

Compositional studies of the Orientale, Humorum, Nectaris, and Crisium lunar basins

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Abstract. We have used full-resolution (250 m/pixel) Clementine images to map the compositions of ejecta from four multiring basins on the Moon: Orientale, Humorum, Nectaris, and Crisium. All basins have relatively feldspathic ejecta, with iron contents ranging from 2 to 6 wt % FeO. Some basins show remarkably homogeneous ejecta blankets (Orientale), while others display distinct compositional zoning within exterior sectors of the basin (Crisium); in some cases this zoning correlates with morphologically observed ejecta facies (Nectaris). The iron-poor composition of most basin ejecta indicates that the crust of the Moon at these locations is feldspathic down to depths of at least several tens of kilometers, the likely sampling depth of basin-forming impacts. The inner rings of all four basins display massifs and small crater floors of nearly pure anorthosite (FeO < 1 wt %), virtually the only such occurrences of this rock type on the Moon. Because basin rings are structurally emplaced topographic elements derived from depths of at least 10–20 km into the Moon, we postulate that basin inner rings are sampling a unique stratigraphic level in the Moon and at these depths, the primordial, pristine anorthositic crust of the Moon is largely preserved. Below this zone of anorthosite is the more mafic region of the lower crust, probably having “highland basalt” composition (FeO ~ 10 wt %, Al₂O₃ ~ 18–22 wt %). The petrologic nature of lower crustal levels remains uncertain but must at least in part include members of the mafic highland suite, such as norites and troctolites.

1. Introduction

The formation of impact basins has had a profound effect in shaping the Moon. These impacts excavated vast amounts of material and redistributed it across the lunar surface. We are using basins as probes to build up a three-dimensional picture of the crust. By studying the variations in composition of basin ejecta deposits, we have the opportunity to look “into” the crust of the Moon to learn about its makeup and origin.

In this paper we discuss the results of a study of several nearside impact basins using the Clementine multispectral data set. The Clementine mission has given us complete coverage of the Moon, allowing all exposed basin ejecta to be characterized. Moreover, the newly developed techniques [Lucy et al., 1995, 1998; Blewett et al., 1997] to derive quantitative iron and titanium contents from full-resolution Clementine images (250 m/pixel) allow us to study ejecta compositions and their variations at unprecedented levels of detail. Using these data to probe the crust of the Moon permits new and detailed study of crustal structure and evolution.

Large impact basins, such as the ones studied in this paper, excavate material from deep within the lunar crust. The exact depth of excavation of these basins, and hence the distance into the crust that they sampled, is not known although estimates have been made [e.g., Croft, 1981a; Grieve et al., 1981; Spudis, 1993]. Associated with the formation of an impact

basin is a transient cavity (a temporary depression, existing momentarily before rebounding back upward) and an excavation cavity (this is the region from which target material is removed as ejecta). These cavities have the same diameter, which is approximately equal to one half to two thirds of the basin diameter [Croft, 1981a; Grieve et al., 1981]. Of key importance is the depth of the excavation cavity, as this represents the maximum depth into the crust that the basin excavated. This is believed to be approximately one tenth of the excavation cavity diameter [Croft, 1981a; Spudis, 1993]. Hence a basin such as the 900 km diameter Orientale probably had a transient cavity of 500–600 km and excavated 50–60 km into the crust.

Although the idea that the crust of the Moon might vary in composition with depth derived from seismic measurements of the crust near the Apollo 12 landing site [Taylor, 1982], detailed work from sample study provided a more detailed picture [Ryder and Wood, 1977; Charette et al., 1977]. Models of vertical crustal stratification gave way to models advocating mostly lateral heterogeneity [e.g., James, 1980] or both [Spudis and Davis, 1986]. These concepts came from study of samples and the limited remote-sensing data provided by Apollo and Earth-based data. From the latter came the recognition that pure anorthosite deposits occur on the Moon, occurring mostly as ring massifs in the largest basins [Spudis et al., 1984; Hawke et al., 1992]. This mode of occurrence suggested that anorthosite was present as a crustal “layer” at middle levels in the crust, the zone uplifted into rings during basin-forming events [Grieve et al., 1981]. In addition, evidence continued to mount

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that the deep crust was substantially more mafic than the upper crust, evidenced both by increasing iron content in basin ejecta as a function of increasing size [Spudis *et al.*, 1996] and by the mafic nature of basin impact melt breccias [Ryder and Wood, 1977; Spudis, 1993]. Our best current estimate of crustal structure is that of a “three-layer” model, with a mafic (basaltic) lower crust overlain by an anorthosite “middle crust” overlain by a mixed-breccia megaregolith of grossly feldspathic composition [Hawke *et al.*, 1992; Spudis *et al.*, 1999a].

2. Method

Clementine mapped the Moon in 11 different wavelengths for 71 days in 1994, providing the first digital data set that can be used to investigate the global composition of the lunar surface. We used the multispectral ultraviolet-visible (UVVIS) data to study the composition of basin ejecta. By producing albedo maps, multispectral images, and quantitative iron and titanium maps [Lucey *et al.*, 1998; Blewett *et al.*, 1997], we are able to look at the composition of basin deposits in complete and unprecedented detail.

Each Clementine frame covers an area approximately 30 × 20 km. Therefore, to study a feature the size of a basin, it is necessary to produce large mosaics. The individual frames receive flat and dark field compensations as well as a photometric correction. They are then reprojected and mosaicked to cover large regions. Reflectance maps are made in the five UVVIS wavelengths (415, 750, 900, 950, and 1000 nm); the 415, 750, and 950 nm mosaics can be combined (blue, green, red) to produce an approximate true color image (in fact, it is slightly reddened). Ratio images are made; these images suppress albedo differences and allow for color differences (a function of composition and maturity) to be seen more easily. These mosaics are combined to produce a multispectral image that is, in essence, a mafic content and soil maturity map. In this false-color ratio image the red channel is controlled by the 750/415 nm ratio, green is 750/950 nm, and the blue channel is the 415/750 nm ratio. The 415/750 and 750/415 ratios indicate the continuum slope which is a function of maturity (the continuum steepens, or “reddens,” as a surface gets more mature owing to the production of metal iron grains by micrometeorite impact and reduction of FeO by the solar wind [Adams and McCord, 1973; Charette *et al.*, 1976]) as well as titanium content in mare basalts. The 750/950 ratio is a measure of the one micron absorption feature associated with mafic minerals, most commonly pyroxene. In this rendition, mature mare surfaces vary from red to blue depending on titanium content (higher titanium content flows are bluer owing to having a shallower continuum), while fresh mare material has a yellow/green color. Mature highland surfaces appear red, while fresh feldspathic highland material is cyan. In addition to the albedo and multispectral image products, the single-filter mosaics can be combined to produce quantitative iron and titanium maps using recently developed techniques [Lucey *et al.*, 1995, 1998; Blewett *et al.*, 1997]. These elemental abundance maps have the same spatial resolution as the standard imaging mosaics and an absolute accuracy of ~1 wt % [Lucey *et al.*, 1998].

We have selected four basins for our initial studies. Orientale is one of the largest, freshest basins on the Moon and traditionally an archetype of multiring impact structures [Spudis *et al.*, 1984; Hawke *et al.*, 1991]. Humorum has been studied with Earth-based spectra [Hawke *et al.*, 1993], which gives us a large, comparative database to interpret the Clementine mul-

tispectral data. Nectaris has been well studied [e.g., Spudis *et al.*, 1989a] and defines the base of the Nectarian stratigraphic system [Wilhelms, 1987]. Moreover, Apollo 16 may have sampled parts of the Nectaris ejecta, so complete understanding of variations in ejecta compositions is important for comprehending sample provenance. Crisium has also been studied previously [Spudis *et al.*, 1989b; Swindle *et al.*, 1990; Blewett *et al.*, 1995], and the data from Apollo X-ray and gamma ray studies have significant overlap for comparison with the new, full-coverage Clementine data. We analyzed both the external and internal deposits of these basins to provide insight into near-side crustal composition.

3. Orientale

3.1. Geologic Setting

Orientale is a young basin whose formation defines the beginning of the Upper Imbrian period (3.8 billion years) [Wilhelms, 1987], located on the western limb of the Moon (centered at 20°S, 95°W). Orientale is well preserved, making it ideal for study. The basin consists of four rings; the basin topographic rim is the Cordillera ring, 900 km in diameter. Moving inward, the basin displays three additional rings, the Inner and Outer Rook Mountains (480 and 620 km in diameter, respectively) and the innermost ring, a scarp-like feature 240 km in diameter, partly buried by the basin-filling mare lava flows. The three ejecta units associated with the Orientale basin are the Hevelius, Montes Rook, and Maunder Formations. The Maunder Formation has both a smooth and a cracked facies [Wilhelms, 1987] and constitutes the melt sheet produced by the basin-forming impact. It lies entirely within the Inner Rook Mountains and has been overlain in the basin center and several other places by the basalts of Mare Orientale. The Montes Rook Formation, a knobby unit, lies predominantly between the Outer Rook and Cordillera Mountains, although locally it may extend slightly beyond the Cordillera ring [Head, 1974; Spudis *et al.*, 1984]. The Hevelius Formation, the main textured ejecta blanket of Orientale, lies outside the Cordillera ring and extends for distances of up to a basin diameter from the rim crest. Outside the Hevelius Formation are smooth, Cayley-type highland plains and abundant secondary impact craters. Geologic maps for Orientale are given by Scott *et al.* [1977] and Spudis [1993]. Plate 1 shows the true-color mosaic of the basin, consisting of ~1500 frames, the multispectral mosaic, a quantitative iron map, and a quantitative titanium map.

3.2. Composition of the Orientale Basin Deposits

All three ejecta units are clearly visible in the multispectral image (Plate 1); all of them are internally homogeneous. The Maunder and Hevelius Formations appear to be similar in composition, while the Montes Rook Formation appears to be slightly more orange. On closer inspection, it can be seen that this color difference is caused by the floors of small craters in the Montes Rook Formation being yellow, while the floors of craters in the Hevelius Formation are blue. As yellow on this composite is caused by enhanced 1 micron absorption (by the mafic minerals pyroxene and olivine), the orange color suggests that the Montes Rook Formation is more mafic in composition than the Hevelius Formation. Surprisingly, this presumed difference in mafic mineral content is not reflected in the iron map, which shows all three units to have a uniform, feldspathic composition (FeO 2–5 wt % and <1 wt % TiO₂).

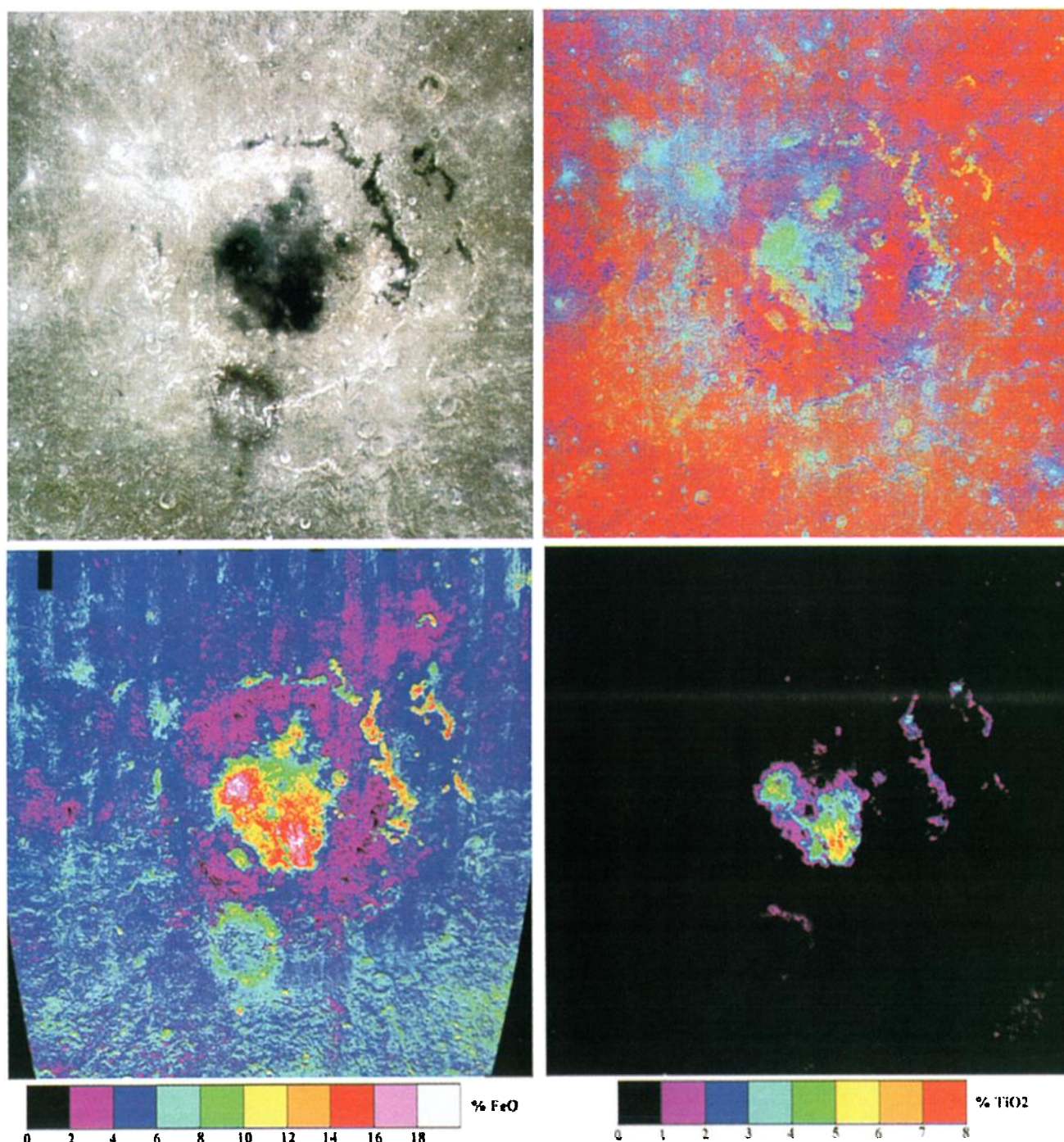


Plate 1. Image products for Orientale basin. Each image covers a region from 0° to 40°S and 75° to 115°W. Clockwise from top left: true-color image, multispectral image, titanium map, and iron map.

We have no obvious answer to this conundrum. We suggest that while the Montes Rook and Hevelius are of slightly different composition, the difference is of a magnitude undetectable with the iron and titanium mapping technique. Previous telescopic observations of the Orientale region had identified the presence of anorthosite (<1.0 wt % FeO) outcrops associated with the massifs of the inner rings of the basin [Spudis *et al.*, 1984]. Our analysis of Orientale with Clementine data clearly shows the presence of anorthosite in both the Inner and Outer Rook Mountains [Bussey and Spudis, 1997]. Anorthosite can be identified by its high albedo, relatively flat reflectance

continuum, and lack of a 1 micron absorption band. Thus, in the multispectral image, anorthosite outcrops are dark blue in color. Looking at Plate 1, dark blue regions are abundant within the Inner and Outer Rook Mountains. These areas appear black on the iron map, indicating that they contain <2 wt % FeO, further evidence that these regions have a highly feldspathic composition. Another particularly interesting occurrence of anorthosite is associated with the crater Kopff. A later superposed crater appears to have excavated anorthositic material (<2 wt % FeO), punching through the mare unit that covers Kopff's floor. This later superposed crater has a diam-

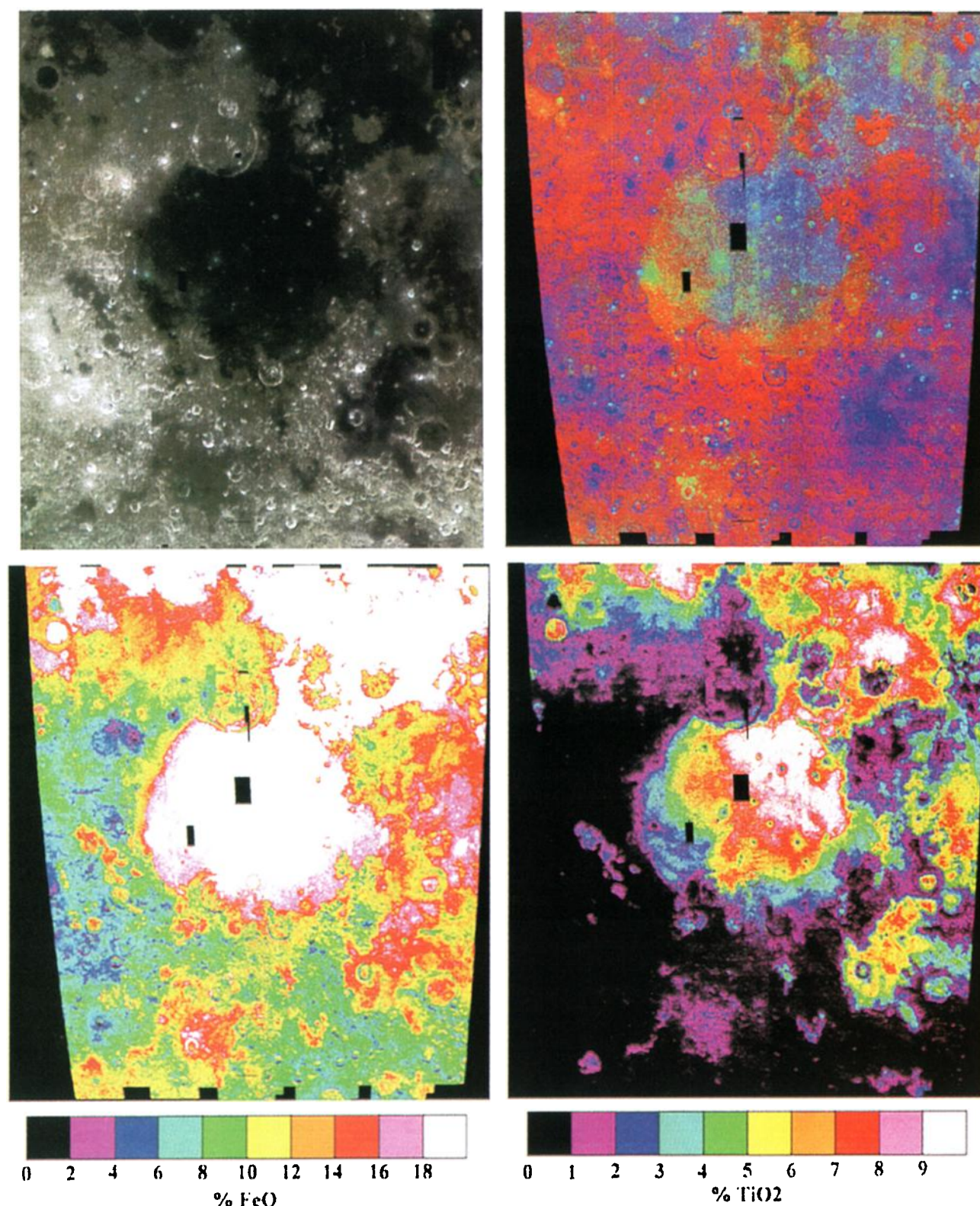


Plate 2. Image mosaics for the Humorum basin. The images cover a region from 10°–40°S and 25° to 52°W. Clockwise from top left: true-color image, multispectral image, titanium map, and iron map.

eter of 4 km, indicating that the mare flow within Kopff is probably less than ~400 m thick. The anorthosite outcrops in the inner rings of Orientale are the result of the structural uplift of an anorthosite layer in the crust. This uplift occurs

during basin formation, associated with the production of basin rings.

Our results suggest that ejecta of the Orientale basin is feldspathic and relatively poor in mafic material. This inter-

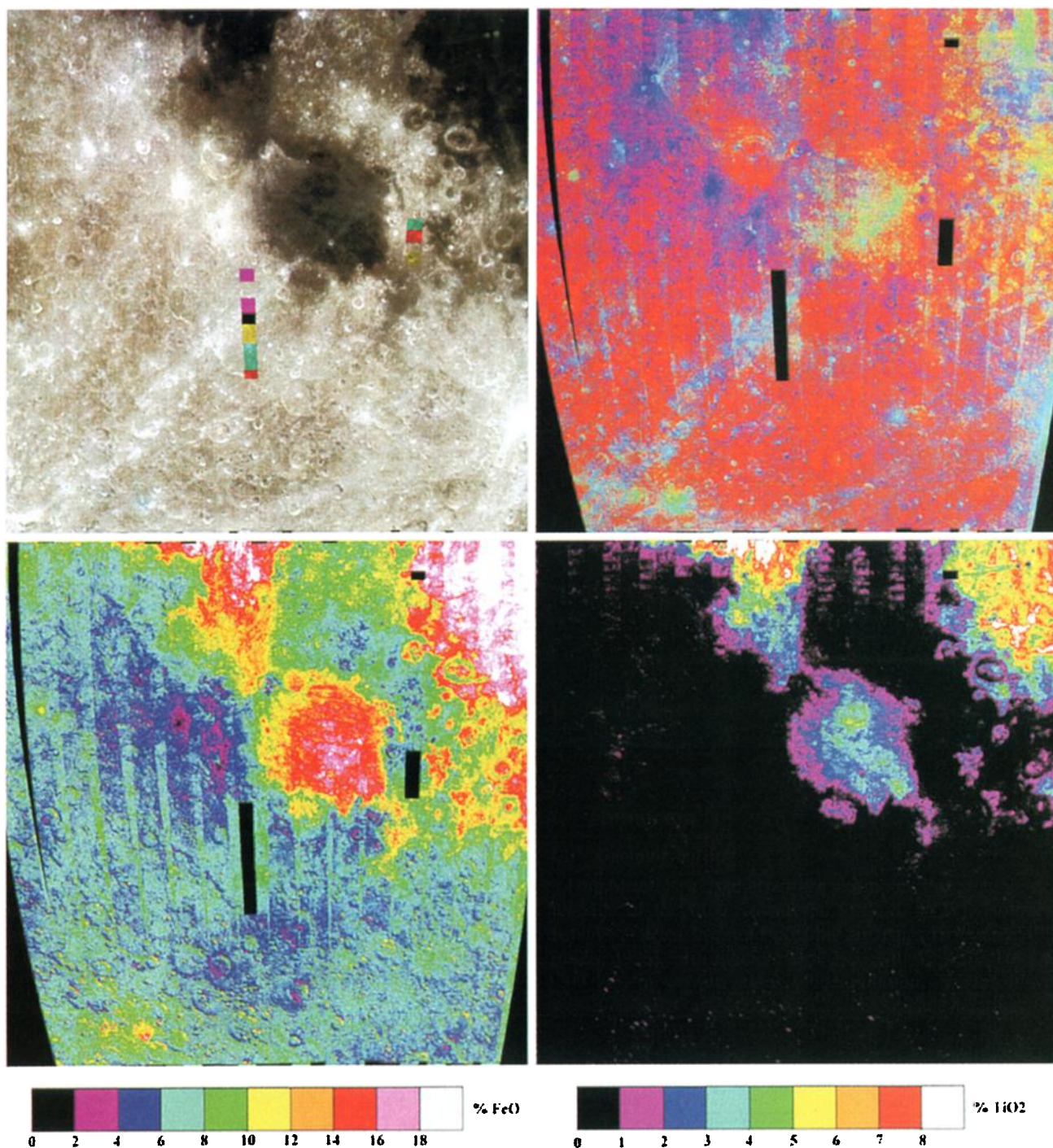


Plate 3. Image products of the Nectaris basin. The mosaics cover the region 0°–40°S and 10°–50°E. Clockwise from top left: true-color image, multispectral image, titanium map, and iron map.

pretation is consistent with previous results [Spudis *et al.*, 1984; Hawke *et al.*, 1991; Head *et al.*, 1993] that indicate Orientale ejecta do not contain significant mafic or noritic material. The new Clementine data are consistent with a basin-forming impact that has excavated mostly upper crustal material [e.g., Ryder and Wood, 1977; Spudis and Davis, 1986], which because of the anomalously large crustal thickness in this region (up to 100 km [Zuber *et al.*, 1994]) may be as deep as 40–50 km [Spudis, 1993].

4. Humorum

4.1. Geologic Setting

Humorum is a Nectarian-age basin on the southwestern nearside of the Moon (centered at 24°S, 40°W). Humorum displays at least five, and possibly six, rings [Wilhelms, 1987; Spudis, 1993], with diameters of 210, 340, 425, 570, 800, and 1200 km, in varying states of degradation. The most well-preserved rings are those of 325 (Doppelmeyer ring), 425

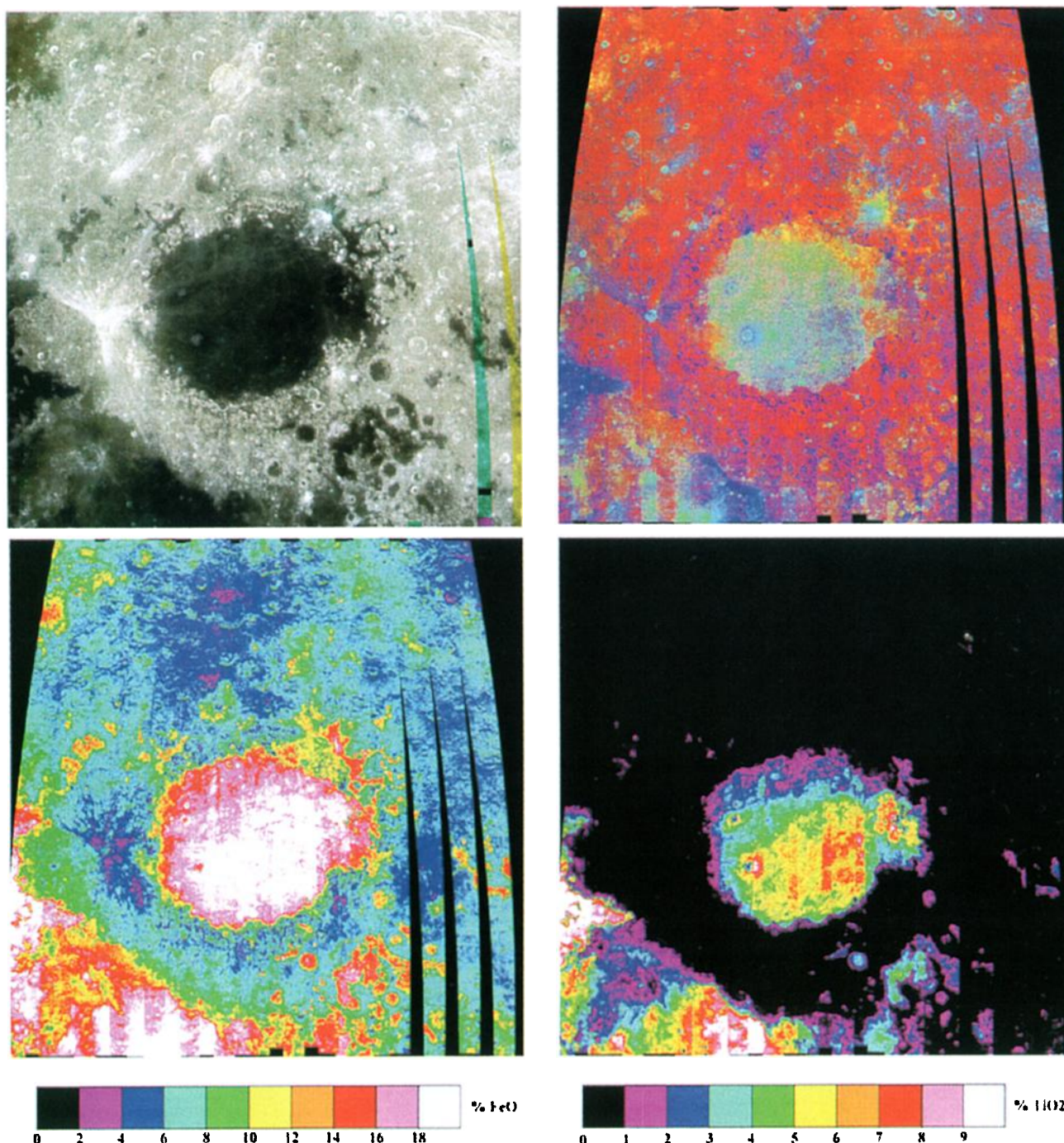


Plate 4. Image products of Crisium basin. The mosaics cover the region 0°–40°N and 40°–80°E. Clockwise from top left: true-color image, multispectral image, titanium map, and iron map.

(Gassendi ring), and 825 km (Letronne ring) diameters. The innermost Doppelmeyer ring is represented by a circular pattern of wrinkle ridges within central Mare Humorum. The Humorum ring structure is uncertain; it is not known which ring represents the main topographic rim of the basin. *Spudis* [1993] considered the 425 km diameter Gassendi ring to be the basin rim but in a later work revised that opinion on the basis of evidence from Clementine altimetry that indicated either the Gassendi or the Letronne ring could be the main rim crest [Spudis and Atkins, 1996]. This dilemma is similar to the situation at Crisium, where two distinct rings of comparable ele-

vation could be interpreted as the rim crest. At Humorum the case for the 800 km Letronne ring being the basin rim crest is supported by the rim elevation being marginally greater (average elevation 0.5–2.5 km) than the 425 km Gassendi ring (elevation 0.0–1.0 km) [Spudis and Atkins, 1996].

The ejecta deposits of Humorum basin are not as well preserved as those of Orientale. The textured ejecta blanket of Humorum, analogous to the Hevelius Formation of Orientale, is best preserved southeast of the basin, where it is formally known as the Vitello Formation. More extensive mare filling and greater age, relative to Orientale, result in none of the impact melt analogues

to the Maander Formation being exposed. A geologic map for Humorum is given by *Wilhelms and McCauley* [1971].

4.2. Composition of the Humorum Basin Deposits

Clementine color data show that the highlands around the Humorum basin are feldspathic but somewhat more mafic ($\text{FeO} = 4\text{--}10\text{ wt \%}$) than the deposits of Orientale [*Bussey and Spudis*, 1996, 1997; *Bussey et al.*, 1997a]. Basin deposits to the west of Mare Humorum appear to be slightly more feldspathic than those to the east, with iron contents of $4\text{--}8\text{ wt \% FeO}$, while small highlands areas just east of the mare have higher iron contents of $6\text{--}10\text{ wt \% FeO}$, a relation not caused by resolution mixing of maria and highlands because individual outcrops of highland (basin) terrain are clearly distinguishable in the mosaics. Numerous patches of mare material occur outside the main mare area, partly covering the basin deposits; these basalt units have iron contents between 12 and 16 wt % FeO.

Abundant small deposits are seen along the inner, mare-bounding ring of Humorum basin that have extremely low iron content. These zones correspond, in part, to small fresh craters for which spectral reflectance data from Earth-based telescopes show no mafic absorption [*Hawke et al.*, 1991, 1993, 1995]. Hawke and coworkers interpreted the spectra to indicate the presence of pure anorthosite deposits. This interpretation is supported by the Clementine iron map (Plate 2), which shows a very low iron deposit ($\text{FeO} = 0\text{--}2\text{ wt \%}$) in association with each previously identified anorthosite occurrence (e.g., Mersenius C) as well as at several newly found locations (e.g., De Gasparis G). These outcrops of anorthosite are similar to those found at other basins we have studied; they occur as ring massifs or small craters superposed on elements of basin ring terrain [e.g., *Spudis et al.*, 1984; *Hawke et al.*, 1991]. They are confined primarily to the Gassendi ring of Humorum, suggesting, by analogy with Orientale, where anorthosite is confined to basin inner rings [*Bussey and Spudis*, 1997], that the Gasendi ring is an inner ring, and that the true topographic rim of Humorum basin is the 800 km diameter Letronne ring, as postulated by *Wilhelms* [1987]. We note that there appear to be many fewer anorthosite outcrops at Humorum than at either Orientale or Humboldtianum [*Bussey and Spudis*, 1996], possibly reflecting a more mafic target for the Humorum basin compared with these other features, or a nonuniform anorthosite layer in the lunar crust. Humorum is on the periphery of the Procellarum geochemical province [*Wilhelms*, 1987; *Haskin*, 1998], which may be partly responsible for the mafic nature of its ejecta. Alternatively, the apparent enrichment of iron in Humorum basin deposits may be caused by the local incorporation of preexisting ancient maria into the basin continuous deposit. The Humorum region is a known site for extensive ancient mare volcanism [*Schultz and Spudis*, 1979, 1983; *Hawke and Bell*, 1981]. During deposition of Humorum ejecta, local mare basalt substrate could have been incorporated into the continuous deposits by energetic local mixing and secondary cratering [*Oberbeck*, 1975]. Such an incorporation would result in an apparently more mafic (i.e., more iron-rich) basin deposit than for ejecta deposited on normal, nonmare highlands terrain.

5. Nectaris

5.1. Geologic Setting

Nectaris is a multiring basin, centered at 16°S , 34°E , whose formation 3.92 billion years ago [*Spudis et al.*, 1984; *Wilhelms*,

1987] defines the beginning of the Nectarian period. Previous compositional studies of this basin using Apollo data were limited to a narrow strip across the northern part of the basin and to Earth-based spot spectra for selected fresh craters [*Spudis et al.*, 1989a]. With Clementine data we are able to analyze the composition of its entire deposits. Nectaris basin structure is poorly developed in the north and east of the basin, probably because of the presence of earlier basins, namely, Tranquillitatis and Fecunditatis, which may have inhibited or subdued the ring-forming process in this sector. The basin rim is 860 km in diameter, represented in the southwestern portion of the basin as the Altai Mountains. Three inner rings are recognized and have diameters of 240, 400, and 620 km [*Spudis*, 1993]. The 400 km ring bounds the mare, and it and the 620 km ring may be analogous to the Montes Rook rings of Orientale basin. Outside the Altai ring, a subdued ring, 1320 km in diameter, underlies the Apollo 16 landing site. The textured ejecta blanket of Nectaris is known as the Janssen Formation, and it lies entirely outside the Altai ring. It is best preserved to the south-east of Mare Nectaris. The Descartes Formation in the western exterior is believed to consist of Nectaris ejecta that has subsequently been modified by secondary impacts from the Imbrium event [*Spudis et al.*, 1989a]. Both Janssen and Descartes Formations thus represent the remnants of basin ejecta analogous to the Hevelius Formation of Orientale. Geologic maps for the Nectaris basin are given by *Wilhelms and McCauley* [1971], *Wilhelms* [1972], and *Spudis* [1993].

5.2. Composition of the Nectaris Basin Deposits

Clementine data (Plate 3) show the highlands to be relatively feldspathic ($\text{FeO} = 2\text{--}6\text{ wt \%}$) [*Bussey et al.*, 1997b], consistent with the results from previous work [*Spudis et al.*, 1989a]. Ejecta in the eastern sector appears to be slightly more mafic ($\text{FeO} = 4\text{--}8\text{ wt \%}$) than deposits on the western side of the basin ($\text{FeO} = 2\text{--}6\text{ wt \%}$). Earth-based spectra had previously identified outcrops of pure anorthosite in the inner, 400 km diameter ring of Nectaris (e.g., in the crater Bohnenberger F) as well as in the walls of the crater Kant [*Spudis et al.*, 1989a]. Our findings support these data (the iron map of the Nectaris basin (Plate 3) shows very low iron contents in association with each previously identified anorthosite deposit) and also indicate more outcrops of pure anorthosite in association with the craters Cyrillus E and Beaumont D.

In general, there appear to be three principal compositions associated with Nectaris, each correlating with different ejecta facies. The Descartes Formation to the west of the basin is the most feldspathic ($\text{FeO} = 2\text{--}6\text{ wt \%}$; $\text{TiO}_2 = 0\text{--}1\text{ wt \%}$). Such an anorthositic composition is consistent with the highly aluminous nature of the Apollo 16 North Ray crater samples [e.g., *Stöffler et al.*, 1985]. The Janssen Formation occurring primarily south and east of the basin rim, is slightly less feldspathic ($\text{FeO} = 4\text{--}8\text{ wt \%}$; $\text{TiO}_2 = 0\text{--}1\text{ wt \%}$) but more extensive. Just within the basin rim are even more mafic deposits, near the crater Censorinus; these knobby highland materials [*Wilhelms*, 1972] may be the Nectaris analogues to the Montes Rook Formation of Orientale basin and have compositions ranging from anorthositic norite to highland basalt ($\text{FeO} = 4\text{--}10\text{ wt \%}$; $\text{TiO}_2 = 1\text{--}2\text{ wt \%}$). The three principal compositions, and their association with specific ejecta facies, are new observations and are possible only because the Clementine data cover the complete basin ejecta blanket.

6. Crisium

6.1. Geologic Setting

Crisium is a Nectarian-age basin on the eastern nearside of the Moon (centered at 17°N, 58°E). Crisium is younger than Nectaris but older than the Imbrium basin [e.g., *Wilhelms*, 1987]; its ejecta may have been sampled by the unmanned Luna 20 mission [*Swindle et al.*, 1990]. Geologic maps for Crisium are given by *Wilhelms and McCauley* [1971], *Wilhelms and El-Baz* [1977], and *Spudis* [1993]. As at Humorum, controversy has attended the determination of the dimensions of the Crisium basin. The original estimate of the basin diameter (~740 km [*Hartmann and Kuiper*, 1962]) corresponds to the ring of rugged massifs bounding Mare Crisium. This interpretation was later questioned [*Wilhelms*, 1987; *Croft*, 1981b], and a discontinuous, scarp-like ring about 1000 km in diameter was proposed as the rim crest of the basin. Topographic data provided by Clementine marginally support the smaller estimate of the rim diameter [*Spudis and Atkins*, 1996], but as at Humorum, it is still not clear which ring is the basin rim crest. Patches of relatively high (elevation of 0.5–1.0 km) terrain are concentrated along the trace of the 740 km ring. However, portions of the large, outer (1000 km) ring also display zones of comparable elevation. The results presented below provide another important compositional clue to the location of the basin rim.

6.2. Composition of the Crisium Basin Deposits

Clementine data (Plate 4) indicate that the deposits of Crisium resemble typical highlands seen around other basins [*Spudis et al.*, 1997]. General compositions appear to be feldspathic and iron-poor ($\text{FeO} = 2\text{--}8$ wt %). In general, basin terrain to the north of Crisium appears to be somewhat lower in iron than those to the south. In part, these southern mafic areas correspond to highlands that display structural troughs, which contain light plains with dark-halo craters [*Spudis et al.*, 1989b; *Spudis*, 1993]. Thus some of these areas may not correspond to true basin ejecta but maybe ancient mare deposits partly covered by highland plains [*Schultz and Spudis*, 1979; *Blewett et al.*, 1995]. Such an interpretation is supported by the observation of numerous, postbasin intertrough mare deposits, such as Lacus Bonitatis (24°N, 45°E), north of the crater Macrobis. These mare ponds are created by inter-ring flooding of mare basalt, partly masking the underlying basin (highland) deposits. Examination of the multispectral image reveals many small craters with mafic signatures, supporting the idea that intertrough basalt flooding has occurred in several areas of the southern basin deposits.

In addition to the broad, large-scale division of deposits, numerous small peaks and fresh craters occurring on or near the topographically prominent 740 km ring display an extremely “blue” signature (i.e., they have very low mafic contents) and also the lowest iron concentrations ($\text{FeO} = 0\text{--}2$ wt %). Examples include a small (5 km) crater south of Eimmart B, Cleomedes G (4 km), and portions of the walls of Proclus (28 km) (The presence of low mafic material in the walls of Proclus supports the telescopic spectral study results of *Blewett et al.* [1995]). By analogy with similar deposits seen at Orientale [*Spudis et al.*, 1984; *Hawke et al.*, 1991; *Bussey and Spudis*, 1997], Humorum [*Bussey et al.*, 1997a; *Hawke et al.*, 1993], and Humboldtianum [*Bussey and Spudis*, 1996], we believe that these features are exposures of pure anorthosite. The pattern of anorthosite distribution at Crisium basin mimics that seen in

these other basins, i.e., the isolated exposure of numerous peaks within an inner basin ring. Pure anorthosites are confined almost exclusively to the mare-bounding 540 km diameter basin ring. The topographically prominent 740 km ring shows anorthosite only in the vicinity and walls of Proclus. If the 740 km diameter ring was an “inner” ring, as required by the “large basin” models of Crisium [e.g., *Croft*, 1981b; *Wilhelms*, 1987], it might be expected to display more anorthosite deposits. However, at Orientale, anorthosites are confined mostly to the Inner Rook ring, and the Outer Rook shows far fewer occurrences. Thus we contend that the 540 km ring of the Crisium basin is most definitely an inner ring, while the 740 km ring may be an inner ring. If the 740 km ring is an inner ring, Crisium is one of the largest basins on the Moon, approaching Imbrium (1200 km diameter) in size.

7. Conclusions

Orientale ejecta deposits are the most feldspathic of the four basins studied in this paper, probably indicating that the basin formed in the thickest crust. Many anorthosite outcrops are associated with the inner rings of the basin, representing material that has been uplifted from within the crust. Anorthosite deposits suggest that the Gassendi ring of Humorum is an inner ring, making the Letronne ring the true topographic ring of Humorum basin. Humorum has the most mafic ejecta of the basins studied. This could be because it hit a more mafic target (i.e., the lunar crust is more mafic in this region) or, alternatively, because Humorum ejecta is locally mixed with preexisting ancient maria, which subsequently makes the ejecta composition appear more mafic. Nectaris ejecta consist of three principal compositions, each one associated with a different ejecta facies. Also, several new outcrops of anorthosite, associated with Nectaris inner rings, are identified. Anorthosite deposits are found in both the 540 and 740 km rings of Crisium. The evidence is thus inconclusive as to which ring is the main topographic ring of the basin. Southern Crisium ejecta appears more mafic than northern ejecta, but this may be due to the presence of ancient buried mare deposits south of the basin, rather than any lateral crustal compositional difference.

Analysis of the composition of lunar basin deposits allows us to investigate the stratigraphy of the Moon's crust. Our findings are consistent with a three-layer model for crustal structure [*Hawke et al.*, 1992; *Spudis et al.*, 1999a]. The uppermost layer (“megaregolith”) is a mixed zone, tens of kilometers thick and feldspathic in nature ($\text{FeO} = 2\text{--}6$ wt %). This zone formed by billions of years of repeated impacts that mixed, crushed, and brecciated the upper portions of the crust. The megaregolith layer overlies what is apparently an almost global zone of nearly pure anorthosite; this anorthosite, now exposed almost exclusively in basin inner rings, is the remnant of the primordial crust of the Moon. This layer has very low iron content ($\text{FeO} < 2$ wt %) and may not be contiguous over the entire Moon (e.g., it may be largely absent in parts of the Procellarum region [*Bussey et al.*, 1998; *Spudis et al.*, 1999b]). The lowest part of the crust, excavated by only the largest basins, such as Imbrium [*Bussey et al.*, 1998; *Spudis et al.*, 1999b] (and possibly Humorum), is much more mafic ($\text{FeO} = 6\text{--}10$ wt %). The petrologic nature of the lower crust remains uncertain, and our future work will attempt to elucidate its occurrences and properties to better constrain crustal structure and origin.

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