DISCOVERY OF METEORITE IMPACT CRATERS

Galileo first turned his telescope to the moon on November 30, 1609, and within a few months he announced that circular pits pockmarked the moon's surface (Whitaker, 1978). Galileo used the Greek word **crater** ("cup") to describe these. Until the middle of this century, a debate raged about the origin of craters. Some scientists thought they were impact features, but others thought that they were volcanic or formed by giant gas bubbles that rose through a molten primeval moon and broke on the surface.

Not until this century were meteorite craters, complete with meteorite fragments, firmly identified on Earth. Further geological fieldwork revealed terrestrial **astroblemes** (from Greek words for "star wounds"), or eroded circular structures that have turned out to be remnants of ancient, eroded meteorite craters (see Table 10-4 and Figure 6-1). These results favored the meteorite theory of planetary craters. Further evidence came when astrophysicist Ralph Baldwin (1949) showed that the properties of lunar craters matched those expected for impact explosions. Next, fieldwork and space probes of the 1960s revealed compelling similarities between known meteorite craters on Earth (Table 10-4) and the ubiquitous craters on other planetary bodies. These similarities included hummocky rim forms and patterns of ejected rubble. Furthermore, fresh craters on various planets have size distributions consistent with size distributions of the interplanetary meteoroids, as noted in Figure 6-4. So the majority of craters larger than a few kilometers across on planetary bodies are now believed to have been formed directly by impact of interplanetary bodies.*

*Unfortunately, astronauts did not investigate lunar craters in enough detail to recover meteorite specimens or specifically prove their meteoritic origin. Also, they did not explore any multikilometer-scale fresh craters.

Craters are interesting in several regards. They are fascinating as weird landscapes and scenes of ancient cataclysms.* Their structures reveal subsurface properties. And their numbers reveal the age of the surface, since the more that craters have accumulated, the longer the surface has been exposed.

MECHANICS OF IMPACT CRATER FORMATION

Due to the combination of orbital speed and planetary gravity, meteoroids typically strike planets at 10 or more kilometers per second. If the planet has an atmosphere, the smaller meteoroids are slowed and do not form craters.

The kinetic energy of high-speed meteorites is converted upon impact into thermal, acoustic, and mechanical energy that distorts, fractures, and ejects rocks. The result is like an explosion centered a few meteorite diameters below the ground, and meteorite impact craters are thus somewhat like bomb craters. When the meteorite enters the ground, it is usually **hypersonic** (that is, moving faster than the local speed of sound), since seismic waves (sound waves in rock or soil) typically move at 1 to 4 km/s. Thus, the rock materials cannot dissipate the impact energy by seismic waves until the meteorite has penetrated and slowed. A **shock wave**, or highly compressed zone in front of a supersonic body, carries a high density of energy and matter and builds up around the impact point, like a shock wave around the front of a supersonic aircraft. The explosion is the spreading of this shock wave, which compresses the rock and initially makes

*A meteoriticist friend tells of visiting Meteor Crater, Arizona. As he stood on the rim, looking at the contorted strata, he imagined the thunderous explosion of the impact, the fiery burst of ejecta shooting upward, and the shock wave racing out across northern Arizona, devastating life throughout the region in a matter of minutes. His mood was broken when a woman approached and remarked, "Oh, my! It's nowhere near as big as the Grand Canyon!"

it deform almost like a fluid around the impact site. The rock bends backward, upward, and outward, excavating a volume of material much larger than the meteorite itself. A relation exists between the kinetic energy of the meteorite and the size of the crater (Figure 10-6), though the crater size also depends to a lesser extent on the nature of the surface materials. Since the explosion center

Table 10-4
Selected Meteorite Impact Craters on Earth

Name	Location	Est. original diameter (km)	Est. age (My)
Sudbury	Ontario	140	1840 ± 150
Vredefort Ring	South Africa	140	1970 ± 100
Popigai	U.S.S.R.	100	30 ± 10
Puchezh-Katunki	U.S.S.R.	80	183 ± 3
Lake Manicouagan	Quebec	70	210 ± 4
Siljan	Sweden	52	360
Kara	U.S.S.R.	50	< 70
Charlevoix	Quebec	46	360 ± 25
Araguainha Dome	Brazil	40	<250
Carswell Lake	Saskatchewan	37	485 ± 50
Clearwater Lakes	Quebec	32, 22[a]	290 ± 20
Manson	Iowa	32	< 70
Slate Island	Ontario	30	350
Lake Mistassini	Labrador	28	38 ± 4
Rieskessel	Germany	24	14.8 ± 0.7
Gosses Bluff	Australia	22	130 ± 6
Wells Creek	Tennessee	14	200 ± 100
Sierra Madera	Texas	13	100
Deep Bay	Saskatchewan	12	100 ± 50
Bosumtwi	Ghana	10.5	1.3 ± 0.2
Kentland	Indiana	9	~300
Redwing Creek	North Dakota	9	~200
Serpent Mound	Ohio	6.4	~300
Middlesboro	Kentucky	6	~300
Decaturville	Missouri	5.6	320
Crooked Creek	Missouri	5.6	320 ± 80
Brent	Ontario	3.8	450 ± 30
Flynn Creek	Tennessee	3.6	360 ± 20
Steinheim	Germany	3.6	14.8 ± 0.7
New Quebec	Quebec	3.2	<5
Meteor Crater[b]	Arizona	1.1	0.02
Wolf Creek[b]	Australia	0.9	?

[a]Two craters lie almost tangent to each other. They may indicate fracture of a meteorite into two pieces in the atmosphere or impact by a body and its satellite.
[b]Meteorites are known at these two locations and at nine lesser sites in various locations, ranging down to clusters of pits caused as a meteor broke up in the atmosphere. The smallest example is an 11-m single pit at Haviland, Kansas.
Source: Based mainly on a 1978 compilation courtesy of Michael Dence; Earth Physics Branch; Department of Energy, Mines, and Resources; Ottawa, Canada.
Note: Table lists probable meteorite impact craters, with known evidence of mineral alteration due to shock wave metamorphism. List is complete down to 28-km diameter, with selected smaller examples.

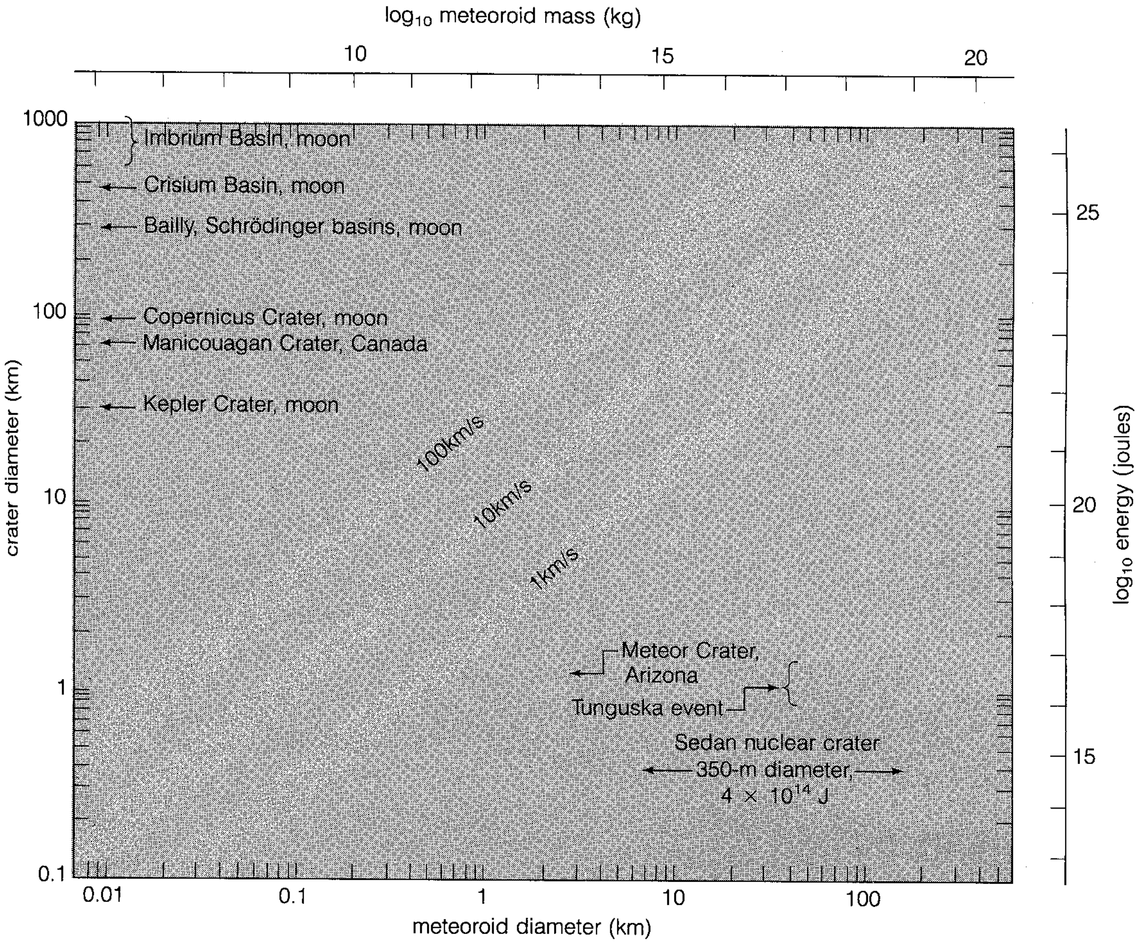


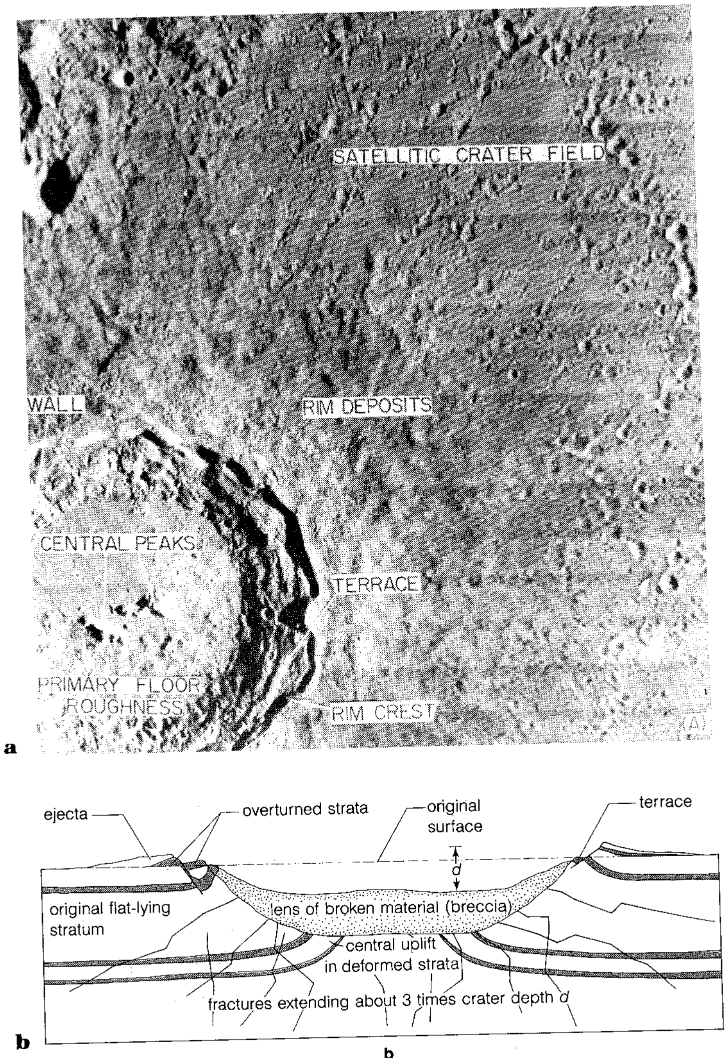
Figure 10-6. The diameter of an impact crater as a function of meteorite size for three different impact velocities. Scale at right gives the estimated energy required to make each crater. Documented craters on Earth and the moon are shown. The assumed meteorite density is 3 g/cm^3. (Crater energy and diameter data from Baldwin, 1963; Wasson, 1974, p. 145; Vortman, 1977)

is below the ground, strata that initially lay flat are heaved upward and outward, bent back, and even overturned in big flaps like petals of a giant flower opening. The rim is built partly from this upthrust rock and partly from excavated debris dumped on the crater edge.

Features of Impact Craters

Craters formed by meteorite impacts are often called **primary impact craters**. Figure 10-7 shows some common features. The rim has a hummocky structure grading outward into a thinner layer of debris. All this externally deposited material is called the **ejecta blanket**. Discrete blocks or clumps crashing down at high enough speed form **secondary impact craters**. Powdered and melted material resolidified as glassy beads is thrown out at very high speed (as much as 1 km/s or more) and leaves long, bright, linear deposits called **rays**. The rays radiate from the primary crater, often with secondary craters clustered along them, as shown in Figure 10-8b. The famous ray system of the 90-km crater Tycho

Figure 10-7. Features of impact craters. **(a)** *Vertical view of the relatively fresh 90-km lunar crater Copernicus. (Courtesy James Head, Brown University)* **(b)** *Cross section of a typical large crater showing additional features (see text).*

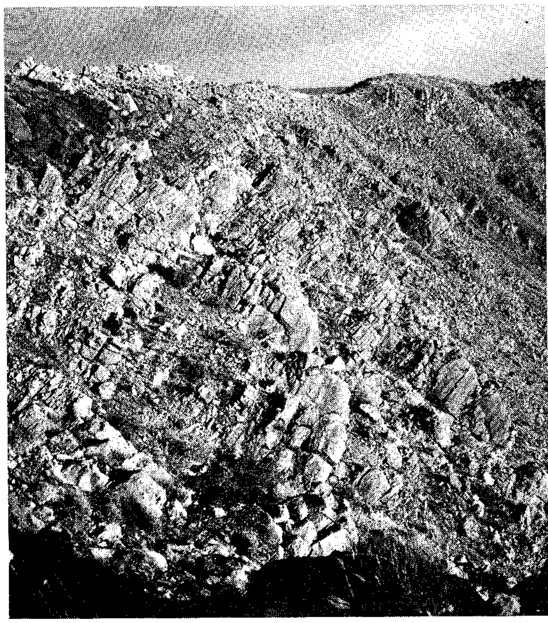


stretches more than 1000 km over much of the moon, as seen in Figure 10-8c.

Drilling reveals other features. The floor is typically a lens-shaped mass of breccia, rubble, and small amounts of lava produced by melting during the impact. This is ejecta that has fallen back into the crater's original cavity. Below this is highly fractured **bedrock** (rock not moved out of its original position). The fractures typically penetrate about 3 times deeper than the depth of the crater itself.

Some idea of the origin of crater features can be gleaned from Figure 10-9, showing the explosion of 91 t of TNT in a cratering experiment. The turbulent cloud around the base of the fireball is expanding, soil-laden gas called a **base surge**, which deposits some of the hummocky, dunelike ejecta around the crater rim. The high-speed jets angling upward may be analogous to the spurts of material that created ray systems.

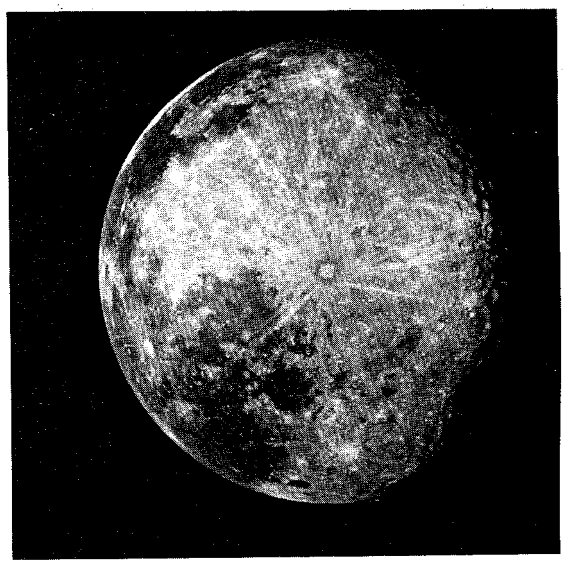
Visibility of crater features from above depends strongly on the lighting angle, as shown by Figure 10-10. Rays are prominent under high light but disappear under low light. But low light brings



a

b

Figure 10-8. Features of impact craters. (**a**) *View along inner wall of Meteor Crater, Arizona, showing upended strata. Original beds (as found nearby) lay flat. (Photo by author)* (**b**) *View toward the lunar crater Copernicus (see Figure 10-7a) on the horizon. Ejecta has been thrown over the Carpathian Mountains (the Imbrium rim, middle distance), littering mare surface with secondary craters and bright rays. (NASA; National Space Science Data Center)* (**c**) *View of the moon, centered directly above the young crater Tycho, showing the Tycho ray system. Note many rays are tangent, not radial, and begin outside a dark nimbus around the crater's rim. This photo was made by projecting an Earth-based photo on a globe and rephotographing the projected image from above Tycho. (Lunar and Planetary Laboratory, University of Arizona)*



c

out relief and allows rim and mountain heights to be measured from the lengths of shadows.

Surface views of modest-sized craters dramatically reveal many features, as shown by Figure 10-11. Hummocky rims and scattered rock fragments are prominent in young impact craters but become muted with time as material is deposited or eroded. Atmospheres inhibit the formation of small craters. For example, Martian craters smaller than about 50 m are absent due to atmospheric breakup of meteoroids as well as erosion (Binder and others, 1977).

Simple Craters, Complex Craters, and Multiring Basins

The structural features of craters change with increasing size. Small craters (about 1 km across) tend to have smooth, bowl-shaped interiors and are called **simple craters**. At larger sizes, the floor flattens. At still larger sizes, the floor develops a **central peak**, or mountain mass, such as shown in Figure 10-12. Central peaks are probably formed by a rebound phenomenon like the rebound of a droplet in a coffee cup. Terraces may also appear on the inner walls, apparently due to slumping of the rim inward. Craters with such features are called **complex craters**.

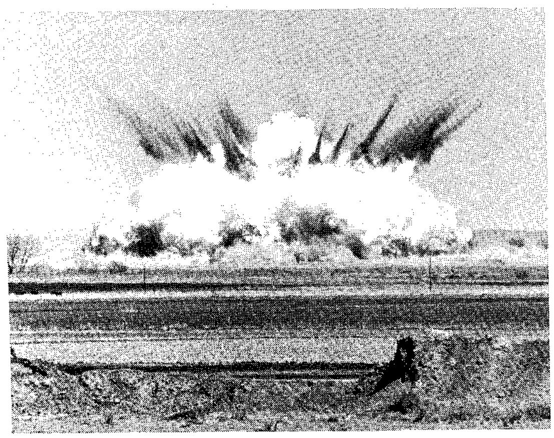


Figure 10-9. Test explosion of 91 metric tons of TNT illustrates features of crater formation (see text). This 1972 test in Colorado produced a crater 39 m across and 7 m deep with secondary impact craters up to 110 m away and ejecta as much as 201 m away. (Photo by author)

The transition from simple to complex occurs at smaller sizes on larger planets. For example, lunar central peaks are most common in young craters larger than 60 km in diameter; Martian central peaks, above 10 to 30 km; and Earth's, above 1 to 3 km. The difference probably relates to the wall height that can be sustained without slumping, given the gravity of the planet.

Although classic lunar central peaks occur only in large craters, some lunar craters as small as 100 m have rough central mounds (Figure 10-13) or terraces (Figure 10-14). This is caused by shallow layers of resistant rock, which disturb the otherwise smooth bowl shape. Experimental impact craters in layered targets show similar effects.

Still other features occur at larger crater diameters. For example, at about 100 to 300 km on the moon, Mars, and Mercury, a rare transitional shape develops, in which the central peak broadens and turns into a ring of hills, or **peak ring** (Hartmann and Wood, 1971), as shown in Figure 10-15.

Finally, the largest impact features are huge systems of concentric rings, called **multiring basins** (or just **basins**). Figures 10-16 and 10-17

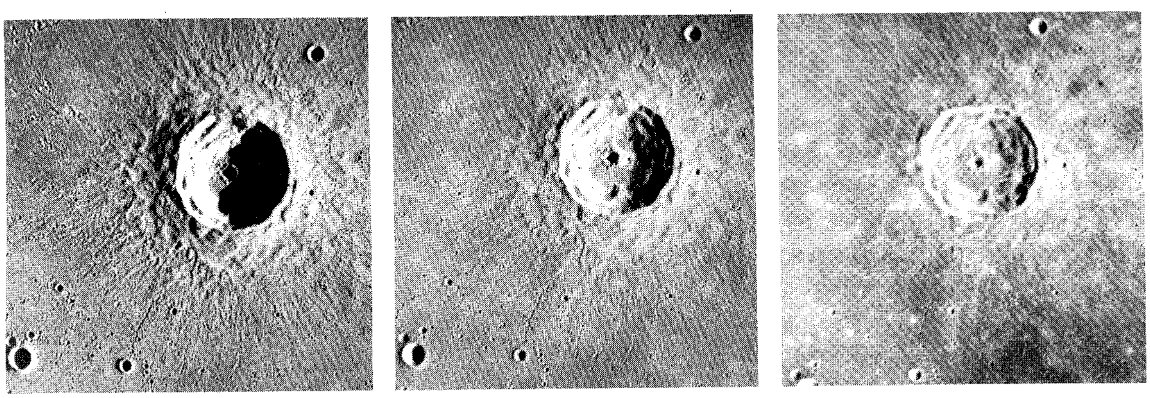
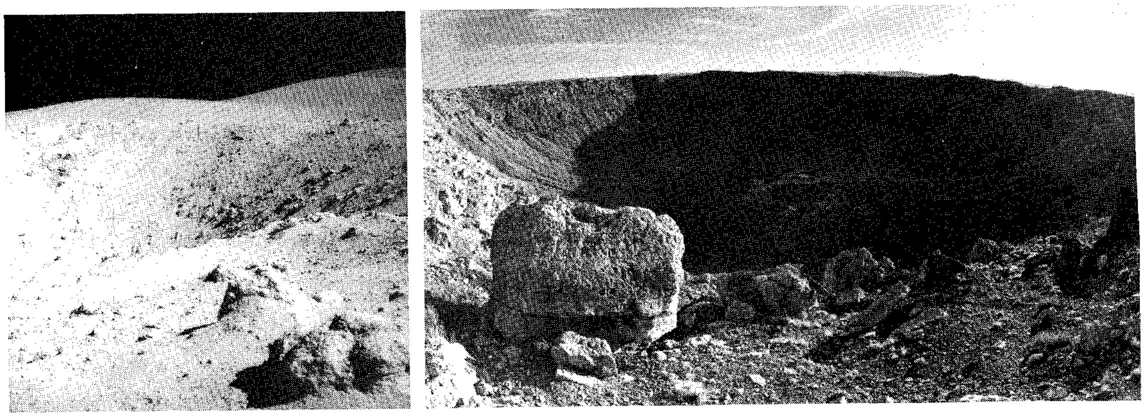
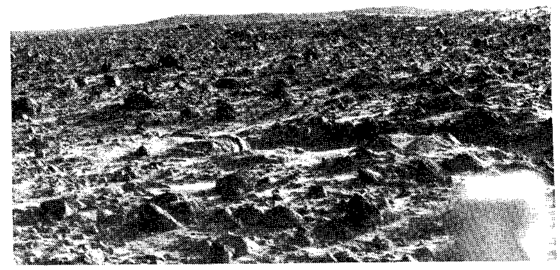


Figure 10-10. Three views of the young, 35-km lunar crater Timocharis under different lighting. Low lighting exaggerates relief, while high lighting brings out ray material and bright crater walls. (NASA, National Space Science Data Center)



a b



c

Figure 10-11. Surface views of impact craters. **(a)** *North Ray crater, near Apollo 16 site in the lunar uplands. Crater is about 900 m across and about 50 My old according to rock sample dates. (NASA)* **(b)** *Interior of Meteor Crater, Arizona, about 1100 m across and 20 000 y old. (Wide-angle photo by author)* **(c)** *Martian crater rim on the horizon, about 2.5 km southwest of Viking 1 site. Crater diameter is about 400 m. (NASA)*

show spectacular examples on three planets. Some of the rings, especially the inner ones, may be only roughly defined circles of hills, sometimes partly flooded by lavas that have covered the basin's inner floor. Other rings, often outer rings such as the Appennine arc around the lunar Imbrium basin, have a well-defined crest resembling the rim of an ordinary crater. These outer rimlike rings may be the true rim of the original impact crater, with other rings being rebound or slump features. Curiously, the rings are often distinctly spaced at intervals of about $\sqrt{2}$ times the inner ring radius (that is, 1.0, 1.4, 2, 2.8 . . . radii from the center). Multiring basins are the largest individual geological structures in the solar system. Some examples on the moon had been recognized before Apollo. Concentric, multiring lunar structures were described by Baldwin (1949, 1963), but they were more clearly recognized as a class after a number of others were discovered by "rectified" photography (projecting ordinary lunar photos on a globe and then photographing selected regions from "overhead." The great Orientale system (Figure 10-16) was discovered in

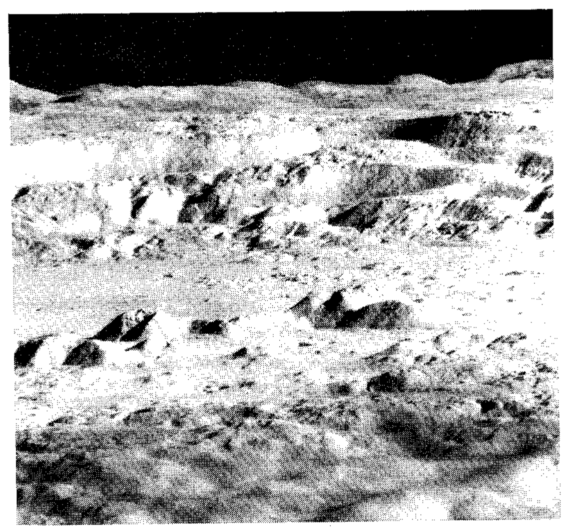
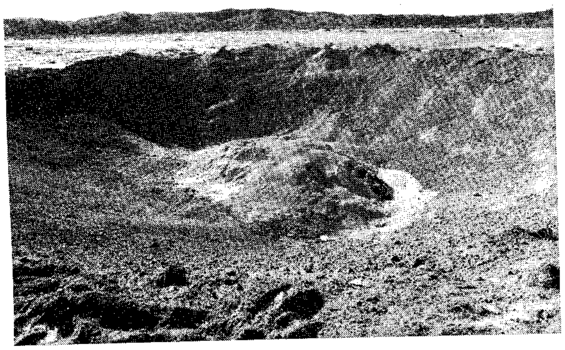
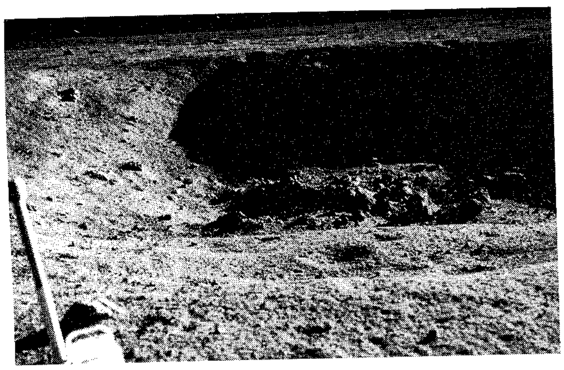


Figure 10-12. Oblique view of the central peak complex on the floor of the lunar crater Copernicus (compare Figure 10–7a). The near rim of Copernicus is at bottom foreground, the peaks in lower center, and the far rim just below the horizon. Boulders and outcrops appear to be present on the peaks. (NASA, Viking Orbiter 2)

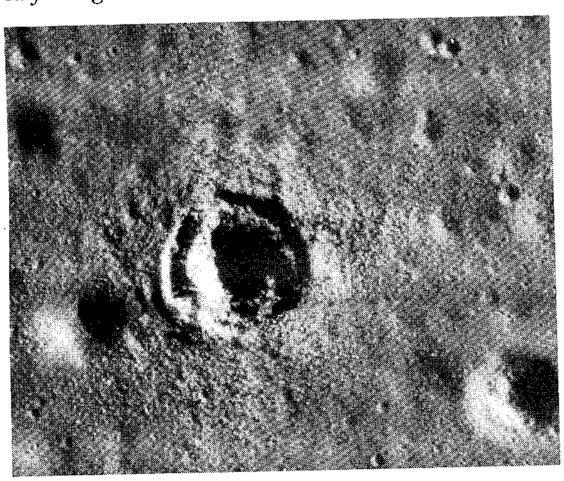


a



b

Figure 10-13. Central mounds in two small craters. **(a)** *Terrestrial test explosion crater about 30 m across, formed by 109 t of explosive. Central mound may be related to a resistant caliche layer below dusty sediments in which the crater was formed. (Miser's Bluff, Arizona; photo by author)* **(b)** *Lunar crater adjacent to Apollo 11 site. Central mound may be related to a resistant lava layer below surface regolith. (NASA)*



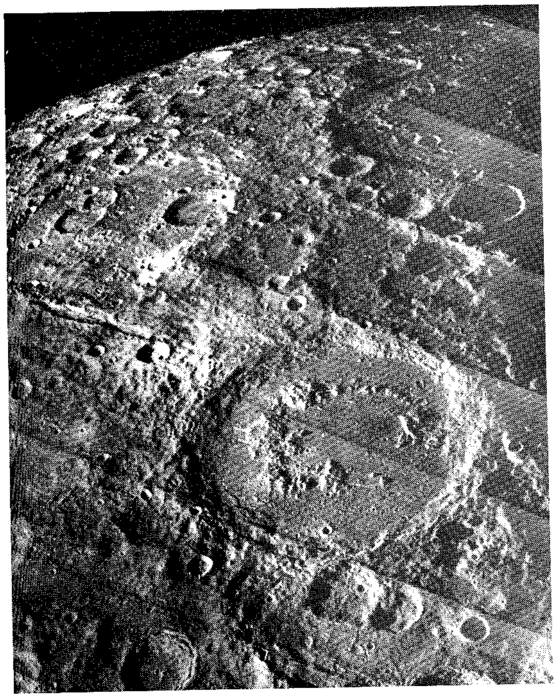
this way by Hartmann and Kuiper (1962) prior to lunar mapping by spacecraft.

Discovery of additional multiring basin systems on Mercury, Mars, Callisto, and Ganymede spurred interest in understanding their formative processes and the roles of giant impacts in establishing crustal heterogeneity on the planets. They appear to provide fracture systems allowing lava to gain surface access (Hartmann and Wood, 1971), and their ring spacings may be indicators of subsurface layering (Wilhelms, Hodges, and Pike, 1977). In addition, they are the centers of vast systems of radiating valleys and ridges that suggest profound fractures radiating from the impact sites (Figure 10-18).

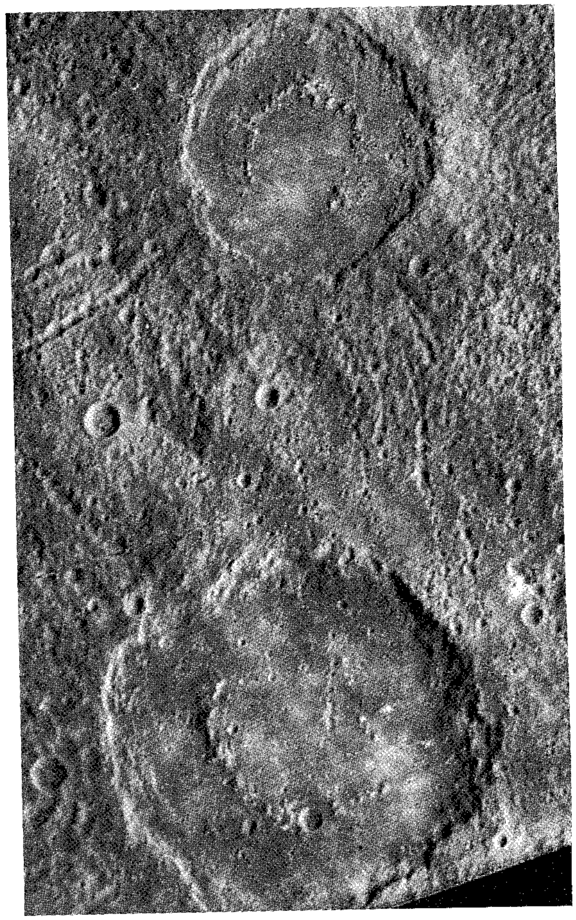
UTILIZING IMPACT CRATERS TO LEARN ABOUT PLANETS

Impact craters give several types of evidence about planets. They excavate and expose material. Their central peaks expose material originally about one-tenth of the crater diameter below the surface. For example, Pieters (1982) found that the central peak of the lunar crater Copernicus has a spectrum not seen in other lunar areas, and interpreted as olivine-rich, upthrust material from a 10 km deep crustal layer. As indicated in Figure 10-19, the structure of an ejecta blanket may indicate properties of the material at the impact site. Figure 10-19 shows one of many Martian ejecta blankets with lobate structure (lobe-shaped sheets extending from the crater). These are unknown on the moon and Mercury. Such craters have been termed **rampart craters**; they are attributed to impacts into soils containing large amounts of ice or water, which formed muddy ejecta flows with entrained gas (Carr and others,

Figure 10–14. (left) Lunar crater about 150 m across in Oceanus Procellarum shows terraced rim and ejecta blanket of boulders averaging about a meter in size. These features may indicate that the crater intruded a layer of intact lava below the regolith surface. (NASA, Orbiter 3)



a



b

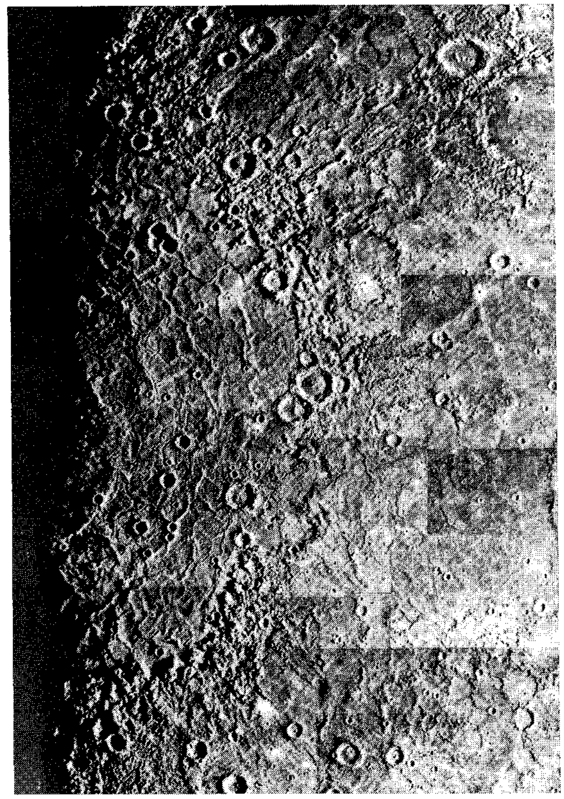
Figure 10-15. Craters with peak rings, a transitional form between central peaks and multiple concentric rings. (**a**) *Lunar crater Shrödinger, about 320 km across.* (**b**) *Mercurian craters Ahmad Baba (top) and Strindberg (200-km diameter, bottom). (NASA)*

1977). Rampart craters are the most common craters in many areas of Mars, though other areas contain primarily the lunar type of crater, probably caused by impacts into drier soil.

On icy satellites such as Ganymede, Callisto (Figure 10-17), Mimas (Figure 10-20a), Tethys (Figure 10-20b), and Dione (Figure 10-21) many of the larger craters (diameter $\gtrsim$ 40 km) show shallow profiles, domed floors sometimes showing central pits, and central peaks that (in a few cases) protrude above the crater rim, a situation unprecedented in the inner solar system. The original floors appear to have been pushed upward. These properties tell us something about the properties of the material in which the craters formed. The material is probably predominantly ice, possibly underlain by more fluid (watery) or rigid (rocky) layers. The surface ice layer would be more fluid than the surface rock layers of terrestrial planets, although the viscosity of H_2O ice at the temperatures of the satellites' subsurface layers is uncertain.

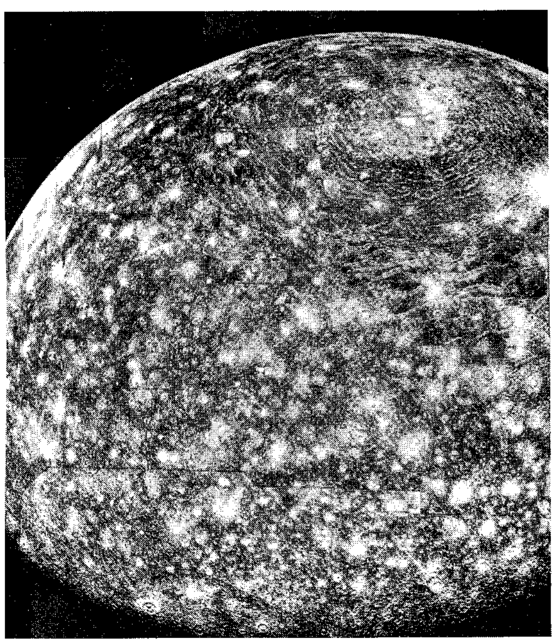
Parmentier and Head (1981) calculated profiles of craters in relaxing viscous ice layers and matched observed craters with models in which the craters formed in a deep ice layer whose viscosity was constant or increased with depth. Large craters (with their greater initial elevation differences) flatten quicker than small craters do, as measured in proportion to their initial depths.

a



b

Figure 10-16. Multiring basins on two planets. The systems nearly match, with outer rings being about 1300 km in diameter, or capable of stretching from the Great Lakes to the Gulf of Mexico. **(a)** *Orientale Basin, on the limb of the moon, discovered in 1962 by Earth-based photos. (NASA)* **(b)** *Caloris Basin on Mercury, discovered in 1974 by Mariner 10. (NASA)*



Craters 10 and 100 km across were found to relax in 30 Gy and 30 My, respectively. Thus, large craters can be subdued or obliterated while small ones survive. These data may explain why some heavily cratered regions of some satellites (Figure 10-21) seem to have strangely flattened intercrater plains and seem to lack large craters.

On the other hand, Voyager analysts (Smith and others, 1982; Strom and Woronow, 1982, private communication) have suggested that these remote worlds have been hit by meteoroids (comets? intersatellite debris?) with size distributions different from those that hit the moon. In this view, differences in crater size distribu-

Figure 10-17. (left) A 2400-km diameter multiring basin system on Callisto. This structure appears to have been smoothed by isostatic adjustment of Callisto's icy crust. (NASA, Voyager 1)

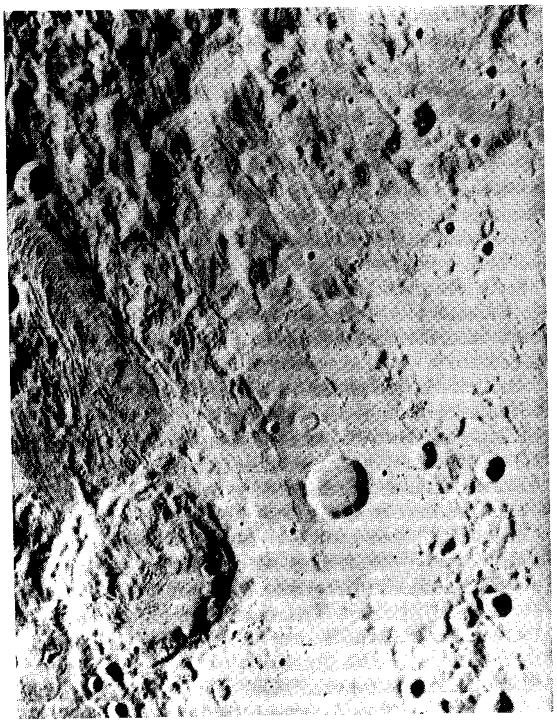


Figure 10-18. Portion of radial pattern around the moon's Orientale Basin. Some larger striations may be faults, while the finer structure suggests a somewhat turbulent flow of material across the surface (upper left to lower right) as ejecta was deposited. Picture width, 275 km. (NASA, Orbiter 4)

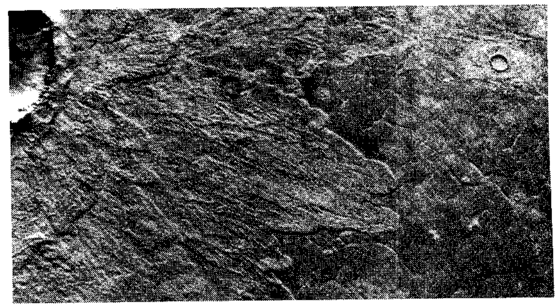


Figure 10-19. Lobate ejecta around the 25-km Martian crater Arandas. This pattern, unique to Mars, is interpreted as due to impact into water- or ice-bearing soil. Patterned ground to the right is also possibly related to the freeze-thaw cycle of ice in the soil. (NASA, Viking 1)

tions reflect differences in impactors more than differences in obliteration processes. The problem deserves more study.

The most important use of craters has been to date planetary surfaces. On an erosion-free surface, such as a lava flow on an airless world, meteorite craters accumulate with time. Thus two types of dating are possible.

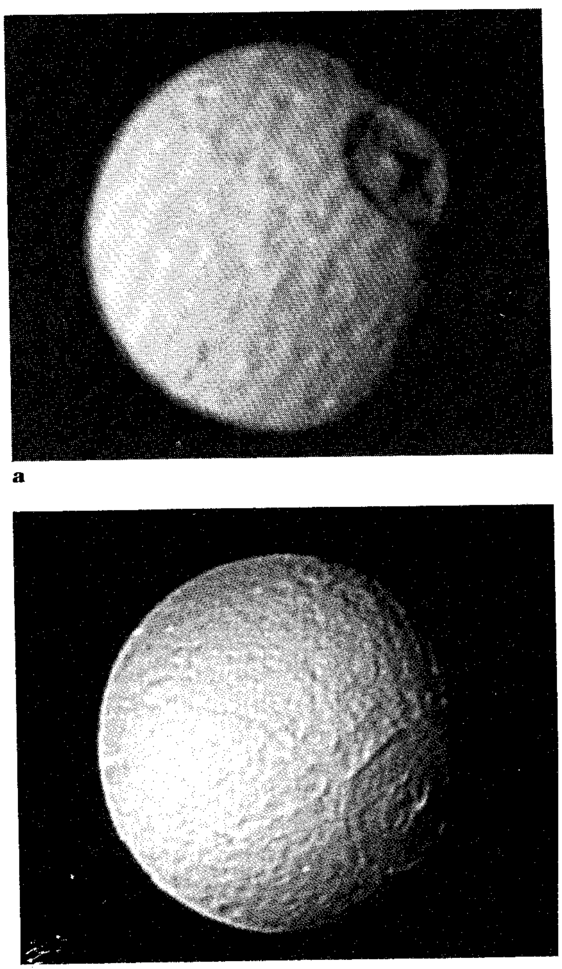


Figure 10-20. Some densely-cratered satellites have acquired craters as large as 38% of the satellite diameter. On these icy moons of Saturn, the large craters appear deformed by an isostatic uplift of the floor, bringing central peaks to levels near or higher than the rims. ***(a)*** *A 130-km crater with a massive central peak dominates one side of 392-km Mimas.* ***(b)*** *A 402-km crater with a subdued rim is prominent in this view of 1060-km Tethys. (NASA, Voyager 1 and 2)*

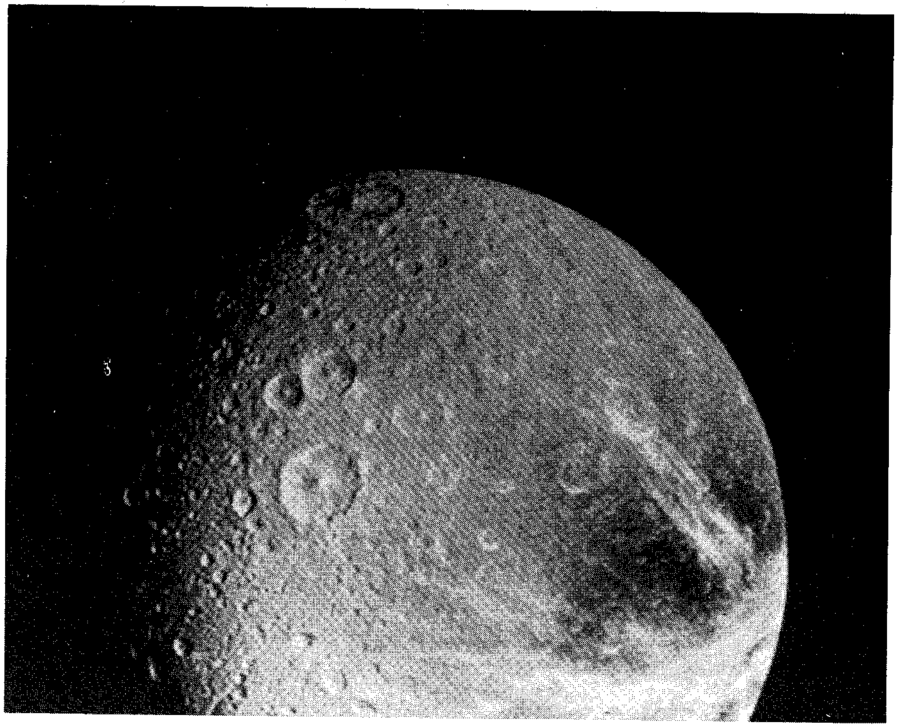


Figure 10-21. Subdued large craters mark heavily cratered terrain on Saturn's 1120-km moon, Dione. Regions along the terminator appear deficient in large craters, relative to similar views of our moon. Nature of dark regions and bright swaths on the trailing hemisphere (right) is uncertain. North at top. (NASA, Voyager 1)

The simpler but less informative type of dating measures the **relative age** of geological provinces by merely measuring their crater densities (craters per square kilometer). On a given planet, a less-cratered province is younger than a more-cratered province. **Stratigraphic relationships**, that is young formations overlapping older formations, assist in establishing the relative ages.

The more exact type of dating determines the **absolute age** in years. This can be estimated if the rate of formation of craters is known, as from Figure 6-4 and Table 6-1. Absolute ages allow comparison of events on different planets. Unfortunately, crater formation rates outside the Earth-moon system remain quite uncertain—errors in age may be a factor of ± 3. These rates could be improved by better knowledge of the numbers and lifetimes of asteroids and comets or by datable rock samples from certain geological provinces on other planets, which could then be used to calibrate the relationship between crater density and relative age for each planet.

Figure 10-22 shows examples of this technique, comparing observed numbers of craters with predicted numbers for surfaces of various ages on 11 planetary bodies. The small, airless worlds have retained the most craters of various sizes. Large, geologically active worlds have younger surfaces and fewer craters. Diagrams such as Figure 10-22 contain key data for understanding the evolution of planetary surfaces in the solar system. Such data are reviewed in further detail by Hartmann and others, 1980.

Stratigraphic Studies of the Earth-Moon System

Once we know the relative ages of features on a planet, we can construct a **stratigraphic column** for the planet, an imaginary vertical col-

Figure 10-22a.

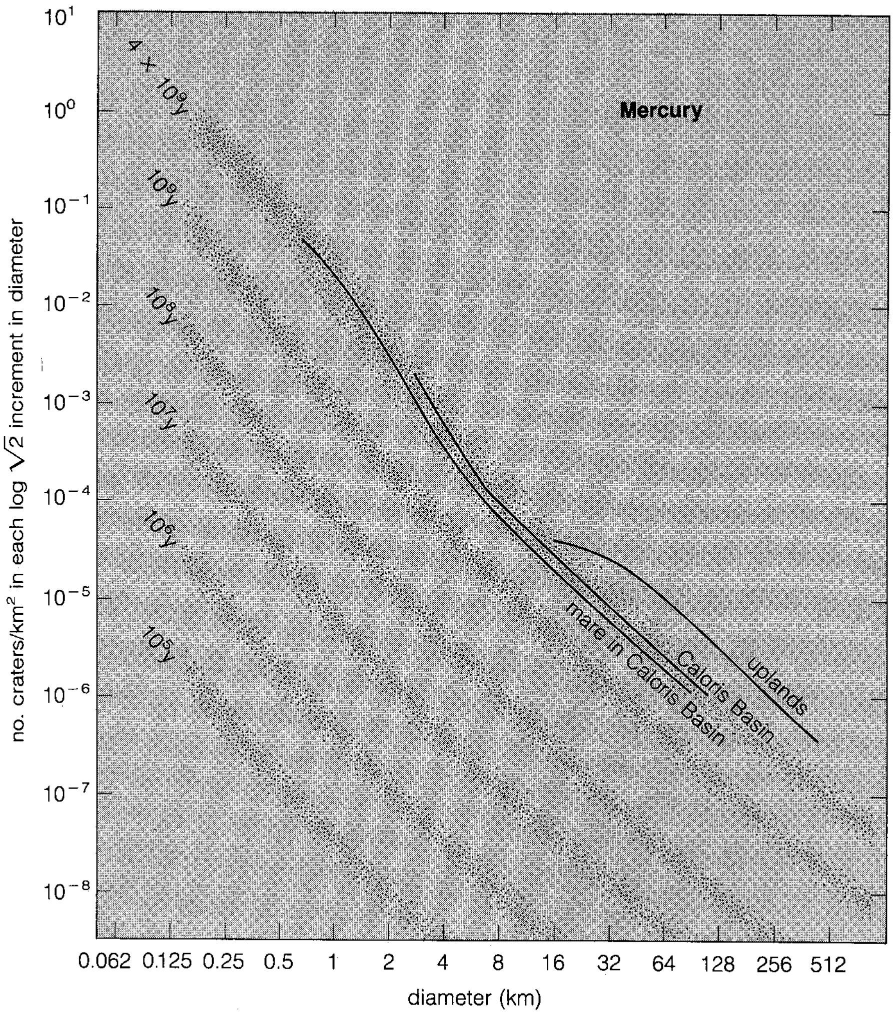
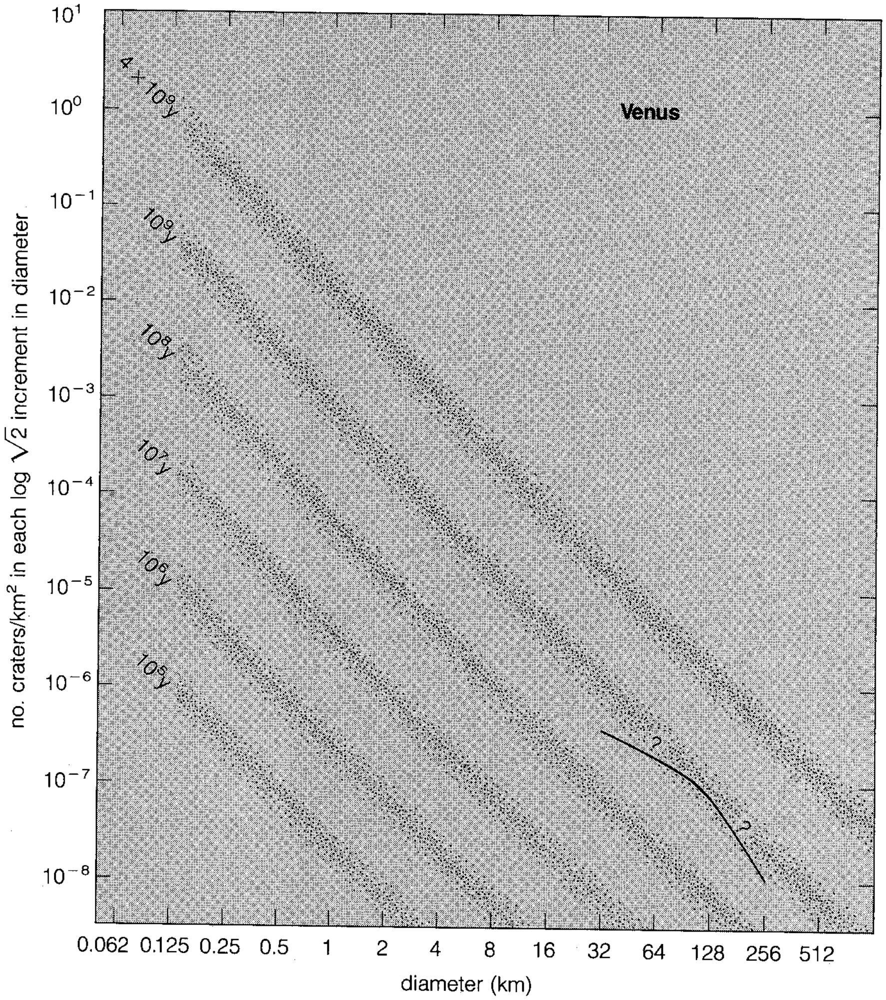


Figure 10-22. Crater counts and isochrons for 11 planetary bodies. Solid lines give schematic observed diameter distribution of craters. Dotted isochrons are estimates of numbers of primary impact craters expected for surfaces that have preserved all craters since the times of formation listed at left. Estimates are based on data such as Figure 6–4. Data show that Phobos, Deimos, the moon, Callisto, Ganymede, and Mercury are relatively primitive bodies with surfaces that are a few billion years old in most regions. Mars has many old surfaces but also some extensive younger volcanics, perhaps a few hundred million years old, and evidence of erosive loss of smaller craters in some regions. Venus (as mapped by radar; Burns, 1982) and Earth have regions that have preserved large craters for at least 1 Gy, but smaller craters have been eroded on Earth and perhaps on Venus. Europa's surface (based on the detection of three 20-km craters) is perhaps 0.1 to 3 Gy old. Io is being resurfaced, probably in less than 0.001 Gy, by volcanic eruptions. (Galilean data based on Smith and others, 1979)

Figure 10-22b.



umn showing the sequence of events in different geological periods and resembling a cross section through an idealized portion of the planet's lithosphere.

Systematic work of this kind was begun when U.S. Geological Survey researchers Shoemaker and Hackman (1962) laid out the beginnings of a stratigraphic system for the moon. Just as terrestrial geologists developed a system of names such as Cambrian and Jurassic (often from locales) to designate periods whose absolute dates were uncertain but whose relative ages were established from fossils, Shoemaker and Hackman chose names such as Imbrian and Copernican (from lunar locales) to designate periods whose relative ages were established from crater counts and overlap relations.

In the 1960s, Geological Survey geologists preparing for the Apollo missions mapped much of the moon's stratigraphy in this way (Mutch, 1970). The Apollo missions then gave absolute calibration for certain geological provinces,

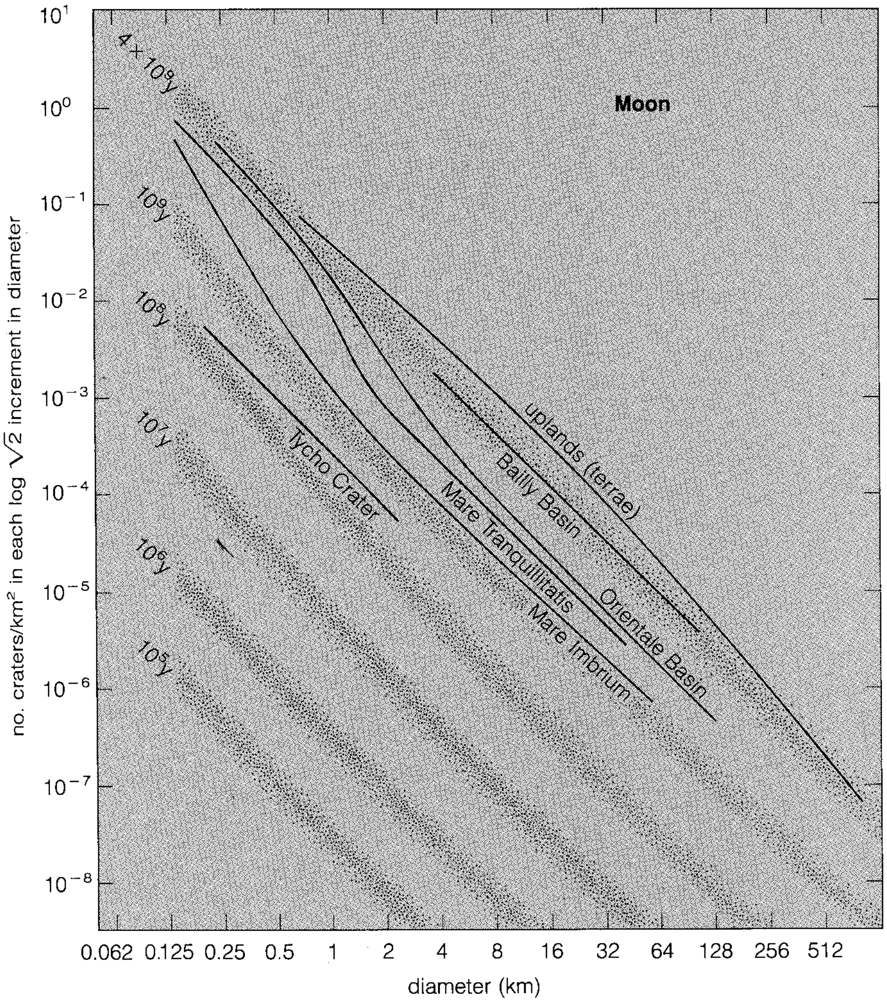
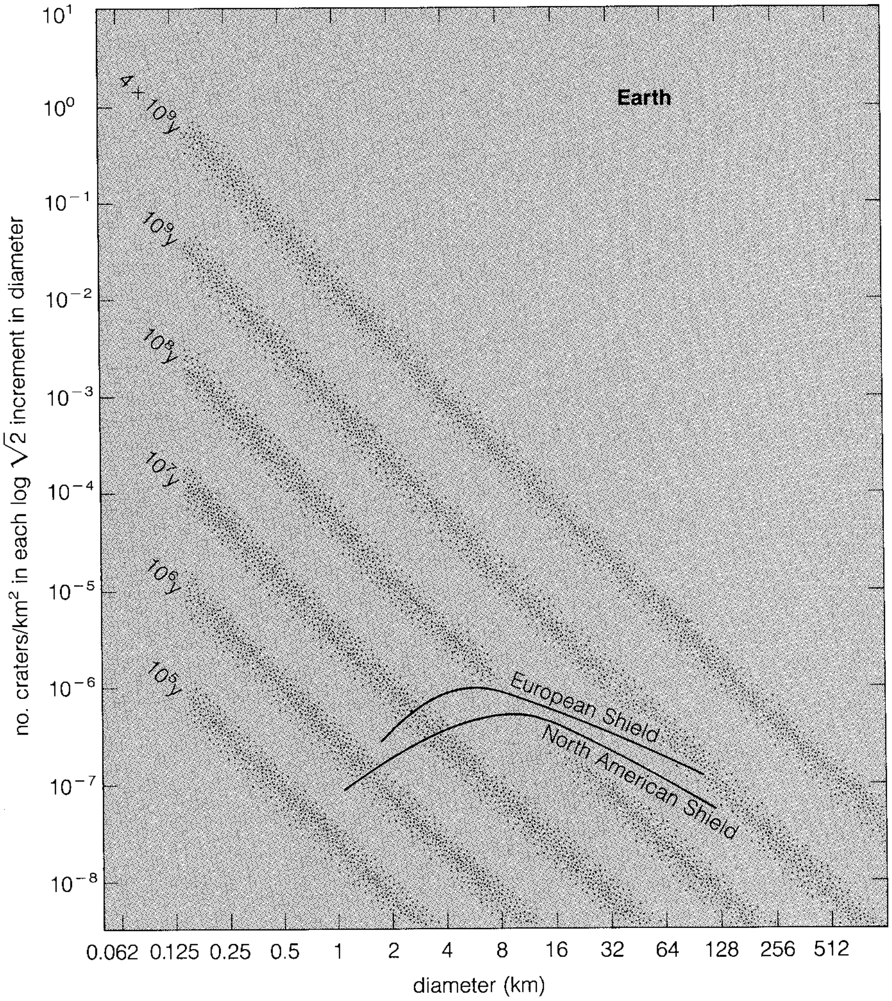


Figure 10-22c.

allowing the time scale based on lunar crater counts to be calibrated globally. Absolute dates can now be estimated for all major lunar features.

Table 10-5 compares the stratigraphic systems that have been built up for the Earth-moon system in this way. Earth's stratigraphic column has a hierarchy of divisions including broad eras and finer periods (and even finer subdivisions). Note that fine detail appears in the terrestrial system only in the last 10% of solar system history (the only interval with a good fossil record and abundant rock samples), while fine detail appears only for the earlier history of the moon. Though stratigraphic names such as Cambrian or Imbrian have been used to indicate dates of geologic provinces, advances in absolute radiometric dating of planetary rock samples have led to widespread quoting of numerical ages (for example, 3.63 Gy) in much of the lunar and general planetary literature. This trend seems likely to continue, since a single system of well-deter-

Figure 10-22d.



mined dates is much preferable to separate stratigraphic terminologies, one developed for each planet.

Crater Retention Ages

What age is actually measured when we count primary impact craters? If the surface is a sparsely cratered, thick lava flow on an airless world, the number of craters measures the time since the flow's origin. But if the flow is on a planet such as Mars, where dust blows into craters and other erosion occurs, small craters may last only (say) 1 My and large ones, 100 My. Then the number of craters of a certain diameter measures not the age of the surface but the length of time a structure with that dimension can withstand erosion. Thus, ages measured by crater counts have been termed **crater retention ages** (Hartmann, 1966). With care, these ages can be used not only to learn about ages of certain features but also to interpret rates of erosive activity (for example, Chapman and Jones, 1977).

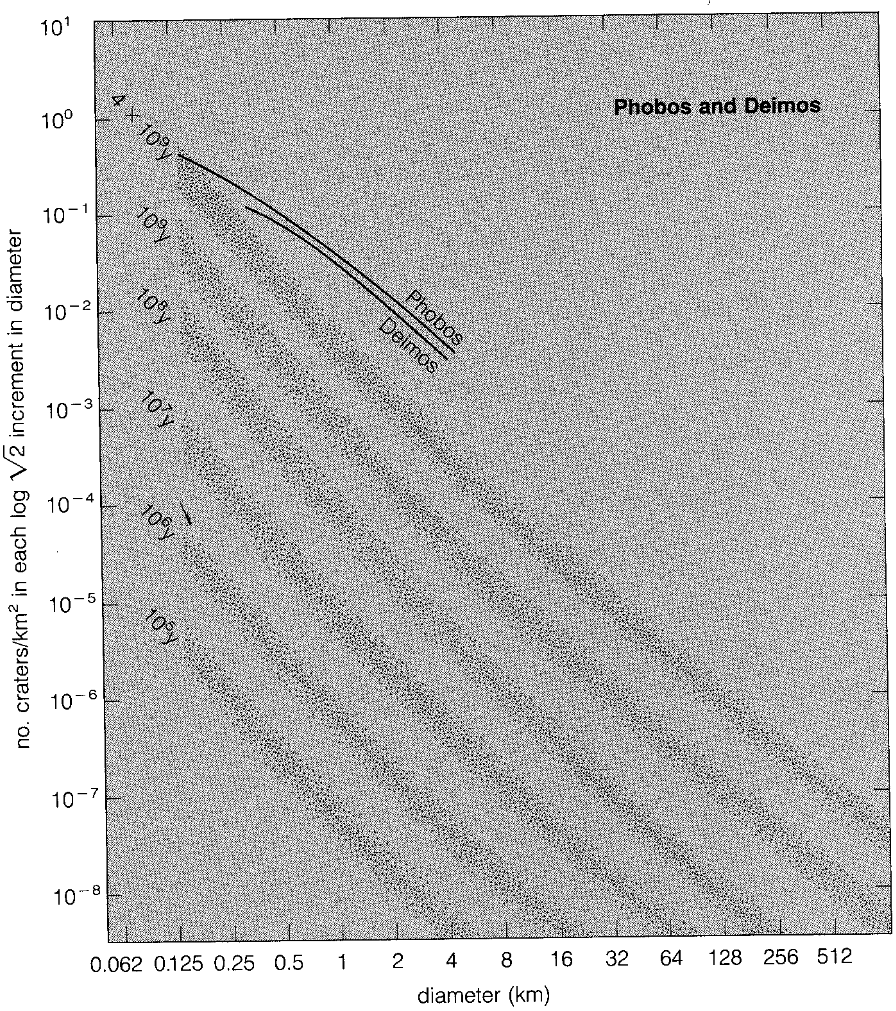


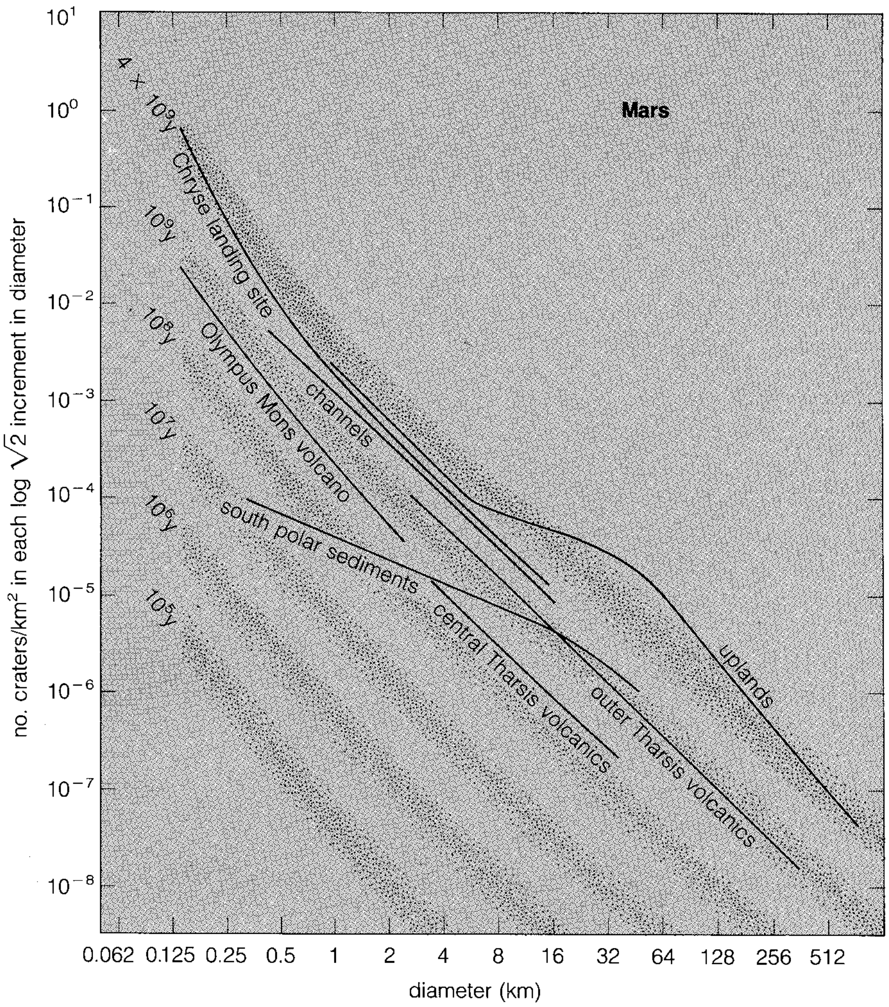
Figure 10-22e.

Steady State Cratering

Consider a fresh lava flow on a planet. As time passes, the surface will accumulate craters. Eventually a point is reached where craters are so crowded that new impacts destroy old craters as fast as they make new ones. The surface thus reaches a condition called **steady state cratering** (sometimes loosely called **crater saturation**), beyond which the observable crater density does not rise. Figure 10-23 shows the most profusely cratered surfaces in the solar system all have a similar density of cratering, roughly 30 times that found among the multikilometer craters on the lunar maria. The similarity of these curves suggests that these surfaces actually reach or approach a saturated steady state, though computer simulations (Woronow, 1978) have led to suggestions that crater densities could attain somewhat higher values.

A surface that is nearly saturated with craters must be ~4 Gy old, because only surfaces dating back to the era of early intense bombardment acquired enough hits to approach a steady state.

Figure 10-22f.



We can't tell from photos whether a given saturated surface has been exposed long enough to absorb enough hits barely to achieve saturation or long enough to absorb many times more hits. Surfaces anywhere in the solar system younger than 3.5 Gy should not approach the crater densities shown in Figure 10-23.

Steady state cratering is also important because it leads to the formation of deep megaregoliths on planets, as described in our previous discussion of megaregolith formation (see Figure 10-5). While cratering has covered only about 3% of the lunar maria with craters larger than 4 km and made a regolith in those areas about 10 m deep, cratering has covered about 100% of the highlands with craters larger than 4 km and thus stirred the surface to a depth of at least 1 or 2 km.

Problems with Small Craters

In order to get an adequate statistical sample of primary impact craters for dating purposes,

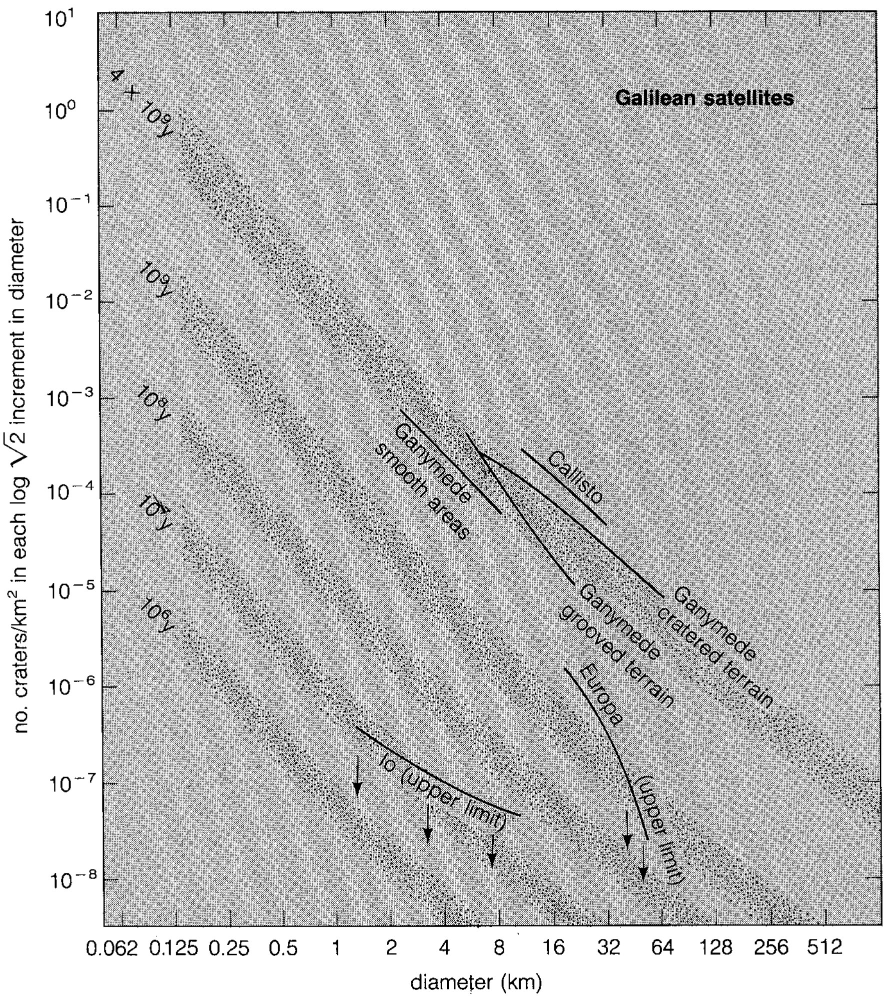


Figure 10-22g.

multikilometer craters must be counted over mare-sized areas hundreds of kilometers across. This restricts crater dating to large, rather coarse geological provinces. Desire to date smaller features, such as individual lava flows or craters such as Copernicus, has led to interest in counting subkilometer-sized craters, which are more abundant. In most planetary regions, a majority of these craters are probably secondary impact craters. Since these cluster around their parent primaries and along rays from primaries, instead of being distributed at random, they are trickier to use for dating. Wilhelms, Hodges, and Pike (1978) find that secondaries as large as 20 km across, which were thrown out of the larger basins, may predominate in the lunar uplands, complicating the situation even more. Furthermore, volcanic processes add uncertain numbers of small craters that may be mistaken for meteorite craters. Clearly, one must be careful when attempting to derive ages by counting small pits. Some investigators have had some success by using morophological criteria to discriminate primaries from secondaries (Neukum and others, 1975).

Table 10-5
Stratigraphic Systems Used for Earth and the Moon

Absolute Time Scale (Gy before present)	Relative Time Scale (Stratigraphic Terminology): Earth — Era	Earth — Period (or system)	Moon — Period (or system)	Events[a]
0				
	Cenozoic			Mammals Modern continents forming
	Mesozoic	Cretaceous		
		Jurassic		Dinosaurs
		Triassic		Ferns, conifers
	Paleozoic	Parmian		
		Carboniferous		
Note expansion of scale (0 to 1Gy)		Devonian		Fish
		Silurian		Early land plants
		Ordovician		
		Cambrian		Earliest well-formed fossils (trilobites, etc.)
	Precambrian or Proterozoic	Late	Copernican	
1				Sporadic large craters forming on Earth and the moon
		Middle		Oxygen increasing in Earth's atmosphere
2		Early		Soft life forms in Earth's seas; stromatolite fossils forming at seacoasts
			Eratosthenian	Decline of mare lava flooding on the moon
3				Crustal and atmospheric evolution on Earth
	Arehaean	Archaean		Early microscopic fossils on Earth (poor record)
			Imbrian	Mare flooding on the moon Oldest terrestrial rocks
4				
			Nectarian	"Modern" basins forming on the moon Intense cratering
5			Pre-Nectarian	Earliest features (mostly obliterated by subsequent cratering) on the moon Planet formation

[a]Events are on Earth unless specified otherwise.
Source: Seyfert and Sirkin (1979).
Note: The Quaternary (0–3 My) and Tertiary (3–62 My) periods are too brief to show within the Cenozoic Era.

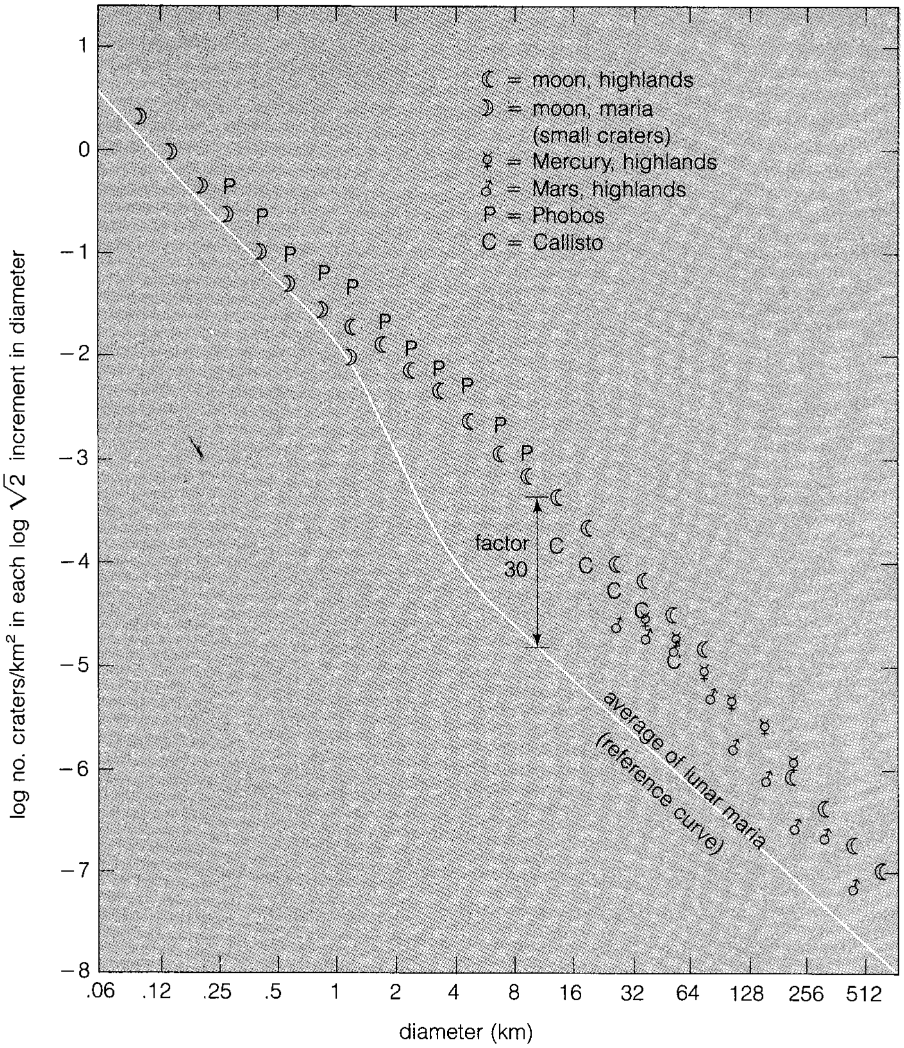


Figure 10-23. Crater counts on some of the most heavily cratered surfaces of the solar system mark a fairly well defined band in the crater-diameter distribution diagram, with about 30 times the crater density on the lunar maria. This band may approach the maximum number of visible craters that can be crowded on a planet, given the size spectrum of impacting meteorites, and it marks surfaces that have developed megaregoliths.

Soderblom and Lebofsky (1972) developed a different technique by noting that if all primaries of a given size began life as bowls of a certain shape, subsequent impacts would have required a fixed amount of time to erode the bowls to a degraded state where their interior walls had a shallow angle of, say, 1°. A parameter called $\boldsymbol{D_L}$ ("***D*** sub ***L***") was defined as the diameter of a crater eroded to this state of degradation. D_L was then used as a measure of the age of the surface. A fair correlation exists between Apollo age data, crater counts, and D_L ages for various surfaces. Since D_L can be found for quite small craters (100 m or so), it is a useful criterion for dating local surfaces.

MICROEFFECTS ON AIRLESS SURFACES

Micrometeorite Effects

We have already discussed cratering and associated effects caused by the impact of *macro*scopic