No. 117 LUNAR CRATER COUNTS. IV: MARE ORIENTALE AND ITS BASIN SYSTEM

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ABSTRACT

Parts I and II present crater count observations of the mare surface and the ejecta blanket of the Orientale basin. Mare Orientale has the crater density of average maria, 1.0, and the ejecta blanket has an unusually low crater density for an upland surface, 2.4. This is the lowest known post-basin crater density, testifying to the youth of the system. Supplemental observations, based on Orbiter photography, are presented in part III. Part IV discusses the physics of the hypothetical, nuée ardente-like cloud which swept out from the impact site, depositing the striated, highly-structured blanket shown in the Orbiter photographs. Part V summarizes the history of the Orientale basin system. The extraordinary clarity of the radial and concentric lineaments is attributed to the youth of the system and the probable coincidence in time of the impact and the beginning of the mare-forming period, with the shocked "crust" collapsing into the plastic substratum along impact-produced fractures.

1. The Mare Surface — Observations

Figure 1 shows the floor of Mare Orientale and Figure 2 shows the diameter distribution of craters there. On Figure 2 the average mare crater density has been drawn and it is seen that no significent departure from this is detected. Normalizing to the average crater density, we can list Mare Orientale as having crater density 1.0 ± 0.1.

The counts used in this determination were made from Orbiter IV photograph 195. Special care was used to avoid contamination from the abundant secondaries of the large unnamed crater in the northern part of the floor, and the data of Figure 2 refer principally to the southern half of the floor. The largest diameters available were limited by the small area of the mare, and the smallest, by the resolution of the Orbiter "medium resolution" photography.

Mare Veris and Mare Autumni, two arcuate strips along the bases of two concentric fault scarps around the basin, appear to have significantly higher crater densities than the central Mare Orientale (see Fig. 2).

2. Orientale Ejecta Blanket — Observations

In view of the relatively young age attributed in earlier *Communications* to the Orientale basin system on the basis of structural studies (Hartmann and Kuiper 1962; Hartmann 1964), it is predicted that the crater density on the ejecta blanket should be considerably less than the ambient, "pure continental" crater density, which refers to the oldest portions of the lunar surface. WRH has speculated (1964, p 177) that the Orientale basin may have originated "late in the period of mare formation," although obviously before the present, uppermost (undisturbed) surfaces of the various nearby maria were laid down.

Now it is possible to test these ideas with the excellent photographic coverage of the whole Orientale region by Orbiter IV. Figure 3 shows a typical portion of the radially striated ejecta blanket east of Mare Orientale, and Figure 4, the crater diameter distribution thereon. It can be seen that the post-basin craters of the ejecta blanket accurately parallel the post-mare craters, and that at least the first of the above predictions is essentially verified: there is more than an order of magnitude deficiency

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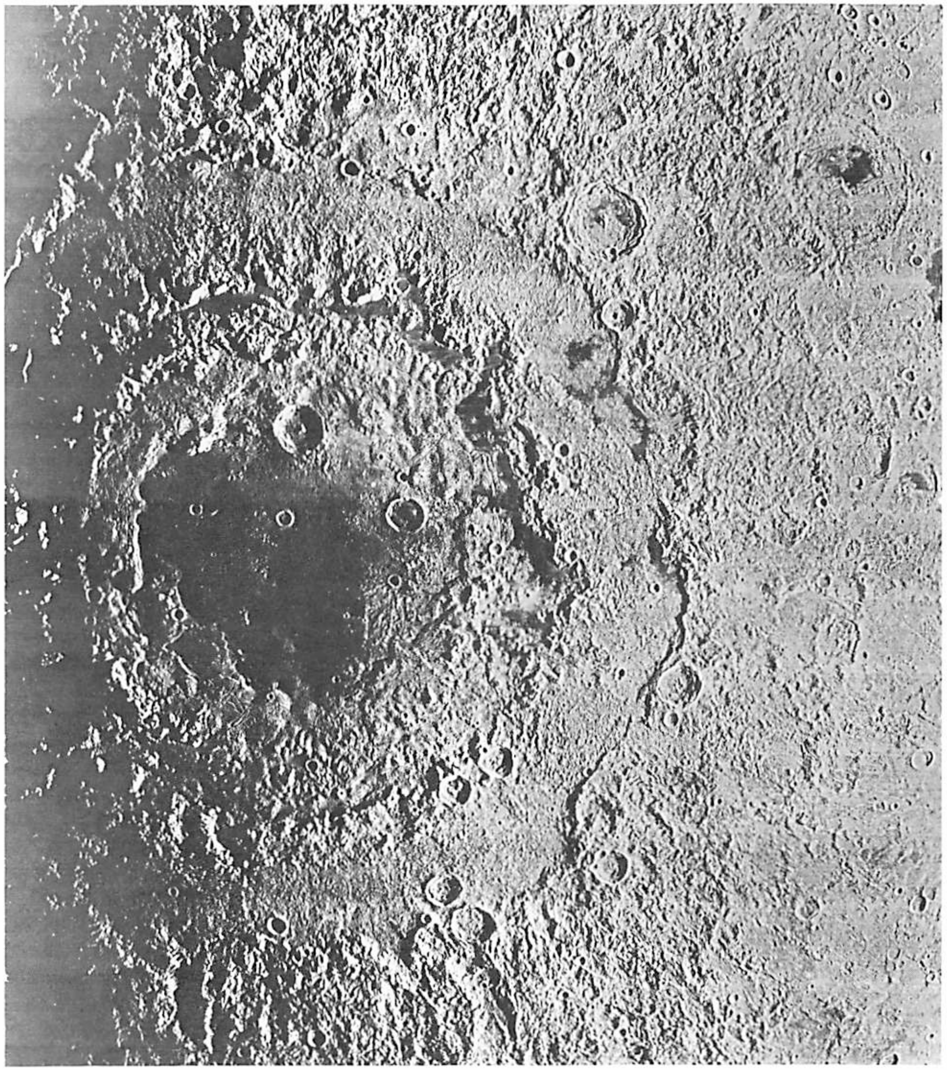

Fig. 1 Mare Orientale and its basin system. The central mare is surrounded by multiple ring-scarps and arcuate maria Veris (NW to E) and Autumni (patchy mare on E). NASA Orbiter IV, Frame 187, medium resolution.

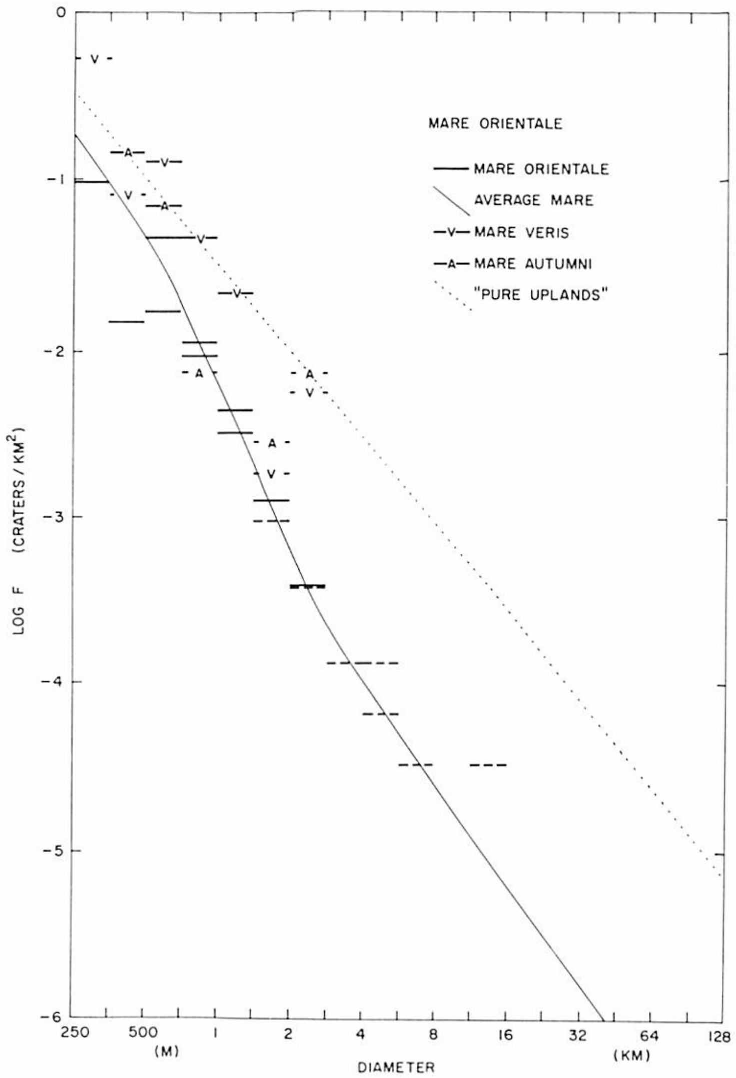

Fig. 2 Incremental diameter distribution of craters in Mare Orientale and nearby arcuate maria, showing coincidence with counts for all maria averaged over the front side. Dashed bars given ½ weight. F defined in Paper I.

of post-Orientale craters over normal "pure continental" density. As for the formation of the Orientale basin late in the mare-forming period, it can be seen that there are measurably more post-basin craters than post-mare craters, by a factor of about 2.4 ± 0.2 (est. P.E.). When compared with the results of Paper III (Hartmann 1968*a*), this figure indicates formation of the Orientale basin somewhat before the oldest exposed mare surfaces were laid down, such surfaces having crater densities of about 1.6 (normalized to average maria). The point in time indicated by crater density 2.4 may have been well into the period of mare formation, even though the earliest of the now-visible surfaces had not yet been formed. Note that these crater density figures do not give relative *ages;* the flux was probably decreasing rapidly at this time and hence the figures are wide upper limits on the relative ages (cf. Paper III). In any case the present data suggest that the Orientale basin is best described as forming not "late" in the mare-forming period, but rather shortly preceding or during that period, before any of the other present maria were intact. The factor 2.4 is the smallest known post-basin crater density (cf. Paper III), indicating that the Orientale basin is the youngest of the great, multi-ring basin systems.

3. The Basin System — Miscellaneous Observations

Figure 3 shows the fine parallel striations of the ejecta blanket surface. These structures have widths of several hundred meters up to 1 km, considerably smaller than the radial and concentric structures attributed to faults and tectonic adjustments in *Communication LPL 36* (Hartmann 1964). Additional dissimilarities are (1) lack of orthogonal (radial and concentric) gridding and (2) occasional pronounced curvature of the striations, often near major relief, (see Fig. 3). The latter characteristic gives the striations a pattern suggestive of turbulent flow.

The faces of the concentric scarps surrounding the Orientale basin are poorly exposed to sunlight in the Orbiter photographs, but in the few locations where the lighting is good, the face appears smooth, perhaps layered over with talus, with only a few outcrops or boulders (Fig. 5). No diagnostic features have been found to date the scarps positively as pre-or post-ejecta blanket.

Within the Orientale inner basin can be seen concentric rilles similar to those of Humorum and other circular maria except that they distinctly *cut across old, unflooded portions of the surface,* (Fig. 6). This shows that the concentric rille patterns are *not* intrinsic to the surficial mare material, but rather are deep-seated products of the basin system development. Probably they result from the sagging of the newly flooded basin, just as the concentric fault scarps are the result of sagging of the "crust" as a whole. Consistent with this, the major rille shown in Figure 6 follows exactly the arc of the incomplete "second ring" of the concentric ring system.

4. Physics of the Ejecta Cloud

It was noted above that the surface of the ejecta blanket around the Orientale basin has the appearance of having been striated by the flow of a fluidized medium over its surface.

One can show that turbulent flow would indeed be expected in cloud expanding from the central explosion and passing surface obstacles of dimension about 10 km, such as those indicated. The Reynolds number is

$$\mathrm{R} = \frac{\mathrm{v\,L}\,\rho}{\nu} \qquad (1)$$

where v is the expansion velocity, L the obstacle or eddy dimension, ρ the density of the expanding cloud, and ν the cloud's viscosity (ν/ρ is the kinematic viscosity). Assuming $\mathrm{v} \geqq 10^4$cm/sec and $\mathrm{L} = 10^6$cm, and since ν for a variety of volatiles and temperatures is $\sim 2 \times 10^{-4}$ gm/sec cm, we have

$$\mathrm{R} \geqq 5 \times 10^{13}\,\rho \qquad (2)$$

It remains to find a value for ρ. The volatile content of meteoritic, basaltic, and granitic material is of the order 10^{-2} by mass. Thus, if only 10^{-4} of the 10^{22} grams dislodged in the Orientale impact were degassed (i.e. even if only the impacting projectile were degassed) we would have 10^{18} gm of gaseous material erupted from the impact site. The striated pattern is clear even beyond the "Rocca ring" of the concentric pattern, which has a radius of about 650 km, and thus if the expanding cloud were of uniform density and hemispherical, then as it swept over the surface 650 km from the impact site, the gas density would be of the order 10^{-6} gm/cm^3, with a much higher density of solid particles, perhaps 10^{-2} gm/cm^3. The figures derived above are lower limits, and it appears clear that the Reynolds number greatly exceeds unity. Taking into account the entrained solids, one finds the gas pressure insufficient to support the cloud, which would thus be compressed against the surface.

The gas cloud will propagate outward at not more than about 10^5 cm/sec, and hence to an

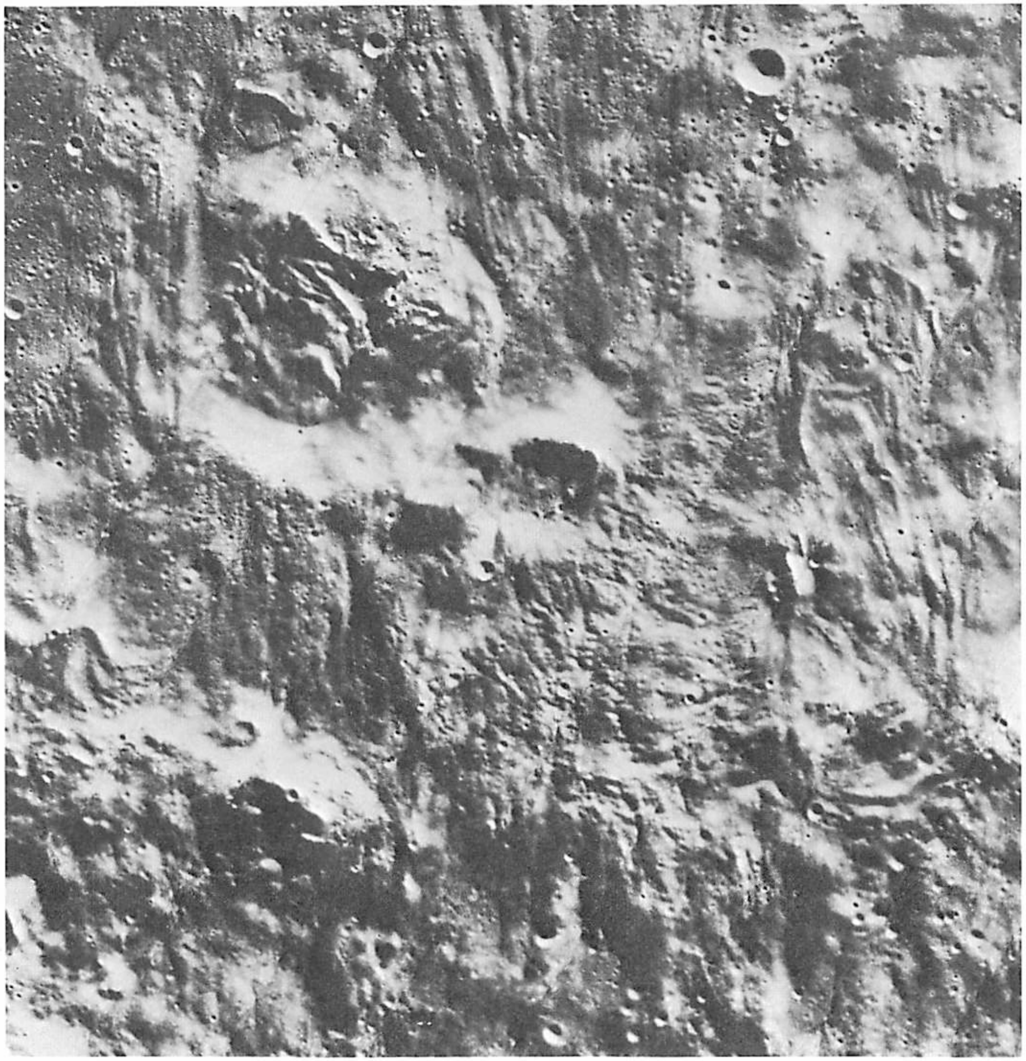

Fig. 3 Portion of the striated ejecta blanket of the Orientale basin (toward bottom). Width of this view is approx. 94 km; the striations are of the order 1 km wide. NASA Orbiter IV, Frame 173, high resolution.

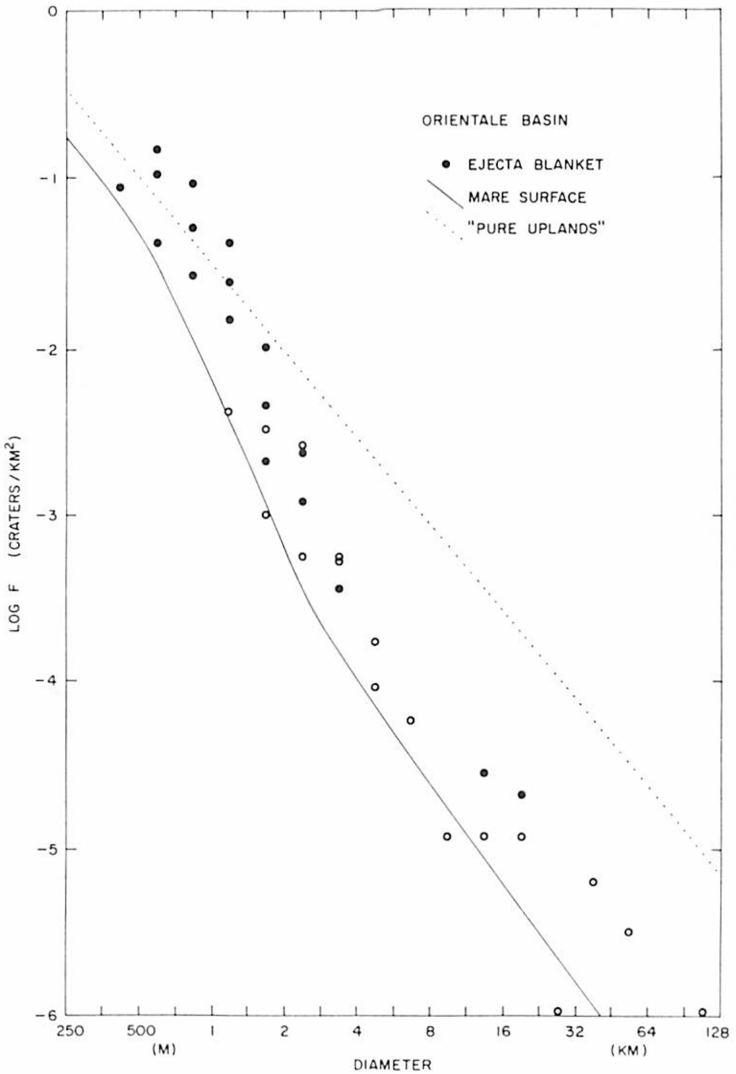

Fig. 4 Incremental diameter distribution of craters on the Orientale ejecta blanket WNW of Mare Orientale. There are significantly more craters than on the mare surface, but with a similar diameter distribution. Open circles given ½ weight.

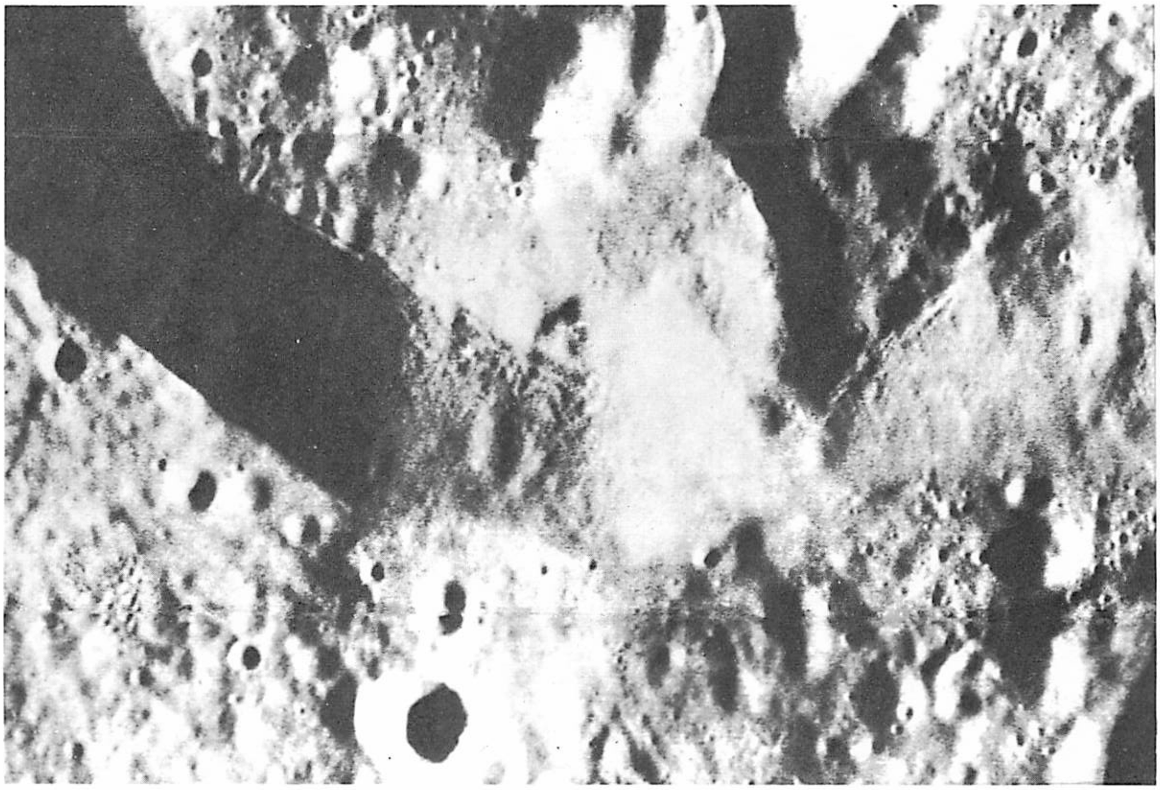

Fig. 5 Portion of the face of the "Eichstadt ring" scarp N of Mare Orientale, showing possible outcrops on the scarp face. NASA Orbiter IV, Frame 195, high resolution.

observer 650 km from the impact site, the rain of material would probably have a duration of several minutes. It would be, in essence, a *fluidized* system. This hypothetical phenomenon has many of the characteristics of a terrestrial nuée ardente flow, "highly heated gas so charged with incandescent ash particles that it resembles a mobile emulsion, yet dense enough to maintain contact with the surface as it rushes down the slopes of the mountain with hurricane force" (Bullard 1962).

The famous Pelée nuée ardente eruption of 1902, which destroyed the city of St. Pierre and 30,000 people, travelled at velocities approaching 10^4 cm/sec and swept over the city in only a few minutes, smashing meter-thick concrete walls and carrying along three-ton masses (Bullard 1962).

The lunar surface, and presumably a freshly deposited ejecta blanket, is loosely coherent particulate matter of no great structural integrity. It thus appears likely that a major impact would send out a nuée ardente-like cloud which would, in the process of depositing an ejecta blanket, cause a storm of several minutes' duration, capable of leaving a surface covered with fine striations of width up to several hundred meters, as observed.

It should be noted that this section represents a supplement to conclusions drawn earlier. In Communications 24 and 36 (Hartmann 1963, 1964), it was argued that the large-scale radial lineaments shown on earth-based photographs were produced by tectonic action, not scouring or grooving by flying fragments. This view is still held, in essence, although some of the best photographs, e.g. Plate 24.7, show some of the fine striations now attributed to scouring by the ejecta. The striated surface, not only near Orientale but also in the case of other basins, was then fractured and broken by radial and concentric faults. Among the older basins, the striations have since been eroded and blanketed. This process has started on the Orientale lineaments, and only the youngest features, e.g. Tycho, lack such masking blankets.

5. *Interpretation of the Orientale Basin System*

In this section we will attempt to give a chronological history of the events that produced the pres-

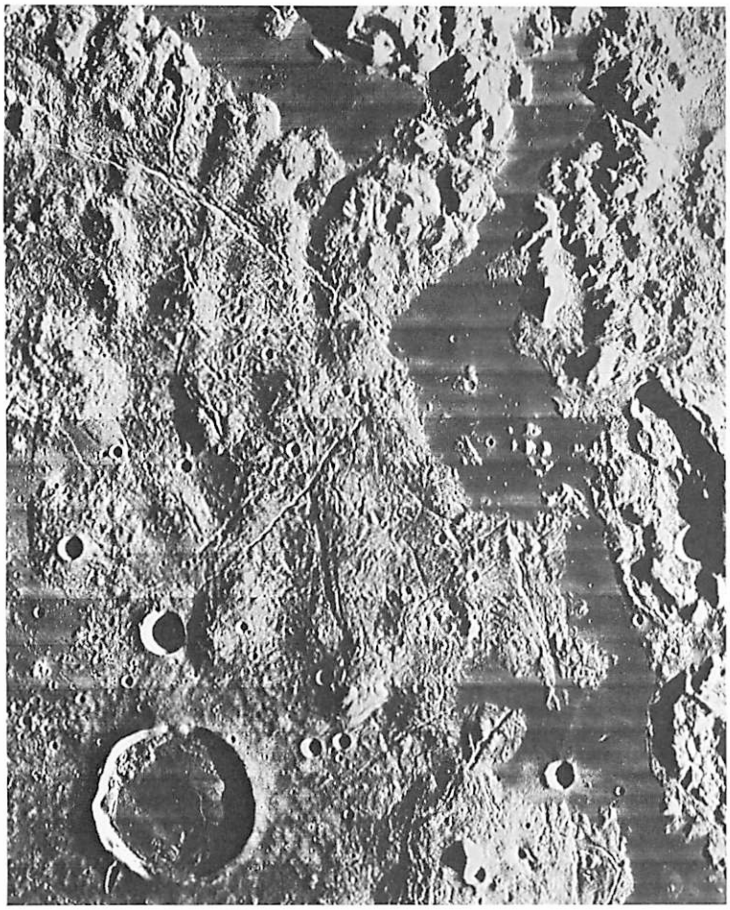

Fig. 6 NE quadrant of the "2nd ring," just inside Mare Veris, showing its expression as a concentric rille cutting across unflooded upland surfaces. This rille is a continuation of the mountainous scarp which forms most of the "2nd ring." NASA Orbiter IV, Frame 187, high resolution.

ent Orientale system. The argument that an impact, rather than a volcanic explosion or collapse, touched off these events is beyond the scope of this paper. Observations contributing to the argument are: the continuity of the crater diameter distribution from craters to basins, correspondence between this distribution and the asteroid fragment mass distribution, evidence for a point-source explosion, huge ejecta blanket, high-order radial and concentric symmetry, and energy considerations.

Baldwin's equation 8-3A (1963, pp 158-162) indicates that an energy of 4×10^{31} ergs (factor 4 est. P.E., depending on scaled depth of burst) was expended in creating the inner Orientale basin, which has a diameter of 390 km. If the impact velocity was 3 km/sec, the projectile's mass was about 9×10^{20} gm and its radius, 40 km (± 20 km est. P.E.). It was thus of size comparable to a moderate present day asteroid and close to or slightly smaller than (especially if the velocity was higher) the most common of Anders' "original" asteroids (Anders 1965). It is an interesting support of Anders' model of size distribution of planetesimals that the largest bodies striking the moon may have just reached the size of his most common "original" planetesimals and that the rest of the impacting bodies display just the distribution of size of their fragments.

The impact occurred at a time when the surface was already pre-stressed by the grid-forming forces, causing the preferential development of fractures by the expanding shock wave in the NE-SW direction and to a lesser extent, NW-SE (Hartmann, 1964; Strom 1964). Inclination of the projectile's trajectory may have also been a contributing factor. The time of this impact, on the crater density scale, was 2.4 ± 0.2, immediately preceeding or just at the beginning of the mare flooding, in accord with the high susceptibility of fracture along the grid lines (subsurface melting and heating being near maximum). Fig. 7, parts 1 and 2 show the impact and the immediately produced, fractured surface.

In the minutes following the impact, a cloud of

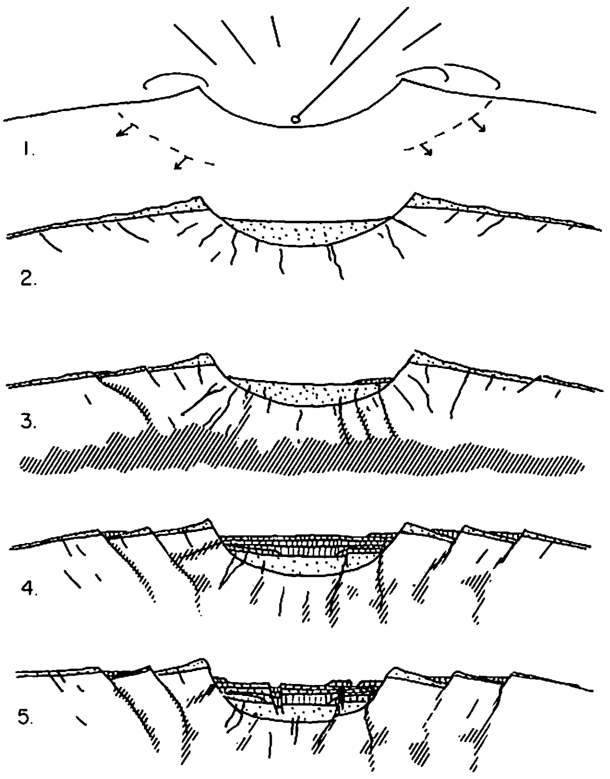

Fig. 7 Schematic history of the Orientale basin structure. Stippling represents ejecta; diagonal hatching, magma; and vertical hatching, lava flows. See text.

vaporized silicate material, volatiles, finely pulverized rock in suspension, and large fragments on ballistic trajectories was erupted and swept across the surface, in nuée ardente fashion, dropping the ejecta blanket now observed and scouring its surface.

The surface beneath the blanket, having been already fractured and perhaps faulted by the grid-producing forces, and still more highly fractured by the impact shock, was ripe for any tectonic adjustments. As subsurface melting and instrusions stepped up, approaching the climax of the mare-forming period, the Orientale surface area resembled a fractured roof, poorly supported from below. As, or perhaps even before, the subsurface magmas extruded onto the surface, gaining access particularly through the breccias of the central basin, the roof sagged and faulted in concentric rings, in the manner proposed by Fielder (1963), except that Fielder pictures the entire process from the beginning to have been endogenic; (it is difficult to account for the highly aligned radial striations and faults in this way). Fielder has pointed out that this sagging and faulting mechanism provides theoretical justification for the $\sqrt{2}$ radius ratios found by Hartmann and Kuiper (1962).

Mare material worked its way up to the concentric faults and extruded at their bases, forming the arcuate maria Veris and Autumnis. Since these maria have a crater density nearly equal to that of the ejecta blanket (Figs. 2 and 4), it appears that the collapse, formation of the scarps, and welling up of the arcuate maria occurred just after the impact, before completion of the central mare. (A number of dark halo craters, probably endogenic and typically two or three km across, increase the crater density in the arcuate maria and support the idea of deep, fault-induced volcanism there.)

The central mare was completed at about the same time as the other average maria (crater density 1.0 ± 0.1). The flooding is illustrated in Fig. 7, parts 3 and 4.

The weight of the mare fill caused the inner basin to continue to buckle downward, and the adjustments took the form of concentric rilles (Fig. 6; Fig. 7, part 5), in some cases the last lavas were extruded along these concentric inner faults, forming mare wrinkle ridges (the wrinkle ridges have been shown by R. Strom to be the sites of some of the last flows in the maria (Kuiper 1966).

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