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Crater Populations on Ganymede and Callisto

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The discovery of heavily cratered surfaces on Ganymede and Callisto by Voyager 1 shows that like the inner Solar System, a period of heavy bombardment also occurred in the outer Solar System. Comparisons among the crater size/density curves of Ganymede, Callisto and the terrestrial planets show several striking features. The overall crater density of the most heavily cratered terrain on Ganymede is down by a factor of about 3 compared to Callisto, and when allowance is made for the difference in crater production rate due to the influence of Jupiter's gravity field it is down by a factor of nearly 6. This indicates that the oldest regions of Ganymede began recording the observed crater population at a later time than Callisto, and therefore Ganymede either experienced a large-scale (perhaps global) diameter-independent resurfacing event or simply developed a rigid crust capable of retaining craters later than Callisto. In either case, this process took place during the period of late heavy bombardment. Based on earlier studies of the terrestrial-planets' cratering record, neither Ganymede nor Callisto is saturated with craters. Compared to Callisto, a diameter-dependent loss of craters in the size range 10–40 km occurs on the grooved terrain of Ganymede and probably results from obliteration of small craters due to the formation of new ice. A similar but less severe loss also occurs on Ganymede's heavily cratered terrain and may be due to an earlier period of ice formation and/or the formation of arcuate troughs in this terrain. Seven different crater curves, in the diameter range of about 40–130 km, representing vastly different crater densities, different surface ages, different terrain types, and even different satellites all possess nearly the same distribution function. This together with other observational evidence strongly suggests that at least in this diameter range the curve basically represents its production function which is completely different from that on the terrestrial planets. This indicates that the population of bodies responsible for the period of late heavy bombardment in the inner Solar System was very different from that responsible for the late heavy bombardment in the outer Solar System. We can only speculate at this early stage that Ganymede and Callisto may principally record a population of bodies that never penetrated the inner Solar System in numbers great enough to leave a recognizable signature.

INTRODUCTION

Mariner and Viking images of Mercury and Mars demonstrated that, like the Moon, these planets have surfaces which are heavily cratered by meteorite impacts. This observation demonstrated that all of the terrestrial planets experienced a period of late heavy bombardment early in their histories. Now the discovery of heavily cratered surfaces on Ganymede and Callisto by Voyager 1 and 2 shows that a period of late heavy bombardment also occurred in the outer Solar System, at least as distant as 5 AU, and probably beyond as well. The proposed Voyager encounters with Saturn, Uranus (1986) and Neptune (1989), may reveal whether the satellites of these Jovian planets have also experienced a period of late heavy bombardment. We use 'late heavy bombardment' to signify the period of cratering immediately post-dating planetary accretion and solidification of the magma ocean (if any). .

The cratering record on the Galilean satellites Ganymede and Callisto provides information on the size distribution of the impacting bodies and on surface modification processes. Impact processes and post-crater modification on icy surfaces such as Ganymede's and Callisto's may be quite different than those on rocky surfaces such as the terrestrial planets'. Although craters on Ganymede and Callisto remarkably resemble those on the terrestrial planets, some important differences exist. Central pits are much more common than central peaks, at least on Ganymede, and many craters appear to have domed floors. Circular bright spots (palimpsests) with very low interior rims commonly occur on Ganymede and probably represent older craters formed on a less rigid surface. Many older craters appear to have floors at about the same level as their surroundings. Most of these traits are probably the result of impact into ice and of visco-elastic relaxation of the icy surface. Impact basins on Ganymede and Callisto also differ from their terrestrial-planet counterparts. On Callisto they display smooth rimless interiors surrounded by closely spaced ridges, probably the result of large impacts into icy target materials [see *Soderblom et al.*, this issue]. On Ganymede, the freshest basin (Gilgamesh, 194 km diameter) is more like those found on the inner planets, but it has a smooth interior surrounded by hummocky terrain with subdued scarps, again probably due to the response of a more consolidated icy surface to a large impact.

The effects of impacts into icy targets on the crater diameter/frequency distribution is not well understood. One effect that has been suggested [*Parmentier et al.*, 1980] is that visco-elastic relaxation will obliterate a certain fraction of the larger craters, particularly early in the history of Ganymede and Callisto when the icy crust may have been more plastic. Also for a given energy of impact, the crater may be larger in icy than rocky material [*Boyce*, 1979]. However, large craters are not as likely to be affected by this difference because crater diameters are largely controlled by gravity scaling.

The primary plotting technique used in this paper is the 'relative size-frequency distribution plot' as recommended by the *Crater Analysis Techniques Working Group* [1979]. This type of plot displays information on the differential size-frequency distribution function $R(D)$, and is the ratio of the observed distribution to the function $dN = D^{-3}dD$. Because most large-crater populations so far encountered in the solar system have slope indices within the range of ±1 of the function D^{-3} they plot as non-sloping or moderately sloping lines on these plots. This makes any changes in the $R(D)$ more obvious and facilitates identifying differences in distribution functions and densities among crater populations which is a major goal of this study. Figures 2 and 3 are from a previous study and use a

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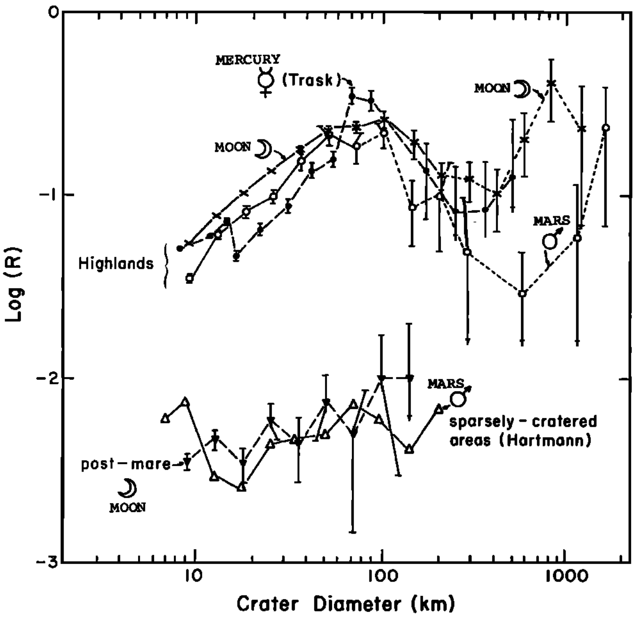

Fig. 1. The crater size-density distributions of the terrestrial planets. The distributions of the heavily cratered terrains are remarkably similar in shape. But the lunar maria have a different crater population. The Martian sparcely cratered regions' curve is from *Hartmann* [1973].

variant of this plot, but the representation of the slope and density of the curves are virtually identical to the '*R*' plots.

TERRESTRIAL-PLANET CRATERING RECORD

One of the most fundamental questions in planetology concerns the origin of the objects responsible for the impact bombardment of the terrestrial planets. An important datum, their size-frequency distribution, constrains theories of their possible origins. The observed crater size/frequency distribution will grossly represent that of the impacting objects, when properly scaled, if the crater population represents its production function. Because interpretations of the crater populations on the Galilean satellites build upon our observations and analyses of the crater populations on the inner planets and particularly on the Moon, a brief summary of the current state of understanding is in order. On the inner planets we consider only craters larger than about 8 km because smaller craters often show considerable variations from location to location, perhaps due to contamination by large numbers of secondaries.

The heavily cratered terrains on the terrestrial planets are sometimes presumed to have been exposed to cratering since the formation of the planets and therefore to be saturated surfaces. However, at least in the case of the Moon, and probably for the other terrestrial planets as well, the cratering record dates from no earlier than the time of solidification of the magma ocean, some 4.4 b.y. ago. Before this time craters would not be retained in the melted outer layer; only after the crust had solidified sufficiently to register craters would the current cratering record begin. Therefore, because the Moon, at least, was completely resurfaced its heavily cratered highlands need not be saturated due to the accretion process.

On the Moon and Mercury, the concept of saturation is the most relevant. 'Saturation' covers the processes of crater obliteration which result from the cratering process itself. These include not only the formation of the craters, but also penecontemporaneous processes such as ejecta emplacement. Crater 'equilibrium' occurs if other obliterative processes actively limit crater densities. These other processes may include dust filling, crater relaxation, or lava flooding. Crater populations which are in either saturation or equilibrium can be said to be in 'steady state.' These terms will be used in these senses throughout the rest of this study.

The lunar highlands has a complex curve, not the simple power-law curve often presumed (Figure 1). The complexity of this curve argues forcefully against interpretations of crater saturation or equilibrium. Further evidence against the steady-state condition comes from Monte Carlo and Markov chain computer simulations [*Woronow*, 1977, 1978], and from analyses of the craters superposed on the Orientale basin and ejecta blanket [*Strom*, 1977]. Woronow found that regardless of the structure of the assumed production function, all densely cratered terrains are well below their saturation densities (Figures 2 and 3). Although a significant proportion of all craters ever formed may not have survived to the present, the diameter dependence of the obliteration process is such that the current population must closely resemble its production function. Strom's analysis of the post-Orientale craters produced a curve which mimics that of the heavily cratered uplands. Because the overall density of craters on the Orientale basin and ejecta blanket is relatively low, it cannot be anywhere near the saturation limit and must be a production population. Because that size/frequency distribution is like the one observed on the highlands, the highlands curve is logically interpreted as representing the same production function.

The above appraisal of the cratering record of the lunar highlands leads to the following conclusions: (1) the lunar highlands are not saturated at crater diameters larger than at least 8 km; (2) the observed size-frequency distribution function for the large craters on the lunar highlands is essentially identical to the production function which generated them; (3) neither the observed size-density function for the larger craters nor their production functions follow a simple power law relationship; (4) extrapolating information on saturation conditions obtained from small craters to these larger craters is not valid; (5) extrapolating the larger-crater curve to much smaller diameters by using a simple power law to represent the highlands population grossly misrepresents the highlands data and consequently does not provide a meaningful reference line at the small crater diameters.

Obviously if the lunar highlands are not saturated with craters greater than 8 km, then the mare surfaces also are not saturated at comparable crater diameters. Therefore, the post-mare crater population represents its production function in this size range. That crater population has a production function which is significantly different from that of the highlands population over the same diameter range (see Figure 1). In the highlands, the population index is about −2 in the diameter range 8–50 km, whereas the post-mare population index is −2.8 over the same diameter range. A Chi-squared test indicates that the two populations are different at the 99% confidence level. Therefore, the Moon has been impacted by at least two populations of objects; one responsible for the period of late heavy bombardment and another responsible for the period of crater formation primarily after mare emplacement.

The overall shape of the crater curve for the heavily cratered highland regions on Mercury is very similar to that of

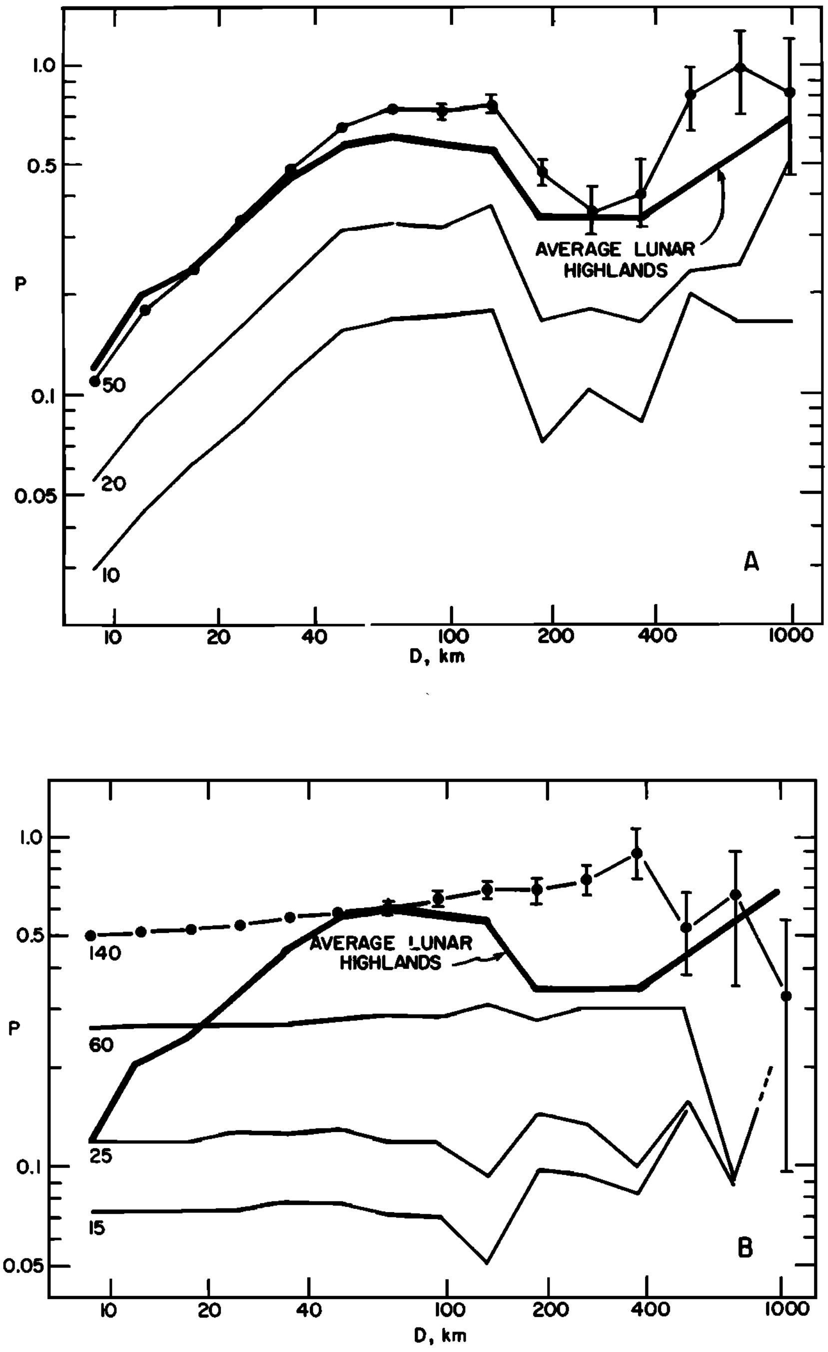

Fig. 2. Markov chain computer simulations of the crater accumulation process which take into account crater overlap and ejecta blanket obliteration of craters. The simulations show that the observed crater population on the lunar highlands must represent its production function quite closely (Figure 2*a*). It could not have been the result of a −3 production function (Figure 2*b*). (From *Woronow* [1978] where R = 3.66 P.)

the lunar highlands (Figure 1). However, the lunar and Mercurian curves shown in Figure 1 differ in two respects. First, the Mercurian crater population has a different average slope for craters between about 15 and 70 km diameter, which implies a relative depletion of sucessively smaller-diameter craters on Mercury. This probably reflects the obliterative effects of intercrater plains emplacement which took place during the period of heavy bombardment of that planet [*Strom*, 1977; *Malin*, 1976]. Secondly, the Mercurian curve shows a knee at about 15 km diameter which has been attributed to an abundance of secondary craters derived from craters and basins of the heavily cratered terrain. Therefore, intercrater plains emplacement and secondary craters probably account for the differences between the lunar and Mercurian crater curves. Furthermore, the Mercurian post-Caloris crater curve is virtually identical in both crater density and slope to that of the lunar post-Orientale curve [*Strom*, 1979, Figure 20], which, in turn, is the same as the lunar highlands curve. This also suggests that the ancient production function was very similar, perhaps identical, for both bodies. To date, a younger crater population similar to the lunar post-mare population discussed earlier has not been recognized on Mercury [*Strom*, 1979]. Perhaps, either it never reached Mercury in numbers large enough to leave a recognizable signature, or the youngest sur-

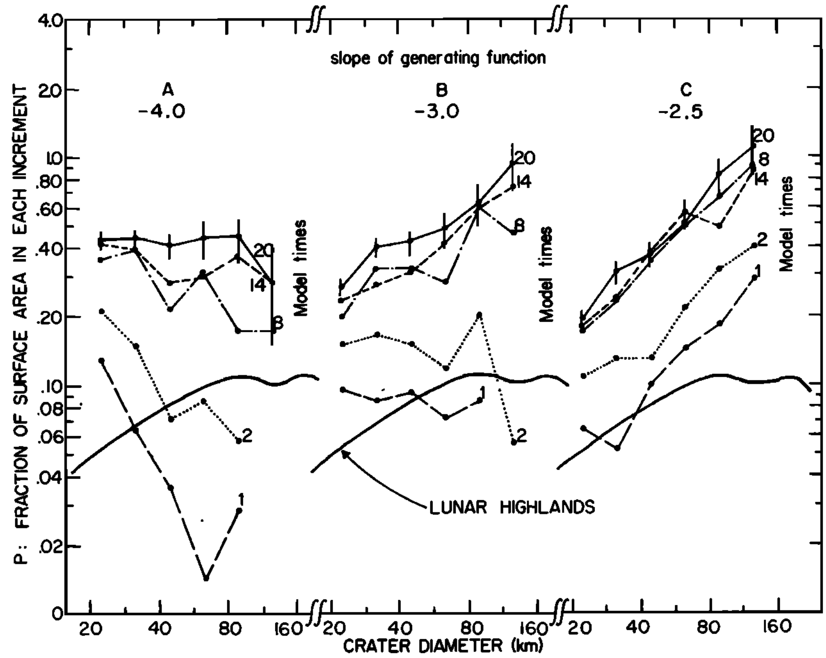

Fig. 3. Monte Carlo computer simulations of various production functions showing their signatures as a function of crater density. Marked deviations from the production functions do not occur until crater densities vastly exceed those found on either the terrestrial planets or the Galilean satellites. (From *Woronow* [1977] where $R = 3.66$ P.)

faces on Mercury were formed earlier than the lunar maria, when the objects responsible for the late heavy bombardment of the highlands still dominated.

The southern cratered terrain on Mars, if one carefully excludes smooth plains units with few superposed craters and with wrinkle ridges, has a size-density distribution on its truly ancient surfaces which are virtually identical to that of the lunar highlands in both crater density and size-frequency distribution as shown in Figure 1. Therefore, although the Martian surface has undeniably been affected by aqueous and aeolian processes, some regions have retained for many eons their initial crater population. Also like the Moon, the northern sparcely cratered plains of Mars record an impacting population with a size-frequency distribution function markedly different from that of the ancient terrains, yet almost identical to that found on the lunar maria (Figure 1). Therefore, both the ancient terrain and the northern plains on Mars mimic, both in overall density and in their size-frequency distribution, the equivalent terrains on the Moon.

In summary, all of the crater populations on the heavily cratered terrains of the Moon, Mars, and Mercury appear to have similar crater populations which must generally represent a single production function. A similar relationship holds for the crater populations of the lunar maria and the Martian northern plains. However, this size-frequency distribution is different from that of the ancient terrains. These data strongly suggest that two populations of objects have impacted the terrestrial planets; one responsible for the period of late heavy bombardment early in the history of Mars, the Moon and Mercury, and probably the Earth and Venus as well, and another primarily responsible for the period of crater formation after mare formation on the Moon and plains formation on Mars. These two populations may represent two separate and distinct origins of the impacting bodies or they may represent one population which evolved with time through mutual collision. If the younger population is missing from Mercury then most likely the two are separate and distinct populations.

Three principal origins have been suggested for the objects responsible for the period of late heavy bombardment in the inner Solar System: (1) they may have originated from the asteroid belt through mutual collisional processes; (2) they may be the remains of planetoids disrupted by gravitational forces due to a close approach to a larger planet; and (3) they may be bodies left over from the final accretion of the planets themselves. The pros and cons of these alternatives are discussed by *Wetherill* [1975]. The contribution from comets is not known.

The issue now raised is whether either the ancient or the more recent impacting populations prevaded the entire Solar System or whether either or both of the populations were localized to the inner Solar System. If we could determine this, then we could place further constraints on the origins of the impacting bodies which affected both the terrestrial planets and the Jovian satellites.

CALLISTO CRATER CHARACTERISTICS AND STATISTICS

The surface of Callisto is dominated by impact craters as large as 600 km in diameter. No extensive areas of smooth plains or other types of nonimpact related topography have been seen. In this sense Callisto is the most extensively cratered, but not necessarily the most densely cratered, body of its size so far discovered in the Solar System. The morphologies of the craters in the size range 10 to 100 km, seen on the highest resolution pictures (~3–4 km/line pair), are remarkably similar to those on the inner planets despite their formation in icy material. However, at resolutions of 3–4 km discerning inner rim terracing or the character of ejecta blankets is impossible. Many of Callisto's craters, unlike those on the inner planets, have central pits; probably due to a response of an icy target material to the impact process. As on the inner planets, the floor structures of the fresher craters vary with diameter (Figure 4). Smaller craters appear deeper and more bowl shaped, whereas larger ones appear shallower with relatively flat floors. Older more degraded craters have floors

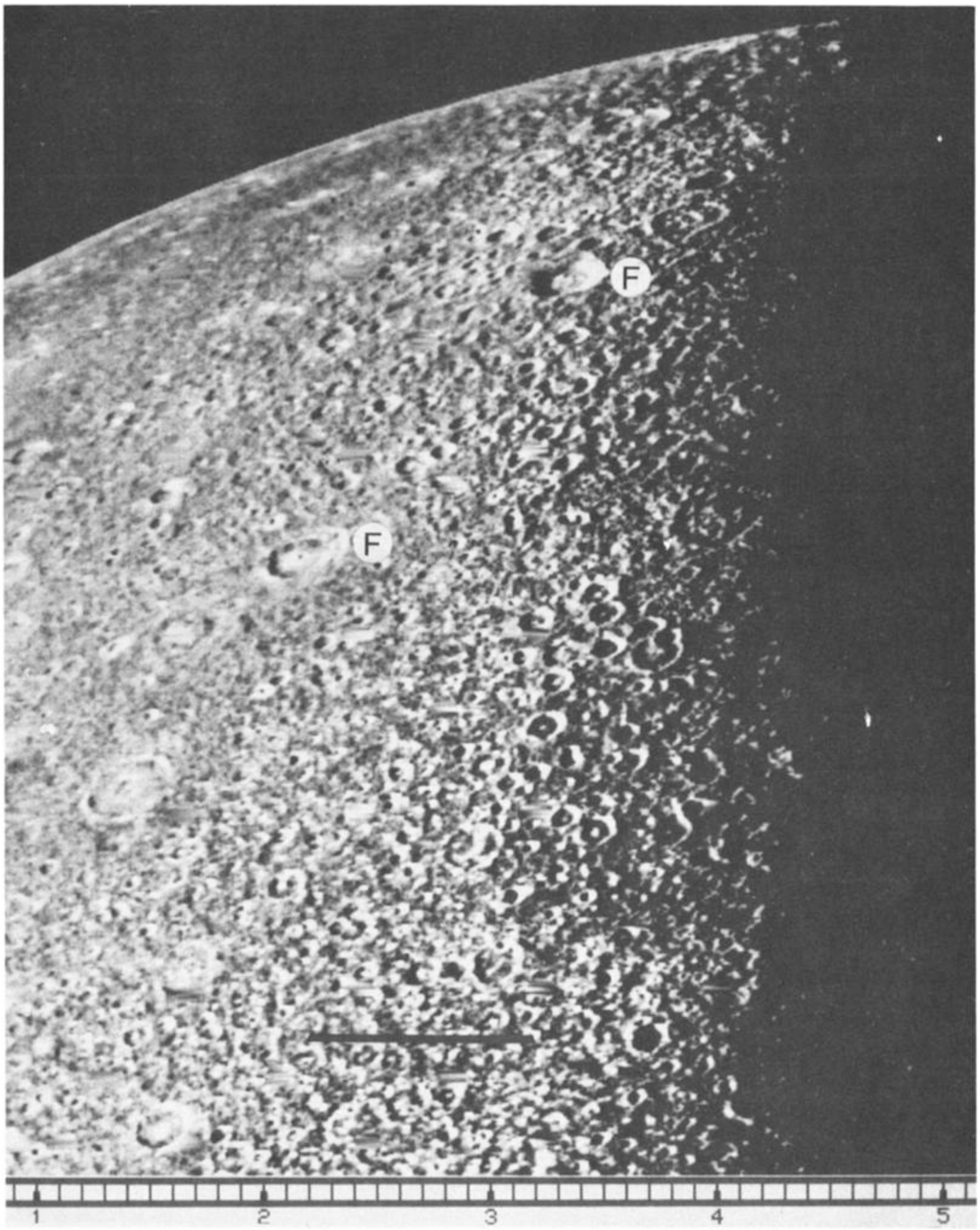

Fig. 4. The heavily cratered surface of Callisto showing the paucity of large craters relative to smaller ones. The letter 'F' indicates relatively fresh craters that are remarkably similar in morphology to that of lunar and Mercurian fresh craters. Black scale bar represents 200 km. FDS 20617.41, south at the top.

which appear to be almost at the same level as the surrounding terrain. However, where not disrupted by subsequent impacts, the rims of most of these craters still appear fairly sharp and well preserved (Figure 5). This suggests that, at least on Callisto, relaxation of the icy crust primarily affects the excavation cavity and largely leaves the uppermost part of the rim intact. This implies that crater obliteration solely by relaxation in an icy crust may not be very effective on Callisto in this size range.

The most heavily cratered regions on Ganymede show a peculiar type of structure termed palimpsests. These structures are circular bright areas with barely discernible rims about half the diameter of the bright area. They occur in the diameter range of about 30 to 80 km and are probably impact scars formed by relaxation of the thin icy crust early in the planet's history when the crust was in a more plastic state, probably at an epoch when the icy crust was just forming. On Callisto these features are extremely rare or absent. Even at the poorer resolution obtained for Callisto these objects should be readily recognizable. The probable absence of these features on Callisto suggests that the observed crater population formed at a time when Callisto's crust was rigid enough to largely preserve their structure and that any palimpsests formed earlier when the crust was more plastic have been obscured by subsequent impacts.

The two largest basins on Callisto (400 and 600 km diameter) have a morphology very different from that of similar sized basins on the inner planets. They are characterized by

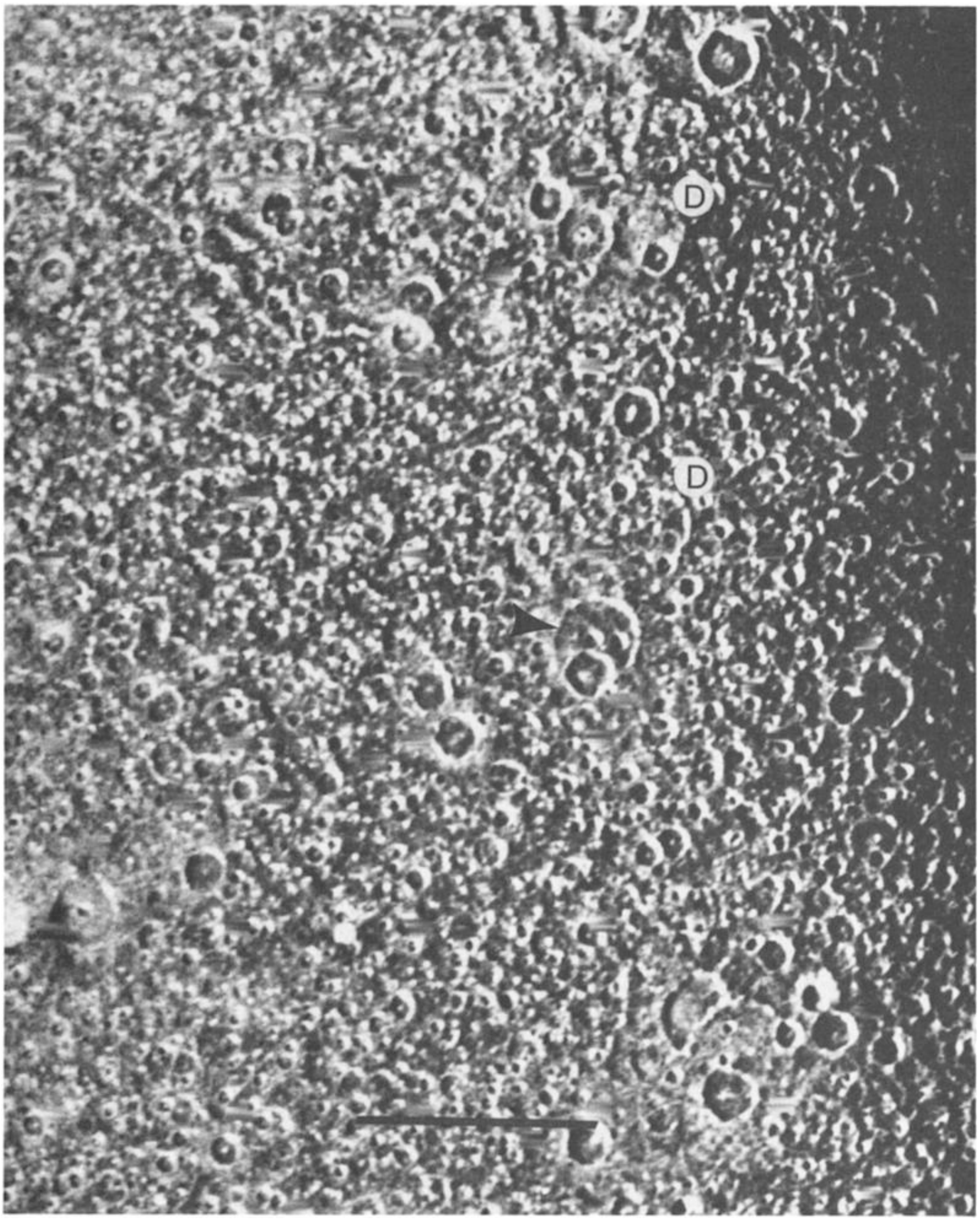

Fig. 5. On this picture of Callisto are indicated several degraded craters (D) which have been rather heavily impacted but are still recognizable. The black arrow points to a crater with its floor at about the same level as the surroundings but still exhibiting a well-defined, sharp rim. There is an absence of large palimpsests on Callisto suggesting that most of the observed craters formed in a relatively rigid crust. Black scale bar represents 200 km. FDS 20617.09, south at the top.

rimless, bright, level, circular areas surrounded by closely spaced ridges extending outward over two basin diameters. This type of structure probably results from the response of the icy crust to very large impacts. The diameter measured for these basins is that coinciding with the bright circular center which most likely nearly corresponds to the excavation crater.

Crater measurements on Callisto in the size range 10 to 100 km were made from the Voyager 2 images taken at quarter phase illuminations with a resolution of ~4 km. These images comprise a mosaic covering about 34 percent of the satellite which was amenable to crater measurements. Craters over about 10 km diameter were counted out to 29° from the terminator and craters over about 30 km diameter out to higher sun angles (see Figure 6). Although the crater measurements extended to smaller diameters, only above 10 km diameter are the counts reliably complete. Craters over about 100 km diameter were measured on other parts of Callisto in order to extend the data to larger diameters and improve the statistics at these sizes. Although about 74 percent of Callisto was searched for craters larger than about 100 km, only 5 craters and basins were found.

The craters were divided into two broad categories: fresh and degraded. Fresh craters are those with relatively sharp well-preserved rims, while degraded ones have more disrupted rims and usually have floors more nearly at the level of the surrounding terrain. Degraded craters most frequently occur at the larger diameters (≥45 km), which may be caused, at least in part, by greater relaxation-degradation at these diam-

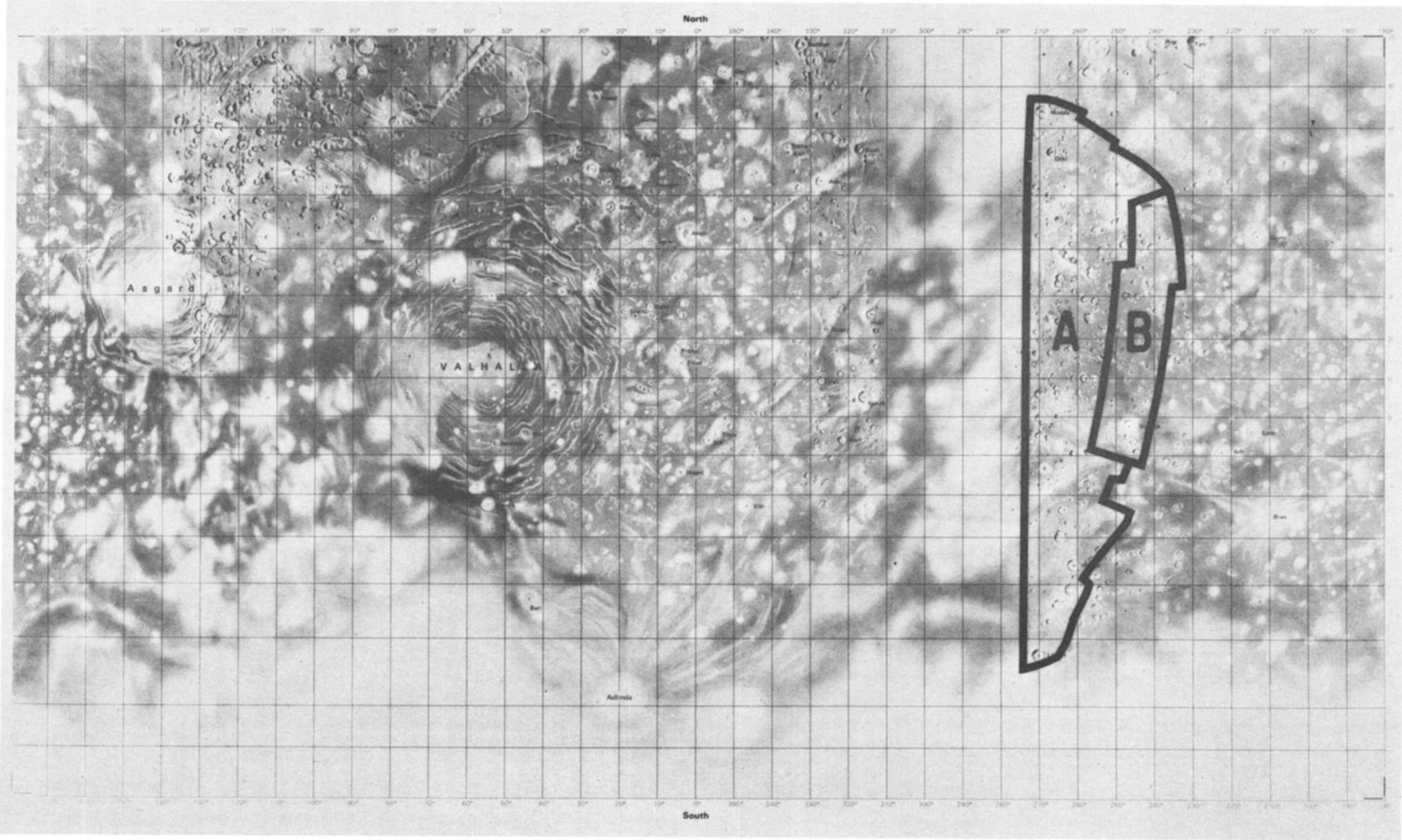

Fig. 6. Map of the regions where crater measurements were made on Callisto. (*a*) Region of measurements complete down to 10 km. (*b*) Region of measurements complete down to 30 km diameter. The rest of the area was measured for craters larger than about 100 km.

TABLE 1. Crater Counts on Ganymede and Callisto

	Callisto		Ganymede			
			Cratered Terrain		Grooved Terrain	
Diameter Range, km	Number of Craters	Area, km^2	Number of Craters	Area, km^2	Number of Craters	Area, km^2
4–5.7			2231	2.4×10^6		
5.7–8.0			1000	2.4×10^6		
8.0–11.3			559	3.4×10^6		
11.3–16.0	1311	4.7×10^6	291	3.4×10^6	216	7.8×10^6
16.0–22.6	696	4.7×10^6	154	3.4×10^6	195	1.3×10^7
22.6–32.0	346	4.7×10^6	106	3.4×10^6	123	1.3×10^7
32.0–45.3	211	6.1×10^6	71	3.4×10^6	79	1.3×10^7
45.3–64.0	92	6.1×10^6	20	3.4×10^6	43	1.3×10^7
64.0–90.5	22	6.1×10^6	6	3.4×10^6	20	1.3×10^7
90.5–128	7	6.1×10^6	1	3.4×10^6	2	1.3×10^7
128–256	2	5.5×10^7			1	1.3×10^7
256–724	3	5.5×10^7			1	1.3×10^7

eters. These data are given in Table 1; they do not follow a simple power law.

GANYMEDE CRATER CHARACTERISTICS AND STATISTICS

The craters on Ganymede appear to show a larger spectrum of morphological characteristics than those on Callisto. This is probably due in part to the higher resolution coverage (~1 km/1p) and in part to the more complex surface history on Ganymede. In general the craters show a range of freshness from sharp rimmed craters with rays and well developed ejecta blankets to very low rimmed flat-floored craters with no discernible ejecta deposits. There appears to be an abundance of central pits, but central peaks are also common. The ejecta blankets on some of the freshest craters have sharp, elevated, and somewhat lobate termini in some ways similar to the rampart craters on Mars (Figure 7). Secondary impact craters are common around the large, fresh and rayed craters. Also like Callisto, the smaller fresh craters are deeper and more bowl-shaped while the larger ones are shallower with flat to somewhat domed floors (Figure 7). The floors of some of the more subdued craters are at about the same level as the surrounding terrain. In most cases the rims are low and in some cases discontinuous, but still relatively sharp. Crater palimpsests are relatively common in the most heavily cratered regions of Ganymede, but appear to be largely absent on the grooved terrain. These structures have been described in the previous section and are shown in Figure 8. Their concentration in heavily cratered regions suggests that when these craters formed the crust was generally in a more plastic and easily deformable state than for later impact into the grooved terrain. A complete description and comparison of crater morphology is outside the scope of this paper; however, the general observations of crater morphology noted on Callisto and Ganymede are consistent with the hypothesis that although relaxation of icy material has been an important process in degrading craters, it has not been very effective at obliterating them. More detailed studies of crater morphologies on Ganymede and Callisto will better define the processes responsible for crater degradation in icy crusts.

On Ganymede crater diameters were measured on two general types of terrain: heavily cratered and grooved. Crater counts on the heavily cratered terrain comprise the two largest areas viewed at highest resolutions by Voyagers 1 and 2; Galileo Regio (2.4×10^6 km^2) and Nicholson Regio (1.0×10^6 km^2). Together these areas encompass about 4% of the total surface area of Ganymede (see Figure 9). The largest area, Galileo Regio, was photographed by Voyager 2 at a resolution of about 1 km whereas Nicholson Regio was photographed by Voyager 1 at a resolution of about 2.8 km. Galileo Regio is a dark circular area characterized by a relatively high crater density and broadly arcuate rimmed troughs. The morphology, spacing (~50 km), and overall geometry of these troughs are somewhat similar to the concentric ridges associated with the largest basins on Callisto (e.g., Valhalla), and they have been interpreted as resulting from a similar process, i.e., a major impact into Ganymede's icy crust [*Smith et al.*, 1979]. The center of the Ganymede ring system is near 30°S and 180°W, but no central bright area occurs at this location. Perhaps the formation of younger grooved terrains and impact cratering have destroyed it or perhaps some other process is responsible for these troughs. Several rimmed troughs are also found on Nicholson Regio and may have similar origins. As discussed later, the formation of these rings may have been, at least partly, responsible for altering the shape of the crater diameter/frequency curve in their vicinities.

The grooved terrain on Ganymede is a complex combination of transecting linear to polygonal segments. Some segments are complexly grooved, others have a very regular grid-like pattern of intersecting ridges, and still others are relatively smooth and featureless. Crater densities on individual segments vary widely and suggest a rather wide range in ages. In order to maximize statistically reliable crater size/frequency distributions, all types of grooved terrain were combined. The regions of grooved terrain on which craters were measured using both Voyager 1 and Voyager 2 images is shown in Figure 9. Not included in the studied areas were regions of included heavily cratered terrain. Craters larger than 16 km diameter were measured over an area of 1.07×10^7 km^2, craters larger than 11.3 km diameter over an area of 5.82×10^6 km^2 and craters larger than 8 km diameter over an area of 2.1×10^6 km^2. The data are given in Table 1. As on Callisto, they do not follow a simple power law.

Although crater measurements extended to diameters smaller than 5 km, only above that diameter are the counts judged to be complete. Areas with heavy concentrations of what appear to be secondary impact craters (clusters, strings and irregularly shaped craters) were not included in the

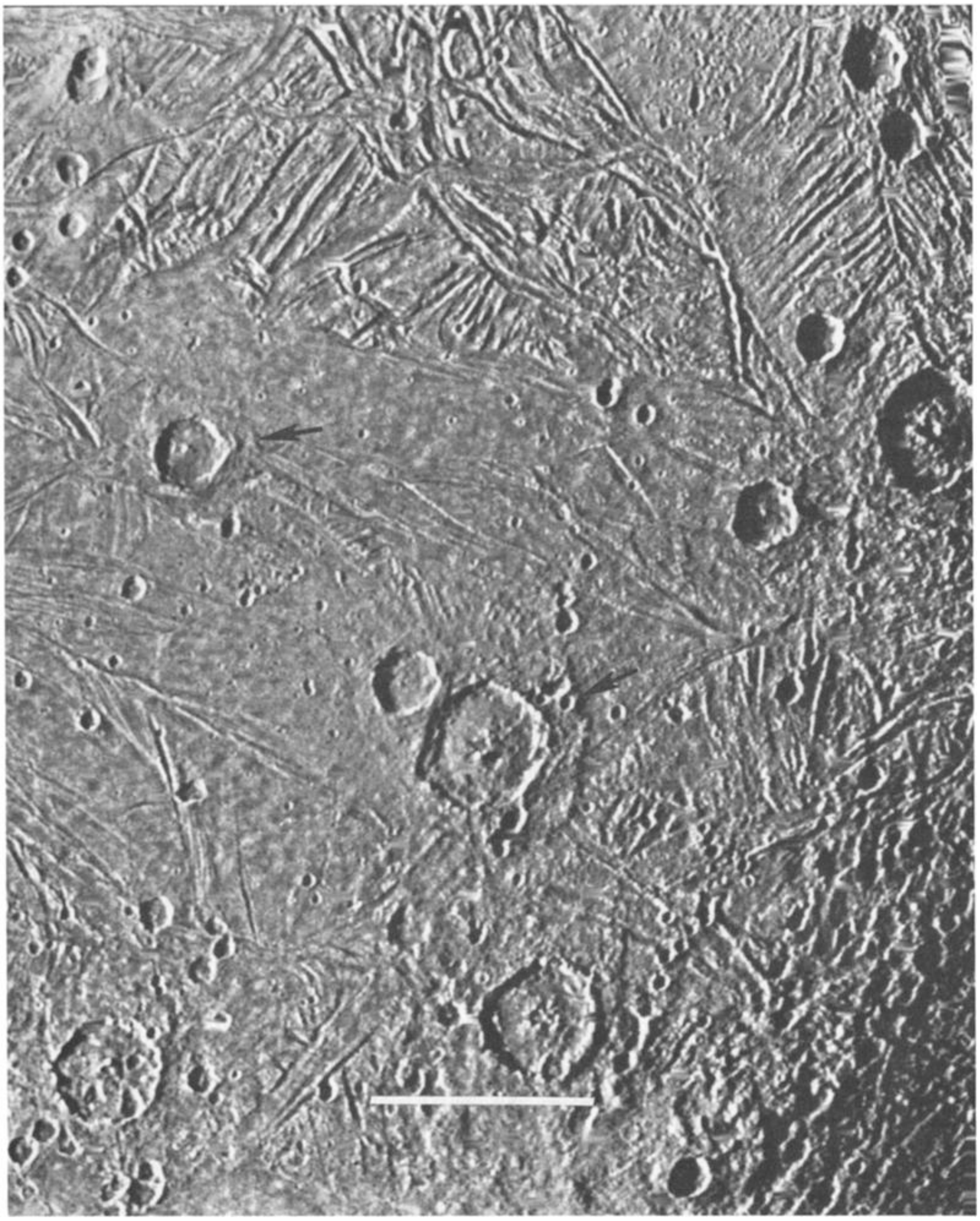

Fig. 7. Grooved terrain on Ganymede showing several fresh craters with ejecta blankets (black arrows) somewhat similar to those associated with Martian rampart craters. The overall morphology of these fresh craters is remarkably similar to lunar craters. Preliminary measurements indicate depths between 0.5 and 1 km which are only slightly less than those associated with lunar craters of similar size. White scale bar represents 100 km. FDS 20639.05, north at the top.

counts on grooved terrain, but their complete exclusion is probably an unrealistic assumption. Therefore, below a diameter of about 10 km, the data may include a significant number of secondaries, particularly in the heavily cratered terrain. As on Callisto, the craters were divided into two broad categories: fresh and degraded. Although the same criteria used on Callisto were followed in assigning craters to these categories on Ganymede, the higher resolution pictures on Ganymede allowed greater certainty in recognizing these crater types. Therefore, the two categories on each satellite may be only very broadly equivalent.

The diameters assigned to the palimpsests are those of the degraded rims surrounding the central, flat-floored region. The larger areas surrounding these central regions are relatively bright and have surface topography much like that of their surroundings. Therefore, the excavation cavity did not extend over the entire bright area. The edges of the bright areas are relatively sharp, compared with normal ejecta deposits, suggesting that they did not result directly from ejecta blanketing. Plausible explanations of these extended regions involve either disruption of the ice (crystal lattice disturbance and/or small-scale fractures) or annealing of the ice. Two mechanisms which may have contributed are (1) seismic disruption and (2) local heating, both as a direct result of a large impact. The outer limit of the bright zone might be the point at which the shock wave decayed below the threshold value

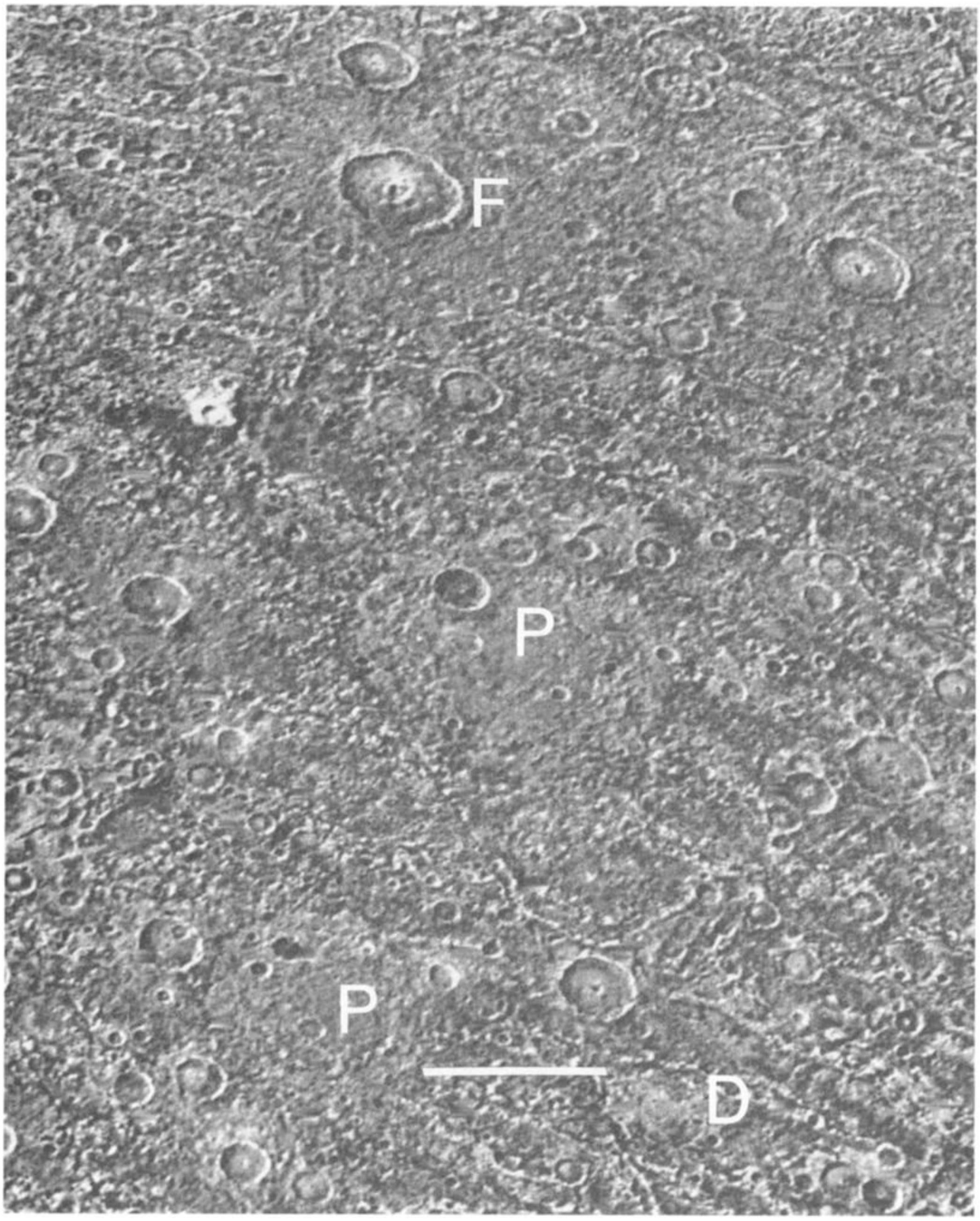

Fig. 8. Region of heavily cratered terrain on Ganymede. The F and D indicate fresh and degraded craters, respectively, and P indicates palimpsests. White scale bar represents 100 km. FDS 20636.59, north at the top.

for either disruption of the ice or where temperatures were raised just enough to allow annealing of pre-existing small scale fractures. Alternatively, a third mechanism may be annealing of the ice over the area where it was mobilized to fill and relax the excavation crater.

PRELIMINARY INTERPRETATION OF THE CRATER COUNTS

Because of uncertainties in such fundamental parameters as the source and composition of the impacting bodies, the reaction of icy targets to hypervelocity impacts, and the diversity and vigor of crater degradation and removal processes, the interpretations presented here must be considered preliminary.

Several striking features are immediately apparent in the crater curves of Ganymede and Callisto, and in their surface appearance compared to those of the Moon and Mercury (Figures 10 to 13). The size/density curves for the heavily cratered terrains on both Ganymede and Callisto differ markedly in both shape and crater density. Being deeper in Jupiter's gravity field, Ganymede should experience about twice the impact flux rate of Callisto [*Smith et al.*, 1979]. However, the most heavily cratered and therefore oldest terrain on Ganymede is less densely cratered than that on Callisto. Although the two curves are nearly parallel between about 50 and 130 km diameter, at smaller diameters considerable differences occur. Finally, neither crater population on Ganymede or Callisto resembles those found on the terrestrial planets. This is not only apparent from the crater curves but also from the striking visual difference in the crater diameter/frequency distribution among Callisto, Mercury and the Moon shown in Figure 10. It is immediately apparent from these scaled photo-

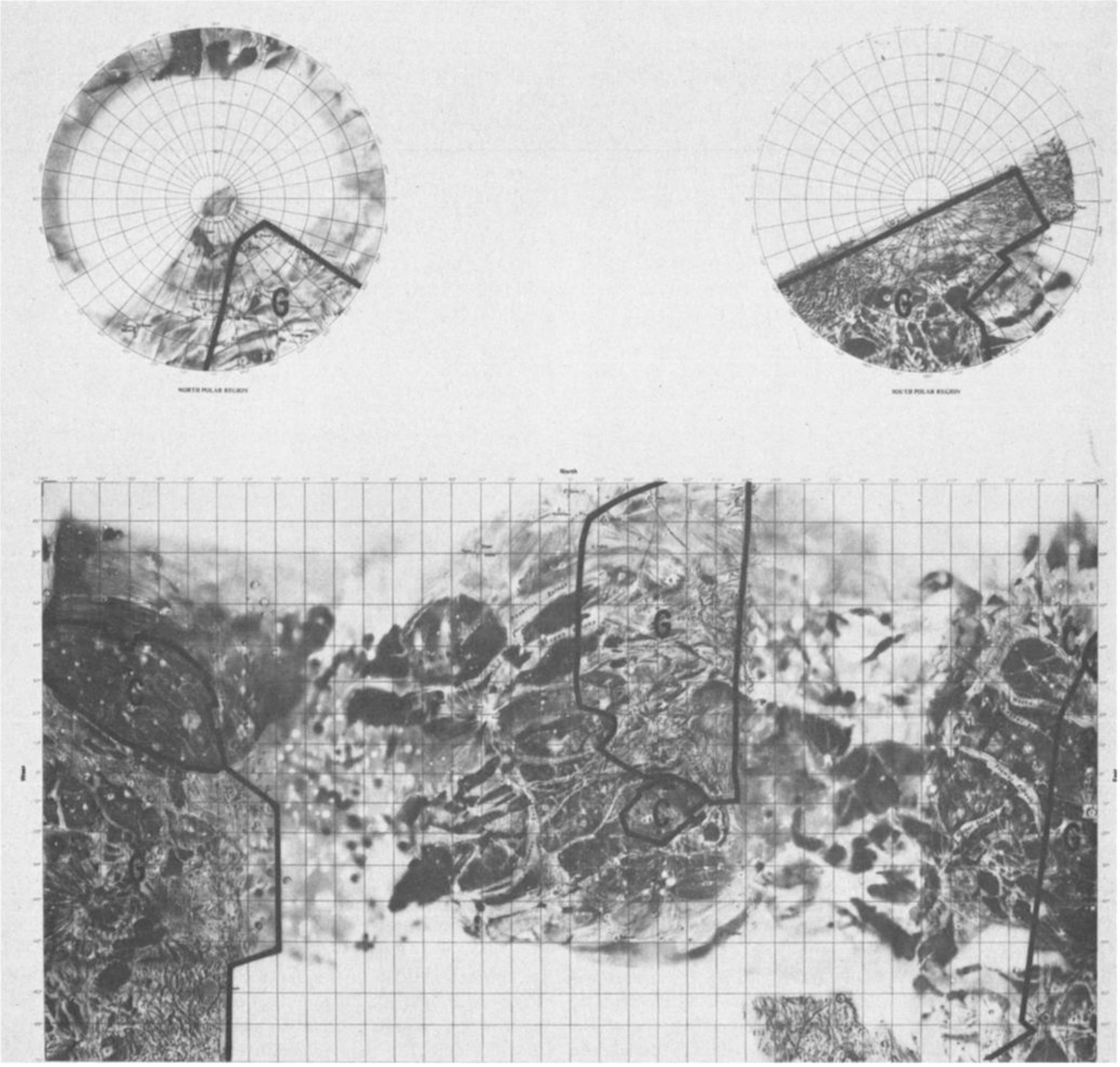

Fig. 9. Map of the regions where crater measurements were made on Ganymede: C, heavily cratered terrain; G, grooved terrain.

graphs that Callisto has a very strong deficiency of large craters and basins compared to both the Moon and Mercury.

The observed overall crater density on the most heavily cratered terrain on Ganymede is down by a factor of about 3 compared to Callisto, and when allowance is made for the predicted difference in crater production rates it is down by a factor of nearly 6. This indicates that the oldest regions of Ganymede began recording the observed crater population at a later time than Callisto. This might be due to a large-scale (perhaps global) diameter-independent resurfacing event, or Ganymede simply may have developed a rigid crust capable of retaining craters later than Callisto. The two possibilities are both consistent with thermal history models by *Cassen et al.* [1980] and *Parmentier and Head* [1979] which suggest that tidal heating, a higher radioactive content, greater accretional heating or some combination of these factors may have delayed the freezing of Ganymede's icy mantle with respect to Callisto's and kept it more thermally active longer. In any event, this process must have taken place during the period of heavy bombardment.

If at least a portion of the crater curves can be demonstrated to represent its production function, then a meaningful comparison of the Jovian satellites' crater population to those found in the inner Solar System allows speculations as to the nature and signature of degradational and obliterational processes on these icy bodies, and may place constraints on the origins of the objects responsible for bombarding both the inner and outer Solar System.

From the previous discussion of the 'terrestrial-planet cratering record,' clearly neither Ganymede nor Callisto is saturated with craters at the diameters considered in this study. On Callisto at diameters of 30 km and greater the crater density is equal to or much less than that of the lunar highlands, and of the Mercurian and Martian highlands as well (Figure 11). At diameters greater than 10 km the crater density in the heavily cratered terrain on Ganymede is also well below that

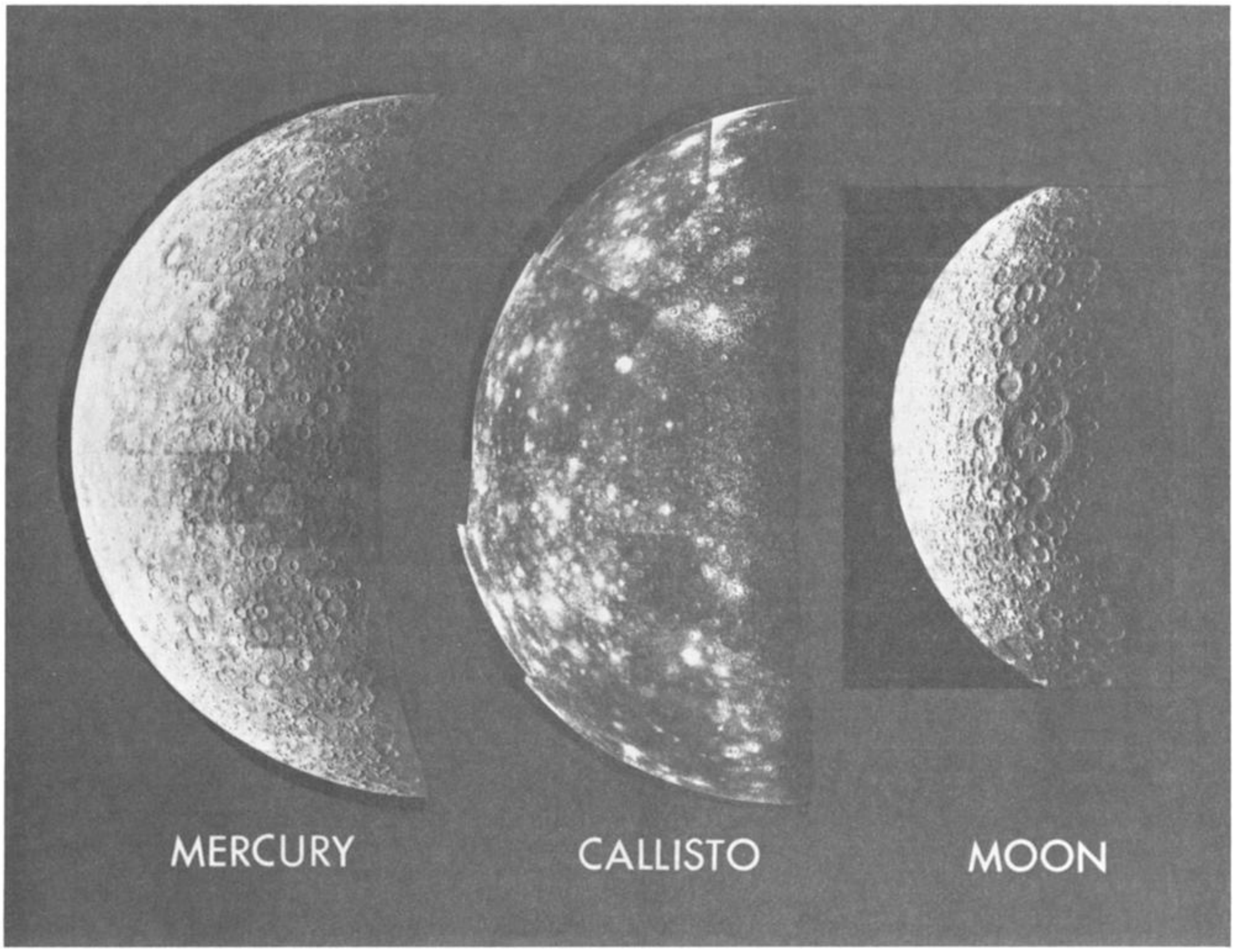

Fig. 10. Scaled comparison of the Moon, Mercury and Callisto seen under similar lighting conditions, but not similar resolutions. The visual comparison vividly demonstrates that the crater size/frequency distribution on Callisto is very different from that on Mercury and the Moon. Callisto has a great deficiency of large craters compared to the Moon or Mercury.

of the lunar highlands. As shown in Figures 2 and 3 these densities are far below the saturation limit for a wide range of population distribution functions. Therefore, the shape of the curves are not the result of saturation. However, at least over some portions of the curves equilibrium effects may be present (i.e., obliteration by crater relaxation or other processes).

Figure 11 shows that the crater curve on Callisto consists of at least two parts. In the diameter range of about 10 to 50 km the curve is practically horizontal on the relative plot (which is equivalent to a −3 distribution function on a differential plot, i.e., $\alpha = -3$ in the equation $dN = KD^{\alpha}dD$, where N is number, D is diameter, and K is a constant). Between diameters of about 50 and 100 km, the nearly −5 slope indicates a very rapid decrease in number of craters with increasing diameter. Although the data are sparse, at diameters greater than about 200 km the rate of decrease may slow. On Ganymede, the size/frequency distribution can also be divided into two parts (Figure 12). In the size range of about 10 to 40 km the curves for both the heavily cratered regions and the grooved terrain slope downward to the left with a slope index of roughly −2. If both Callisto and Ganymede were impacted by the same population of objects, then evidently a diameter-dependent obliteration of craters occurred in this size range on Ganymede but perhaps not on Callisto. By examining the curves for the fresh and degraded craters on the two planets, we can get an idea of the manner in which this obliterative process operated. The size-density curves of the degraded craters on both bodies show a high degree of diameter dependence (Figure 13); the smaller the crater diameter, the fewer the proportion of degraded craters. If this is a valid observation and not a problem in recognizing small, degraded craters, then it means that the process is dominantly one of crater obliteration for the smallest craters, progressing toward one of degradation for the larger craters. On the terrestrial planets one process that behaves this way is crater and ejecta overlap. Small craters are most often either left unscathed or totally obliterated by each subsequent impact while larger craters are more often partially overlapped and thereby degraded. Although crater overlap may contribute to the observed crater removal, we do not believe it to be the dominant process because of the low crater densities, particularly on the grooved terrain.

Comparison of the crater curves for the cratered and grooved terrains shows that the grooved-terrain curve bends downward more steeply than the cratered-terrain curve at less than about 40 km diameter. This suggests the recent process of crater removal on the grooved terrain has been more efficient than any on the cratered terrain. Apparently the formation of grooved terrain (i.e., new ice emplacement) preferentially obliterates small craters (perhaps, up to 70 km diameter)

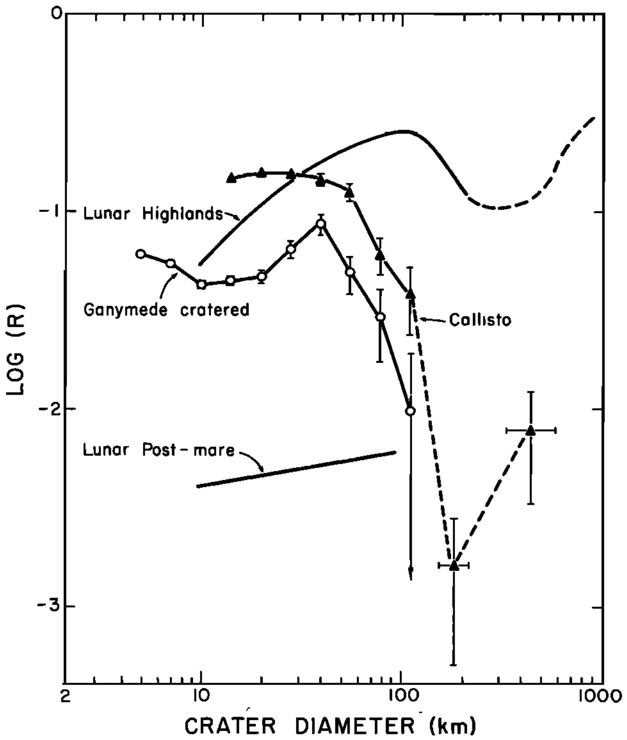

Fig. 11. Curves for the crater populations measured on the heavily cratered terrains of both Ganymede and Callisto, with the lunar curve for reference. The differences between the Moon, Callisto and Ganymede are much greater than are the similarities. The Ganymede and Callisto curves are similar beyond about 50 km diameter, but differ substantially at smaller diameters.

but only degrades larger craters. Figure 14 shows an area of grooved terrain where the formation of new ice has destroyed a large portion of the rims of several craters. Smaller ones, of course, would have been completely obliterated. The proposed preferential obliteration of small craters even on the cratered terrain may have been the result of an ancient episode of grooved-terrain formation (now hidden by the recratering) associated with the resurfacing or later crustal freezing mentioned earlier. Alternatively, the formation of the arcuate troughs may have been responsible for the loss of the smaller craters.

At diameters smaller than about 10 km the curve for the heavily cratered terrain on Ganymede turns up slightly. Whether this is indicative of the primary cratering population or not, we cannot ascertain without comparable diameter coverage on Callisto. However, secondary craters of sufficient size and perhaps of sufficient abundance to account for this upturn occur on Ganymede. At smaller diameters on Callisto the curve may not be the production function, but it sets an upper limit of about −3 for its slope. If an ancient episode of obliteration, similar to that proposed for Ganymede, operated on Callisto as well, then the production function could have an index more negative than −3. In any case, it is far from the −2.3 index observed on the terrestrial planets.

All terrains on both Ganymede and Callisto show a decrease in slope index for craters greater than about 50 km. Two plausible explanations for this decrease are: (1) a great deal of crater obliteration due to crater relaxation in the icy crust, the vigor of the process increasing with crater size [*Parmentier et al.*, 1980], or (2) the curves basically represent the production function with a deficiency of impacting bodies in this crater size range compared to that for the terrestrial planets. We tend to favor the latter explanation for the following reasons. Figures 11 through 12 show that seven different crater curves, representing vastly different densities, on different terrains and even on different satellites all possess this steep-slope index (~−4.7) distribution function. Furthermore, as pointed out earlier, even though older craters up to about 100 km diameter have been degraded, i.e., flat floors at about the level of the surrounding terrain, their rim sharpness is more or less preserved, suggesting that relaxation is not very effective at totally obliterating craters. If the paucity of craters in this diameter range was solely due to obliteration by relaxation, then one would expect a very different distribution function between, for example, fresh craters preserved over long time periods in rigid ice, and degraded craters perhaps formed at a time when the ice was better able to flow. Therefore the observed large variations in crater densities, but similarities in slope among the many different terrains, ages, degradational classes, and even satellites, argue against this diameter range being solely the result of equilibrium. Furthermore, the absence of palimpsests on Callisto suggests that the presently observed crater population formed when the icy crust was rigid enough to retain the craters basically intact, with a minimum of obliteration due to plastic relaxation of the ice. The conclusion is that it is basically a production function.

Three important consequences devolve from these interpretations. First, because of the similarity of the curves for the degraded and the fresh craters (over the range 30 to 130 km) the process degrading them must be nearly diameter-independent. Second, although significant proportions of craters have been degraded, the process which degrades them is not too effective in totally obliterating them. If the degradational process is crater relaxation, then it effectively stops at a stress

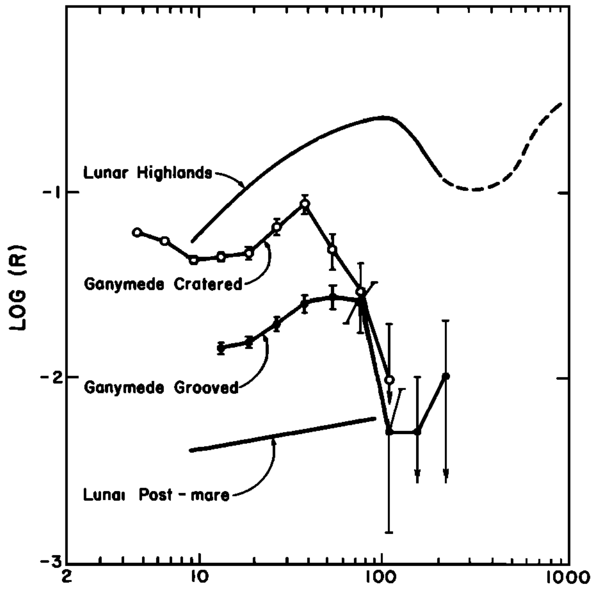

Fig. 12. Comparison of the crater populations on Ganymede's grooved and heavily cratered terrains, with the lunar curve for reference. The grooved terrain is similar in slope to the heavily cratered terrain for diameters above 30 km, but at smaller diameters a progressive loss of smaller craters has increased the slope index of the grooved terrain compared to that of the heavily cratered terrain. Also notice that the grooved terrains which were measured are of at least two ages, one being about as densely cratered as the heavily cratered terrain, the other much less cratered.

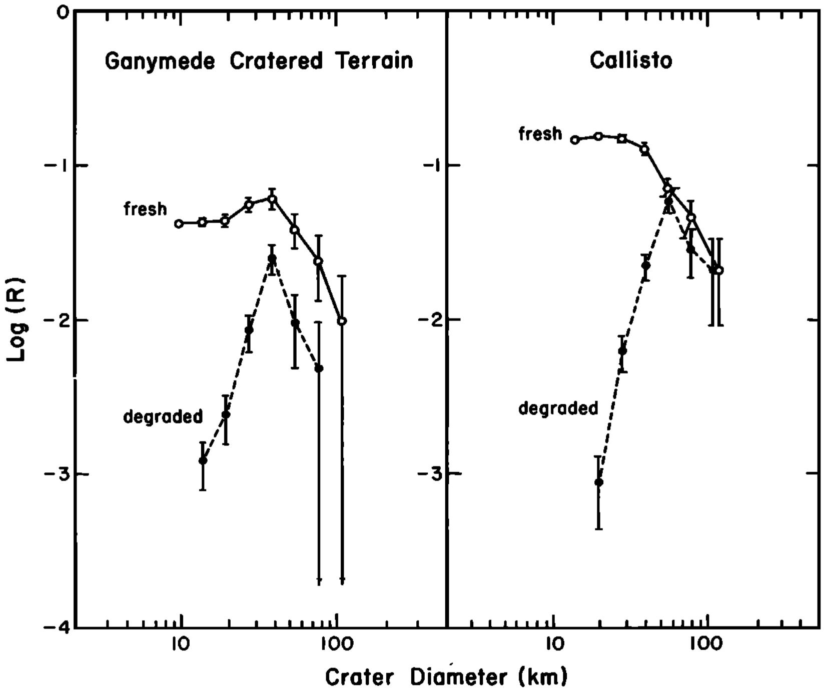

Fig. 13. Curves for the fresh and degraded craters on both Ganymede and Callisto. The degraded craters represent only a small fraction of the small craters, but a substantial proportion of the larger ones. Both planets have similar curves.

level which is still high enough to leave a residual topography which is identifiable as a crater. Observational evidence for this has already been presented. Third, the production function in at least the Jupiter region (5 AU) is vastly different from that in the inner Solar System. We can only speculate at this early stage that Ganymede and Callisto may principally record a population of bodies that never penetrated the inner Solar System in numbers great enough to leave a recognizable signature.

At diameters greater than about 150 km the data sets are too sparse to be certain of the shape of the curves, and to interpret them would certainly be 'treading on thin ice.' However, from the Callisto data set, one might reasonably deduce that the steeply downward trend is reversed beyond about 250 km diameter, i.e., large impacts are slightly more abundant on Callisto than might be expected from the frequency of the immediately smaller impacts.

The above arguments were constructed to support the proposition that the crater populations of Ganymede and Callisto have not sustained significant crater losses due to relaxation of the icy crust. Although many analyses of relaxation times on these satellites suggest that craters could be obliterated on time scales short compared to the surface exposure ages, to date these studies have greatly simplified a difficult problem. For example, they often represent the craters as monofrequency sine waves although the craters are clearly far more complex structures. The high frequency components of the craters, such as their sharp inner and outer rims and their central structures will last many times longer than the crater bowls themselves. In the case of the palimpsests, for example, although their bowls are apparently nearly fully relaxed, under low enough illumination angles the remnants of the rims can still be easily recognized. In fact that is how we are able to assign a particular diameter to those structures.

Although the reality of complete crater relaxation must be considered an open question from the point of view of physical modeling, we recognize how readily the shape of the crater curves lend themselves to interpretations of crater obliteration by relaxation. The close proximity of the grooved and cratered terrains' curves beyond diameters of 60 km suggest abutment against an equilibrium limit. Yet we must be aware that this similarity spans only two diameter bins (64 to 128 km), with large associated error bars. But a segment of the Callisto crater curve also nearly parallels those of Ganymede at the large diameters, again suggesting attainment of equilibrium, but at a greater density than on Ganymede perhaps because the relaxation process may be slower on Callisto. However, an upturn occurs in the curves of both Callisto and Ganymede's grooved terrain at still larger diameters, this is not in obvious concord with an interpretation of equilibrium conditions.

We do not believe that these curves truly represent attainment of equilibrium, but even if we accept such a conclusion, we can still make strong arguments that the crater production function recorded on the Galilean satellites was not the same one recorded in the inner Solar System. We will do this by reductio ad absurdum. Let us assume that the lunar highlands' distribution was initially impressed on the ancient terrain of Callisto. We adjust the total crater flux at Callisto so that the minimum amount of crater obliteration would be required in order to ultimately evolve the observed Callisto curve from the lunar highlands' production function. This is done by assuming that no craters in the 8 to 11 km diameter range were obliterated on Callisto and none were obliterated at any diameter on the lunar highlands. If, for each diameter bin, we now calculate the percentage of all craters which would have to be obliterated in order to evolve the Callisto curve, we obtain the solid line in Figure 15. The other curves are for varying degrees of crater enlargement. Such a calculation is conservative not only because it assumes that no 8 km craters were obliterated, but also because it assumes that craters on the Moon and Callisto follow the same scaling relationship. If, as *Boyce*

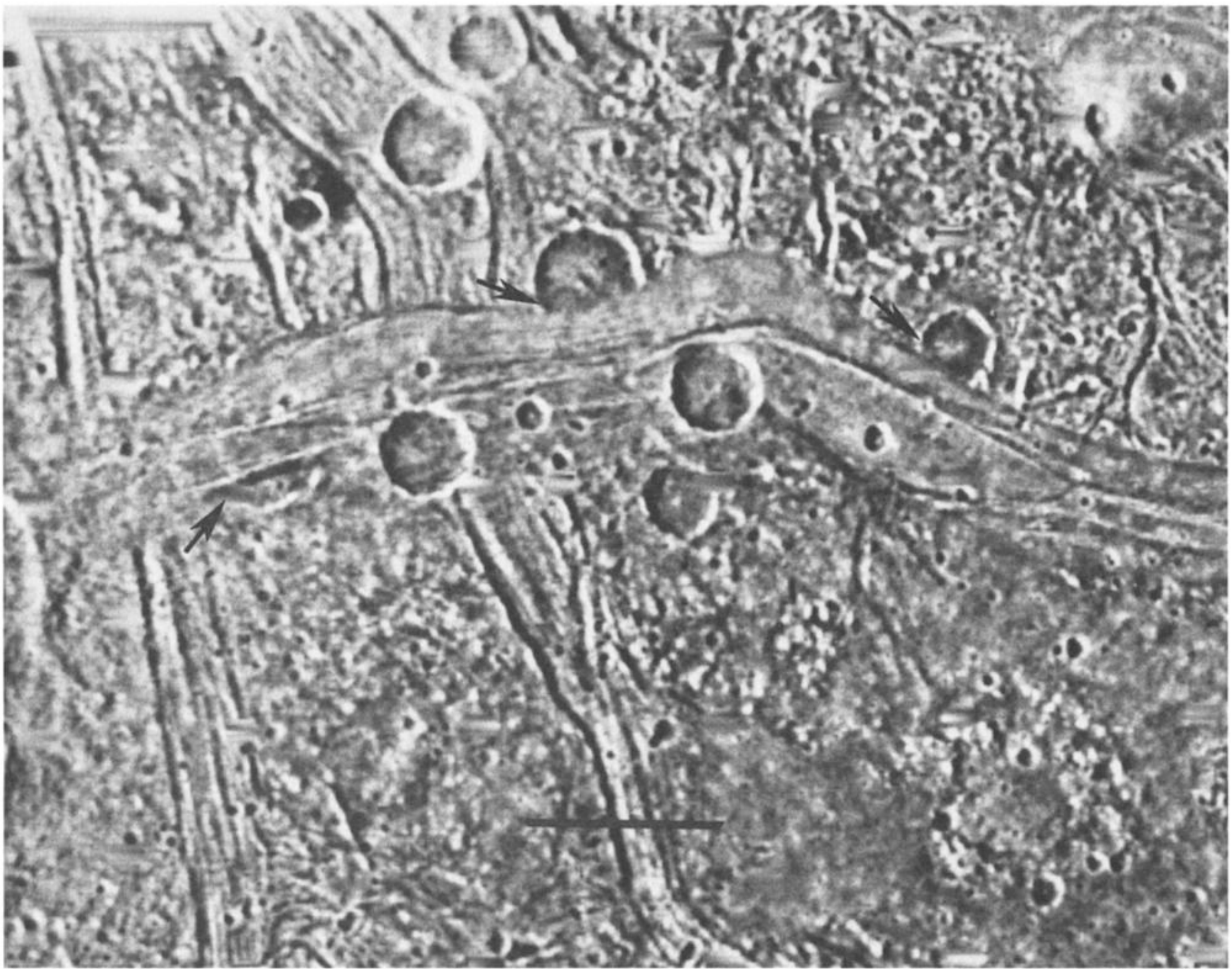

Fig. 14. The formation of a segment of grooved terrain on Ganymede has removed a portion of the rims of several large craters (black arrows). Similar new ice formation must have totally obliterated many smaller craters. This process probably accounts for the overall lower crater density on grooved terrain than cratered terrain and the greater diameter-dependent obliteration of the smaller craters shown in Figure 12. Black scale bar represents 50 km. FDS 20637.38, north at the top.

[1979] has suggested, craters in ice will be larger than their equivalents formed in rocky substrates, then the degree of obliteration required to develop the observed Callisto curve from that of the Moon is also greater. The dotted and dashed lines in Figure 15 show cases for enlargement factors of 1.4× and 2× for craters on Callisto. The most conservative case requires that more than 90% of all craters larger than 80 km diameter would have to have been obliterated by relaxation. This is far more obliteration than is consistant with the appearance of the surface. If so many of these large impact structures and their ejecta deposits were totally obliterated by relaxation, some would still have left easily recognizable scars in the form of circular areas depleated in craters. Only if essentially all of the large bodies impacted very early in the cratering history would their crater scars now all be recratered to densities indistinguishable from the average background; but accepting such a scenario would immediately concede that the cratering histories of the terrestrial planets and of the Galilean satellites were different.

One may contend that low crater-density scars do exist; the best example being the Valhalla basin. However, our statistics include Valhalla and all degraded basins with measurable diameters. Therefore, these are not yet obliterated by relaxation and count among the observed craters and not among the low crater-density scars. We are forced to accept, therefore, that we can not subject Callisto to the lunar highlands' cratering history, add the phenomenon of crater relaxation and develop a surface such as the one actually observed. Consequently, we conclude that the crater production functions were different for the inner Solar System and the Jovian region.

SUMMARY

Several lines of evidence suggest that the crater curve on Callisto and Ganymede in the diameter range of about 50–130 km basically represents the production function. In the diameter range of about 10 to 40 km Ganymede has apparently suffered crater losses on both the grooved and cratered terrains that may or may not have occurred on Callisto. In the case of the grooved terrain this loss is probably the result of the formation of new icy material over some unspecified period of time. The overall crater density is significantly less on the grooved terrain compared to the cratered terrain indicating that it is younger. This is consistent with observed stratigraphic and transectional relationships between the two types of terrain. The loss of small craters in the heavily cratered terrain may have been due to the formation of ancient

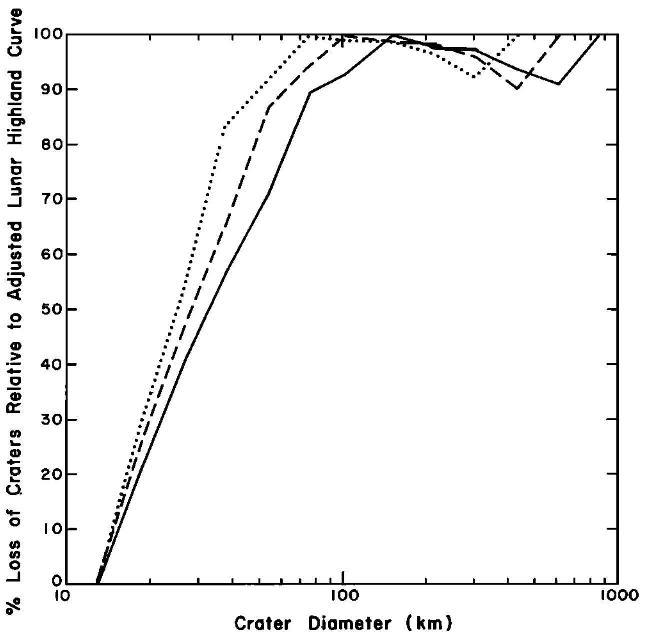

Fig. 15. If we assume that the same population which impacted the lunar highlands impacted Callisto, then a large proportion of craters would have to have been obliterated to obtain the present Callisto population. This graph shows the percent loss of craters on Callisto as a function of crater diameter. The solid line assumes that equal sized craters result from equally energetic impacts into icy and rocky material; dashed line assumes 1.4× enlargement and dotted 2× enlargement in ice compared to rock.

grooved terrain which is now unrecognizable because of heavy recratering and/or obliteration due to the formation of the numerous troughs. The overall crater density of the most heavily cratered (oldest) terrain on Ganymede is significantly less than on Callisto, particularly when account is taken of the greater crater production rate predicted at Ganymede due to Jupiter's gravity field. This indicates that either widespread resurfacing has taken place on Ganymede, or that its icy crust became rigid enough to retain craters at a later time than Callisto's. In any event, the responsible mechanism must have acted during the period of intense bombardment.

Finally, the population of objects responsible for the period of intense bombardment at Jupiter appears to have been very different from that responsible for the period of heavy bombardment on the terrestrial planets. This population of objects may have been primarily a family of bodies that never penetrated the inner Solar System in numbers great enough to leave a recognizable signature. It seems unlikely that this population was largely derived from the asteroid belt because of the difficulty in acquiring the large energies necessary to reach the orbit of Jupiter. Furthermore, if we are dealing with two very different populations there is no assurance that the impact flux history at Jupiter was the same as that in the inner Solar System. Deciding between hypotheses regarding the origin of the objects responsible for the period of late heavy bombardment is not yet possible. However, the observed cratering records on Callisto and Ganymede suggest two broad alternatives for the origin of the impacting bodies: (1) if the objects responsible for the late heavy bombardment in the inner Solar System were remnants left over from the accretion of the planets, then this can not also be the case at Jupiter unless the objects had a very different diameter/frequency distribution; however, a major argument against an accretional origin is the short lifetime (half life 30–70 m.y.) of such objects [*Wetherill*, 1975]; (2) a model proposed by *Wetherill* [1975] for the origin of the objects responsible for the period of late heavy bombardment in the inner Solar System involves perturbation of Uranus and Neptune-crossing objects into Saturn and then Jupiter-crossing orbits which eventually evolve into orbits similar to short-period comets. A single, randomly timed Roche limit breakup of a large body ($\sim 10^{23}$ g) due to a close encounter to the Earth or Venus would then produce the objects which formed the craters. If this mechanism operated, then one might expect that the population of the Jupiter-crossing objects would differ from those in the inner Solar System and that the impact rate would be quite different as well. Whether or not the surface of Callisto and Ganymede record the impact of such objects is not known. All that can be said at this time is that any model for the origin of the objects responsible for this period of intense bombardment at Jupiter and in the inner Solar System must take into account the population difference in these two regions.

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