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REMOTE SENSING STUDIES OF THE ORIENTALE REGION OF THE MOON: A PRE-GALILEO VIEW

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Abstract. We have acquired both an extensive data base of visible and near-infrared spectra and multispectral images (ultraviolet and visible) of the Orientale region of the Moon. Our results show that the eastern Inner Rook Mountains are composed of anorthosite. Portions of the main ring of the Humorum basin and the inner ring of Grimaldi are also composed of anorthosite. Other deposits within the Orientale basin and the major ejecta unit outside the basin are dominated by noritic anorthosites; mature surfaces have spectra nearly identical to those taken of areas in the vicinity of the Apollo 16 site. Thus, it appears that Orientale ejecta are more mafic than materials that are thought to have originated at depth (i.e., the anorthosites in the Inner Rook Mountains). There are large areas that have mare basalt signatures mixed with highland rock types, indicating the existence of ancient, pre-Orientale mare volcanism. Present mare surfaces in the Orientale region contain basalts of intermediate to very low TiO_2 content.

Introduction

The Orientale region of the Moon (Figure 1) was the focus of the Galileo encounter with the Earth-Moon system in December, 1990. Orientale is the youngest and best preserved of the giant multiringed impact basins on the Moon. It straddles the western limb; about half of it is visible from Earth. This region is geologically fascinating, and unanswered questions abound. We do not know the surface composition of the western limb area with certainty, nor do we know how the composition varies with depth. A detailed study of the region will address both problems because Orientale, like other basins, is a natural drill hole into the lunar crust. Smaller craters and basins are also present in the area, so in principle we can obtain a fairly detailed picture of crustal stratigraphy. Furthermore, we can use compositional data and inferred stratigraphy to test models of the mechanics of basin formation. Finally, we can determine the characteristics of the volcanic products that partially fill the basin and occur in other areas outside it, and also measure the extent of pre-Orientale mare volcanism.

We have been conducting a variety of spectral observations of the Orientale region. Our present efforts continue work reported previously [Spudis et al., 1984]. We combine both visible and near-infrared spectral observations with multispectral imaging. The purposes of this report are 1) to present the preliminary results of this effort; 2) to address the fundamental questions outlined above; and 3) to provide a framework in which to interpret the observations made by the Galileo mission.

Methods

Over 100 near-infrared reflectance spectra were obtained at the 2.24-m telescope of the Mauna Kea Observatory (MKO) during a series of observing runs conducted during favorable lunar librations. In addition, two observing runs were conducted utilizing the University of Hawaii 60-cm (Air Force) telescope and fifty spectra were obtained. The Planetary Geosciences Division indium antimonide spectrometer was used. By using the f/35 oscillating secondary mirror on the 2.24-m telescope in its stationary mode, it was possible to use an aperture 0.7 arc sec in diameter. Therefore, it was possible to collect spectra for relatively small areas (5-10 km) near the lunar western limb. The lunar standard area at the Apollo 16 landing site was frequently observed during the course of each evening and these observations were used to monitor atmospheric extinction throughout each night. Extinction corrections were made using the methods described by McCord and Clark [1979]. Analyses of pyroxene band positions and shapes as well as continuum slopes were made using Gaussian-band fitting and other techniques described by McCord et al. [1981]. Continuum-removed spectra for a wide variety of geologic units are presented in Figures 2a and 2b. Spectra relative to the Apollo 16 site are presented in Figure 2c for a radial traverse of Orientale ejecta deposits east of the basin.

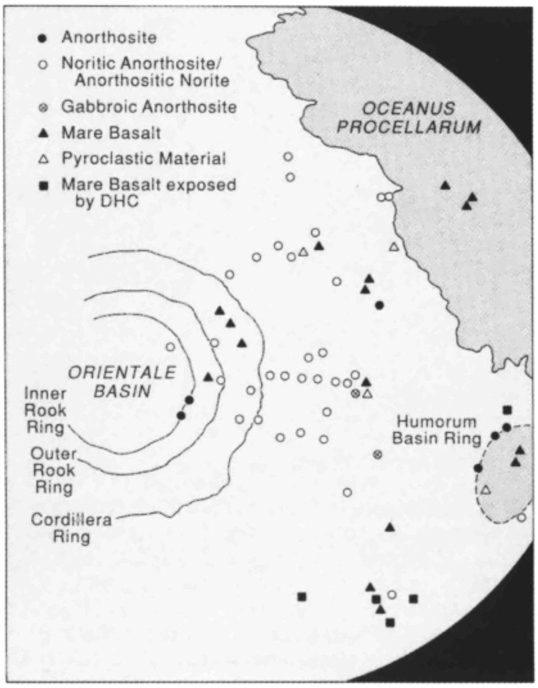

Fig. 1. Sketch map of the Orientale region. The various symbols indicate the lithology of the areas for which near-infrared reflectance spectra have been obtained and interpreted.

Digital multispectral images of the Orientale region were obtained at one of the MKO 60-cm telescopes simultaneous with some of the spectral observations. Images were obtained in UV, visible and near-infrared wavelengths (0.375, 0.40, 0.73, 0.86, 0.90, 0.93, 0.96, and 1.00 μm, each with 10 nm

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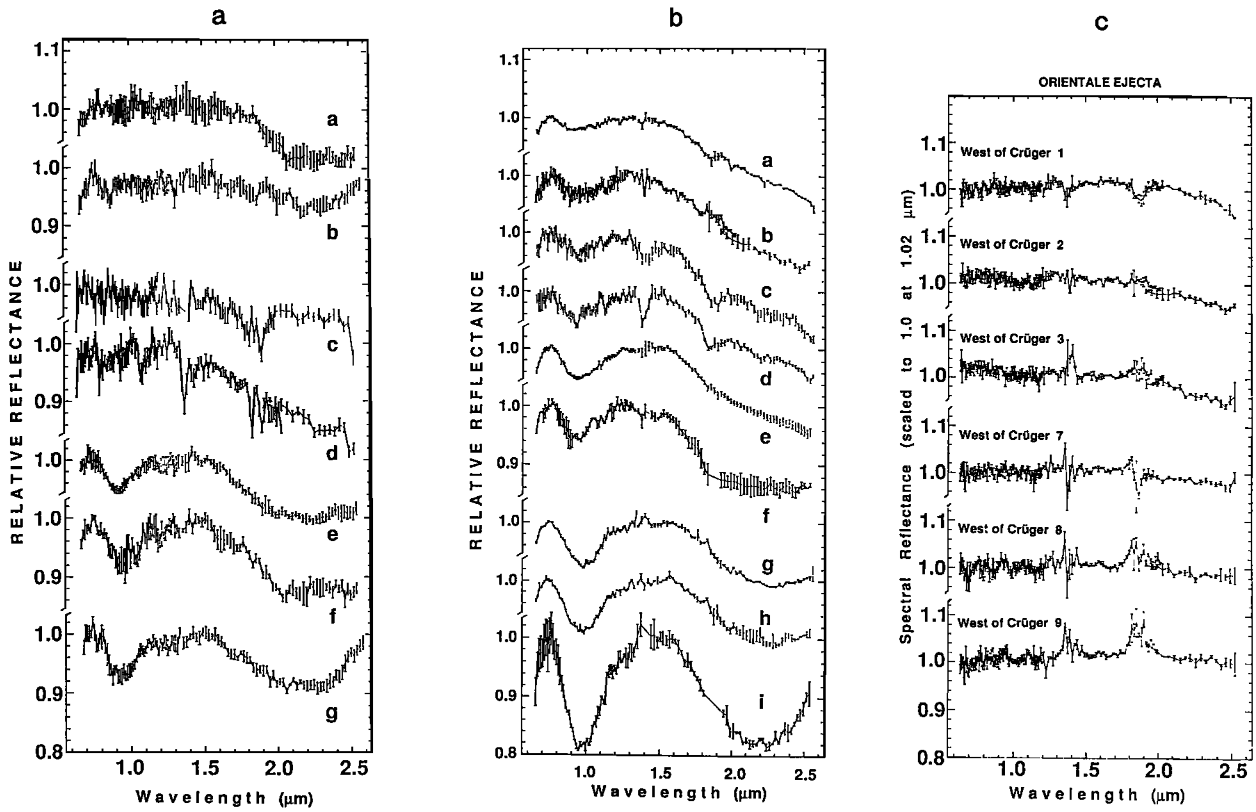

Fig. 2. (a) Reflectance spectra after continuum removal (straight line estimated for 1 µm absorption feature) for selected features on the western limb of the moon: a - Orientale interior 2 (Inner Rook Mts.); b - Orientale interior 1 (Inner Rook Mts.); c - Mersenius C (Humorum ring); d - Gassendi E and K (Humorum ring); e - Eichstadt H; f - Eichstadt K; g - Outer Rook Mountains 1 (unnamed 15 - km - diameter crater). (b) Reflectance spectra after continuum removal for selected features in the Orientale region: a - Crüger west rim; b - Highlands west of Crüger 2; c - Crüger G; d - Darwin C; e - Olbers A interior; f - Schickard X; g - Crüger mare 2; h - Crüger mare; i - Nöggerath F bowl. (c) Spectra relative to the Apollo 16 site for a radial traverse of Orientale ejecta deposits east of the basin. The areas for which these spectra were obtained are shown in Fig. 1.

bandwidth) with a 376x585 element Thompson CCD installed in a commercial astronomical CCD camera produced by Photometrics, Inc. Observations of the Mare Serenitatis standard site were made for photometric calibrations.

Charette et al. [1974] developed a technique for determining titanium content of mature mare soils from spectral measurements by showing that a nonlinear correlation exists between the slope of the ultraviolet continuum (defined by a ratio of 0.40 to 0.56 µm) and the titanium content of mature mare soils. This correlation has been utilized by several workers to determine the titanium content of mare areas (e.g. most recently by Johnson et al. [1990]). We attempted to use this technique to measure the titanium content of mare deposits in the Orientale region. Unfortunately, the 0.56µm filter we used was damaged and so images at the same wavelengths as those used by Charette et al. [1974] could not be obtained. However we did collect data at 0.73 and 0.40 microns, and we make the assumption that the 0.40/0/73 µm ration will be closely correlated with the 0.40/0.56 µm ratio, both ratios being dominated, in measurements of mature mare surfaces, by TiO_2 content. We used as a standard a region including both Mare Serenitatis, which exhibits low TiO_2 values, and Mare Tranquillitatis, which has some of the highest TiO_2 abundances (~9.0%). The 0.40/0.73 µm ratio values for Orientale region mare deposits which are similar to those of Mare Tranquillitatis will be high in TiO_2 and values similar to those in Mare Serenitatis reflect low TiO_2 values. In addition, a rectified color composite of near-IR multispectral imaging intended to show the distribution of anorthosite and noritic material in the Orientale region was prepared.

Results and Discussion

Locations and lithologic classifications of the spectral data appear in Figure 1 and representative spectra are shown in Figure 2. We discuss the results in terms of geological location.

Orientale Interior

With the exception of the Inner Rook massifs, all the highlands units inside the Orientale basin appear to be composed of either noritic anorthosite or anorthositic norite [Spudis et al., 1984]. Spectra obtained for portions of the Maunder Formation with mature regolith surfaces are almost identical to those taken in the vicinity of the Apollo 16 site. They are also like those obtained for many mature surfaces outside the basin (Figure 2c, see below). The Maunder Formation is composed of smooth plains that grade laterally outward into rough-textured material, and is thought to be composed largely of impact melt [Head, 1974; Moore et al., 1974; McCauley, 1977; Scott et al., 1977]. Spectra of fresh surfaces on the Montes Rook Formation, a hummocky unit thought to be primary basin ejecta [McCauley, 1977; Scott et al., 1977], and of the massifs of the Outer Rook Mountains are similar to one another (Figure 2a) and indicate the presence of plagioclase and low-Ca pyroxene [Spudis et al., 1984]. Mature surfaces on the Montes Rook Formation are similar in composition to those in the Apollo 16 area.

The Inner Rook Mountains are markedly different from other units within the Orientale basin. Our previous data [Spudis et al., 1984] indicated that two of these mountains are composed of anorthosite (Figure 2a). Imaging data confirm this view; the entire eastern Inner Rook Mountains contain only minute amounts of low-Ca pyroxene. Thus, it appears that the Inner Rook ring of the Orientale basin is a mountain range composed of anorthosite. The plagioclase absorption band at 1.25 µm occurs in some spectra, but not in all, suggesting different shock histories for different parts of the Inner Rook ring.

Orientale Exterior

The Hevelius Formation occurs outside the prominent Cordillera ring and probably contains large amounts of primary ejecta from Orientale. It consists of hummocky to lineated to swirl-textured deposits that extend to almost one basin-diameter (930 km) beyond the Cordillera scarp. We have taken numerous spectra of this deposit, including several radial traverses across it. Spectra for a typical radial traverse are shown in Figure 2c relative to the Apollo 16 standard. The Hevelius Formation is surprisingly uniform in composition (Figures 1 and 2) and strikingly similar to Apollo 16. It consists largely of noritic anorthosite, like much of the interior deposits in Orientale. The Hevelius Formation grades outward into smooth and then undulating highlands plains deposits, some of which also appear to be similar in composition to the Apollo 16 highlands.

Crüger Region

Spectral observations of the Crüger region have been reported and discussed by Hawke et al. [1989]. Crüger is a 46-km diameter, mare-filled impact crater. Spectra of its west rim and of Darwin C (a 16-km crater southwest of Crüger) indicate that the highlands are composed of noritic anorthosites here also (Figure 2b). However, the spectrum for the 8-km diameter crater Crüger G exhibits a pyroxene absorption feature minimum beyond 0.95 µm, which indicates a gabbroic anorthosite composition. Gabbroic anorthosite was also exposed by Byrgius A, a 19-km diameter impact crater south of Crüger [Pieters, 1986]. The area east of Crüger has unusual characteristics on the composite image. Some areas mapped as highlands exhibit a mare basalt signature. This suggests that parts of this region were the sites of pre-Orientale mare volcanism.

Grimaldi Region

Grimaldi is a small (430 km) two-ringed impact basin [Hartmann and Kuiper, 1962]. Our spectral data (Figure1) indicate that there might be anorthosites on its inner ring, analogous to those in the Inner Rook ring of Orientale. We have obtained one spectrum of an anorthosite from a portion of the inner ring. Other spectra for the inner ring exhibit a very shallow pyroxene absorption feature, which indicates the presence of very minor amounts of orthopyroxene. These areas may also prove to be composed of anorthosites. Other highlands deposits emplaced in the Grimaldi region as a result of the Orientale impact event appear to be composed of noritic anorthosite.

Schiller-Schickard Region

Although this region is over 1000 km from the Cordillera ring, it has been heavily affected by the Orientale impact event. This area contains numerous unusual features. These include the crater Wargentin, the Schiller-Zuccius impact basin, the larger crater Schickard (D=227 km), whose floor contains mare deposits as well as a light plains unit and a high density of dark-haloed impact craters [Schultz and Spudis, 1979]. Hawke and Bell [1981] and Bell and Hawke [1984] presented spectral data which demonstrated dark-haloed impact craters excavated ancient mare basalts from beneath light plains deposits in the Schiller-Schickard region (Figure 2b). They concluded that early (>3.8 Ga) mare deposits existed in the Schiller-Schickard region prior to the Orientale impact and that these basaltic units were covered with a thin layer of highland debris as a consequence of the formation of Orientale basin. Spectra for the light plains deposits in this region exhibit relatively strong "1µm" bands. Either Orientale primary ejecta in the region contains more pyroxene than similar materials in other areas or pyroxene-rich local material was incorporated in the light plains deposits by Orientale secondary craters.

Humorum Region

Humorum is an old multiringed basin east-southeast of Orientale. Our data indicate that anorthosites are exposed on the main ring of this basin (Figures 1 and 2a). Spectra obtained for small craters in the highlands northwest of the basin indicate the presence of a mare basalt component, which suggests that the region experienced mare-type volcanism prior to the formation of the Orientale basin.

Titanium Abundance for West Limb Mare Deposits

On the whole, the ratio values of Orientale region mare deposits compared to those of the Serenitatis/Tranquillitatis region indicate intermediate to very low TiO_2 contents. There is significant variation among and even within deposits. Table 1 summarizes the results of our analysis. Our highest confidence is in values for Grimaldi and Crüger mare fills, intermediate confidence in Lacus Veris and Lacus Autumni, and lowest confidence in Mare Orientale. However, despite these uncertainties we believe that all of the measured mare deposits are intermediate to very low in TiO_2 (less than 2±1%).

TABLE 1. Relative TiO_2 values

Location	0.40/0.73 µm Ratio	Width of Distribution	Qualitative TiO_2 value
Serenitatis (central):	0.3296	±0.009	low
Tranquillitatis (north):	0.3668	±0.012	high
Grimaldi:	0.3252	±0.008	low
Crüger:	0.3068	±0.004	very low
Lacus Autumni:	0.3168	±0.003	low
Lacus Veris (south):	0.3272	±0.005	low
(north):	0.3380	±0.004	intermediate

Summary of Observations

Our data show the following important facts:

1) Anorthosites occur in the Inner Rook Mountains of Orientale, the inner ring of Grimaldi, and the main ring of Humorum. Imaging spectroscopy shows that the entire eastern Inner Rook Mountains (the only portion visible from Earth) are composed of anorthosites. Anorthosites are also associated with the rings of Nectaris [Spudis et al., 1989].

2) Orientale ejecta are strikingly like the surface materials in the region where Apollo 16 landed. This similarity indicates similar mineralogy, noritic anorthosite. Thus, Orientale ejecta is more mafic (10-20% low-Ca pyroxene) than the Inner Rook Mountains (no more than a few percent pyroxene). This situation is also true for the Nectaris, Humorum, and Grimaldi basins.

3) Isolated areas in the Orientale region show the presence of gabbroic rocks, but in general Orientale ejecta are noritic anorthosites, which contain much more low-Ca pyroxene than high-Ca pyroxene.

4) Ancient (pre-Orientale) mare volcanism apparently occurred in several areas of the western limb.

5) Visible mare basalts are intermediate to very low in TiO_2.

Implications

The presence of anorthosite in the Inner Rook Mountains presents an interesting puzzle. In most cratering schemes, these mountains are depicted as material derived from great depths, perhaps as much as 50 km. The basin ejecta, on the other hand, came from shallower depths. Thus, it appears that somewhat more mafic rock (noritic anorthosite) overlay anorthosite at the Orientale target. This is at odds with the simple picture of a magma ocean that produced an anorthosite crust that was subsequently intruded from below by more mafic magmas.

One interpretation of these observations is that the primitive crust was originally anorthosite. Its upper few to perhaps 20 km were reworked by impact, forming a primitive, anorthositic megaregolith on the Moon. Younger Mg-rich magmas traveled readily through the unfractured lower parts of the anorthosite crust, but slowed as their hydrostatic heads were dissipated in the brecciated upper crust. Thus, they stopped in this fractured crust and assimilated anorthosite [Warren, 1986]. The result was a more mafic upper crust overlying anorthosites.

The Role of Galileo

One of the great problems with studying Orientale from the Earth is that we cannot observe the western half of the basin and its vast ejecta blanket. Apollo geochemical groundtracks do not cover this region, nor is photographic coverage by Lunar Orbiter or Apollo spacecraft adequate. The Galileo flyby of the Moon provided the first good observations of the western Orientale region. Our data indicate that most of the ejecta ought to be noritic anorthosite. Galileo data for the western Inner Rook Mountains are especially interesting. Our observations suggest that these massifs will be anorthosites. If they are not, it will indicate that the crust is extremely complex at depth, or that our understanding of the dynamics of impact basin formation is inadequate. Finally, it will be important to outline the extent of pre-Orientale, ancient mare volcanism. Because the crust tends to thicken toward the farside and because maria are rare on the farside, we predict that the extent of ancient mare volcanism will also decrease.

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