This crater penetrates the Hevelius Formation and exposes subjacent material from the pre-Orientale floor unit. The spectrum obtained for Grimaldi H has a shallow absorption band centered at 0.93 µm (Figure 2c). The mafic mineral assemblage is dominated by low-Ca pyroxene, and a noritic anorthosite lithology is indicated. The results of the analysis of the Grimaldi H spectrum, as well as other spectra that were obtained for the original, pre-Orientale floor material of the Grimaldi basin, indicate that this unit is composed of noritic anorthosite or anorthositic norite. The noritic anorthosite composition is most common. The pre-Orientale floor material within the inner ring should be dominated by impact melt and melt-rich deposits formed by the Grimaldi impact event [*Head*, 1974; *Hawke and Head*, 1977] and may represent the average composition of the upper portion of the pre-impact target site.

It is difficult to determine the compositions of the Grimaldi ejecta deposits because of the proximity of the younger Orientale basin as well as the extensive mare flooding east and northeast of the basin. Still, some information can be obtained. Sirsalis is a 42-km crater located southeast of Grimaldi (Figure 1). This impact crater should expose Grimaldi ejecta from beneath the relatively thin and discontinuous facies of the Hevelius Formation. The analysis of a spectrum obtained for the interior of Sirsalis indicates that the dominant lithology is anorthositic norite (Figure 2c). Several spectra were collected for both fresh craters and mature surfaces in the highlands east of Crüger and south of Sirsalis (Figure 1). At this distance from Orientale basin, local material, as opposed to primary Orientale ejecta, should dominate the deposit emplaced as a result of the Orientale impact [e.g., *Oberbeck*, 1975]. The "local" material in this area should be dominated by Grimaldi ejecta. Most of the spectra obtained for this area indicate the presence of anorthositic norite although two craters (Crüger C and De Vico) expose noritic anorthosite. The generally more mafic compositions of the deposits east of Crüger contrast with the less mafic compositions west of this unusual crater.

North of Grimaldi basin, Cavalerius crater (diameter = 58 km) exposes highlands material that should have included a high proportion of Grimaldi primary ejecta (Figure 1). Near-infrared reflectance spectra were obtained for two portions of the interior of Cavalerius (Figure 2b). Both spectra indicate that the areas for which the spectra were collected are dominated by noritic anorthosite. Other craters northwest of Grimaldi that have excavated Grimaldi ejecta have spectra that indicate the presence of anorthositic norite or, less commonly, noritic anorthosite. The spectral data presented here show that the Grimaldi ejecta deposit is dominated by anorthositic norite and noritic anorthosite.

The results of the spectral studies described above allow the reconstruction of the pre-impact stratigraphy of the Grimaldi target site. The upper portion of the target site was composed of anorthositic norite and noritic anorthosite. These pyroxene-bearing compositions dominate the primary ejecta deposits of Grimaldi as well as the original, pre-Orientale floor unit. Both the Grimaldi primary ejecta material and the floor deposit were derived from the upper portions of the pre-impact target site. In contrast, pure anorthosite was exposed by at least two fresh craters from beneath the surface of massifs in the Grimaldi inner ring. The spectral data indicate that major portions of the inner ring are composed of pure anorthosite. We propose that this peak ring was formed by the rebound of deep crustal material from beneath the Grimaldi transient crater cavity during the modification stage of the basin-forming event. In our model, the outer ring represents the main topographic rim of Grimaldi basin. The spectrum of Damoiseau D demonstrates that, at least locally, anorthosite must be present beneath the pre-Orientale floor unit. The currently available evidence strongly suggests that the Grimaldi pre-impact target site consisted of a layer of pyroxene-bearing highlands material overlying a crustal unit composed of pure anorthosite. The existence of anorthosite at Damoiseau C, a small crater just outside the Grimaldi outer ring, demonstrates that the Grimaldi transient crater cavity fully penetrated the pyroxene-bearing layer and excavated minor amounts of anorthosite. It is important to note that pure anorthosites have now been identified on the inner rings of Orientale, Nectaris, Humorum, and Grimaldi basins [*Spudis et al.*, 1984, 1989, 1992; *Hawke et al.*, 1991, 1992a,b, 1993]. In all instances, it appears that the anorthosites have been derived from an anorthosite layer that underlies a more pyroxene-rich unit.

Gabbroic Units

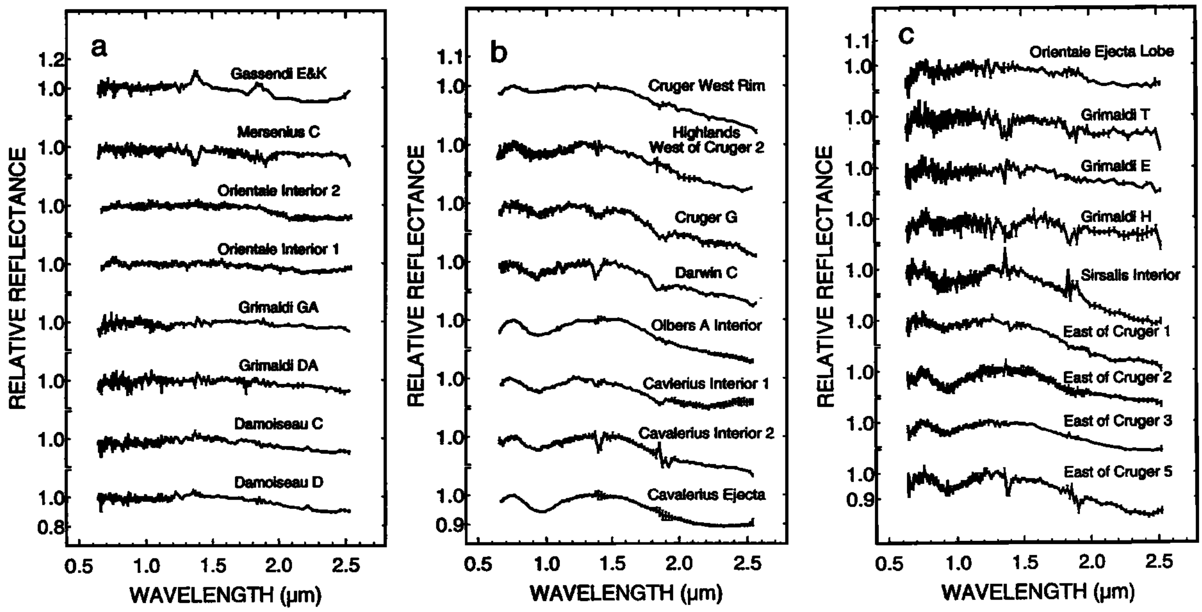
In a previous study [*Hawke et al.*, 1989a], it was noted that the spectrum obtained for Crüger G crater (diameter = 8 km) was very different from spectra collected for nearby features. The Crüger G spectrum exhibits a "1 µm" absorption feature centered longward of 0.95 µm, indicating a mafic mineral assemblage dominated by high-Ca pyroxene (Figure 2b). Crüger G is located southwest of Crüger crater and is centered on the rim crest of a large, degraded pre-Orientale impact structure northeast of Darwin (Figure 1). Crüger G exposes material from beneath the deposits emplaced as a result of the Orientale impact event.

We have now identified material with a mafic assemblage dominated by high-Ca pyroxene in two additional areas in the Grimaldi region. One is a small crater southwest of Crüger E, and the other is associated with Olbers B crater (Figure 1). Both of these impact craters expose material from beneath the material emplaced by the Orientale impact event. Additional work will be necessary to fully understand the nature and origin of these gabbroic units.

Pyroclastic Deposits

Numerous localized dark-mantle deposits (LDMD) of pyroclastic origin have been identified in the Grimaldi region [*Coombs*, 1988; *Coombs and Hawke*, 1992; *Hawke et al.*, 1989a,b], and near-IR reflectance spectra were obtained for several deposits. Localized dark-mantle deposits are generally associated with small (< 3 km), endogenic dark-halo craters.

The spectra of the LDMD in the Grimaldi region (Figure 2d) can be assigned to the three spectral classes described by *Lucey et al.* [1984], *Coombs* [1988], and *Hawke et al.* [1989b]. The spectra obtained for the Grimaldi LDMD (68.3° W, 5.2° S) are typical of Group 1 ("1 µm" band centers near 0.93-0.95 µm, band depths generally 4-5 %, "checkmark-like" shape. Group 1 spectra are somewhat similar to those collected for typical lunar highlands units. Although major amounts of highland material



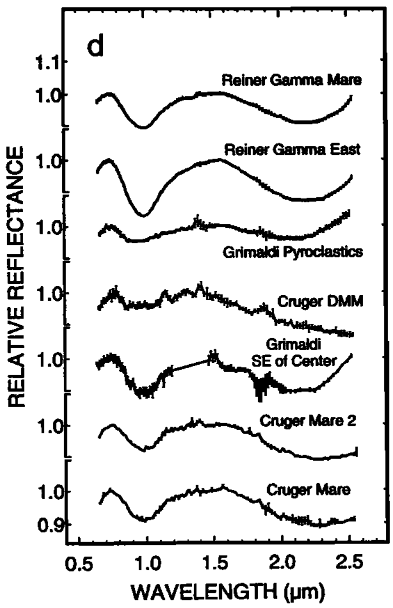


Fig. 2 (a) Reflectance spectra (after continuum removal) for anorthosite deposits in the Grimaldi region and elsewhere on the western limb of the Moon. The upper four spectra were obtained for anorthosites associated with the rings of Orientale and Humorum basins (Spudis *et al.*, 1984; Hawke *et al.*, 1991, 1993). (b) Reflectance spectra after continuum removal (straight line estimated for 1 μm absorption feature) for selected highlands features within and southeast of the Grimaldi basin. (c) Reflectance spectra after continuum removal for selected highlands units in the Grimaldi region. (d) Reflectance spectra after continuum removal for selected mare and pyroclastic deposits in the Grimaldi region.

are present in Group 1 deposits, the relatively broad, asymmetric, and shallow "1 μm" bands indicate the presence of one or more additional components such as volcanic glass or olivine.

The spectra obtained for various portions of the Lagrange C LDMD are members of Group 2 as is the spectrum of an endogenic dark-haloed crater on the western floor of Riccioli crater. The spectra in Group 2 exhibit "1 μm" bands that are centered at or beyond 0.96 μm. These bands are deeper (~7%) and more symmetrical than those in Groups 1 and 3 and indicate the presence of Ca-rich pyroxene. Group 2 spectra closely resemble those obtained for mature mare surfaces, and the deposits in this group clearly contain very large amounts of mare basalt.

The Crüger dark-mantle spectra (Figure 2d) were included in Group 3 by *Coombs* [1988] and *Hawke et al.* [1989a,b]. The spectra in Group 3 exhibit moderately deep (5-7 %), broad, asymmetrical absorption bands in the "1 μm" region, best explained by a mixture of olivine and pyroxene [*McCord et al.*, 1981; *Coombs*, 1988; *Hawke et al.*, 1989a,b].

Mare Basalt Units

A limited number of near-infrared spectra have been obtained for the mare units in the Grimaldi region (Figures 1 and 2). Two spectra were collected for the mare deposits within Crüger crater, and both exhibit "1 μm" absorption bands centered at about 0.98 μm, which indicates that the mafic assemblage is dominated by high-Ca pyroxene [e.g., *Adams*, 1974]. The slightly greater band depth (8.8%) and shallower continuum slope (0.66) of the Crüger Mare spectrum compared to the depth (7.3%) and slope (0.69) of the Crüger Mare 2 spectrum is due to the presence of a small, relatively fresh impact crater in the area for which the Crüger Mare spectrum was obtained [*Hawke et al.*, 1989a]. This small crater exposes crystalline mare basalt from beneath a mature regolith rich in glassy agglutinates.

Previous studies [*Hawke et al.*, 1989a, 1991] determined an intermediate TiO_2 abundance for the basaltic fill in Crüger and indicated that the basalts of Lacus Aestatis have slightly lower TiO_2 concentrations. The results of a recent analysis of the Galileo SSI data are consistent with these observations (*Williams et al.*, pers. com., 1995). These workers determined that older mare basalts in Crüger (3.57 Ga) and in western Lacus Aestatis (3.46 Ga) were emplaced before younger mare units in Rocca A (3.18 Ga).

Two spectra were obtained for the mare deposits within the inner ring of Grimaldi basin (Figures 1 and 2). Both spectra exhibit "1 μm" absorption bands centered between 0.98 μm and 1.0 μm. The spectrum for an area southeast of the center of the mare unit (Figure 1) has a band depth of 10.3% and a steep continuum slope (0.78). In contrast, the spectrum collected for the southern portion of the Grimaldi mare unit exhibits a shallower band (8.6%) and continuum slope (0.67). Our previous studies of the Grimaldi mare deposits have indicated a TiO_2 abundance of 2-3% [*Hawke et al.*, 1991, 1992b]. The spectral parameters and TiO_2 values are in general agreement with those reported by *Greeley et al.* [1993] and *Williams et al.* (pers. com., 1995) based on the Galileo SSI data.

Conclusions

1) Much of the Grimaldi region is covered by the Hevelius Formation, a highlands unit that was emplaced as a consequence of the Orientale impact. Analyses of spectra obtained for both fresh and mature surfaces on the Hevelius Formation indicate that the unit is composed of noritic anorthosite and anorthositic norite. 2) Olbers A crater excavated noritic anorthosite from beneath a slightly more mafic surface unit. 3) Gabbroic material was excavated from beneath Orientale-related deposits by small impact craters in three portions of the Grimaldi region. 4) The original, pre-Orientale floor unit and the primary ejecta deposits of the Grimaldi basin are dominated by noritic anorthosite and anorthositic norite. 5) The inner ring of Grimaldi basin is composed, at least in part, of pure anorthosite. Anorthosites were also exposed by Damoiseau D and C craters. 6) The anorthosites on the inner ring and elsewhere within Grimaldi were derived from a layer of pure anorthosite that exists at depth beneath a more pyroxene-rich unit. Pure anorthosites have now been identified on the inner rings of Orientale, Nectaris, Humorum, and Grimaldi basins [e.g., *Spudis et al.*, 1984, 1989; *Hawke et al.*, 1991, 1992a,b, 1993]. 7) All of the localized pyroclastic deposits in the Grimaldi region for which near-infrared spectra have been obtained exhibit spectral parameters that allow them to be assigned to the three spectral groups described by *Coombs* [1988] and *Hawke et al.* [1989b]. 8) The mare basalts within Grimaldi have mafic assemblages dominated by high-Ca pyroxenes and exhibit TiO_2 abundances of 2-3%. These findings are in general agreement with those reported by *Greeley et al.* [1993] and *Williams et al.* (pers. com., 1995).

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B.R. Hawke, P.G. Lucey, C.A. Peterson, Hawaii Institute of Geophysics and Planetology, University of Hawaii, 2525 Correa Rd., Honolulu, HI 96822 (e-mail: chrisp@baby.pgd.hawaii.edu)

C.R. Coombs, Department of Geology, College of Charleston, 66 George St., Charleston, SC 29424

P.D. Spudis, Lunar and Planetary Insitute, 3600 Bay Area Blvd., Houston, TX 77058

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