LUNAR COLOR BOUNDARIES AND THEIR RELATIONSHIP TO TOPOGRAPHIC FEATURES: A PRELIMINARY SURVEY

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Abstract. By combining UV negatives with IR positives of the full Moon, it is possible to suppress albedo differences and to enhance color differences between various lunar regions. Areas within the lunar maria exhibit the greatest color variations, and many have sharp boundaries. In contrast, the terrae in general show only feeble color variations, although small terra regions situated near or surrounded by maria sometimes display enhanced redness.

The mare color boundaries in some cases coincide with the edges of clear-cut lava flows, the bluer material overlying the redder. One wedge-shaped area of bluer material corresponds with a prominent sinuous rille, the rille source being situated precisely in the point of the wedge. This area has obliterated portions of two ray systems, showing that the bluer material was deposited later than both the surrounding redder material and the ray material. On the other hand, rays from the crater Olbers A cross both colored areas impartially. Other examples of ray obliteration by bluer deposits are found elsewhere. From Apollo and Surveyor analyses, it is found that there is an apparent correlation between degree of blueness and titanium content of the surface materials.

The following conclusions may be drawn:

(a) The various maria were deposited over considerable lengths of time; this does not support the fusion-through-impact hypothesis.

(b) The bluer materials, which appear to be those of high Ti content, are the more recent.

(c) The hypothesis that sinuous rilles are lava drainage channels is supported.

(d) The terrae covered by this study are mostly monotonous, suggesting constant composition, but a few anomalously red isolated regions may be of substantially different composition.

1. Lunar Surface Colors

The existence on the lunar surface of areas displaying slightly contrasting tints has long been known, and an excellent review and bibliography of this subject may be found in McCord (1968). Until recently, the most convincing demonstration of the presence of such color variations was the group of six small-scale photographs of the Moon taken through UV and IR filters by Wright (1929). These images show notable differences, but a detailed comparison is difficult because of the swamping effect of albedo differences.

The writer appears to have been the first to attempt to apply the technique of 'composite analytical photography' (Zwicky, 1953) to the Moon. With certain provisions concerning the response characteristics of photographic emulsions, it should be possible to eliminate reflectivity differences and to isolate color differences by combining a negative taken through a filter of one color with a positive made from a negative taken through a filter of a different color. On the assumption that reflectivity varies approximately with wavelength for each different colored area, the greatest contrasts should be obtained with the greatest wavelength separation.

Experimental composites made in 1959 from the Wright prints showed that the method was feasible, although differential scales prevented accurate registration of positives and negatives. Further preliminary composites prepared from plates taken

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by the writer with the 82-in. reflector of the McDonald Observatory on 1964 May 29 showed considerable promise; two of these and a Wright composite are reproduced in Kuiper *et al.* (1965).

Recently, the same negatives were used to produce far more trust worthy composites. Details of the procedure are beyond the scope of this preliminary survey, and will be published at a later date. A mosaic was prepared from the four best UV-IR plate pair composites, which is reproduced in Figures 1 through 3. Since these represent IR minus UV, lighter areas are redder, darker areas bluer.

2. Brief Description of Composites

Figure 1 includes all of Mare Imbrium and much of its surroundings. Many familiar landmarks, such as Sinus Iridum, Mare Frigoris, Timocharis etc. are virtually lost to view, while many unfamiliar markings and boundaries make their appearance, especially in Mare Imbrium and Sinus Roris. Some boundaries are quite sharp while others are fuzzy. The terra regions on the NNW limb show very little color variations, but

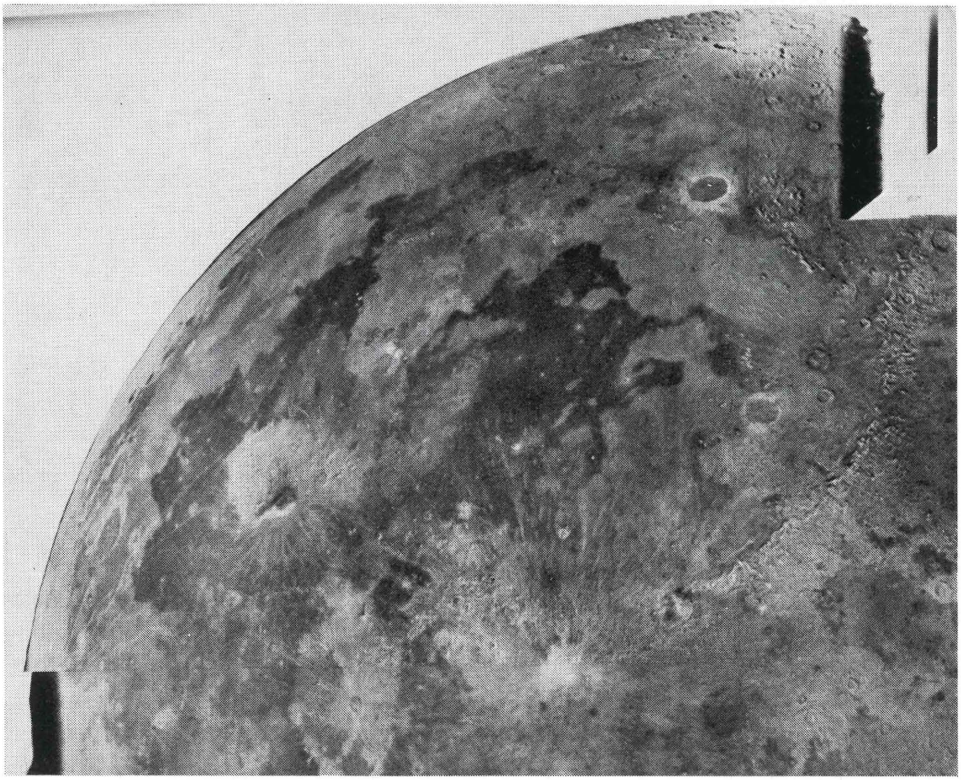

Fig. 1. IR minus UV composite photograph of Moon's NW quadrant. Redder regions, such as the walls of Plato and Wood's Spot near Aristarchus, appear lighter.

the rims of Plato and Archimedes, Mt. La Hire, the S. rim of Aristarchus, and the two peculiar mountains Gruithuisen gamma and delta (see Figure 5). are seen to be abnormally red. Abnormally blue areas are found in and to the north and west of Aristarchus, in Eratosthenes, in Sinus Roris and elsewhere. The color contrasts in northern Mare Imbrium and Sinus Roris appear to be the most intense on the Moon.

Figure 2 portrays the area immediately to the south of Figure 1, and includes Mare Nubium, Mare Humorum and southern Oceanus Procellarum. Color contrasts in

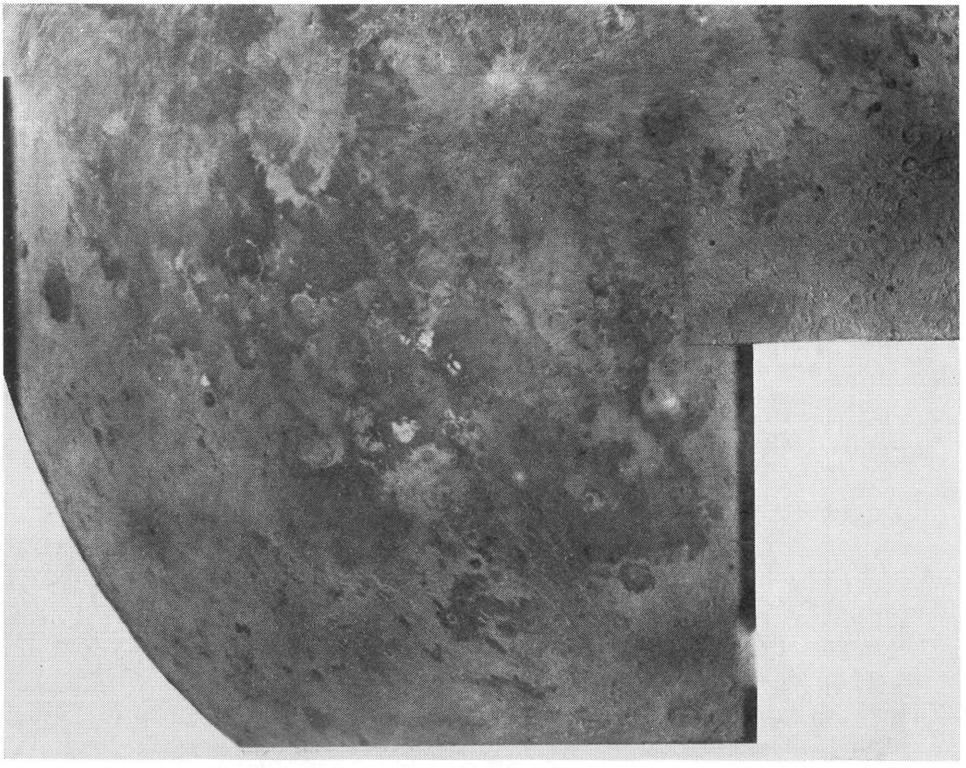

Fig. 2. Composite photograph of SW portion of Moon. Note the lack of color boundaries in the terra regions.

these maria are less intense than those in Mare Imbrium, and the boundaries are mostly poorly marked. The most notable features are the oval reddish area surrounding Kepler, and the reddish border to Mare Humorum. The terra regions near the limb are seen to be devoid of color differences apart from mare puddles and bright craters, but some anomalously red features are prominent. These are the peculiar bright mountain Hansteen alpha, the southern tip of Montes Riphaeus and some low hills to the SE, the helmet-shaped area at the inlet to Mare Humorum, and an area surrounding the anomalous craters Lassell C, G, and K.

Figure 3 adjoins the previous figures, and includes Maria Tranquillitatis, Serenitatis, Vaporum and part of Fecunditatis. The most prominent feature is the boundary between the first two of these maria, which extends to form a border of bluish material to each. Numerous small areas showing color contrasts are widely scattered over the whole region.

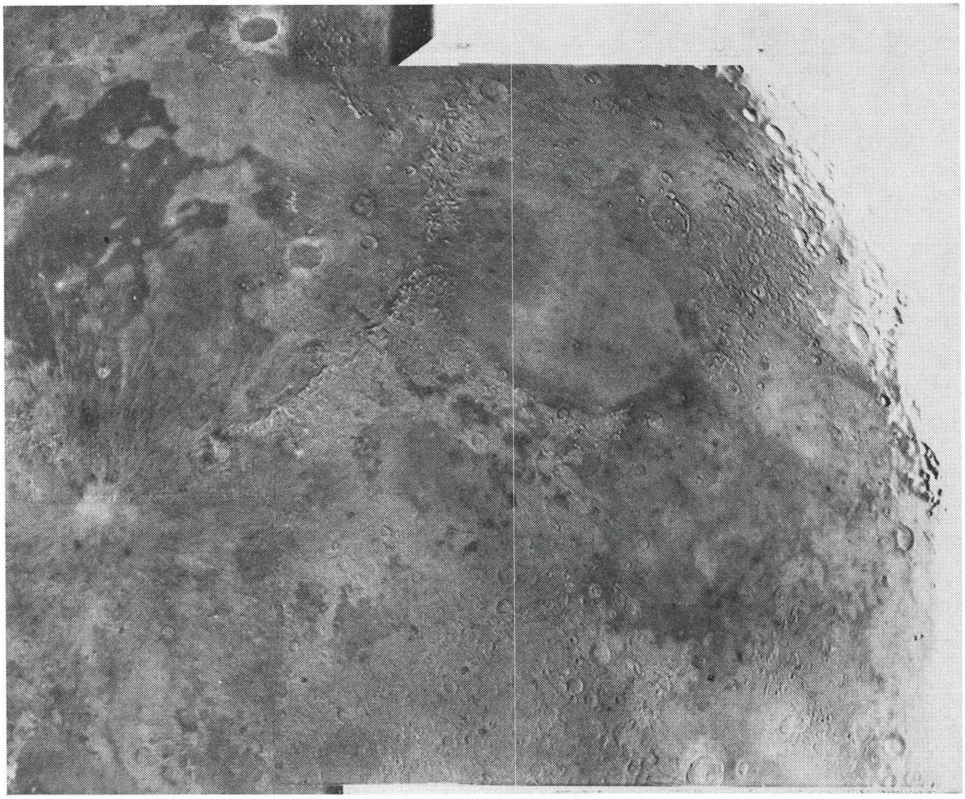

Fig. 3. Composite photograph of NE portion of Moon. The low sun angle gives spurious effects in shadows and bright crater rims.

3. Mare Imbrium Colors and Topography

Strom noticed some years ago that one of the color boundaries in Mare Imbrium corresponded exactly with one of the major flow fronts which stretch from near Euler to a point east of LeVerrier (see Kuiper *et al.*, 1965, pp. 31, 32). The Apollo 15 metric camera photography has provided some spectacular views of most of the southern and central regions of this unique system of lava flows, with the result that it is now possible to correlate other color boundaries with flow fronts. Preliminary results of this study are shown in Figure 4, where full lines indicate definite flow fronts, dashed

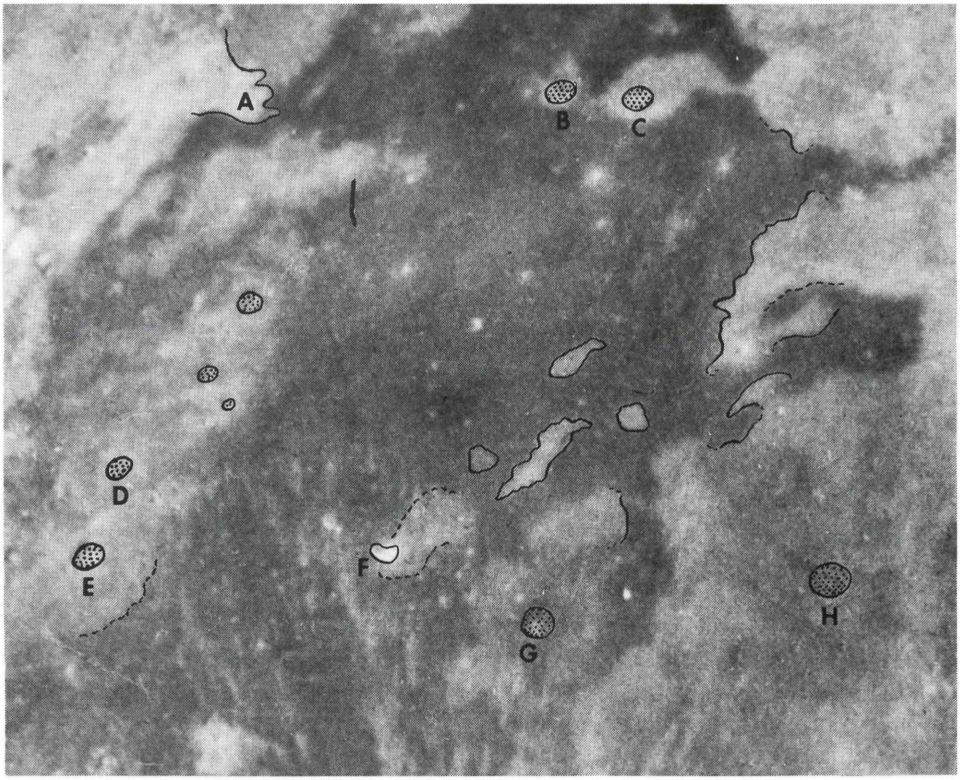

Fig. 4. Central and western Mare Imbrium, showing correspondence between color boundaries and flow fronts. A, Prom. Heraclides; B, Helicon; C, LeVerrier; D, Delisle; E, Diophantus; F, Mt. La Hire; G, Lambert; H, Timocharis.

lines possible fronts. The four irregular patches of redder material lying north of Lambert are seen to be enclosed by low flow fronts (i.e. they are 'kipukas'), confirming the theory that the redder material represents an earlier filling of the Imbrium basin.

A preliminary examination of the Apollo 15 photographs, viewed both monoscopically and stereoscopically, leaves little doubt that the source of the 'blue' material comprising the major flows is situated somewhere to the southwest of Euler. The lavas have flowed in a general north-easterly direction, indicating the direction of slope which existed in Mare Imbrium at the epoch of the eruption. The point of termination of the flow system, near Le Verrier, is very near the center of Mare Imbrium, which suggests that the older filling of redder lavas never ponded to form a level surface, and that the later bluer lavas simply ran downhill to the lowest area at the center. These photographs also show clearly that most if not all of the mare ridges were formed subsequent to the solidification of the flows. Thus several flows appear to cross ridges whose height is many times the thickness of the flows, an impossibility had the ridges preceded the flows.

4. Sinus Roris Colors and Topography

From Figure 1 it is seen that the eastern portion of Sinus Roris is one of the 'bluest' extended areas covered in this study. Strom (1970) noticed that the pointed southern extremity of this area coincided exactly with the source of a prominent sinuous rille (S_M). This, of course, is a very strong argument in favor of the theory that sinuous rilles are lava drainage channels, the rille being the course of the main lava stream

Fig. 5. Full Moon photograph of Sinus Roris and northern Oceanus Procellarum, showing covering of ray systems by bluer material, and correspondence between the sinuous rille Rima Sharp I and the bluest region. A, region of very 'blue' material; B, region of less 'blue' material; C, abrupt cut-off of rays from Pythagoras; D, abrupt resumption of rays; L, Lichtenberg and half-covered ray system; R_S Rima Sharp I and its source S_S; R_M, anonymous rille, named here the Mairan rille, and its source S_M; M, 'red' mountains, Gruithuisen gamma and delta.

while thinner flows spread over the adjacent surface. That this 'blue' area represents a later flow over a previously existing 'red' covering is proved by the fact that portions of two prominent ray systems are covered up by it. Figure 5 is a full Moon view of the region on which the boundaries of the blue material are shown; A is the area of bluest material, while B is somewhat less blue. The rays seen to the north of these areas, which appear to emanate from Pythagoras, stop abruptly at C, and resume again at D. L is the ray crater Lichtenberg, formed in the older 'red' material. At first sight, the ray system appears to be similar to that of Proclus, i.e. with an occluded zone. However, a closer examination of available photographs shows that this is not the case, and that part of the system has been covered up by the blue deposit B. Similar occurrences may be seen in Mare Imbrium, e.g. the 'blue' material closing the entrance to Sinus Iridum has covered some rays (again, apparently from Pythagoras) which are quite prominent on the redder material of the Sinus. On the other hand, rays from the craters Aristarchus, Olbers A, and an anonymous farside crater, cover both the red and blue materials impartially.

5. Time Sequence of Events

We may now set up a time sequence of events for both Mare Imbrium and Sinus Roris as follows:

A. Mare Imbrium

(1) Formation of Imbrium Basin.
(2) Flooding of Basin by 'red' basalts, but center still lower than edges.
(3) Formation of crater Pythagoras and its ray system.
(4) Partial flooding by 'blue basalts' from sources SW of Euler.
(5) Formation of mare ridges, and craters Aristarchus and Copernicus.

B. Sinus Roris

(1) Flooding by 'red' basalts.
(2) Formation of Pythagoras and Lichtenberg and their ray systems.
(3) Deposit of bluish basalts B (Figure 5).
(4) Deposit of blue basalt A (Figure 5) and formation of Mairan and Sharp rilles (R_M and R_S).
(5) Formation of mare ridges.
(6) Formation of Aristarchus, Olbers A etc. and their ray systems.

6. Interpretation of Color Differences

These could be due to compositional differences, physical differences (grain size, rock admixture, etc.) or solar wind effects. The general physical similarity between regolith samples from different sites, the virtually uniform photometric characteristics of the lunar surface, and other considerations, lead one to the conclusion that different colors indicate different compositions. Goetz *et al.* (1970) reach a similar conclusion.

Strom (1970) noted that of the elements likely to produce color, only Titanium content correlated with color, the bluer materials being richer in Ti. Results from more recent Apollo missions have not contradicted this observation, see Table I, and McCord *et al.* (1972) independently reach the same conclusion.

TABLE I

Chemical Analysis of Regolith

Color	Site	Mission	TiO_2 %	FeO %
Bluest	Mare Tranquillitatis	Surveyor 5	7.6	12.1
—	Mare Tranquillitatis	Apollo 11	7.5	15.7
—	Sinus Medii	Surveyor 6	3.5	12.4
—	Oc. Procellarum	Apollo 12	2.9	16.5
—	Fra Mauro	Apollo 14	1.8	10.0
Reddest	Tycho	Surveyor 7	<1	5.5

7. Conclusion

The application of the technique of composite analytical photography to the lunar surface appears to be a powerful tool for the interpretation of the history of the lunar surface. Small differences in composition apparently cause readily detectable color differences. Correlation of the colored areas with topographical features sometimes allows a reliable time sequence of events to be drawn up. A more detailed analysis will be published at a later date.

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