Oklahoma Geological Survey Circular 100, 1997

Extraterrestrial Impact Craters

Paul D. Lowman, Jr.
Goddard Space Flight Center
Greenbelt, Maryland

ABSTRACT.—Craters are the most common landform in the solar system, with the notable exception of the Earth and the volcanically resurfaced satellite Io. This paper describes impact craters on the Moon, Mercury, Mars, and Venus and gives a brief account of craters on the icy satellites of the outer planets. The Moon's craters are well preserved because of the lack of tectonic reworking and Earthlike erosion and deposition. There is a complete gradation from micrometer-size impact craters to multiring basins over 2,000 km wide. The circular mare basins, essentially large impact craters, were evidently formed at about the same time—3.9 b.y. ago—and localized prolonged basaltic eruptions, thus forming the maria. Mercurian craters are morphologically similar to those of the Moon, but the higher gravity restricted distribution of impact ejecta. Mars is an intermediate planet in terms of crustal evolution and has undergone erosion and deposition; it retains considerable surface ice. Some impact craters on Mars are morphologically different from those of airless planets in that they have lobate ejecta blankets of apparently fluidized ejecta. Mars is notable for a higher than usual population of elliptical primary craters, possibly formed by infall of captured satellites. Venus has a thick and dense atmosphere and consequently a lower population of small impact craters than occurs on other extraterrestrial bodies. Venusian craters have a number of unique features, such as long fluidized ejecta outflows probably formed by entrained gas. The Venusian crater population appears to express major volcanic resurfacing, although it is not yet clear whether this was a single episode or an equilibrium process. Small bodies, notably the icy satellites of the outer planets, have abundant impact craters, but these have been altered on bodies such as Ganymede by ice flowage. On Europa, occasional releases of water may lead to resurfacing and thus erase impact craters. Early impact cratering in general appears to represent the last stages of planet or satellite accretion, although impacts have evidently also broken up small bodies.

INTRODUCTION

Impact craters are uncommon on Earth, primarily because the Earth is an active planet whose crust is continuously reworked or resurfaced, but in the solar system as a whole, they are the most abundant landform on most solid planets and satellites. Extraterrestrial craters except for those of the Moon were unknown until close-range investigation became possible with the beginning of space flight, but they have now been found on every solid body except the Jovian satellite Io, which is continually resurfaced by tide-induced volcanism. Ephemeral craters, so to speak, were observed forming in the "Great Comet Crash" of 1994, when comet Shoemaker-Levy 9 hit Jupiter in a series of spectacular impacts whose atmospheric effects were still visible a month after the last impact (Hammel and others, 1995).

Having been geologically inactive for roughly 3 b.y. (Fig. 1), and with no atmosphere or hydrosphere, the Moon provides an easily visible and accessible museum of impact craters. This review will therefore concentrate on this "museum" of abundant, varied, and often pristine examples. Emphasis will be throughout on the characteristics of craters. A number of important topics, such as age estimation from cratering rates, are beyond the scope of the review and will be mentioned only briefly (Taylor, 1992).

LUNAR IMPACT CRATERS

Although mapped and named for centuries, lunar craters were generally considered volcanoes until the late 19th century. One reason for this is that the existence of meteorites, i.e., bodies that fall from the sky, was not accepted by western sci-

---

Paul D. Lowman, Jr., Goddard Space Flight Center, (Code 921), Greenbelt, MD 20771.

Lowman, P. D., Jr., 1997, Extraterrestrial impact craters, *in* Johnson, K. S.; and Campbell, J. A. (eds.), Ames structure in northwest Oklahoma and similar features: origin and petroleum production (1995 symposium): Oklahoma Geological Survey Circular 100, p. 55-81.

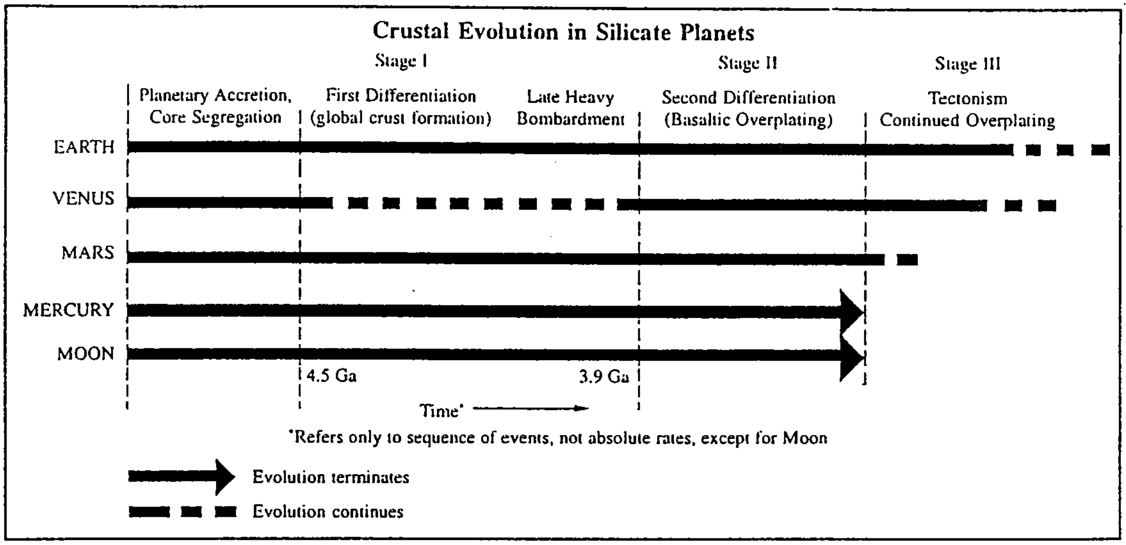

Figure 1. Comparative crustal evolution in the Moon, Mars, Venus, and Earth (from Lowman, 1989).

entific authorities until the late 18th century (Nininger, 1959). Volcanoes in contrast were well known, and it was natural to consider the Moon's craters calderas, an interpretation championed as late as 1971 (Green, 1971). The first modern authority to present a convincing case for their impact origin was G. K. Gilbert (1893), whose treatment of the Imbrium Basin is still considered valid today.

An impact origin for most lunar craters was convincingly argued by Dietz (1946), but it was the monumental study by Baldwin (1949) that convinced most scientists. Innumerable explosion craters had been produced during and after two world wars, and Baldwin showed that shell, bomb, and explosion craters fell on a smooth log-log depth vs. diameter plot (Fig. 2). Furthermore, four known terrestrial impact craters and dozens of lunar craters appeared to follow the same relationship.

The study of impact cratering was enormously stimulated by the beginning of space exploration. Assuming an impact origin for lunar craters of the Tycho-Copernicus type, and building on the work of Gilbert, the U.S. Geological Survey began systematic mapping of lunar geology under the sponsorship of NASA (the National Aeronautical and Space Administration) (Shoemaker and Hackman, 1962). The basic soundness of this work has been generally confirmed by the Apollo results and many other investigations of three decades. Lunar impact craters can be discussed in detail with considerable confidence, starting with relatively small, simple examples and working up to multiring basins covering much of the lunar surface area. The microscopic "zap pits" are well known and will not be described here.

It is important to appreciate the peculiarities of the lunar environment before comparing its craters with those of other bodies. Most important are the low gravity (one-sixth that at the Earth's surface) and absence of an atmosphere, which affect the later stages of crater excavation and distribution of ejecta. Another factor is the total absence of water in the Moon's outer layers; unlike the Earth or Mars, impacts on the Moon hit a totally anhydrous target.

Before going to examples, it will be convenient to introduce the concepts of "simple" and "complex" craters as they are applied to the Moon (Fig. 3). Small craters, a few kilometers wide, are generally "simple"; craters become "complex" at diameters of a few tens of kilometers. Figure 4 shows a large array of simple craters in a 5-km-wide area of Oceanus Procellarum, a reasonably typical mare area. The largest crater is close to the size and structure of the well-known Meteor (Barringer) Crater of Arizona. Its subdued topography suggests considerable age, very possibly several hundred million years. It is essentially a simple hole in the ground, with little structure. However, it will be noticed that a number of smaller craters nearby show concentric terraces. A closer view of such a double ring crater is shown in Figure 5. In light of what is now known about the lunar maria, this structure can be explained (Oberbeck and Quaide, 1968) as the effect of impact on a regolith (i.e., unconsolidated fragmental material) a few meters thick overlying solid rock (in this area, basalt).

The best example of a nearly pristine complex crater is 85-km-diameter Tycho (Fig. 6), whose age is estimated to be on the order of 100 m.y. despite its fresh appearance (Hörz and others, 1991). Its

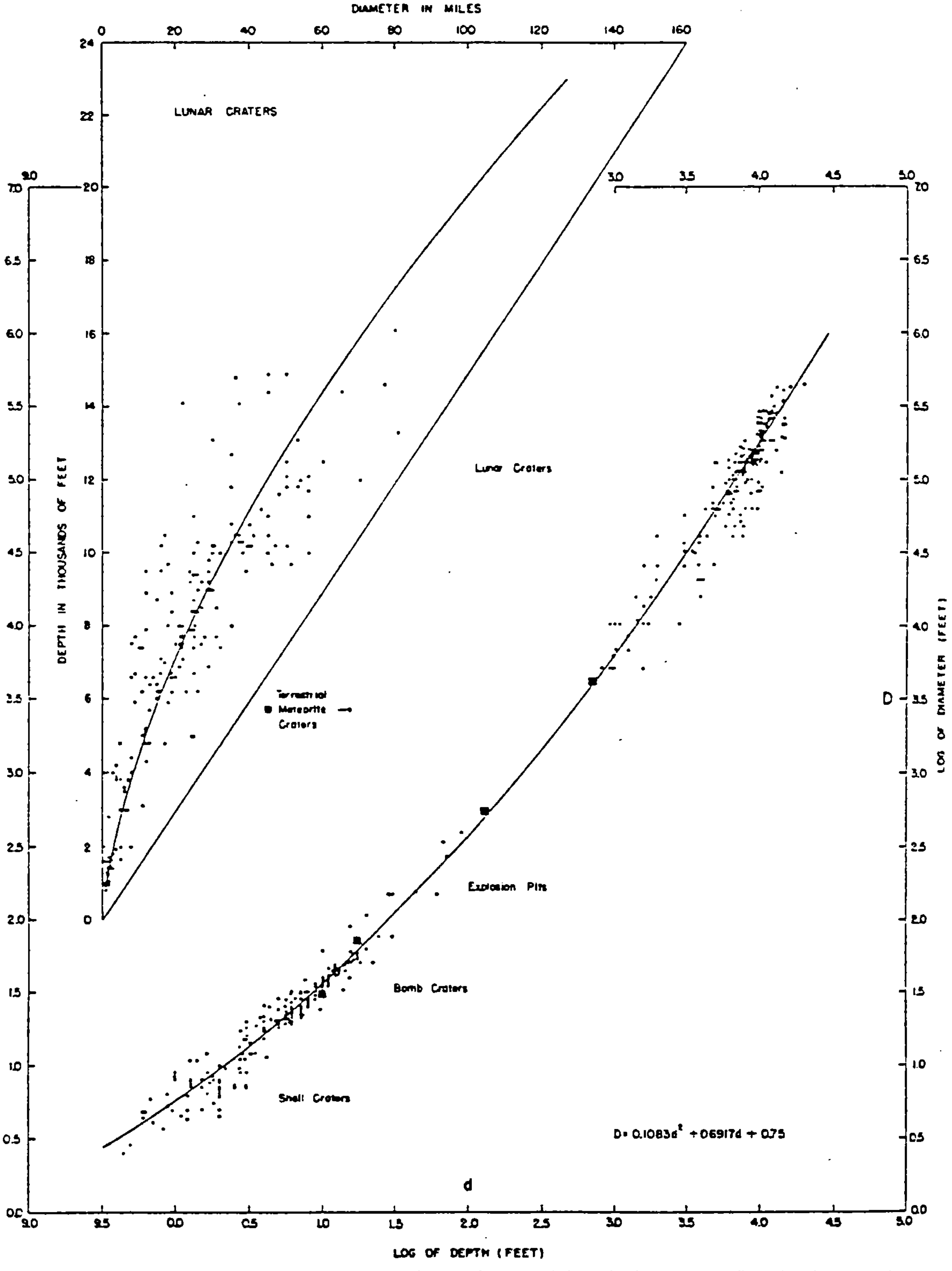

Figure 2. Relationship between diameter and depth of terrestrial explosion craters (bomb, shell, etc.) compared with lunar craters (from Baldwin, 1949).

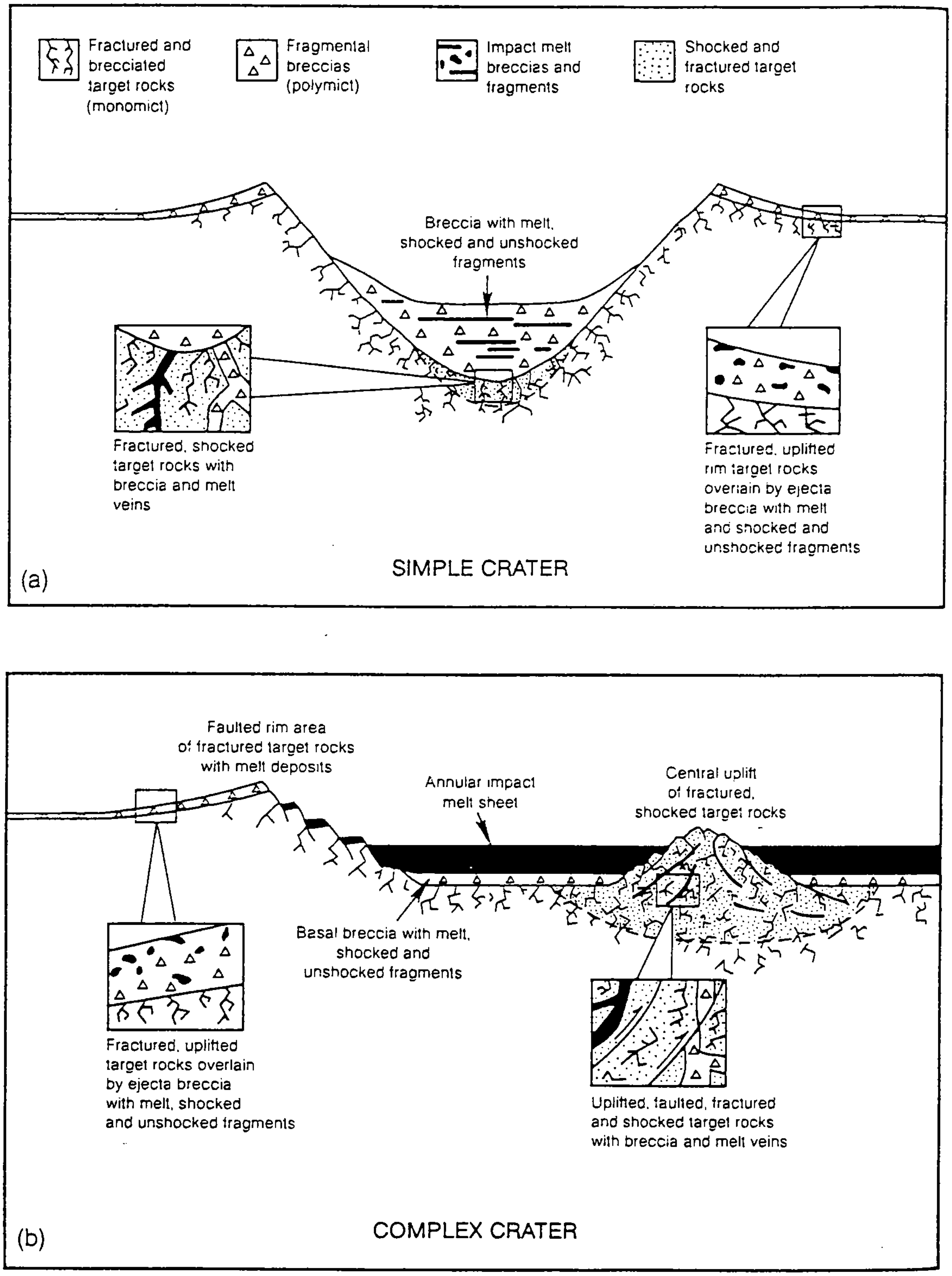

Figure 3. Schematic cross sections of simple and complex impact craters as these terms are now used (from Hörz and others, 1991).

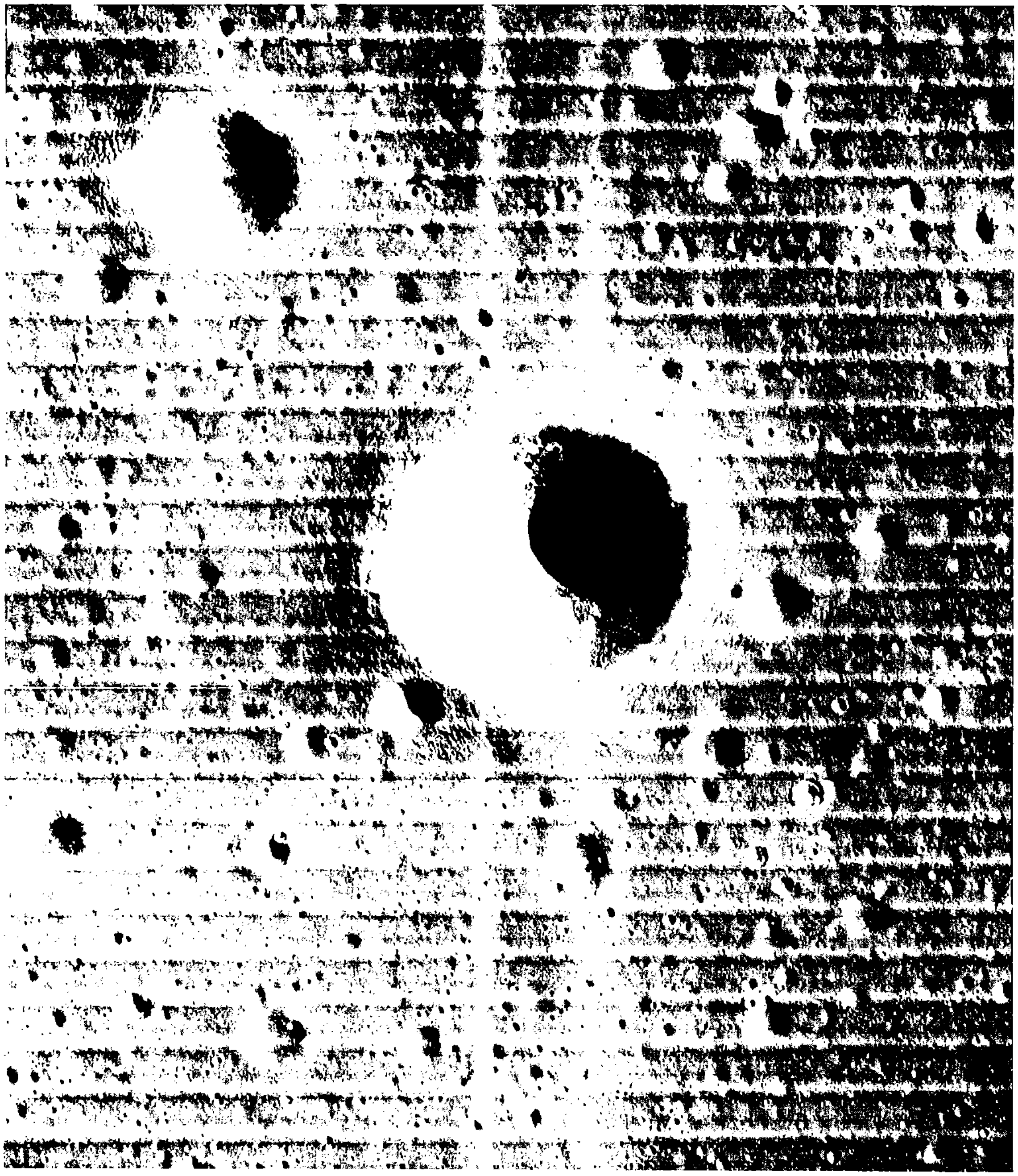

Figure 4. Lunar Orbiter picture of craters in Oceanus Procellarum, in an area about 5 km wide. Note small, double-ring craters.

relatively young age is also indicated by its optical and radar brightness, and its high thermal inertia, all indicating a thin or absent regolith. The features shown in the idealized diagram (Fig. 2) can be easily identified in Tycho: the raised rim, ejecta blanket, concentric terraces, impact-melt sheet, and central peak or uplift. The floor (Fig. 7) of Tycho is a rugged terrain with little or no regolith and very few superimposed later impact craters. This material is interpreted as impact melt and fallback breccia.

Another relatively young and fresh crater, Aristarchus, is shown in Figure 8. The general form of Aristarchus is that of a typical complex impact crater, but here the impact may have triggered some sort of internal activity. Aristarchus was

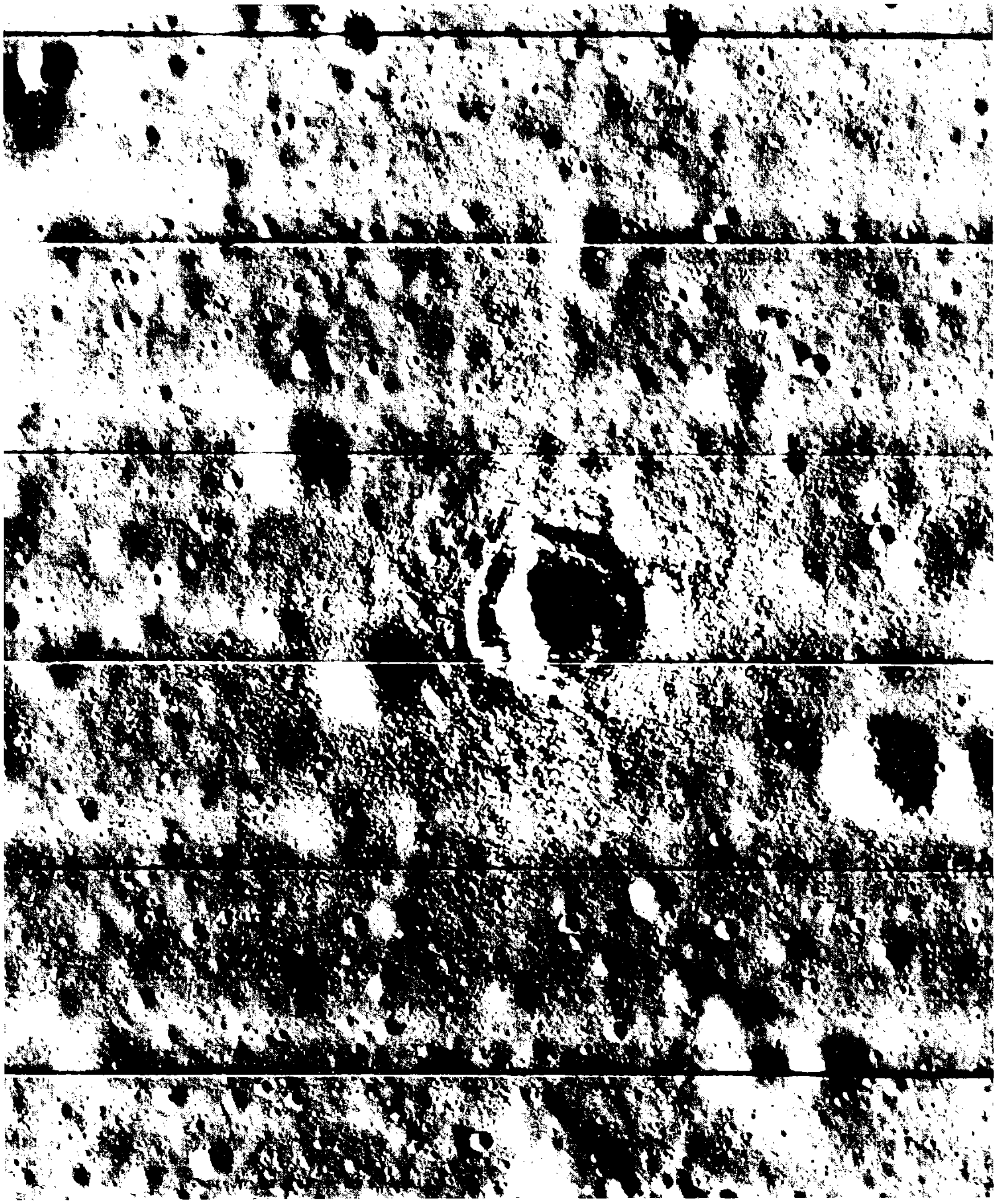

Figure 5. Lunar Orbiter high-resolution picture of fresh crater 130 m wide in Oceanus Procellarum, showing double-ring structure expressing impact effect in regolith over solid bedrock.

observed in 1963 by astronomers engaged in telescopic mapping to be emitting glowing reddish clouds of some sort, observations confirmed later by others. The Apollo 15 and 16 missions detected radon coming from the vicinity of Aristarchus, and since radon has a half-life of only a few days, its internal origin is undoubted. The actual relationship between impact and the internal activity in this area is not known. The sinuous rille shown in Figure 8 is almost certainly a volcanic feature,

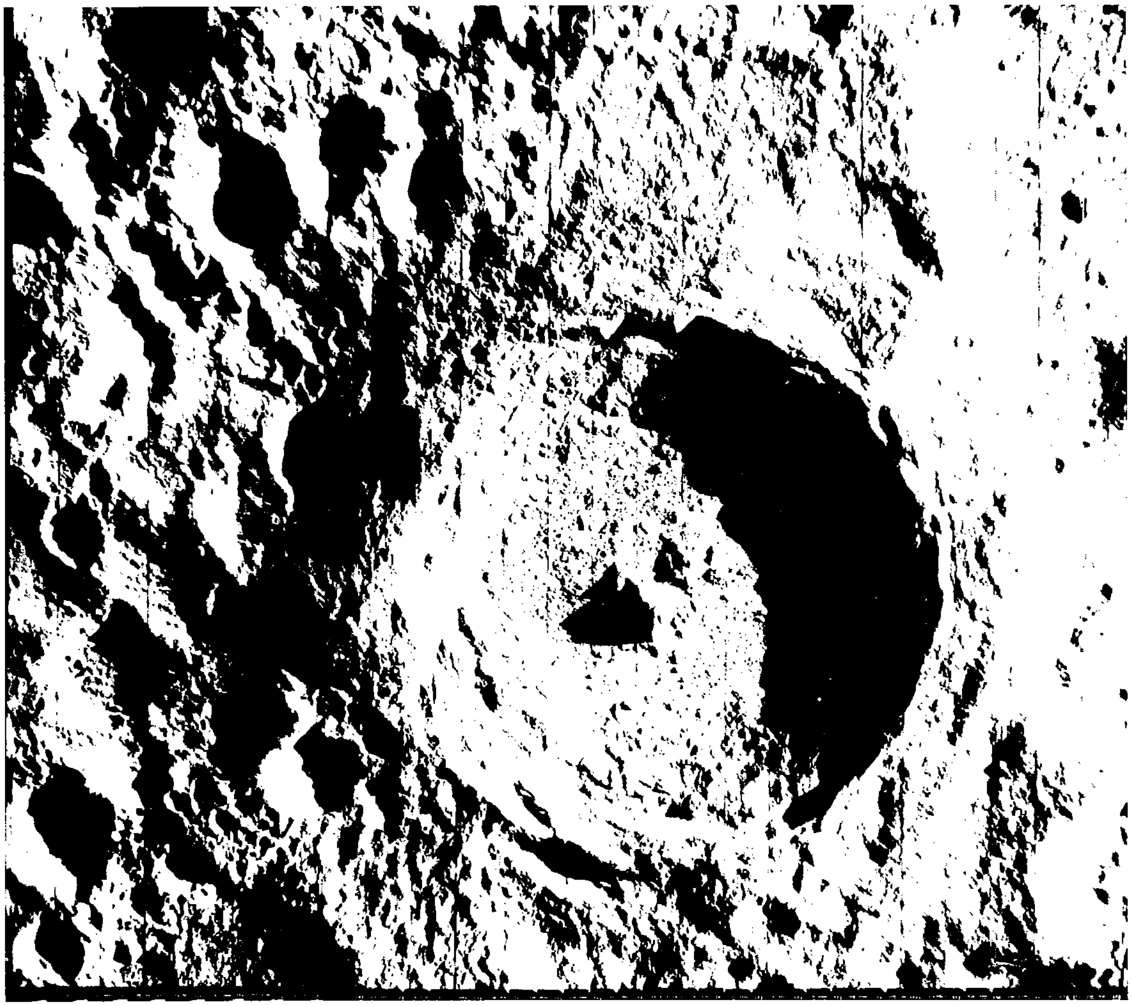

Figure 6. Lunar Orbiter picture of crater Tycho, 85 km wide; Sun from right, north at top.

probably a lava drainage channel, and it may well be that the impact simply localized gas emissions in an area inherently active to begin with. However, Aristarchus shows that major impacts on the Moon may have had more pervasive effects that crater formation alone.

Another, but older, complex crater, Copernicus, is shown in a classic telescopic view of the Moon (Fig. 9), which can be used to discuss several other crater categories. The greater age of Copernicus can be inferred from its more subdued topography and greater density of younger impact craters, well displayed in what was termed "The Picture of the Century" when transmitted from Lunar Orbiter in 1966 (Fig. 10). Figure 9 shows the Copernican ray system, as well as the chains of secondary craters formed by falling low-velocity blocks of ejecta from Copernicus. The rays overlie all features for several hundred kilometers around, superposition relationships showing that Copernicus is the youngest major feature. The similar crater Eratosthenes, to the northeast, is overlain by Copernican rays and no longer has visible rays of its own. Features of similar relative age are assigned to the Eratosthenian System (Shoemaker and Hackman, 1962).

Other types of craters are extremely well displayed in Figure 9. The largest of all is the Imbrium Basin, first interpreted as a gigantic impact crater by G. K. Gilbert (1893). This interpretation was confirmed by the Apollo missions, in particular Apollo 14, which landed on the ejecta blanket (Fra Mauro Formation) of the Imbrium Basin. The basin is actually a multiring structure, as shown by Spudis (1993), although this is not obvious because of subsequent basalt flooding. The excavation of the basin by impact of an asteroidal fragment was estimated by Spudis to have taken sev-

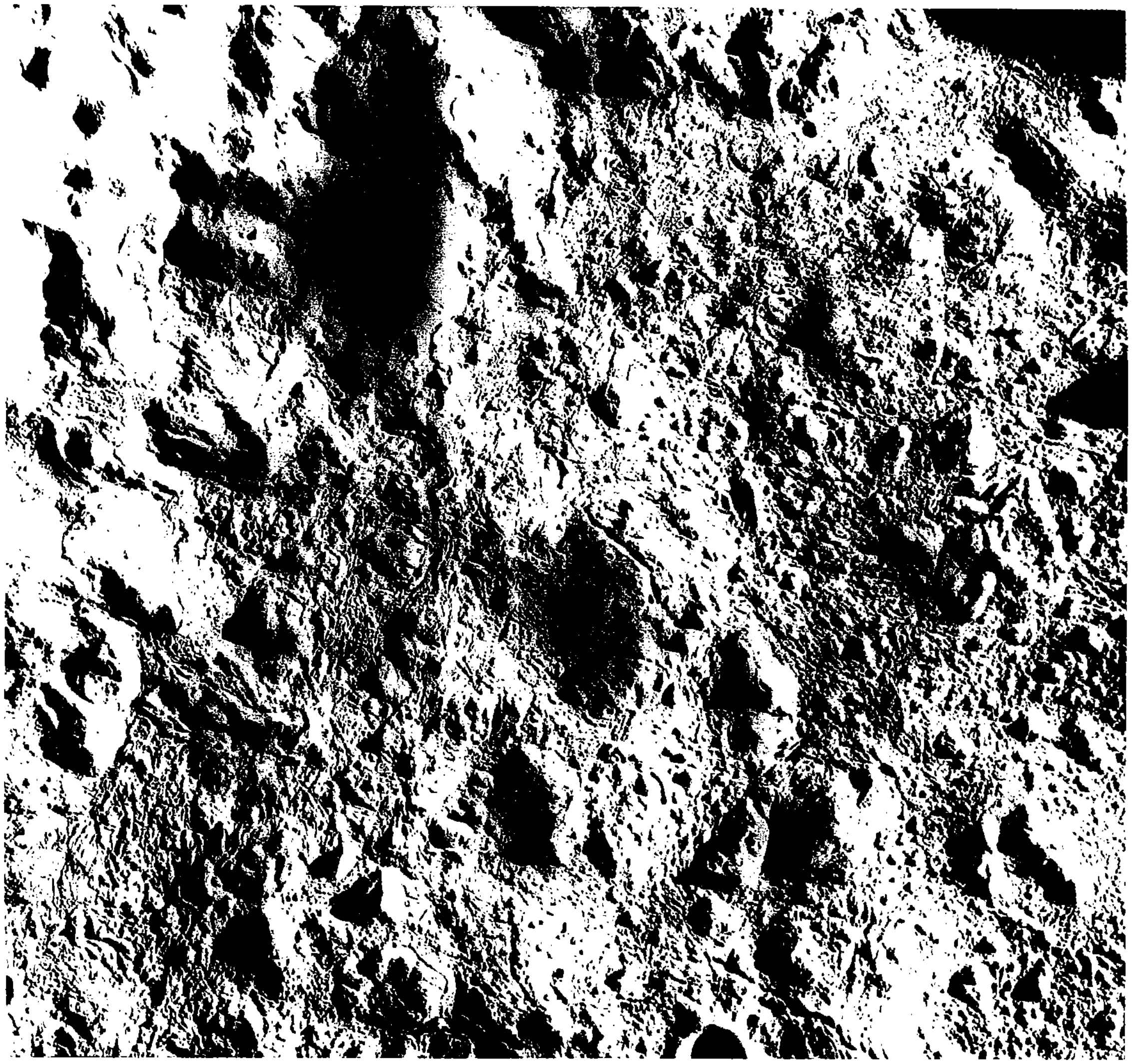

Figure 7. Lunar Orbiter picture of floor of Tycho, showing impact melt and breccia.

eral hours, an estimate since supported by the prolonged duration of the Shoemaker-Levy 9 cometary impacts on Jupiter.

Another category of impact crater has important implications for age relationships in the Imbrium Basin. Archimedes, Plato, and Sinus Iridum are essentially similar to Tycho and Copernicus, but have been filled and embayed by the basalts of Mare Imbrium. These stratigraphic relationships show that a significant time elapsed between excavation of the Imbrium Basin (which must have destroyed all preexisting topography) and the eruption of the mare basalts. Radiometric ages of these basalts, and exposures of lava flows at the Apollo 15 site, indicate that they were erupted in multiple episodes over several hundred million years. The relationship between impact and volcanism here is fairly well understood. The Imbrium impact evidently fractured the lunar crust and mantle to depths of several hundred kilometers, reaching a zone in which basaltic magma was being generated by more or less normal petrologic processes. It has been suggested by Ryder (1994) that basalts enriched in potassium, rare earth elements, and phosphorus (and therefore known as KREEP basalts) as well as other trace elements from the Imbrium Basin were impact induced.

It has been shown that the morphology of lunar craters changes with increasing size. Beyond the transition from simple to complex, there is a progression from craters to multiring basins. Departure from the complex-crater shape typified by

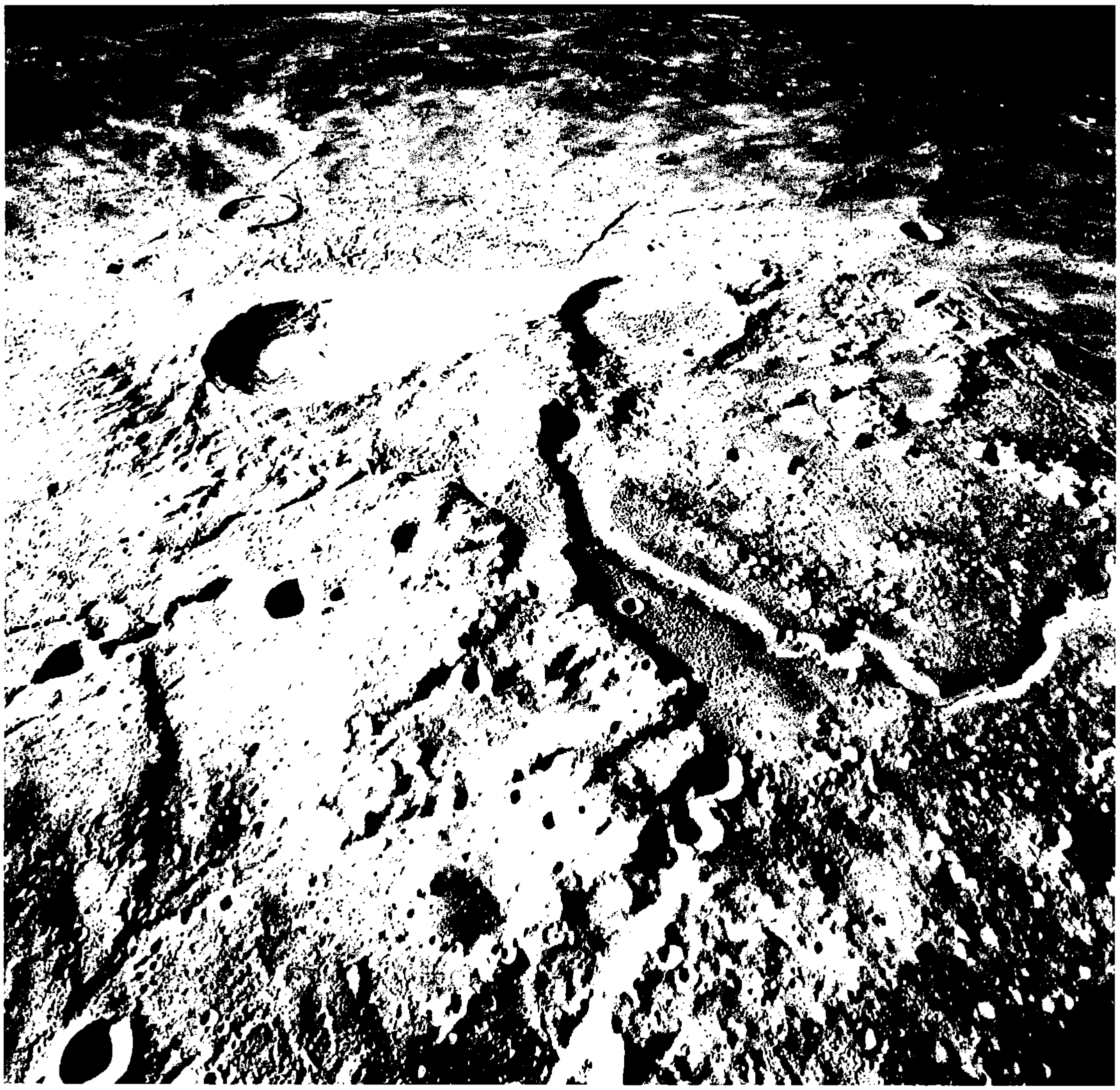

Figure 8. Apollo photograph of crater Aristarchus, 40 km wide, looking south; Schroter's Valley at lower right.

Tycho begins, on the Moon, at diameters of around 150 km, with formation of rings of isolated peaks on the crater floor. At larger diameters, well-developed inner rings appear. An excellent transition example is the 320-km-diameter two-ring crater Schrödinger (Fig. 11). As pointed out by Shoemaker and others (1994), the fractures in Schrödinger indicate continuing postimpact isostatic uplift. The dark halo crater on the floor further suggests relatively late, perhaps Copernican, volcanism in Schrödinger. Many other transitional examples are found on the Moon, but I will skip these to go directly to what Spudis (1993) calls the "archetype" basin: Orientale.

This is the multiring Orientale Basin, on the Moon's west limb (Fig. 12), nearly 1,000 km wide and never seen in its entirety until this Lunar Orbiter view was obtained. The Orientale Basin is the youngest and best-preserved multiring basin on the Moon, exhibiting structure largely concealed or destroyed in Mare Imbrium. Multiple rings begin to appear, on the Moon, when crater diameters reach a few hundred kilometers (Hörz and others, 1991). Their formation is, to say the least, not fully understood; an authoritative treatment of the subject is that of Spudis (1993). Spudis has suggested a composite mechanism for multiring basin excavation, in which the outer ring is produced by inward slumping, the next inner rings by structurally controlled slumping, and the innermost rings by acoustic fluidization (i.e., wave formation). These events are followed by

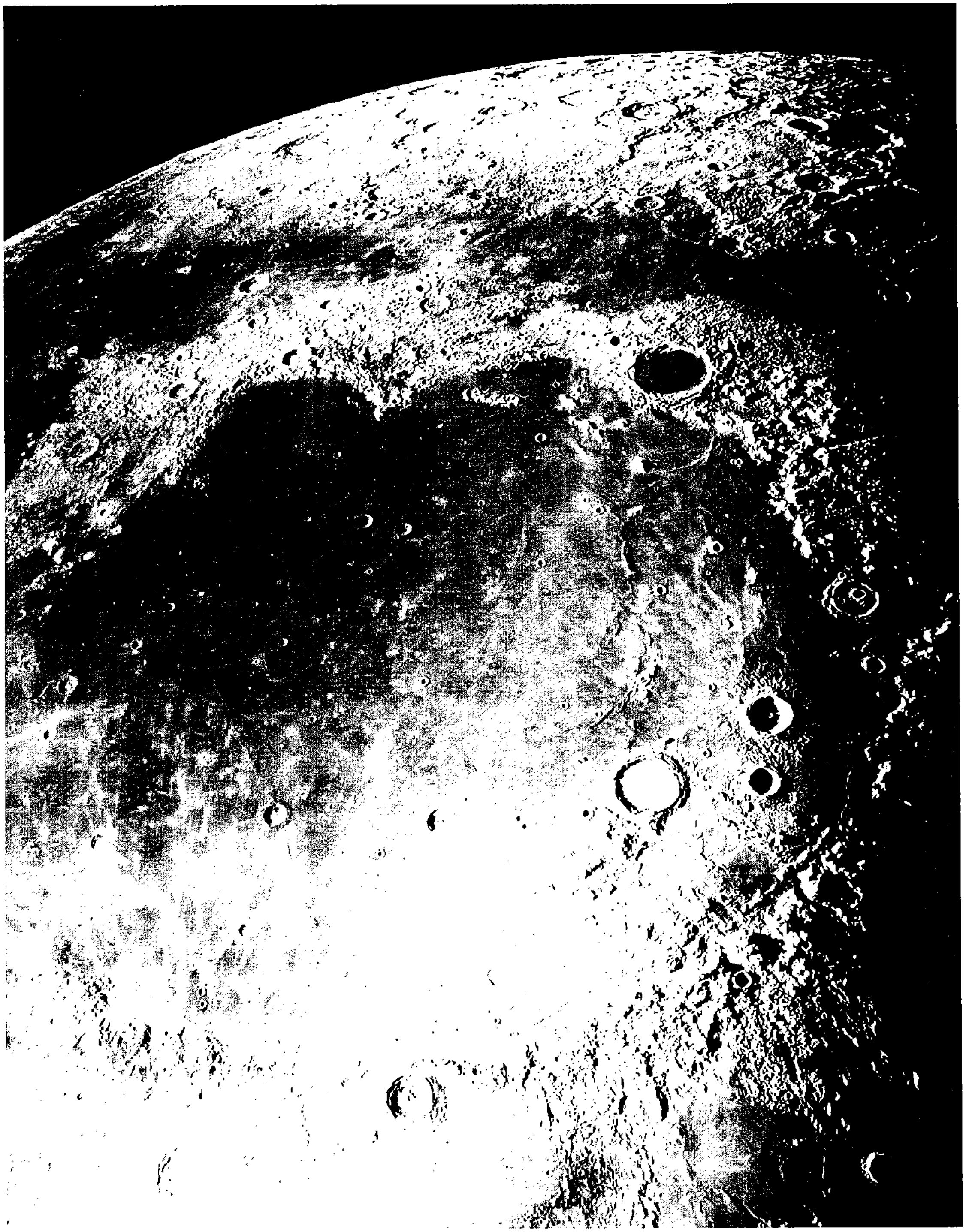

Figure 9. Mount Wilson 100-in. telescope view of Mare Imbrium, north at top. Crater Copernicus, 90 km wide, at bottom left.

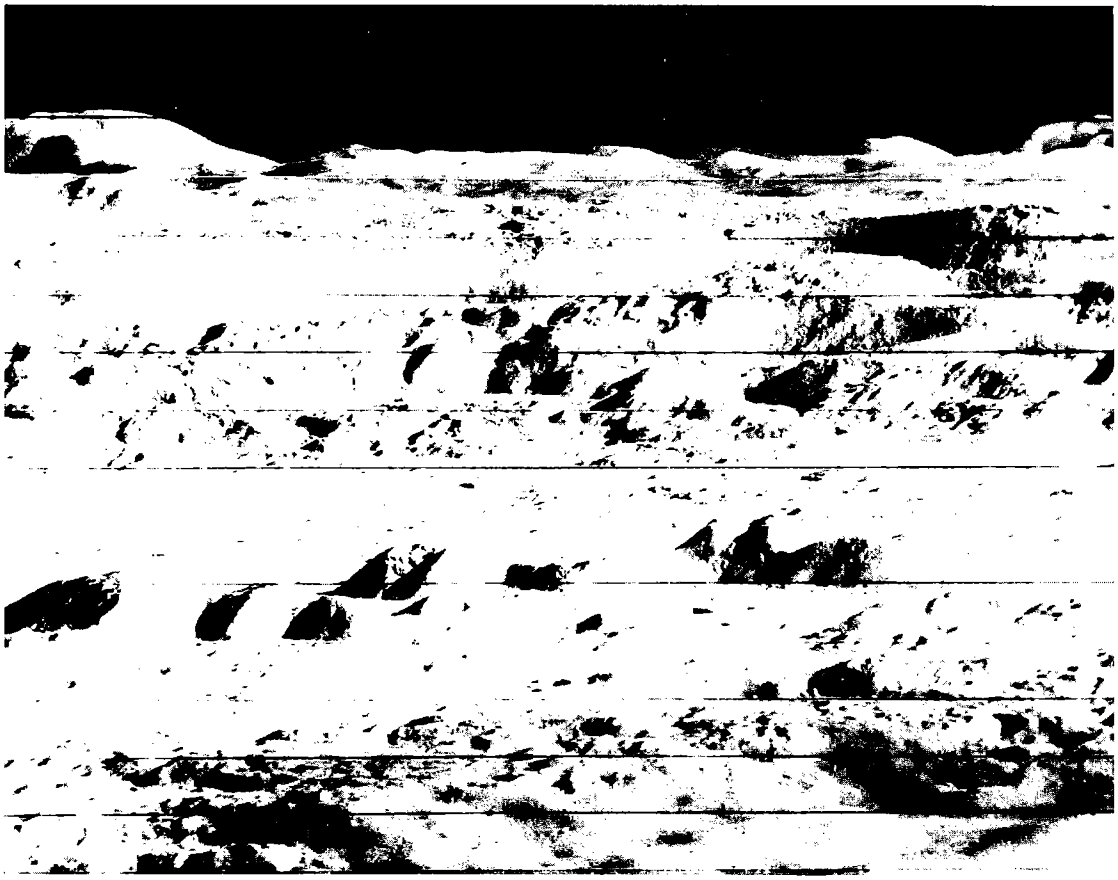

Figure 10. Lunar Orbiter oblique view to north of crater Copernicus.

isostatic uplift and repeated eruptions of mare basalts. Evidence for these events is well displayed in the Orientale Basin. The isostatic uplift is indicated by the well-known "mascons," or positive Bouguer anomalies (Muller and Sjogren, 1968).

There are many other multiring basins on the Moon, recently confirmed by laser altimetry from the Clementine mission (Spudis and others, 1994). The largest of these is the south pole Aitken Basin. It is 2,500 km wide and so old that its form has been almost completely obliterated by smaller, more recent craters, but the laser data demonstrate its reality. It is visible in a Galileo picture (Fig. 13) as a dark area southwest of Orientale. The extreme age of this basin suggests that the body that formed it was one of the planetesimals that formed the Moon, rather than an intruder from outside the Earth-Moon system. However, further investigation—in particular, surface missions that can return samples for radiometric dating—would be needed to confirm this speculation.

The review has by no means covered all the varieties in this impact-crater "museum." There are elliptical primary craters, chains of impact craters, floor-fractured craters, and others. However, having now presented the main varieties, I now turn to impact craters on other bodies, beginning with the Moon's near twin, Mercury.

MERCURIAN IMPACT CRATERS

Like the Moon, Mercury appears to be a primordial body whose internal evolution has long since stopped (Fig. 1). However, Mercury is unique in several ways, notably its high density, implying a very large iron core. Bruce Murray has in various talks aptly characterized this planet as like the Moon on the outside, but like the Earth on the inside. A Mariner 10 view (Fig. 14) illustrates this; an uninformed viewer could easily mistake Mercury for the Moon, from its marelike smooth plains and densely cratered highlands. However, there are differences in lunar and Mercurian impact craters, as discussed by Strom (1984).

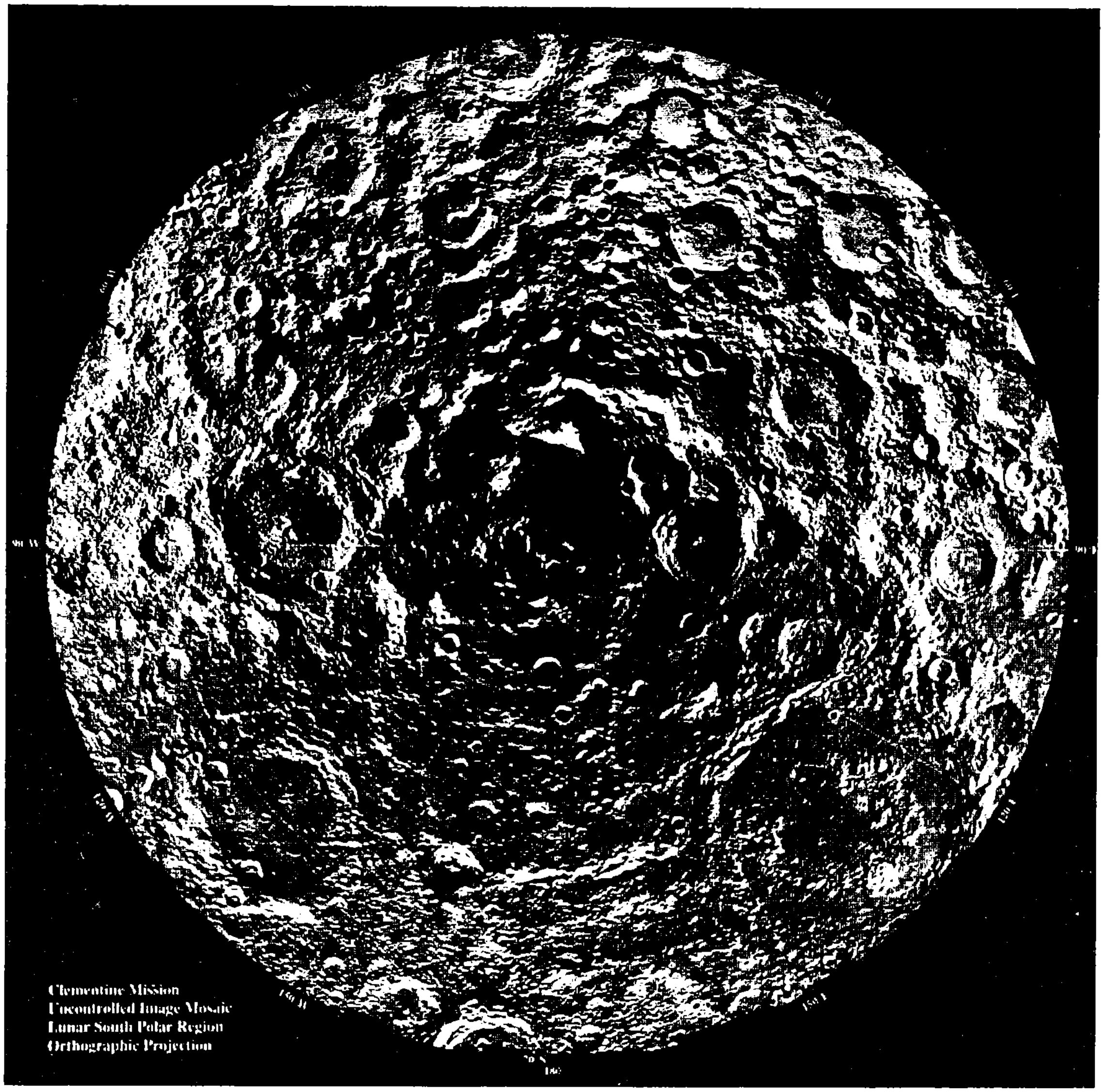

Figure 11. Clementine mosaic of about 1,500 ultraviolet and visual (750 nm band) images of the south polar region of the Moon. Crater Schrödinger, 320 km diameter, at lower right.

The main differences involve the ejecta deposits. First, for a given crater diameter, the continuous ejecta blanket on Mercury is only about one-third that for a comparable lunar crater. This is clearly the result of Mercury's stronger gravity field, about twice that of the Moon, which reduces the range of impact ejecta. Like the Moon, Mercury has no sensible atmosphere, so gravity governs ejecta range, if other factors are equal. Similarly, the secondary craters formed during Mercurian cratering events tend to be more concentrated closer to the source primary crater. Furthermore, the Mercurian secondary craters are generally deeper and better preserved than comparable lunar secondaries, also the presumed effect of the stronger gravity field.

Craters on Mercury show changes in morphology with diameter comparable to those on the Moon. The transition from simple to complex craters, defined as for lunar craters, occurs at about the same size range, suggesting that it is governed primarily by structure of the target rock rather than by gravity. However, details of crater structure on Mercury and the Moon differ. A study by Cintala and others (1977) showed that the population of features such as terraces in the lunar maria

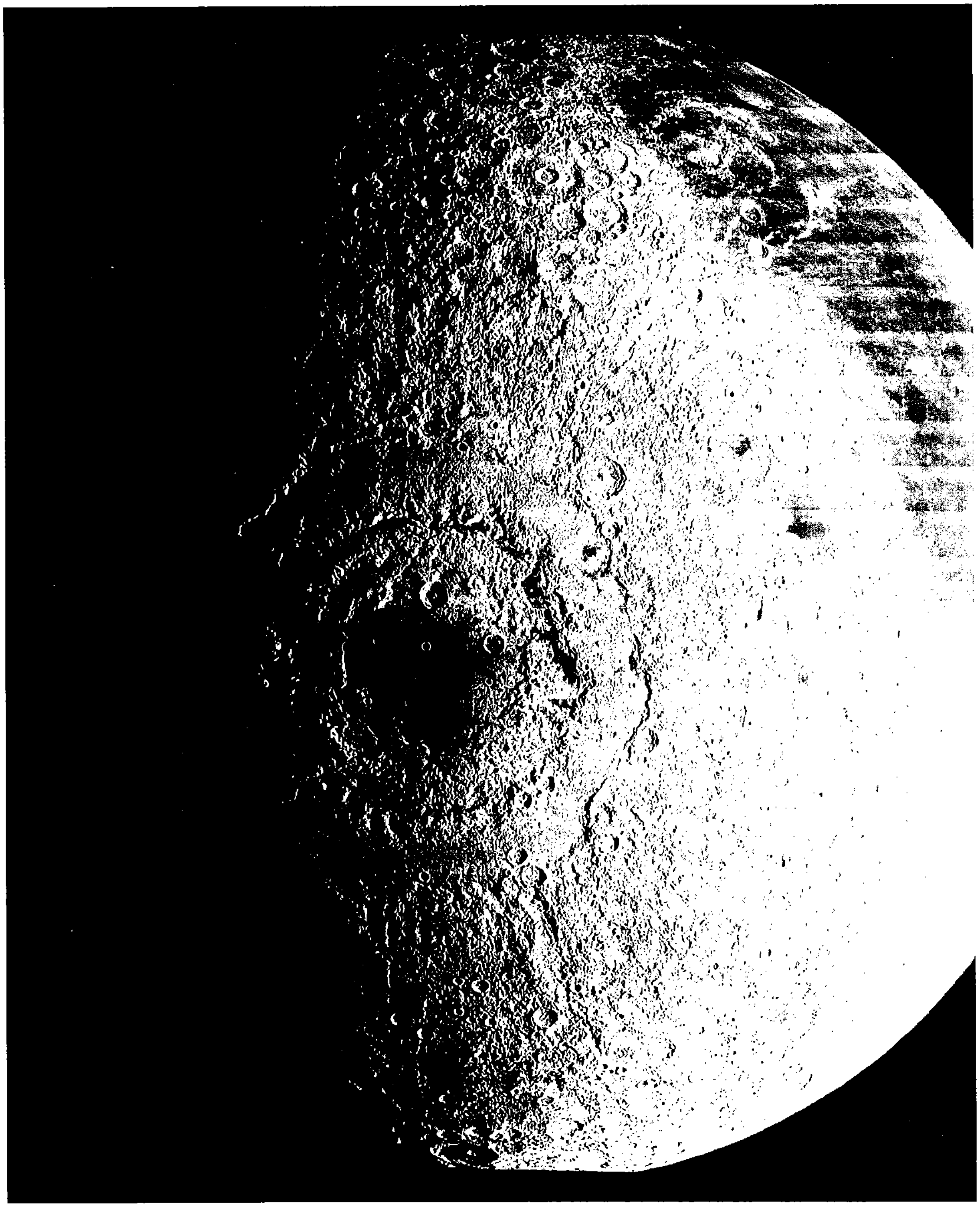

Figure 12. Lunar Orbiter picture of Orientale Basin. North at top. Earthside to right.

and the Mercurian smooth plains is similar. The maria are known to consist of layered lava flows, suggesting that the Mercurian smooth plains similarly consist of such flows.

Mercury has a population of multiring basins (Fig. 15) similar to that of the Moon. Mercury is of course an independent planet, and the existence of multiring basins on it implies that these basins are part of normal planetary accretion. This finding may have implications for the origin and early

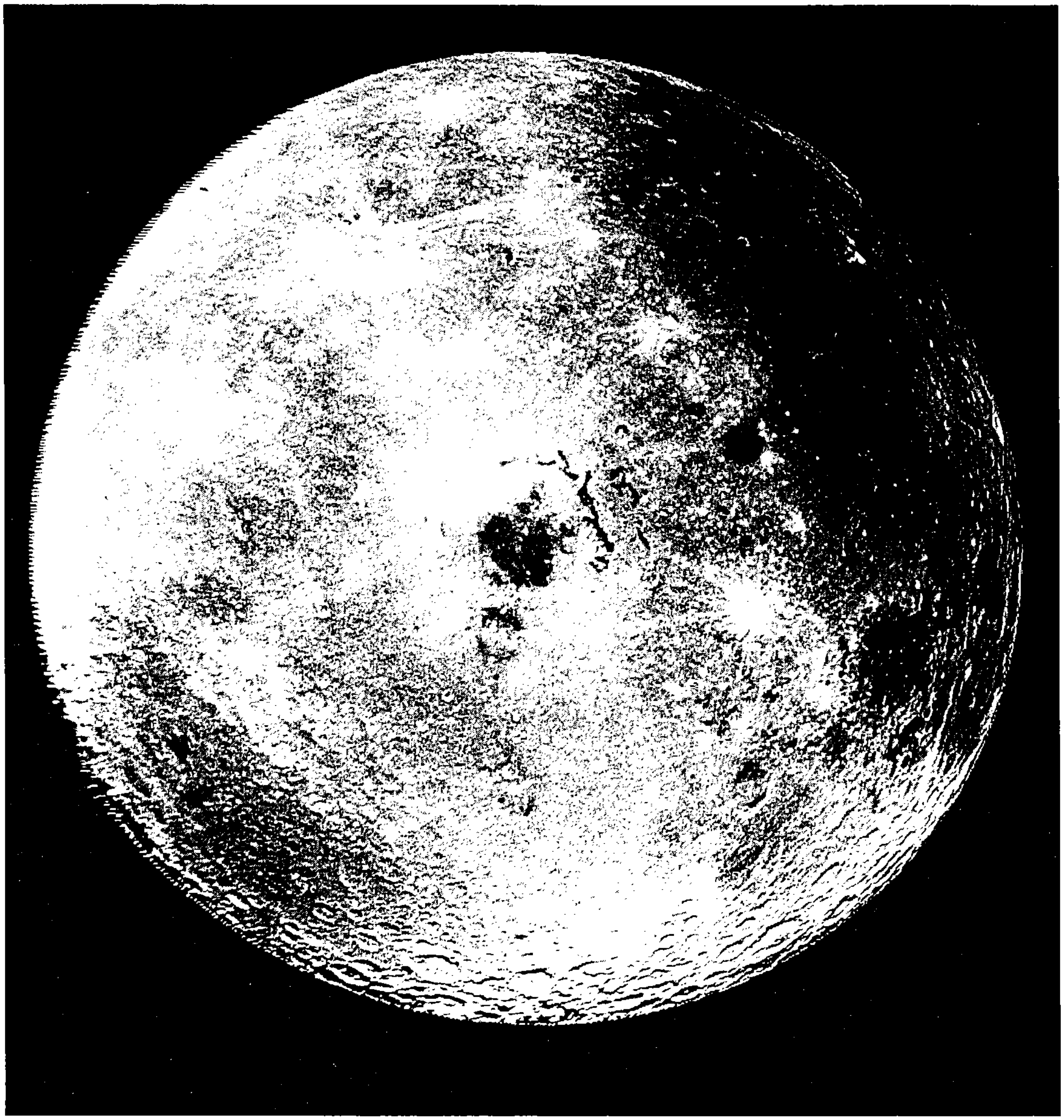

Figure 13. Galileo picture of Orientale Basin, with high Sun angle emphasizing albedo variations and mare basalts. Earthside to right.

evolution of the Moon. A unique process for the formation of the Moon, such as a giant impact in the currently favored theory (Melosh, 1992), would lead one to expect differences in the accretion process. The Mercurian highlands are not saturated with craters like those of the Moon, but the general population of craters and multiring basins is similar. Given the still-unresolved question of how the Moon was formed, this problem might be worth approaching by comparisons of the Moon with Mercury.

MARTIAN IMPACT CRATERS

Following the sequence of crustal evolution shown in Figure 1, I now examine impact craters on Mars. Mars is a transitional planet in several ways, bridging the gap between clearly primordial bodies such as the Moon and Mercury and the highly evolved Venus and Earth. Mars has a significant if unbreathable atmosphere and has clearly had a significant hydrosphere at one time. In terms of crustal evolution, it appears to have

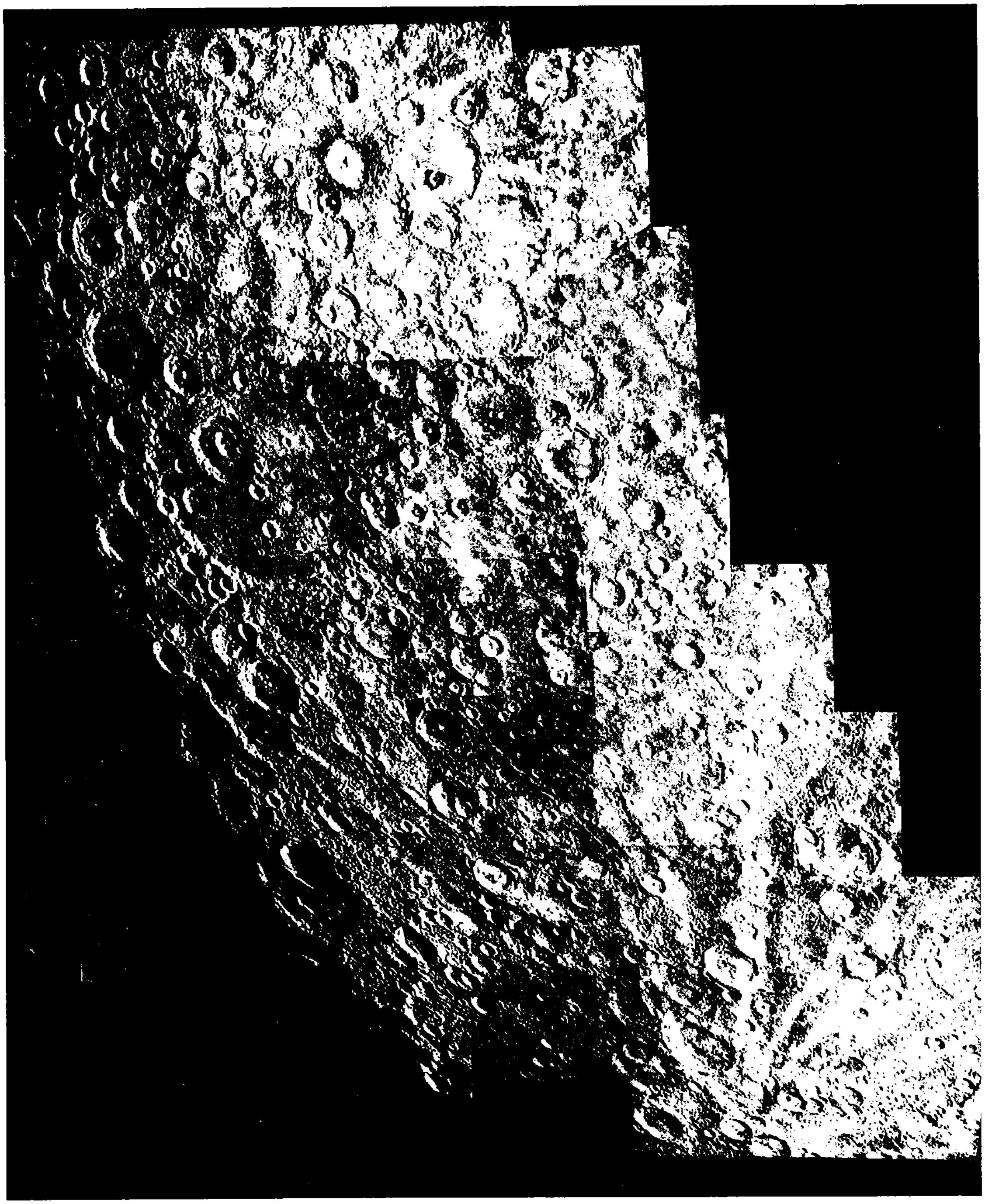

Figure 14. Mariner 10 picture of Mercury highlands, showing similarity with lunar highlands.

entered the stage of true, internally caused tectonism; features such as the Valles Marineris represent, perhaps, incipient fragmentation of a "one-plate planet" as J. Head has termed it in several presentations. Because of its processes of tectonism, volcanism, erosion, and deposition, Mars combines many geologic features of the Earth with those of the Moon.

The geomorphology of Mars is in fact extraordinarily complex (Fig. 16); the landforms are a var-

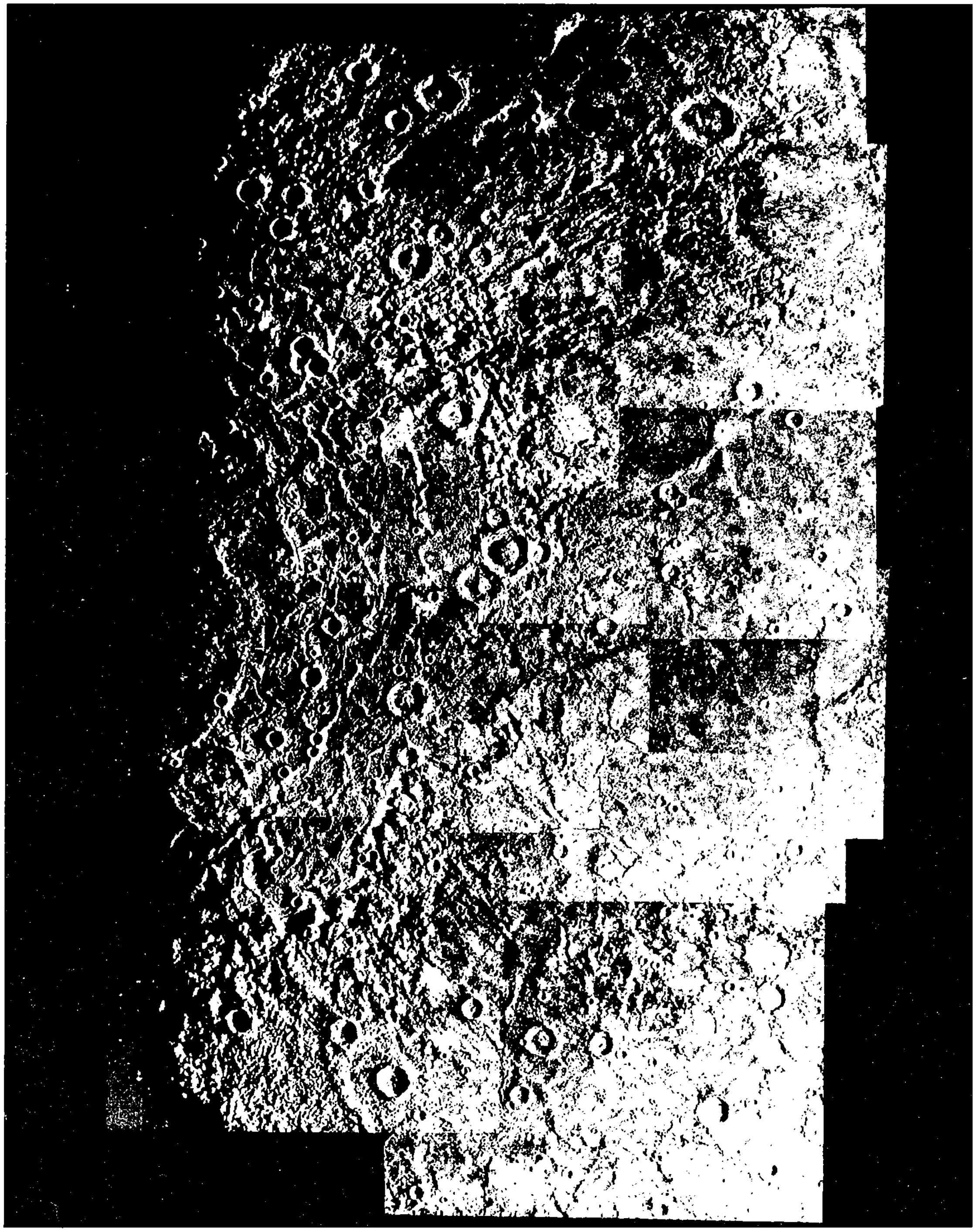

Figure 15. Mariner 10 mosaic of Caloris Basin, Mercury; 1,300 km diameter (cf. Orientale Basin, Fig. 12).

ied array of fluvial, aeolian, tectonic, volcanic, and perhaps glacial features on which are superimposed a dense array of randomly placed impact craters (Carr, 1981). These craters are in turn generally modified by erosion and deposition. Nevertheless, the pristine examples seen on the Moon and Mercury have counterparts on Mars.

The simple to complex transition in crater form takes place in the 5- to 10-km-diameter range on Mars, compared to about 20 km on the Moon (Pike

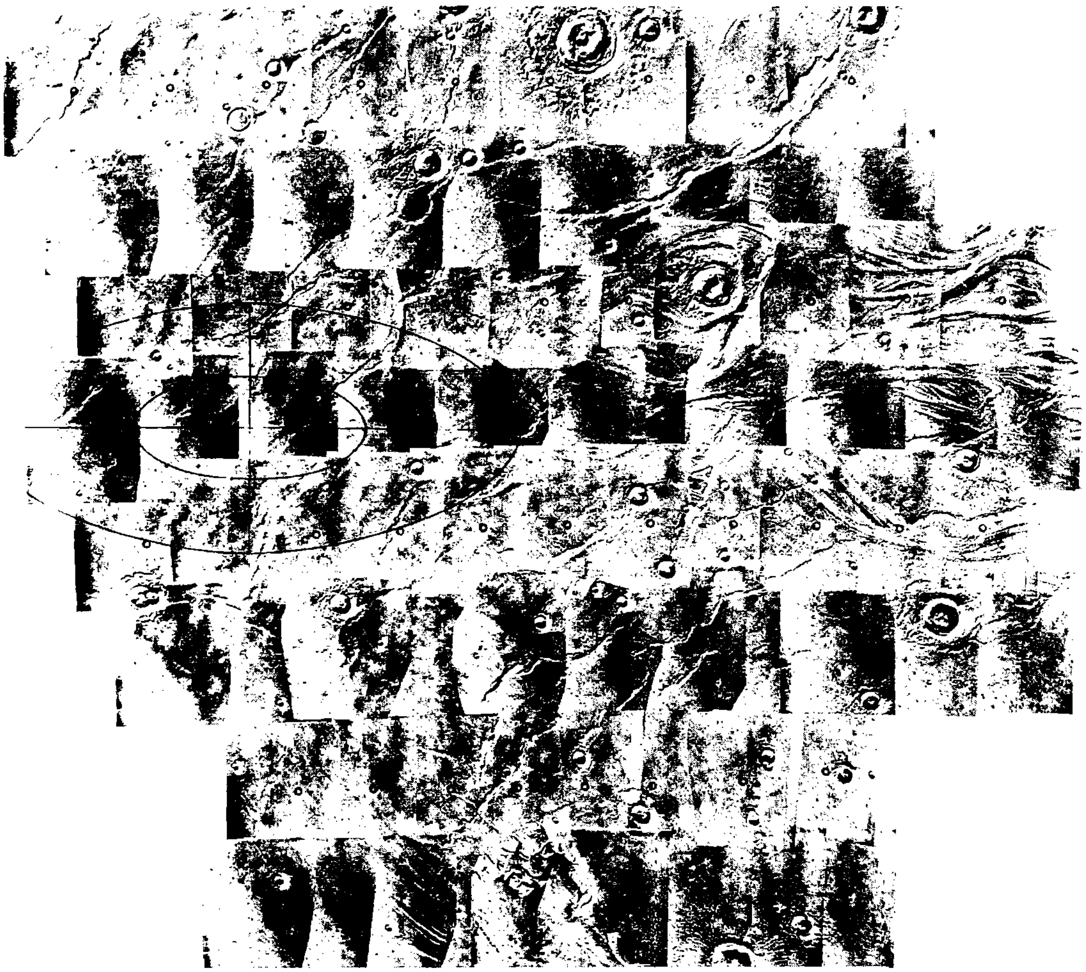

Figure 16. Viking Orbiter mosaic of Viking 1 landing-site region in Chryse Planitia on Mars. North at top; area about 240 km wide. Erosion patterns indicate flow from left to right. Note lobate ejecta around craters.

and Arthur, 1979; Carr, 1981), and Martian craters are proportionately shallower than those on the Moon. The size vs. frequency distribution curves for Mars have complex slopes (Carr, 1981), a phenomenon still not understood but evidently resulting from various erosional, depositional, and volcanic processes that obliterate craters.

The most characteristic features of Martian impact craters are shown in Figure 16, a Viking Orbiter view of the Viking 1 landing site in Chryse Planitia. Geology of this site has been described by Greeley and others (1977). In brief, it is a low-lying plains region that has been scoured by floods from the adjacent, higher, cratered terrain. Chryse Planitia is fundamentally similar to the lunar maria, as indicated by the low crater density, wrinkle ridges, and chemistry of the landing site. The role of running water is obvious, and the geomorphology resembles that of the Channeled Scablands of Washington State. The impact craters are notable for their distinctive ejecta patterns, which gave rise to the informal term "splosh craters" or "fluidized ejecta craters" (Carr, 1981). The characteristic lobate patterns imply more-fluid ejecta than corresponding lunar craters, which could result from ice or water in the ejecta or the effects of the Martian atmosphere. Such patterns occur only around large craters, perhaps reflecting the depth of ground water (Boyce, 1979). The existence of ground water on Mars is supported by the many slump features and chaotic terrain elsewhere.

Another type of crater more common though not unique to Mars is the elliptical primary impact variety (Fig. 17). There are a few such craters on the Moon, but Schultz and Lutz-Garihan (1982) have catalogued >170 elliptical craters >3 km wide

Figure 17. Viking Orbiter view of an elliptical impact crater (containing a younger volcano) and its lobate ejecta blanket on the north flank of the volcano Ceraunius Tholus.

on Mars. Their primary, high-velocity origin is indicated by the elongated central ridge and prominent ejecta blankets, quite different from the low-velocity secondary craters seen on the Moon. The example shown incidentally illustrates the complexity of Martian geology; this elliptical crater was formed on the flank of an apparently older volcano, Ceraunius Tholus, but a younger volcano

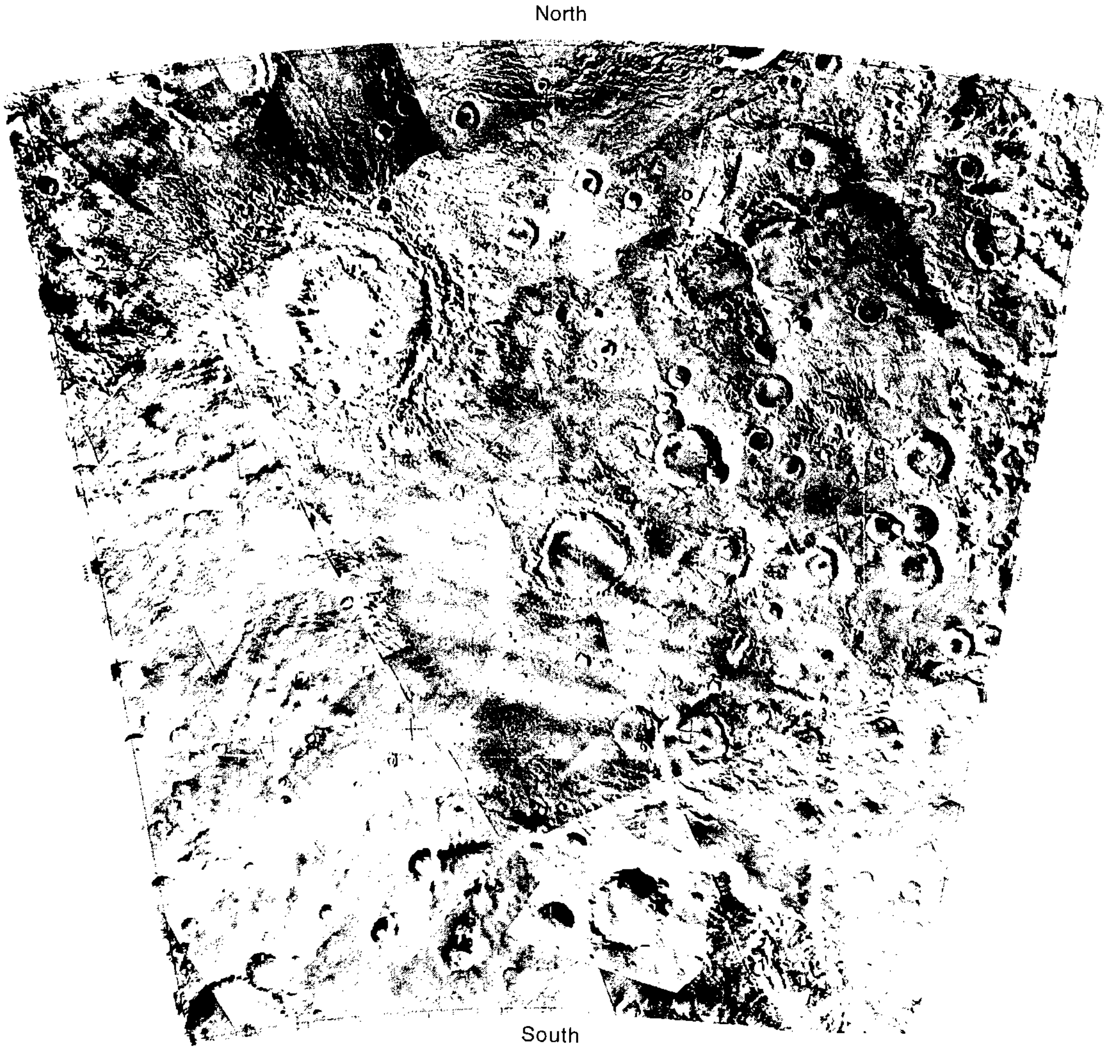

Figure 18. Viking Orbiter mosaic of area centered on lat 55°S, long 75°W, with 250-km-wide double-ring crater.

evidently erupted inside it later. The reason for the relative abundance of elliptical craters on Mars is not known, but Schultz and Lutz-Garihan (1982) suggested that they may have been formed by the infall of lost satellites.

The class of the largest impact craters, multiring basins, is now recognized on Mars. Schultz and Frey (1990) have catalogued 30 multiring basins, but this has been a difficult task in photogeology because of the pervasive effects of postimpact volcanism, erosion, and deposition. Some examples, such as the 250-km-diameter multiring crater Lowell (Fig. 18), are easily recognized. However, as shown in Figure 19, covering the northeast quadrant of the 1,850-km-diameter basin Argyre, fine structure of the rings has frequently been almost obliterated by surficial processes. There is no pristine Orientale Basin on Mars.

The geologic effects of basin-forming impacts on the Moon are fairly obvious: essentially they caused localization of later basaltic volcanism. However, Mars is demonstrably a more evolved and volatile-rich planet, and large impactors may have had correspondingly greater secondary effects. The Tharsis volcanic complex, for example, may have been localized by an early impact basin (Schultz and Frey, 1990), a more evolved magmatic process than the lava flows of the lunar maria. This interesting speculation tends to support the proposal of Grieve (1980) that the first continental nuclei on Earth were impact stimulated, although the reality of these "nuclei" is controversial (Lowman, 1989). An even more funda-

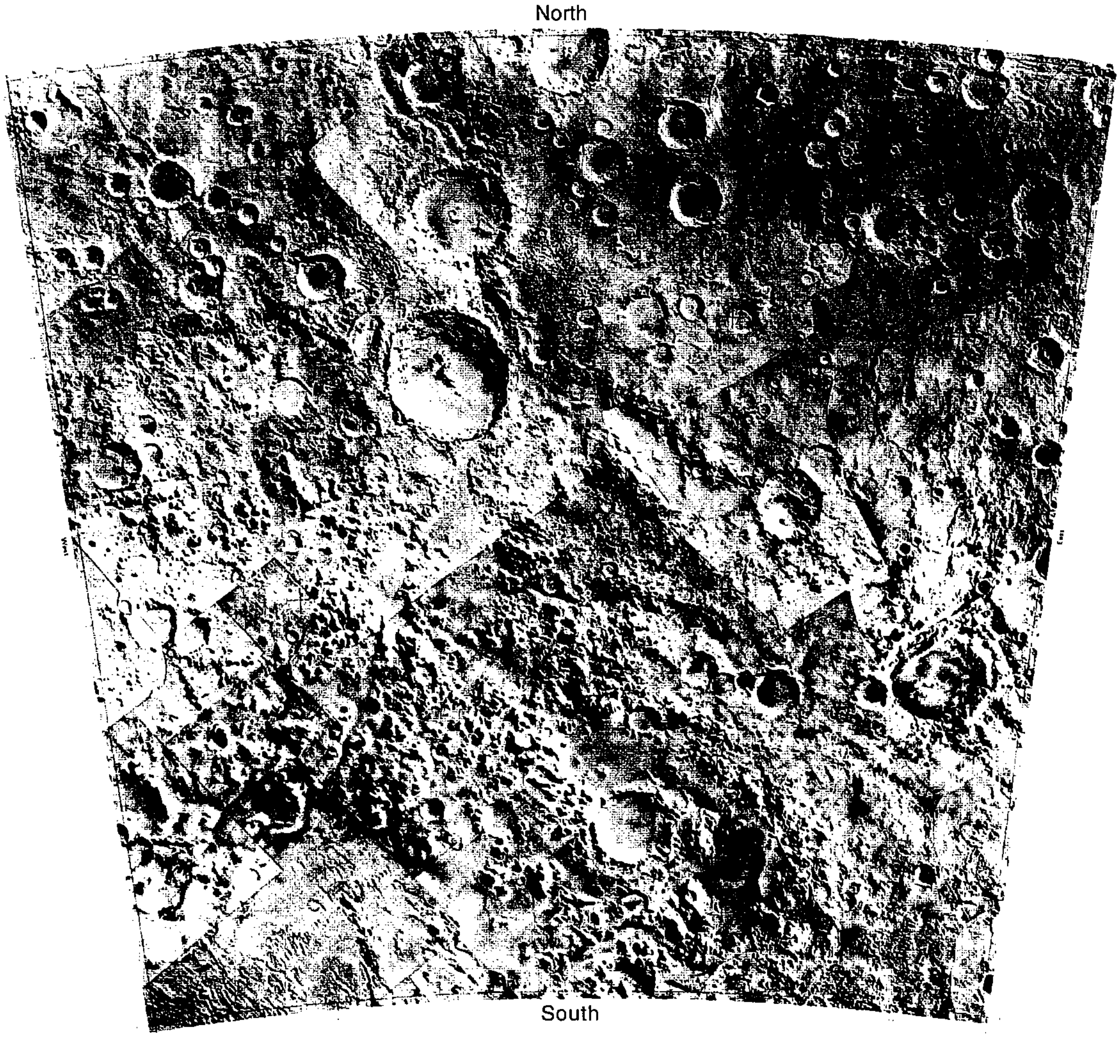

Figure 19. Viking Orbiter mosaic of area centered on lat 40°S, long 35°W, showing outer rim of Argyre Basin. Bottom of area about 900 km wide.

mental result of basin-forming impacts on Mars may have been the crustal dichotomy (Schultz and Frey, 1990) between the low-lying basaltic plains of the northern hemisphere and the higher cratered terrain to the south. This is apparently analogous to the mare vs. highlands topography of the Moon; however, the maria are relatively thin lava flows overlying highland crust, and the lunar "dichotomy" may thus be more superficial than that of Mars.

VENUSIAN IMPACT CRATERS

Venus is commonly referred to as Earth's "sister planet," being close to it in size and mass. Its geology was completely unknown until Earth-based and especially Venusian orbital radar surveys could be carried out. The most recent of these, by the Magellan spacecraft in the 1990s, covered almost the entire planet with high-resolution imagery, revealing a highly evolved and probably active planet. Despite Venus's continuing planetary evolution, well over 800 impact craters have been described on the 89% of the surface covered through the early part of the Magellan mission (Schaber and others, 1992). For comparison, roughly 130 impact structures (many no longer bearing topographic craters) are currently known on Earth (Grieve, 1991).

The surface environment of Venus must be taken into account to understand the nature of its

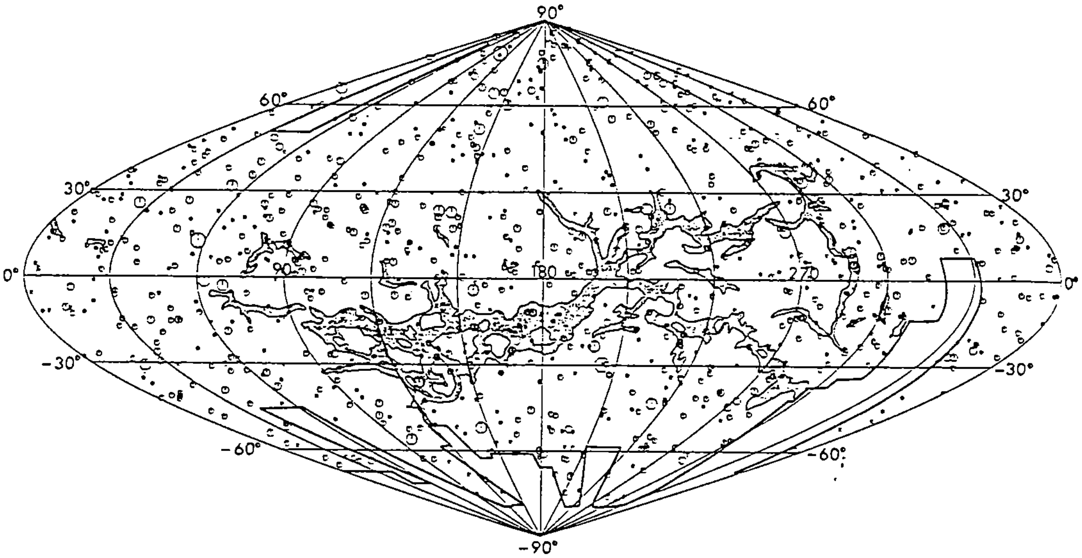

Figure 20. Map of Venus, sinusoidal equal-area projection, showing 842 impact craters, observed on 89% of surface (from Schaber and others, 1992).

impact craters. Most important is its enormously dense CO_2 atmosphere, with surface pressures of about 100 bars. The greenhouse effect of this atmosphere, coupled with the planet's closeness to the Sun, produces surface temperatures of >400 °C. The planet appears to have no significant water. There is abundant evidence of volcanism, confirmed by surface analyses made by Soviet gamma-ray spectroscopy from landed spacecraft, and comparable tectonism.

As summarized by Schaber and others (1992), the crater population appears to be uniformly distributed over the planet (Fig. 20). The size-frequency relationship for craters of >35 km diameter appears similar to that for other planets, but the abundance of craters is much lower. Craters smaller than 35 km are much less abundant than on other nonterrestrial bodies, which can be explained as the result of atmospheric filtering; small meteoroids do not penetrate the atmosphere. There are numerous diffuse "splotches," i.e., radar-visible features, thought to result from the air blast of meteoroids destroyed by the atmosphere. Large craters, >35 km in diameter, show about the same sequence of morphologies with increasing size as do those elsewhere (Fig. 21), up to multiring basins (Fig. 22). However, ejecta patterns of Venusian craters are frequently unique to that planet, in particular having radar-bright (presumably rough) outflows that in some cases extend several crater diameters (Fig. 23). These have been interpreted as impact ejecta with a great amount of gas and impact melt, forming flows resembling lava or nuees ardentes.

Some craters on Venus have clearly been partly flooded by lava or modified by tectonism, but there seem to be few transitional examples, most being pristine at the resolution of Magellan images. Schaber and others (1992) interpreted this finding as indicating major resurfacing by volcanism before about 0.5 Ga. This "catastrophic resurfacing model" has, however, been disputed by Phillips and others (1992), who have interpreted an "equilibrium resurfacing model" as more likely. The equilibrium resurfacing model implies that the resurfacing, i.e., the volcanism, is more randomly distributed in time and space.

This summary has touched on only the most conspicuous aspects of impact cratering on Venus, a topic whose study is only beginning. Interested readers are urged to consult the already-large literature on this controversial subject.

IMPACT CRATERS ON SMALL BODIES

As noted earlier, every known solid body in the solar system except the continually resurfaced Jovian satellite Io has impact craters or multiring basins. Dozens of satellites and even a few asteroids and comets have now been explored by spacecraft, so a full discussion of these bodies and their craters is impossible here. However, a few examples will be instructive.

Perhaps the most interesting craters are those on the icy satellites of the giant planets Jupiter, Saturn, Uranus, and Neptune. First revealed in detail by the decades-long Voyager missions—one

Figure 21. Magellan mosaic of Lavinia region of Venus, showing three impact craters with diameters ranging from 37 to 50 km. Bright tones indicate rough terrain, here formed by ejecta blankets.

of the great explorations of all time—these satellites have proven to be strange beyond imagining in terms of terrestrial planet geology. Almost all are essentially small planets made of water ice, rather than the familiar silicate minerals, although their mean densities indicate that some have rocky cores. Their geology is remarkably varied. Some satellites, such as Callisto (Fig. 24) are clearly inactive and essentially primitive, judging from their saturation population of impact craters. Some, such as Ganymede (Fig. 25) are transitional, with complex tectonic features in the ice but with a dense crater population. The Saturnian satellite Enceladus (Fig. 26) has a surface most of whose area has been reworked by internal ice tectonism, but with some densely cratered areas. The Uranian satellite Miranda (Fig. 26) is partly covered by large ridged ovoids, or "coronae," of unknown but presumably internal origin (Smith and others, 1986), the remaining area being heavily cratered.

Perhaps the strangest (by silicate-planet standards) impact structures are those on Ganymede (Fig. 25). In addition to more or less normal impact craters and complex ridged terrain of apparent internal origin, there are large light-colored patches. These have been interpreted (Smith and others, 1979) as the traces of former impact craters, or "palimpsests," since largely removed by solid-state flowage of the Ganymede ice. The huge, concentric structure on Callisto (Fig. 24), named Valhalla, is thought to be the trace of a former multiring basin. Thus, the satellites of the outer planets bear the ice analogues of the family of impact structures now familiar from the terrestrial planets and the "crater museum," the Moon.

Figure 22. Magellan image of Cleopatra impact crater, 105 km diameter, on Maxwell Montes, lat 65.9°N, long 7°W.

SUMMARY

Impact craters were recognized on Earth in initially a very hesitant and speculative manner; they were treated as a kind of geologic freak. But in the last half of the century, and in particular since the beginning of interplanetary flight, craters are now known to be the single most common landform in the solar system. Many of them represent the final stages of planet and satellite formation, the tail-off of creation, so to speak. Once formed, impact craters are geologically valuable as age indicators (with many caveats and assumptions) and as index marks against which tectonic deformation of a moon or planet can be gauged. They have localized true volcanism on silicate planets and possibly ice-water volcanism on ice satellites. Perhaps most important, their abundance and continuing formation reminds Earthlings that the universe is a violent place and that planets everywhere are probably subject to the bombardment seen in this solar system. One answer to the question "Where is everybody?" may be that other species and civilizations have short lifetimes in geologic terms, and that catastrophic impacts knock down communicative extraterrestrial communities before they can be contacted by their galactic neighbors.

REFERENCES CITED

Baldwin, R. B., 1949, The face of the Moon: University of Chicago Press, Chicago, 239 p.

Boyce, J. M., 1979, A method for measuring heat flow in the martian crust using impact crater morphology: U.S. National Aeronautics and Space Administration Technical Memorandum 80339, p. 114–118.

Carr, M. H., 1981, The surface of Mars: Yale University Press, New Haven, Connecticut, 232 p.

Cintala, M. J.; Wood, C. A., and Head, J. W., 1977, The effects of target characteristics on fresh crater morphology: Preliminary results for the Moon and Mercury: Proceedings of the 4th Lunar Science Conference, p. 3409–3412.

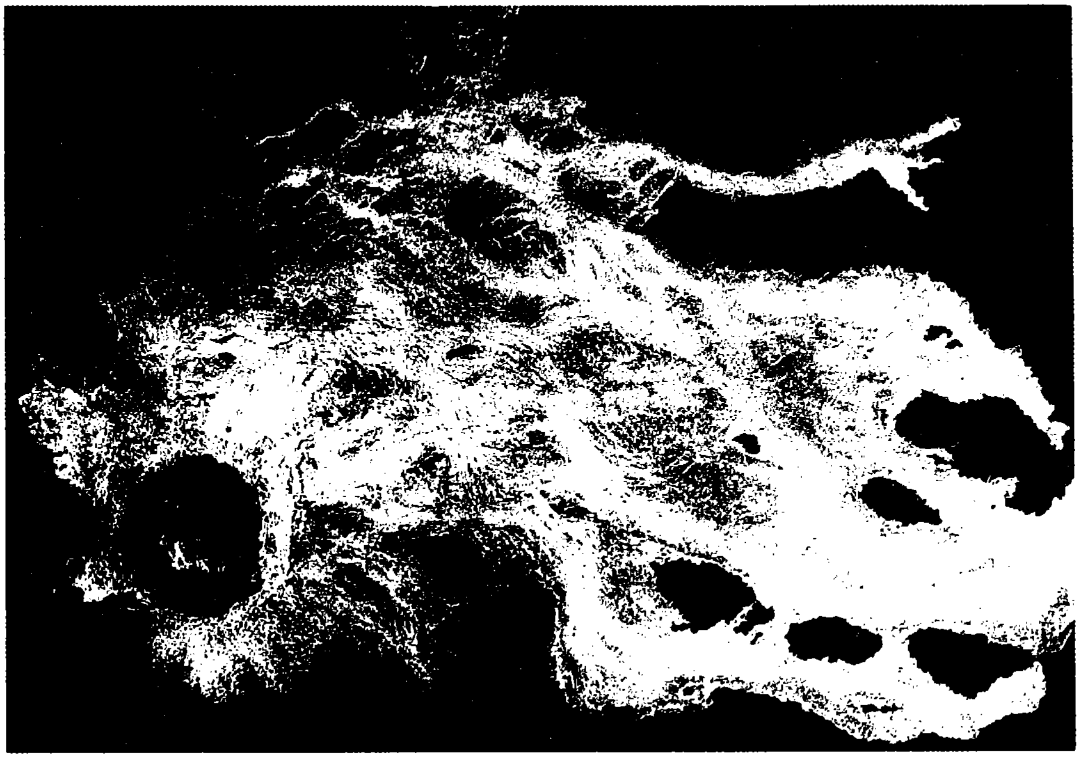

Figure 23. Magellan image of unnamed double-ring impact crater, 70 km diameter, at lat 4°S, long 156°E, with outflow deposits extending 370 km from rim (from Schaber and others, 1992).

Dietz, R. S., 1946, The meteoritic impact origin of the Moon's surface features: Journal of Geology, v. 54, p. 359–375.

Gilbert, G. K., 1893, The Moon's face, a study of the origin of its features: Philosophical Society of Washington Bulletin, v. 12, p. 241–292.

Greeley, R.; Theilig, E.; Guest, J. E.; Carr, M. H.; Masursky, H.; and Cutts, J. A., 1977, Geology of Chryse Planitia: Journal of Geophysical Research, v. 82, p. 4093–4109.

Green, J., 1971, Copernicus as a lunar caldera: Journal of Geophysical Research, v. 70, p. 5719–5732.

Grieve, R. A. F., 1980, Impact bombardment and its role in proto-continental growth on the early Earth: Precambrian Research, v. 10, p. 210–217.

_____ 1991, Terrestrial impact: The record in the rocks: Meteoritics, v. 26, p. 175–194.

Hammel, H. B., and others, 1995, HST imaging of atmospheric phenomena created by the impact of comet Shoemaker-Levy 9: Science, v. 267, p. 1288–1296.

Hörz, F.; Grieve, R. A. F.; Heiken, G.; Spudis, P.; and Binder, A., 1991, Lunar surface processes, *in* Heiken, G.; Vaniman, D.; and French, B. M. (eds.), Lunar sourcebook, a user's guide to the Moon: Cambridge University Press, Cambridge, p. 61–120.

Lowman, P. D., 1989, Comparative planetology and the origin of continental crust: Precambrian Research, v. 44, p. 171–195.

Melosh, H. J., 1992, Moon, origin and evolution, *in* Maran, S. P. (ed.), The astronomy and astrophysics encyclopedia: Van Nostrand Reinhold, New York, p. 456–458.

Muller, P. M.; and Sjogren, W. L., 1968, Mascons: lunar mass concentrations: Science, v. 161, p. 680–684.

Nininger, H. H., 1959, Out of the sky: an introduction to meteoritics: Dover Publications, New York, 336 p.

Oberbeck, V. R.; and Quaide, W. L., 1968, Estimated thickness of a fragmental surface layer of Oceanus Procellarum: Journal of Geophysical Research, v. 32, p. 4697–4715.

Phillips, R. J.; Raubertas, R. F.; Arvidson, R. E.; Sarkar, I. C.; Herrick, R. R.; Izenberg, N.; and Grimm, R. E., 1992, Impact craters and Venus resurfacing history: Journal of Geophysical Research, v. 97, p. 15,923–15,948.

Pike, R. J.; and Arthur, D. W. G., 1979, Simple to complex impact craters: The transition on Mars: National Aeronautics and Space Administration Memo 80339, p. 132–134.

Ryder, Graham, 1994, Coincidence in time of the Imbrium basin impact and Apollo 15 KREEP volcanic flows: the case for impact-induced melting,

Figure 24. Voyager image of Jovian satellite Callisto (about the size of Mercury), with multiring impact basin Valhalla.

in Dressler, B. O.; Grieve, R. A. F.; and Sharpton, V. L. (eds.), Large meteorite impacts and planetary evolution: Geological Society of America Special Paper 293, p. 11–18.

Schaber, G. G., and others, 1992, Geology and distribution of impact craters on Venus: what are they telling us?: Journal of Geophysical Research, v. 97, p. 13257–13301.

Schultz, P. H.; and Lutz-Garihan, A. B., 1982, Grazing impacts on Mars: a record of lost satellites: Journal of Geophysical Research, v. 87, supplement, p. A84–A96.

Schultz, R. A.; and Frey, H. V., 1990, A new survey of multi-ring basins on Mars: Journal of Geophysical Research, v. 95, p. 14,175–14,189.

Shoemaker, E. M.; and Hackman, R. J., 1962, Stratigraphic basis for a lunar time scale, *in* Kopal, Z.; and Mikhailov, Z. K. (eds.), The Moon; IAU Symposium 14: Academic Press, New York, p. 289–399.

Shoemaker, E. M.; Robinson, M. S.; and Eliason, E. M., 1994, The south pole region of the Moon as seen by Clementine: Science, v. 266, p. 1851–1854.

Smith, B. A., and others, 1979, The Galilean satellites and Jupiter; Voyager 2 imaging science results: Science, v. 206, p. 927–950.

_____ 1986, Voyager 2 in the Uranian system: imaging science results: Science, v. 233, p. 43–64.

Spudis, P. D., 1993, The geology of multi-ring impact basins: Cambridge University Press, New York, 263 p.

Spudis, P. D.; Reisse, R. A.; and Gillis, J. G., 1994,

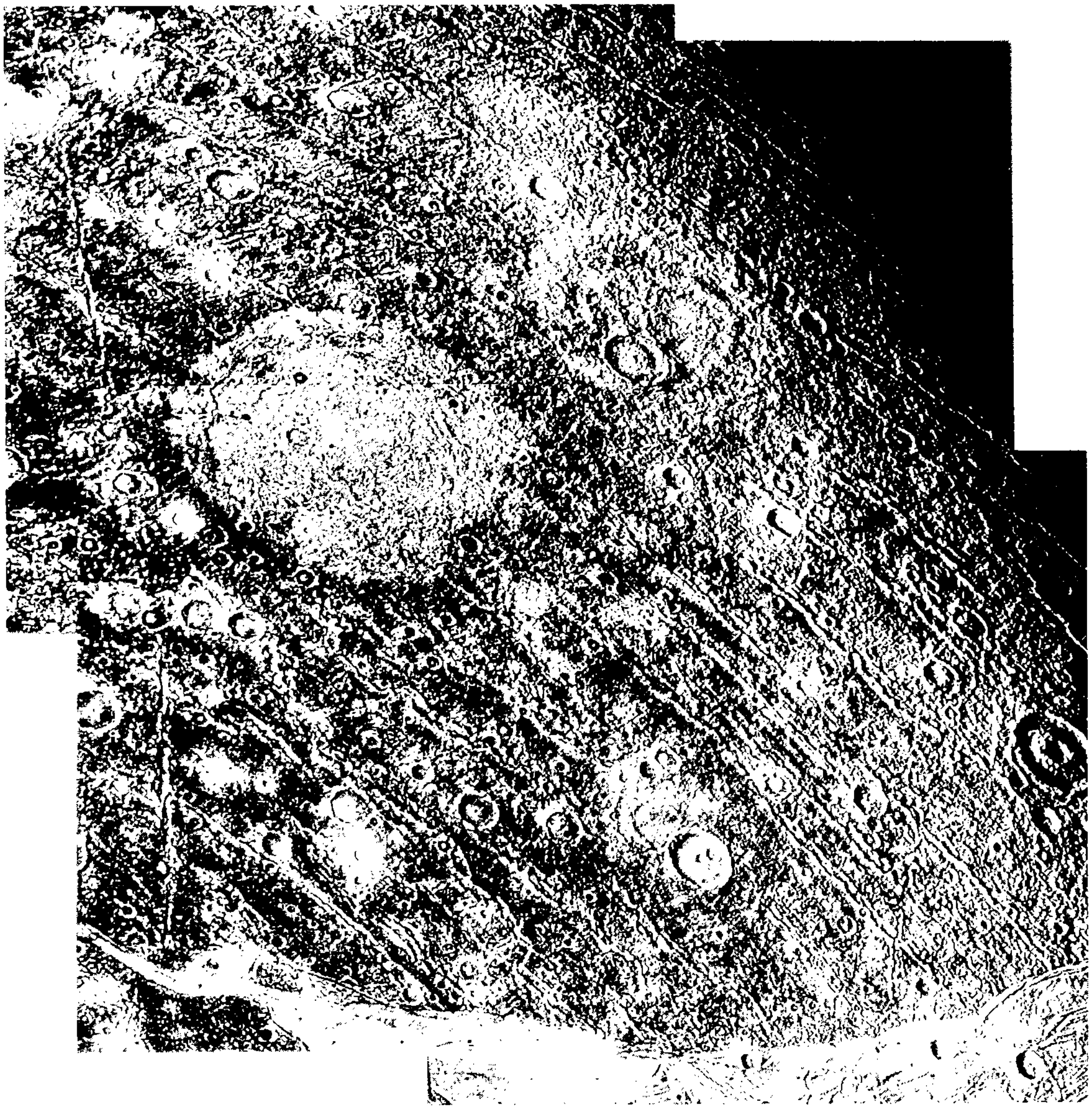

Figure 25. Voyager image of Jovian satellite Ganymede, showing reworked impact craters (palimpsest) and ridges, all in the satellite's icy outer layer.

Ancient multiring basins on the Moon revealed by Clementine laser altimetry: Science, v. 266, p. 1848–1851.

Strom, R. G., 1984, Mercury, *in* Carr, M. H.; and others (eds.), The geology of the terrestrial planets: National Aeronautics and Space Administration, Washington, D.C., NASA SP-469, p. 13–55.

Taylor, S. R., 1992, Solar system evolution: Cambridge University Press, New York, 307 p.

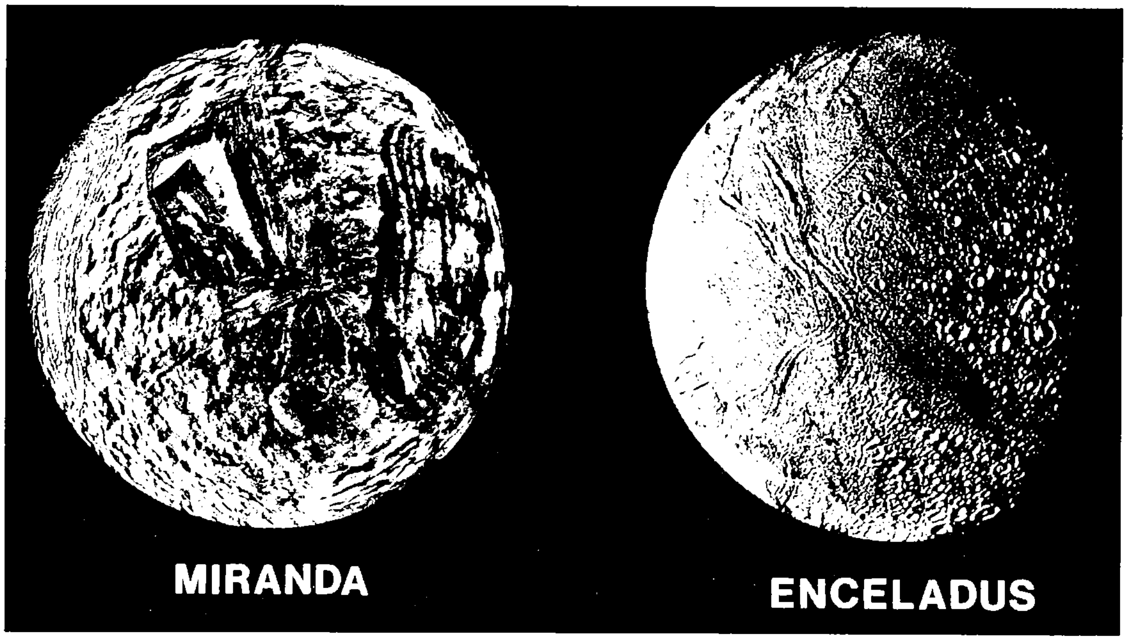

Figure 26. Voyager image of Uranian satellite Miranda and Saturnian satellite Enceladus.