No. 119 LUNAR CRATER COUNTS. VI: THE YOUNG CRATERS TYCHO, ARISTARCHUS, AND COPERNICUS

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ABSTRACT

The crater densities inside the craters Tycho, Aristarchus, and Copernicus are found to be respectively 0.1, 0.3, and 0.5 times the mean crater densities on maria. Ages of 2 x 10^8, 1 x 10^9, and 2 x 10^9 yr are inferred. The interior of Copernicus exhibits a number of recognizable volcanic structures. Rays accompanying these craters are probably finely pulverized ejecta and are destroyed on a time scale of about 3 x 10^9 years by stirring and mixing of the upper layers of the lunar surface to a depth on the order of a centimeter. Primary impact craters exhibit approximately a —2 power law diameter distribution to diameters as low as 250m, indicating that most hectometer-size craters (which together define a much steeper power law) are not primary impact craters.

1. Introduction

One method of dating lunar features is to divide the observed crater densities (craters/km^2) by the adopted cratering rate (craters/km^2 yr). Unfortunately, the cratering rate for the larger craters ($D > 2$ km) is uncertain, probably by a factor at least three (Vedder 1966, Hartmann 1965), while for smaller craters it is widely believed that there is significant contamination by non-primary-impact craters, probably including collapse depressions and secondary impact craters (Kuiper 1965, Shoemaker 1965). These make it difficult to identify the true primary impact craters and hence lead to uncertainties in the crater density.

Nonetheless, this method has recently been applied to the lunar crater Tycho by Strom and Fielder (1968) who counted craters of diameter *D* of the order 100 m and, using the best estimates of flux for appropriate sized meteorites, derived an age for Tycho of 1.6 x 10^8 years. (Strom and Fielder are presently applying the method to Aristarchus and Copernicus as well).

An independent approach is the method of this series of papers: we compare the observed crater densities with the average mare crater density, noting that the maria apparently mark a quite restricted epoch in lunar history (paper III, Hartmann 1968). In this series we use *relative* crater densities, 1.0 being the value assigned to the average mare. The usefulness of the scale lies in the fact that empirically-determined crater densities can be expressed *independent of D* for various lunar structures, giving a relative age scale. Absolute ages can later be given if one has further knowledge of the age of the maria and the time-development of the cratering rate. However, it is important to note that the relative crater density is most reliably determined only for $D > 2$ km, again because of the difficulties of interpretation of smaller craters of varied origin (e.g. paper I, Hartmann 1967).

2. Observations

Orbiter photographs show that Tycho has an unusually rough interior, that Aristarchus is only slightly less rough, and that Copernicus is noticeably

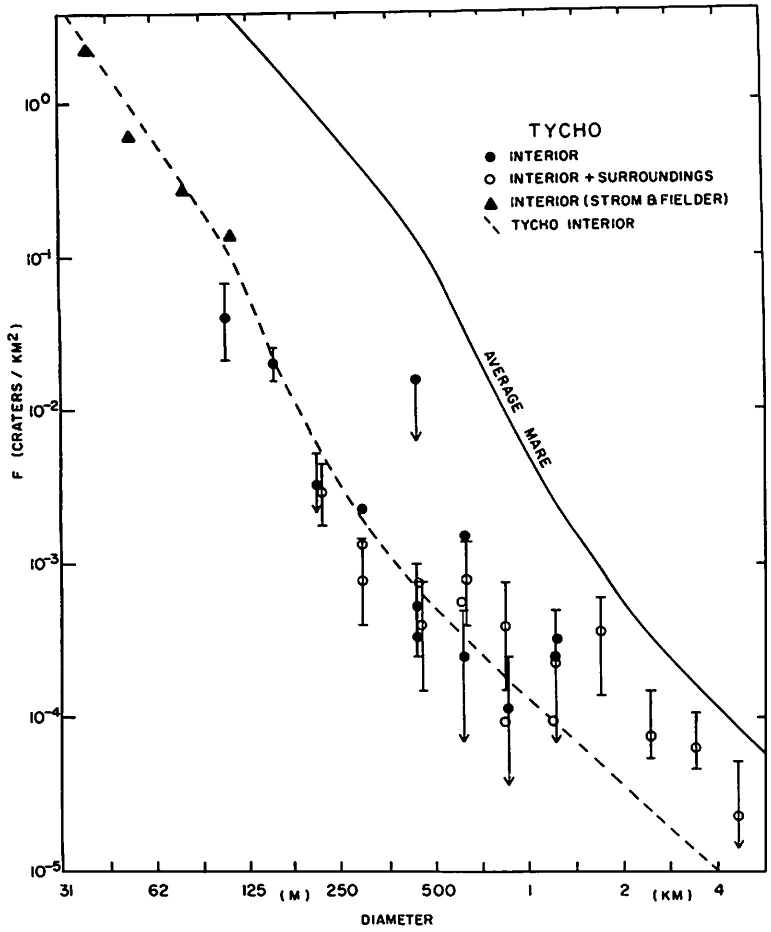

Fig. 1 Crater diameter distribution for Tycho; numbers refer to increments of $\sqrt{2}$ in D. Statistical errors are indicated for some of the data points based on few craters. The dashed curve (Tycho *interior*) is fairly well determined, being based on both the adopted slope of -2 at $D > 2$ km and on the data points.

smoother than Tycho, some sections having a flooded appearance. Coupled with their well-known ray systems, the sharp rim detail, and their thermal anomalies, this is strong evidence not only that the craters are young, but also that in the sequence named they increase in age. While no observable debris blanket overlies Tycho, one is just beginning to form in Aristarchus. Most of the rest of the moon, as shown by the Surveyors (Gault, et.al. 1967, p. 203) is blanketed by a fragmental layer of meter or decameter depth.

Crater counts bear out these inferences. Since all three craters have few overlying craters, the statistics are poor, particularly for the larger D values. Tycho, for example, has only one crater of $D > 1$ km within its rim. While it would thus appear difficult to get a meaningful relative crater density applicable at $D > 2$ km, it must be remembered that diameter distribution law apparently universally has an exponent (slope) of $-2(\pm 0.1)$ at these larger diameters, and this knowledge aids us in obtaining a well-defined crater density.

Figure 1 shows the results obtained from Tycho. Strom and Fielder have allowed me to convert their data to my system of plotting, and their counts are included. Although counts outside the rim of Tycho were made in an attempt to get more area and better statistics, these were kept separate from the interior counts, because Strom and Fielder (1968) showed that the exterior counts were both higher and variable from one stratigraphic unit to another. From this fact, they concluded that Tycho had a "multiphase" development in time, and that the exterior flow units may in fact be older than Tycho. Alternate interpretations are that Tycho secondary craters cause the variable excess in exterior crater counts, or that some other type of crater (e.g. collapse depressions) have not been adequately sorted out of these counts. In my own counts of Tycho, as in previous papers of this series, no effort was made to sort out craters of different origins, unless stated.

It can be seen that the relative crater density (measured at $D > 2$ km) in Tycho is 0.1 with an estimated P.E. of 20%. The curve drawn in Figure 1 is an estimated fit, using not only the datum points but also the slope of -2 at $D > 2$ km as parameters. Strom and Fielder's finding that crater density is higher outside Tycho than inside is now confirmed for diameters larger than those used by them.

Figure 2 shows the data for Aristarchus. Among craters larger than 125 m diameter, all counts for Aristarchus fall above those of Tycho. However, at smaller diameters the curve has a significantly different behavior, testifying again to the density irregularities among the craters of $D \sim 100$ m in various regions. Aristarchus is found to have a relative crater density of 0.3 with 20% estimated P.E.

Copernicus presents a more complicated problem because of its modified interior, apparently partly flooded and peppered with volcanic structures. For this reason, separate counts were made on the walls in an effort to obtain data less affected by the presence of non-impact craters. Figure 3 presents this data. Copernicus is found to have a relative crater density of 0.5, with 30% estimated P.E. The exterior crater density, as in the case of Tycho, is larger than the interior crater density.

3. *Volcanism in Copernicus*

Figures 4–7 illustrate several features of the Copernicus floor indicative of extensive volcanic activity. These include structures which match in morphology both cinder cones and rimless collapse calderas. Many of the pits are closely clustered, again suggesting volcanism.

The normal lunar maria, which lack abundant cinder cones and calderas, appear to be fluid basalt flows on the basis of both morphology (Kuiper 1965) and chemistry (Turkevich, et al. 1967). The deficiency of cinder cones and kilometer-scale calderas is probably correlated with the fluid nature of the lunar flood basalts (Rittmann 1962). The floor of Copernicus, on the other hand, is closer in form to many terrestrial volcanic fields. The Pinacate field of Sonora, Mexico, for example, is about 40 km across (compared with 50 km for the Copernicus floor) with central peaks, calderas (up to $D = 1.6$ km), tuff rings, and scattered cinder cones. Figure 8 illustrates some of these features. The "crater density" of Pinacate calderas, rings, and cones combined

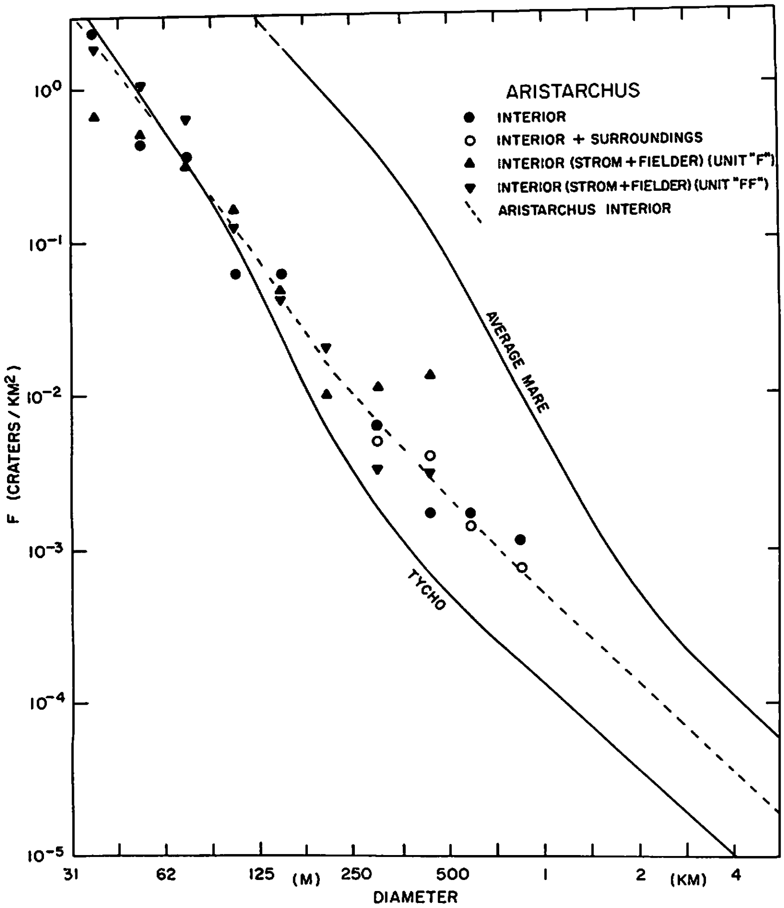

Fig. 2 Crater diameter distribution for Aristarchus. The curve of Fig. 1 is added for comparison.

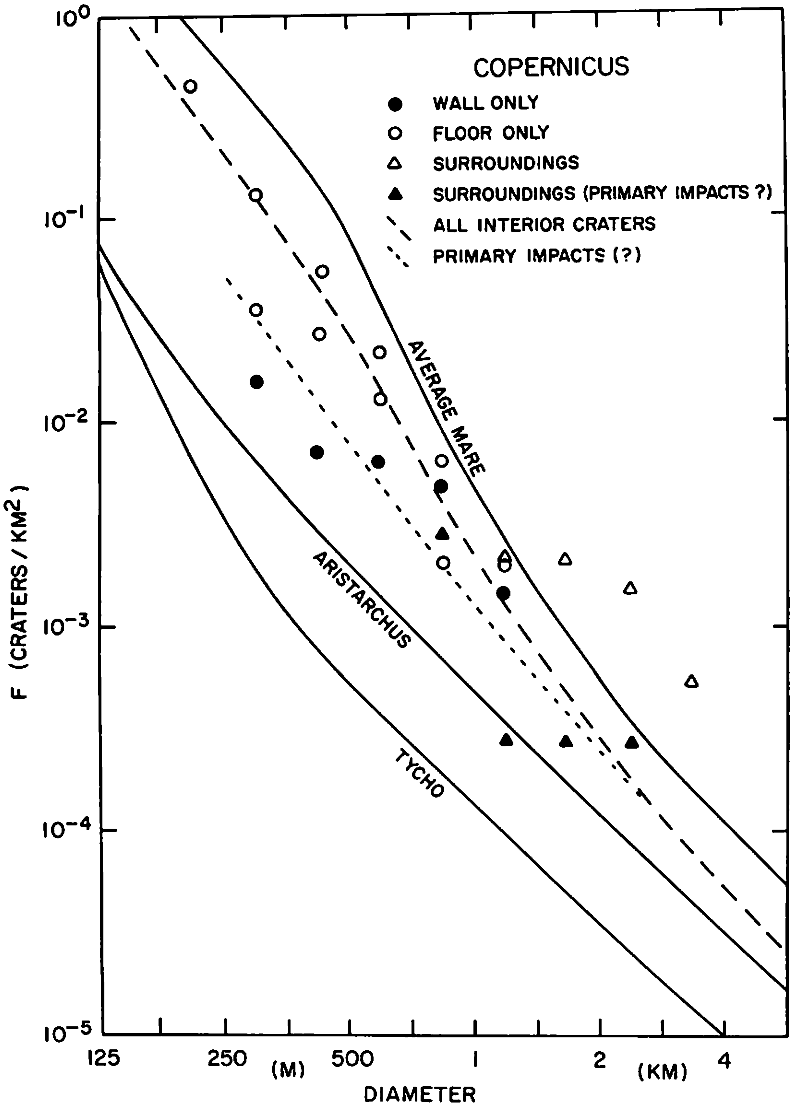

Fig. 3 Crater diameter distribution for Copernicus. The Tycho and Aristarchus curves are added for comparison. The curve with the short dashes, based on the solid data points, indicates the inferred distribution for primary impacts. The curve with the long dashes includes *all* craters (open data points), many of which are evidently endogenic or due to secondary impacts.

runs within an order of magnitude of the combined crater density, less suspected impacts, on the Copernicus floor at all diameters charted in Figure 3. Again, Figure 9 illustrates a rimless collapse pit characteristic of the Hawaiian shield volcano, Kilauea. The late volcanism in Copernicus may well have been less fluid than the mare volcanism, with less volatile content, i.e. more like terrestrial shield volcanoes than like flood basalts.

It is concluded that the floor of Copernicus initially resembled the floor of Tycho, and then began to be blanketed, reaching and passing an intermediate state exemplified by Aristarchus, and that at some stage, about a third of the floor was flooded by mare material during a period of volcanic activity. This material did not come from outside, as the Copernicus wall is nowhere breached, but probably was aided in its rise from the moon's interior by the subsurface brecciation and fracturing resulting from the Copernicus impact. The marked slumping and terracing of the Copernicus walls may have aided by this activity, and in fact may be directly due to settling to conserve the volume of the extruded lava. Further, since crater walls define zones markedly out of isostatic adjustment, faulting and lava extrusion around walls and the edges of crater floors is not unexpected.

4. *Conclusions*

The results for the three craters studied are combined with other areas in Figure 10. Tycho appears to be the youngest structure of its size on the moon. The volcanism in Copernicus explains the rapid rise

Fig. 4 Cinder cone-like structure on the floor of Copernicus. Oriented with light from above. Orbiter photograph courtesy NASA.

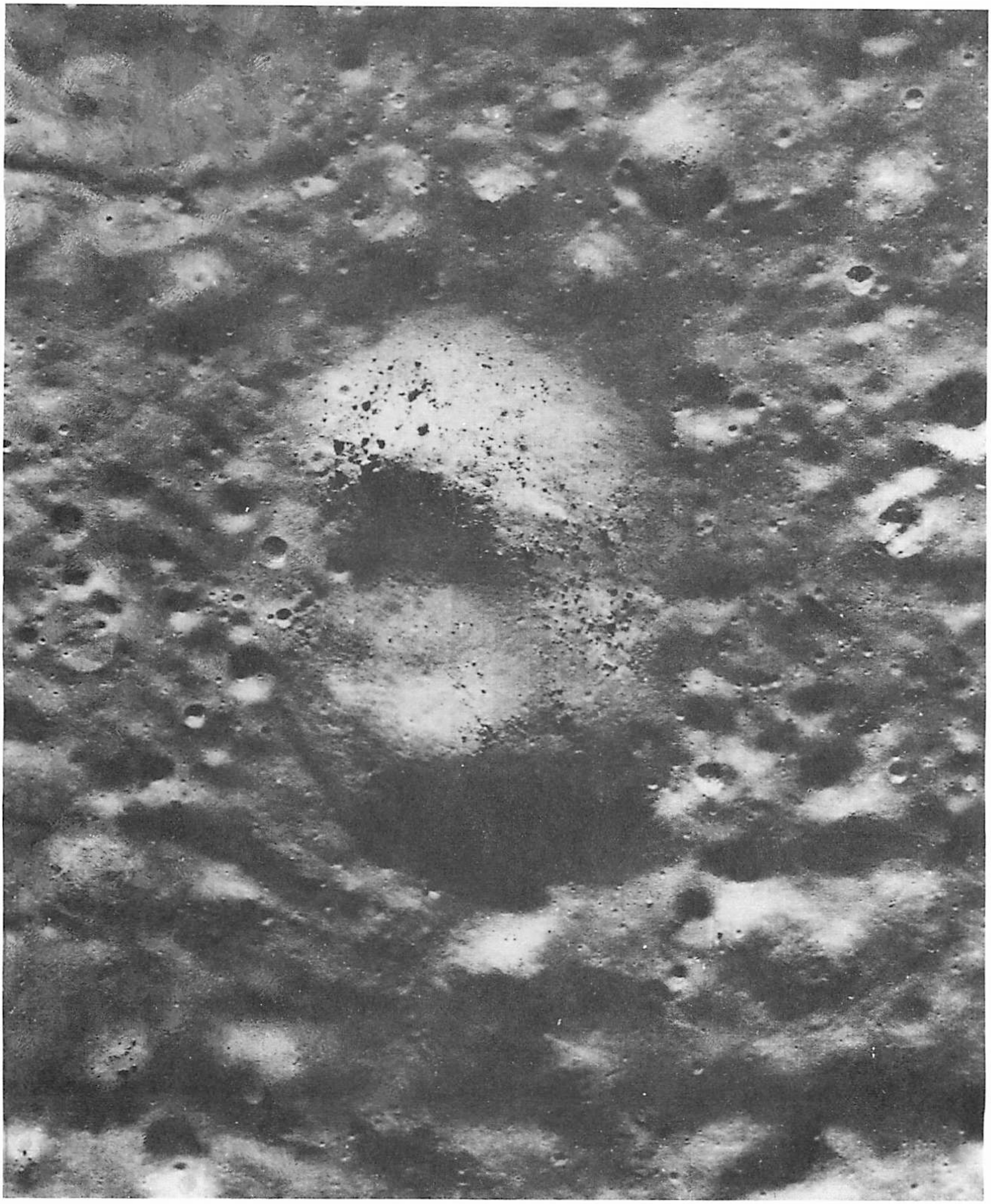

Fig. 5 Breached cinder cone-like structure on the floor of Copernicus. Oriented with light from above. Orbiter photograph courtesy NASA.

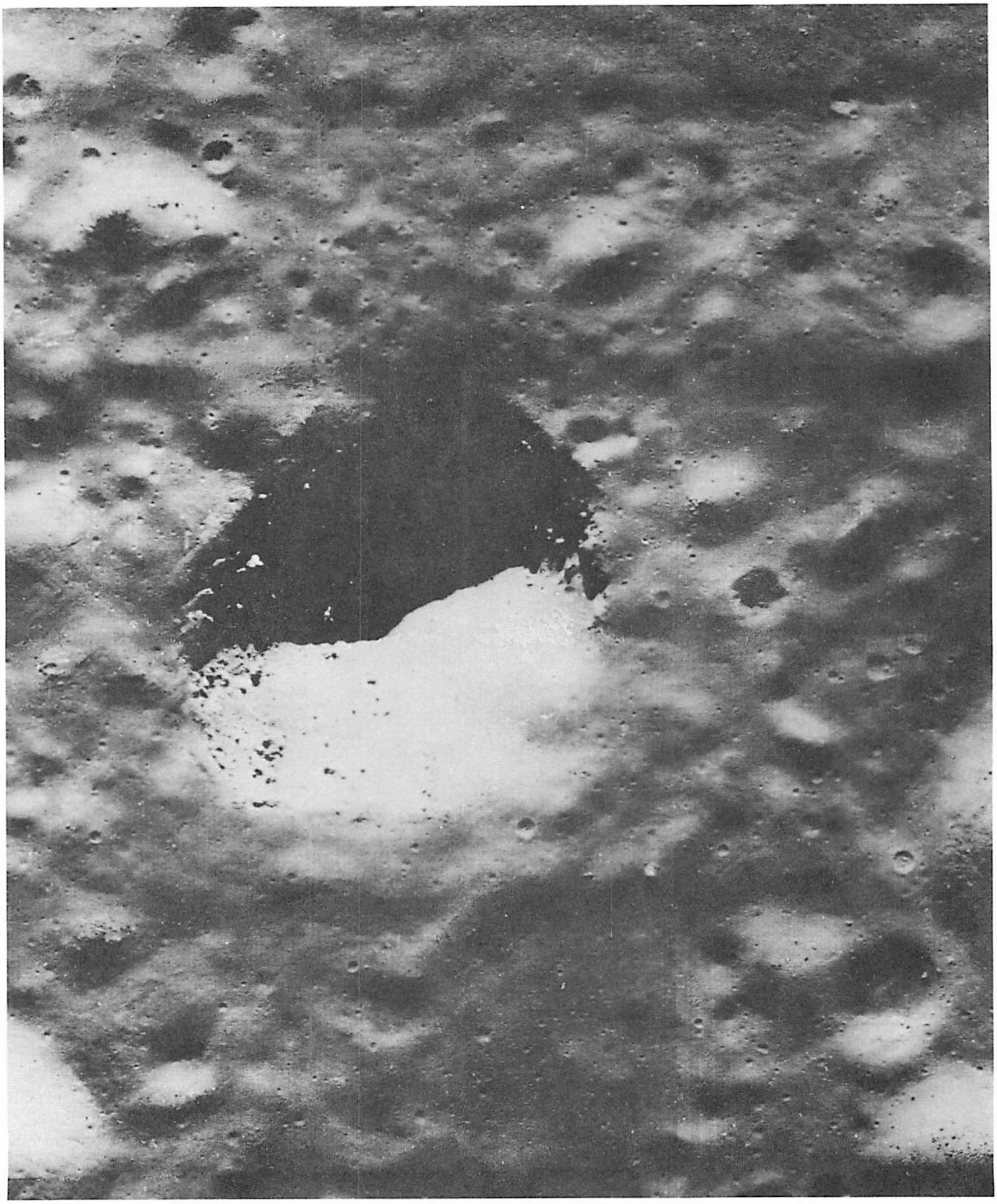

Fig. 6 Apparent rimless collapse pit on the floor of Copernicus. Oriented with light from above. Orbiter photograph courtesy NASA.

Fig. 7 Apparent primary impact crater (note raised rim, debris, rays) cf. Fielder and Guest in this volume of *Comm. LPL*. Oriented with light from above. Orbiter photograph courtesy NASA.

in Figure 10 of craters of $D < 2$ km relative to the density in Tycho or Aristarchus; many of these hectometer-scale craters must be endogenic. Figure 10 contains support for a speculation in paper I, based in turn on a suggestion by Kuiper, Strom and LePoole (1966), that the size distribution for primary impact craters continues at a slope of about -2, gradually steepening, well below the $D = 2$ km limit to as little as $D = 250$ m. That is, in Tycho and Aristarchus, where the crater density is very low and contamination by still younger secondaries or volcanic pits is minimal, the curves retain a low slope, but in Copernicus and the mare it is already quite steep at $D = 1$ km because of non-impact contamination. The former behavior was found in paper I for craters on the wall of Alphonsus, but not on its flooded floor.

Absolute ages may be estimated on the basis of previous models of the cratering rate and the age of the maria, as estimated in current literature. Various LPL publications, including my own, have argued (for a number of reasons including thermal histories of meteorites, meteorite fluxes, and analysis of Martian craters) that the mare age is approximately 4 x 10^9 yr and that the post-mare cratering rate has gradually increased with time, so that it is now of the order of twice its average post-mare value (for a detailed model, see Hartmann and Hartmann 1968). Further defense of these conclusions is beyond the scope of this paper. On the basis of these inferences, ages can be assigned to the Tycho, Aristarchus, and Copernicus on the basis of the observed crater densities, and these ages are reported in Table I.

TABLE 1
AGE SCALE

	RELATIVE CRATER DENSITY	ESTIMATED EQUIVALENT AGE
"Pure" Uplands	30	4.5 (10^9) yr
Average Mare	1.00	4 (10^9) yr
Copernicus	0.5	2 (10^9) yr
Aristarchus	0.3	1 (10^9) yr
Tycho	0.1	2 (10^8) yr
Oldest Martian Craters*		4 (10^9) yr

*The compatibility of the Martian crater ages with the expected formation epoch of the Martian surface supports the other values given here (cf. *LPL Comm.* 65). Recently reported increases in the number of Martian craters counted on reprocessed Mariner photographs can only push the age further back toward 4.7 x 10^9 yr.

Although Table I gives the interpretation favored here, it should be noted than an alternative interpretation holds that the cratering rate is roughly ten times higher than that inferred from meteorites because of a cometary component that does not survive passage in the earth's atmosphere (Shoemaker, private communnication), and that the maria are only about 2 x 10^8 yr old, the cratering rate having been nearly constant since the beginning. According to this model the ages of the three craters (and the Martian features) are only about 1/20 of the values in Table I, or even less. Such values already have been suggested at Surveyor news conferences (e.g. an age of "one million years . . . 500 times younger than that of the lunar maria" — Aviation Week, *88*, p. 17).

Such low ages are not supported by considerations of terrestrial impacts. The body which formed Tycho was probably of the order of 10^{17} or 10^{18} gm mass, on the basis of cratering theory. Even if it were cometary, with density 1 gm/cm^3, and velocity as high as 40 km/sec, it must have had a diameter exceeding 2 km. The compression wave velocity in lake ice is 3.4 km/sec (a value approximately valid for many materials), indicating that the shock wave generated as the bolide struck the atmosphere would propagate through it in about a second (while heating effects, etc. would necessarily take longer). But since most deceleration occurs below 40 km height (Heide 1964), a 40 km/sec bolide would strike the ground by the time its rear portion received a signal that it had struck the atmosphere. Slower projectiles would still have only a few seconds to break up, and the ablative effects would be less. Heide (1964) estimates that at 40 km/sec, a 10^6 gm mass would lose only 32% of its mass, and hence much larger masses would survive intact, consistent with the above. Therefore, even cometary bolides large enough to create Tycho would survive to strike the earth's surface, and if Tycho's age were only 10^7 years there should be several examples of 80 km astroblemes of such youthfulness on the earth's continents, which is not the case.

The preferred value of 2 x 10^8 years would lead to a prediction of several Tycho-sized craters on earth formed in *this* time span, but in this case, few or none would be observable because of erosion and major cycles of orogeny. Of possible large candidates for astroblemes, the Rieskessel is 2 x 10^7 years old (but only 23 km in diameter), and Clearwater Lakes (26, 31 km), Manicouagan (65 km), Sudbury (48 km), and Vredefort Ring (40 km) are all 10^8 years old or older, in support of our conclusion.

The conclusion that Tycho, Aristarchus, and Copernicus are about 0.2, 1, and 2 x 10^9 years old,

Fig. 8 Collapse craters, cinder cones, and lava flows on flanks of Pinacate shield volcano, Sonora, Mexico (photo by R. Laidley).

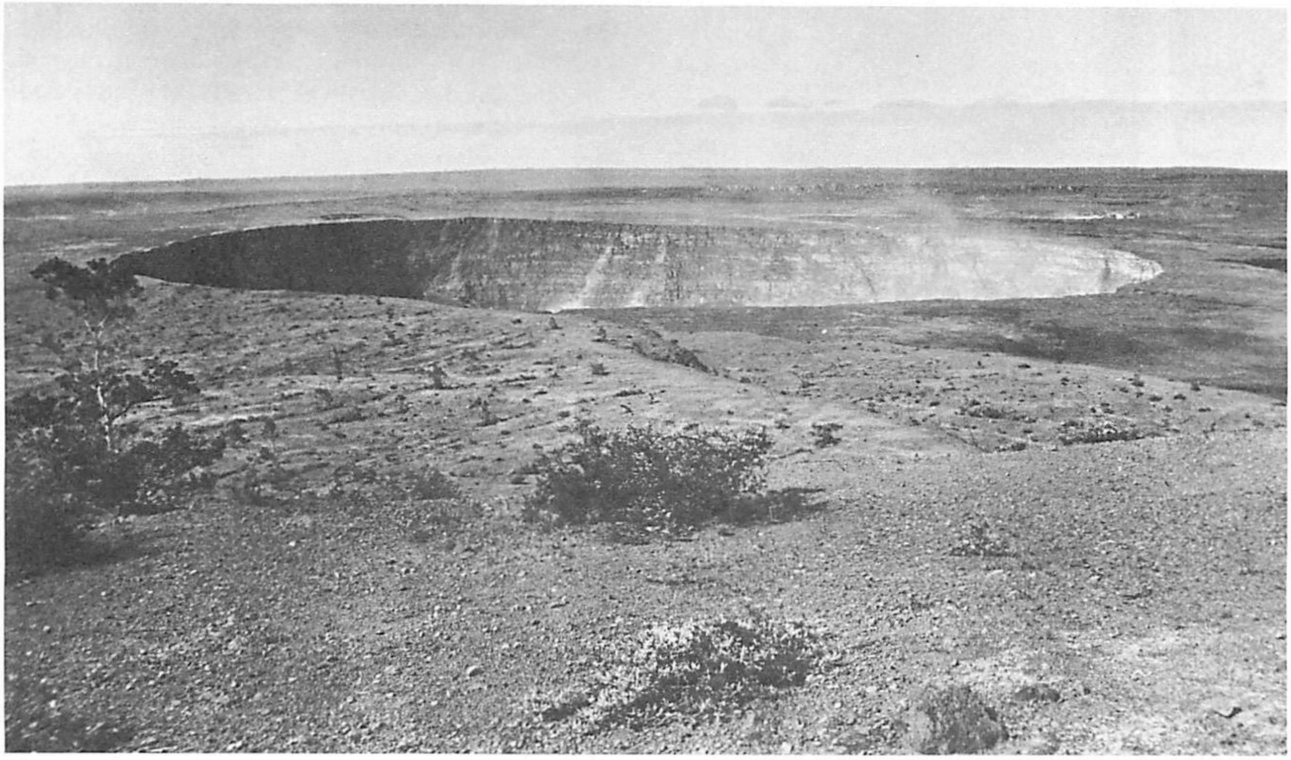

Fig. 9 Rimless collapse pit Halemaumau. Kilauea shield volcano, Hawaii (photo by author).

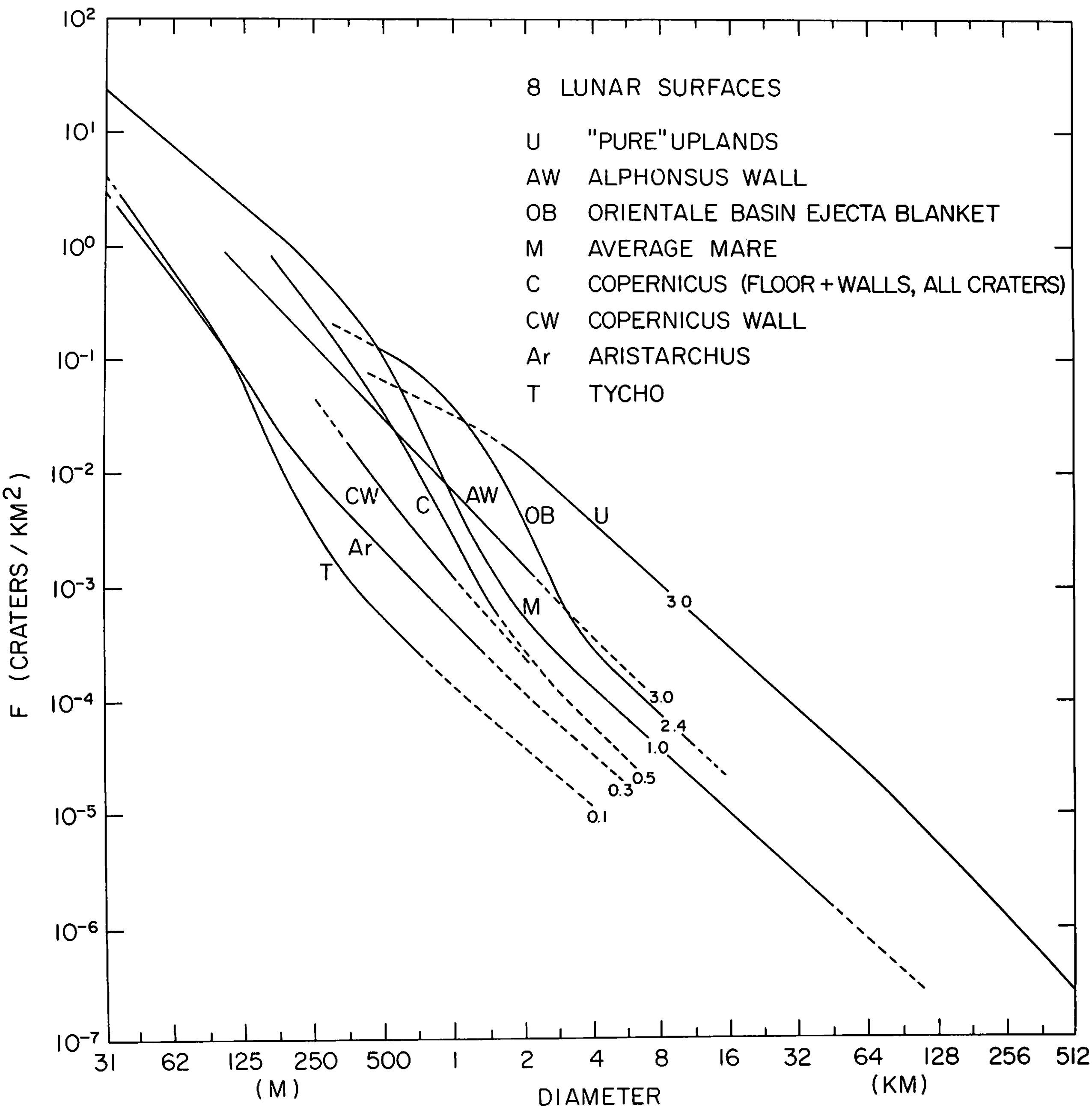

Fig. 10 Summary of crater counts for three young lunar craters compared with other type-areas. Note approximate parallelism at D > 2 km with a slope of about —2, and varying slopes for D < 2 km, apparently due to admixtures of endogenic craters and secondary impacts.

respectively, raises problems about their ray systems. Hapke's (1965) conclusion that exposure to the solar wind causes darkening of the lunar surface in some 10^5 years would appear to account not only for the uniform and unique colorimetry of the moon, both in the visual (Hapke 1965) and infrared (Binder, Cruikshank, and Hartmann 1965; Wattson and Hapke 1966; Cruikshank 1968) but also loss of rays among the older ray-craters. A longer ray-lifetime than 10^5 years is not a qualitative problem, since Hapke himself pointed out that the meteoritic flux causes a turnover of the uppermost microns of the lunar surface in about 10^5 years. Thus, a thick ray deposit (of depth < 10 m; Kuiper, et al. 1965, p. 61) should last considerably longer than the darkening time. However, the implication of the present work is that more than 10^9 years, i.e. 10^4 turnover-times, is required to erase rays. One might expect the surface layers to be saturated with darkened material more rapidly.

This suggests that radiation-darkening is neither the principal nor the only agent destroying rays. Probably the rays owe much of their brightness to small particle size relative to background particles; i.e. they are finely pulverized rock ejecta. Therefore, it requires not mere turnover of the upper microns or millimeters of surface, but thorough surface mixing of the ray deposit and background fragmental layer, with preferential burying of the fine particles, to destroy a ray. [Moreover, the relevancy of radiation-darkening has been called into question by two observations: 1) the difficulty of avoiding oil discoloration in the irradiation experiments, and 2) the observation that the uppermost surface layers of the moon are lighter, not darker, than the subsurface; Gault, et al. 1967]. Mixing to a depth of 1 cm, sufficient to bury the small particles, requires a period of the order of 3×10^9 years at the present bombardment rate, and thus this model is compatible with our derived crater ages.

It is concluded that the ages of the three craters studied are essentially as given in Table I; that Copernicus displays a number of familiar volcanic structures on its floor; that the diameter spectrum of primary impact craters does not rise as steeply at $D < 2$ km as the observed spectrum of all craters in the maria; and that the derived crater ages are consistent with a model which holds that the rays are finely pulverized material being mixed with the background material and hence rendered invisible in a time period of the order 3×10^9 years.

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