The Geological History of the Moon (1987)

U.S. Geological Survey Professional Paper 1348

http://ser.sese.asu.edu/GHM/

I have read this fascinating account of the geology of the Moon and have extracted parts of it and edited it for our 4-H astronomy project. You can get the complete story for free using the link above.

Figure 1 near side of the Moon

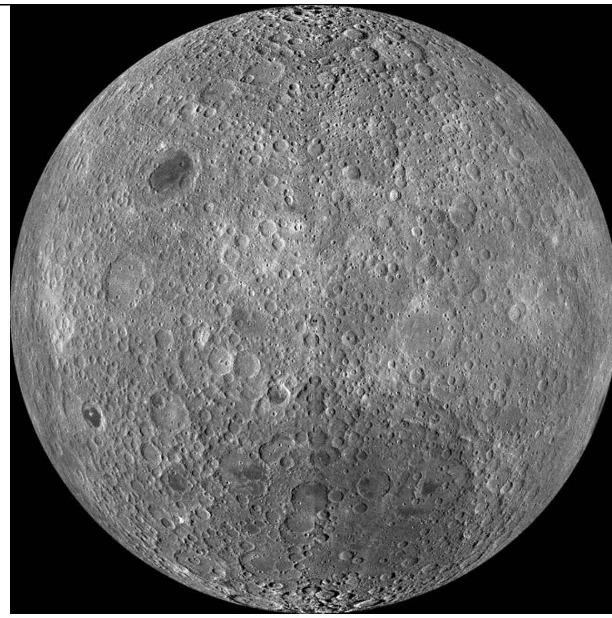


Figure 2 far side of the Moon

When I was a child, astronomers had never seen the far side of the Moon. Imagine their surprise when the Soviet probe named Luna 3 sent back the first images of the hidden side in early October, 1959. I think Galileo would have been surprised as well if he was living then.

The most obvious geological features on the Moon are the dark seas. The darker shade of the seas is due to the type of rock found there. It is volcanic rock called basalt. Remarkably, nearly all of the seas (called maria) are located on the near side of the Moon. About 30% of the near side is covered with maria while only 2% of the far side is covered with maria.

If you look carefully at the near side photo above, you might notice that the seas are mostly circular in shape. Some overlap each other, especially on the west side (to the left). The seas are actually huge craters that were filled with lava seeping out from the interior of the Moon. It is believed that the crust of the Moon is thinner on the near side than the far side. Therefore, lava could make its way through the thinner crust with relative ease on the near side, which is why that side has most of the seas.

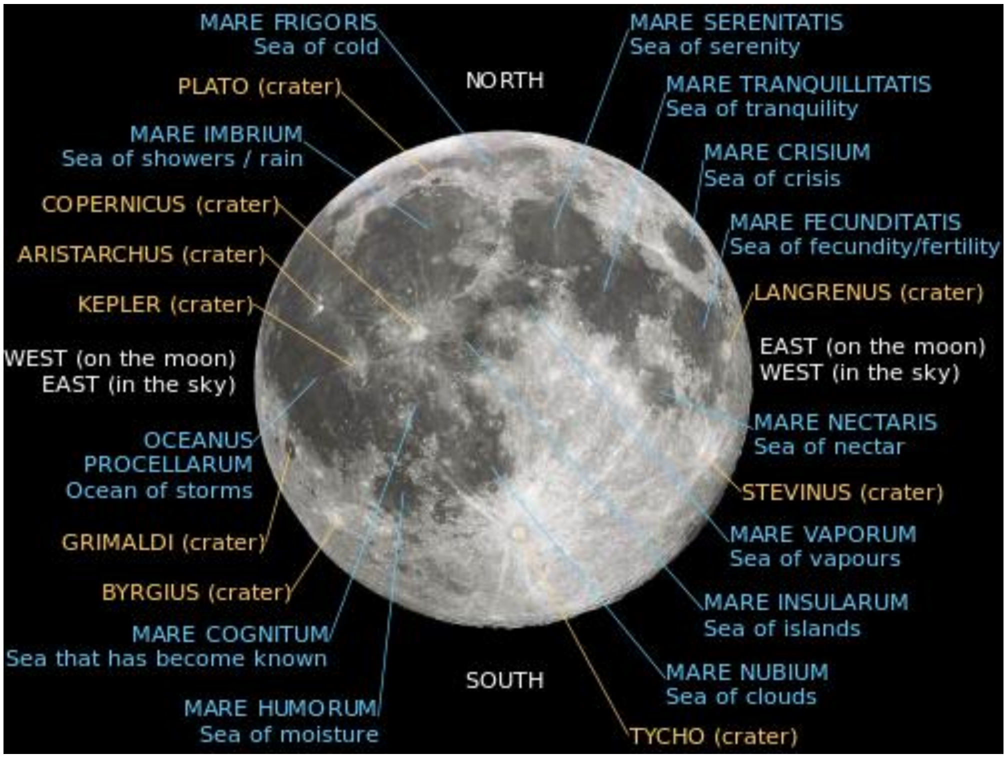


Figure 3 the seas of the Moon

The Italian astronomer Giovanni Battista Riccioli (1598-1671) introduced the system of naming features on the Moon that we use today. I believe that most if not all of the names of the seas that we still use today come from Riccioli.

The borders of the seas are actually the rims of giant craters, forming circular rings or partial rings. For example, the southeast rim of Mare Imbrium is made up of a series of mountains named Montes Apenninus (named after the Apennine Mountains that run along the center of the peninsula of Italy).

(continued on next page)

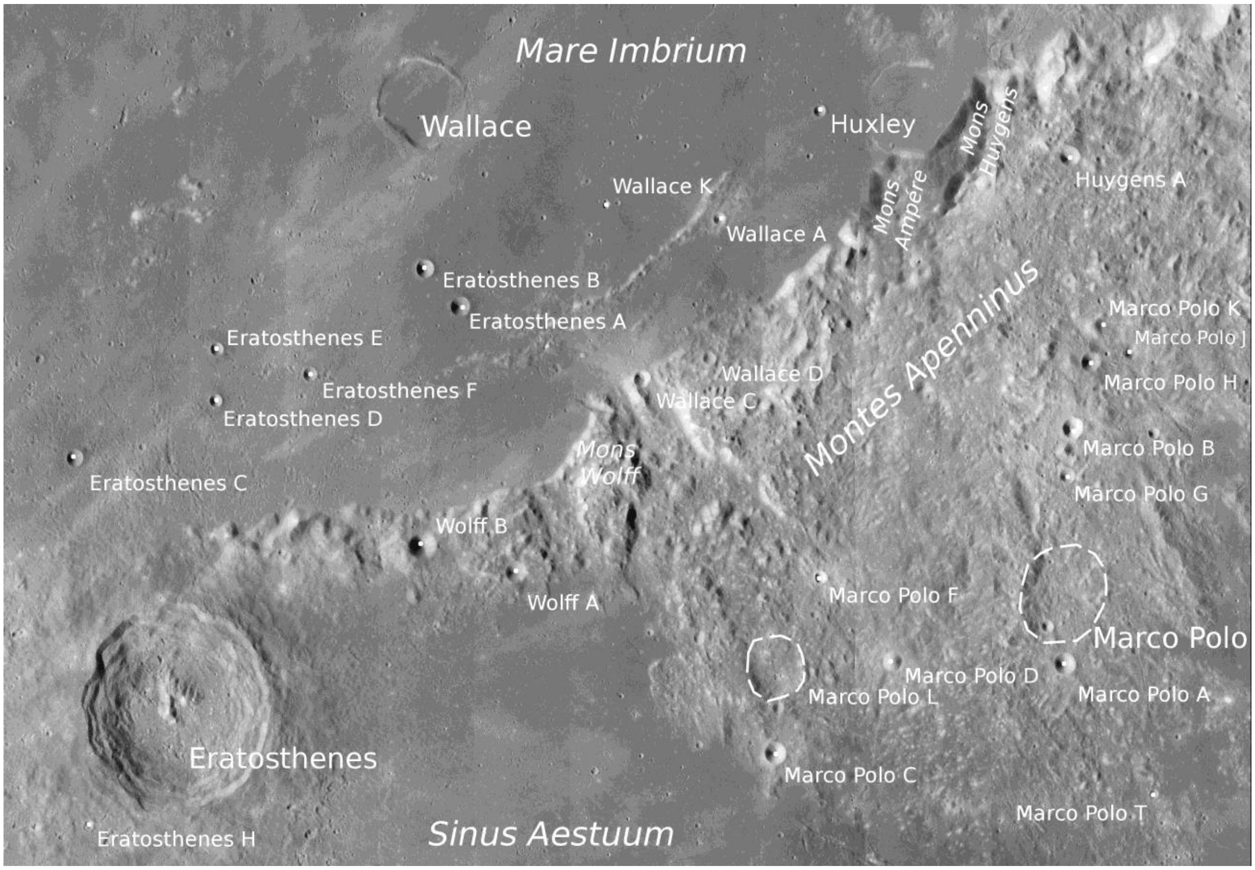


Figure 4 Montes Apenninus - note Mons Huygens in upper right, the highest mountain on the Moon

The lighter colored parts of the Moon are the highlands (Terrae [plural] Terra [singular]). The kinds of rocks that make up the highlands are lighter in color than the volcanic rock of the maria. The volcanic rock of the maria was formed by lava, which leaked through the crust of the Moon and settled on the lower parts of the surface inside the giant craters. The higher parts of the Moon surface were never covered in lava and that is the reason we can see their lighter colored rocks today.

Compared to the highlands, the maria are fairly smooth and flat. There are not nearly as many craters on the maria. However, if we look carefully and with high magnification in the telescope, we can see that there are still quite a few craters on the maria and its surface is not completely smooth. Long ridges (dorsa) can be seen on the maria, like wrinkles. There are also narrow troughs or grooves (rilles).

One of the first things Galileo noticed when observing the Moon with his telescope was the craters. Craters on the moon come in all sizes, some almost as large as the Moon itself and some just inches across. The smallest ones can't even be seen in the Hubble Space Telescope! There are many more craters found in the highlands than in the seas. Most craters have rims elevated above the surrounding surface and floors inside that are below the surrounding terrain. We can classify the craters by their size:

Small (less than 16 to 21 kilometers in diameter) – relatively featureless interiors (like a simple bowl)

Large – more complex, they have peaks in the center, circular wall terraces & other interior land forms

Exterior to the crater there may be a short rim flank or a more extensive flank with a coarse concentric structure near the rim, grooves on a lower rim flank, and numerous smaller secondary craters (usually 1 to 3 crater radii from the rim). The secondary craters are formed at the same time as the primary crater, as a result of material ejected during the explosion when the object that formed the primary crater collided with the surface of the Moon. For relatively young craters (a few hundred million years old), bright rays 100s or 1000s of kilometers long are present, radiating away from the crater (for example you can see the rays of crater Tycho in Figure 1, the crater is near the bottom of the Moon).

(continued on next page)

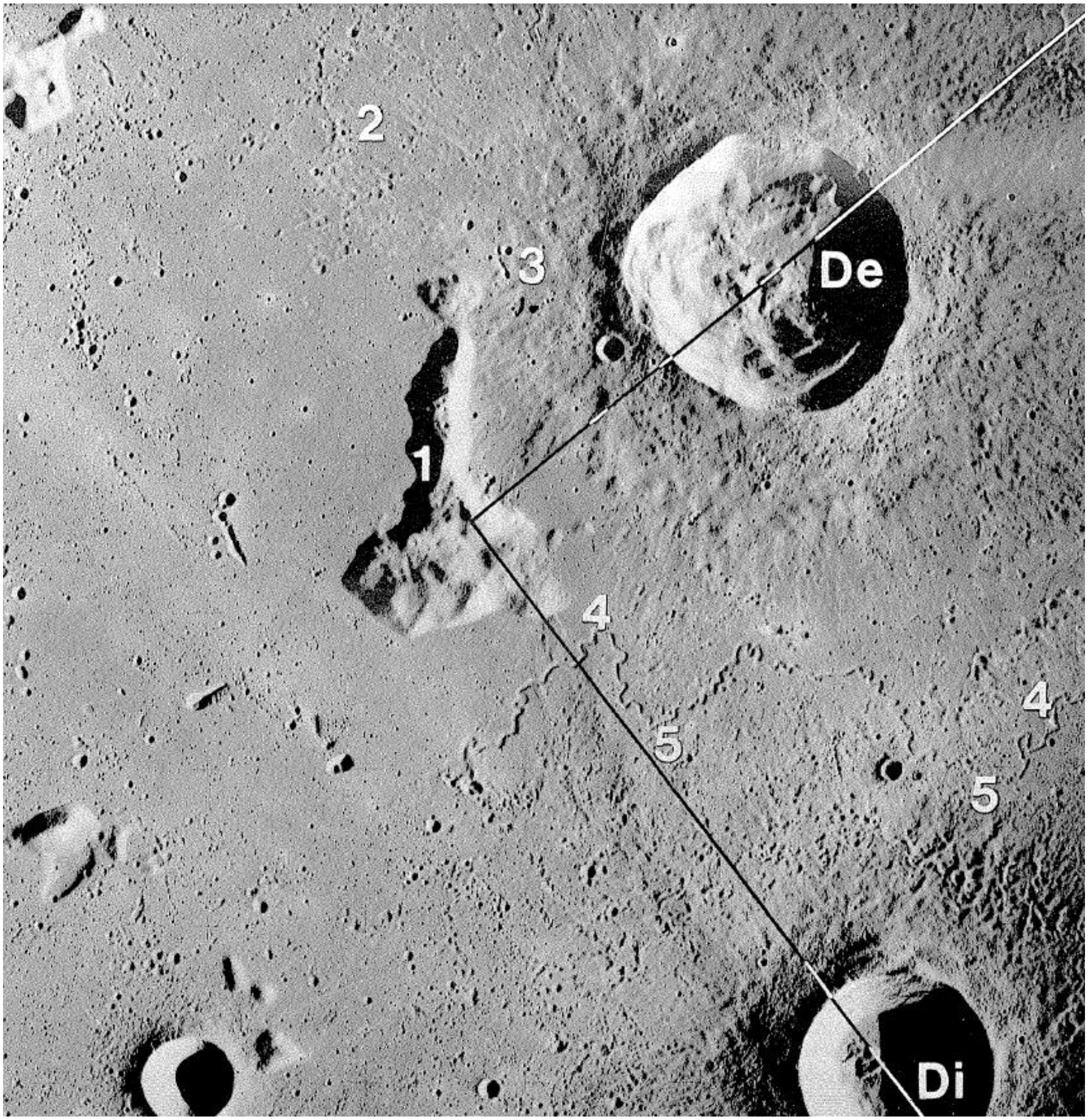


Figure 5 the craters Delisle (De; 25 kilometers in diameter) and Diophantus (Di; 18 kilometers in diameter)

Figure 5 provides a close view of the lunar surface of Mare Imbrium. The relatively smooth surface of the sea allows us to see some of the fine details of craters and other feature. The top portion of a mountain (labeled 1) remains above the floor of the sea. The bottom part of the mountain was covered up by the lava when it flowed into the Imbrium basin (basin is another name for a giant crater). The surface of the sea (that is the surface of the solidified lava) is marked by the number 2. Material ejected from the collision that formed crater Delisle can be seen on top of the sea surface. This material is known as ejecta (labeled number 3). Also notice the sinuous rille (canyon with lots of curves) labeled with the number 4. There are many secondary craters of the crater Diophantus (in the area labeled with the numbers 5).

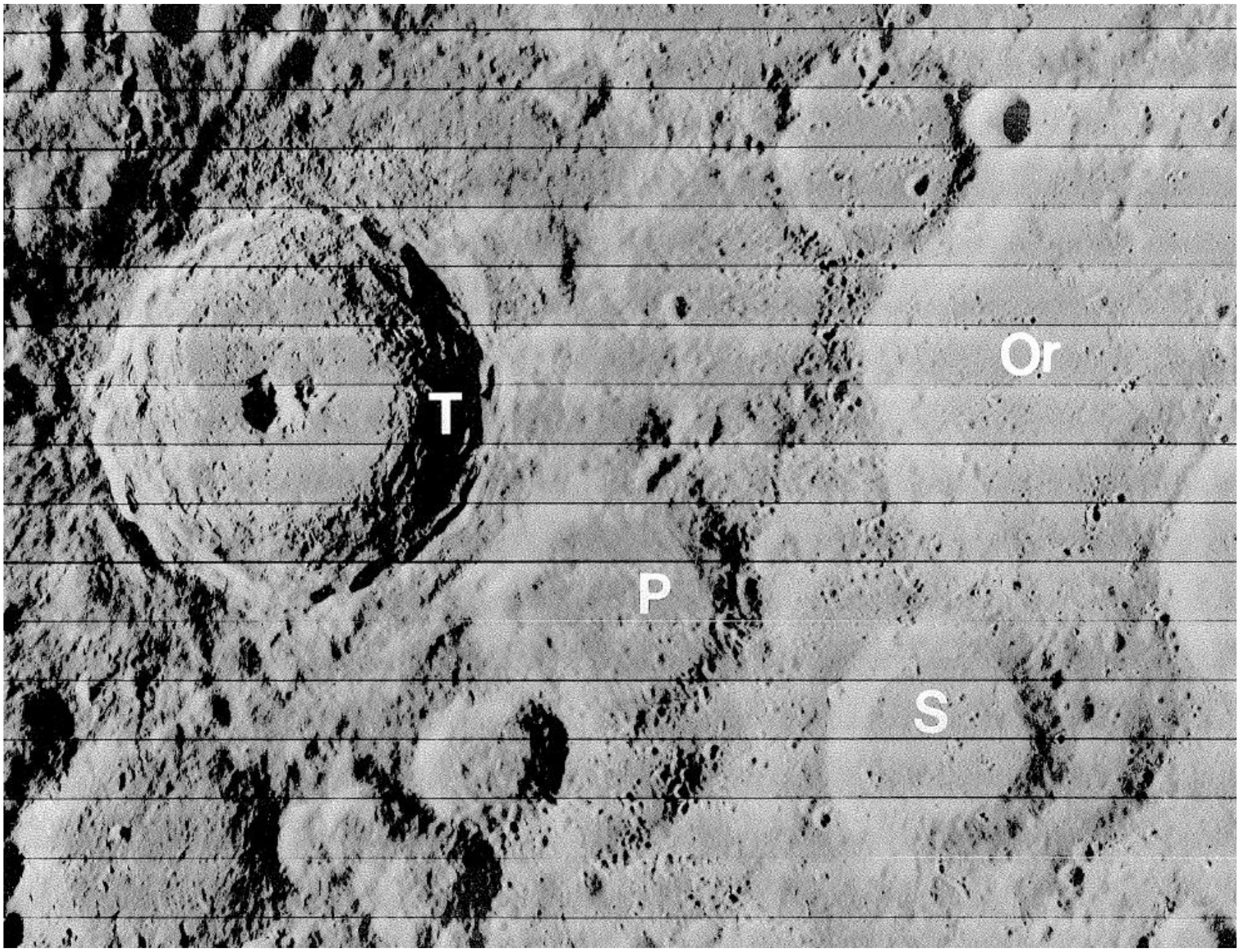


Figure 6 craters Tycho (T; 85 kilometers diameter), Orontius (Or), Pictet (P) and Saussure (S)

Figure 6 provides a nice comparison of craters of different ages. The very young crater Tycho (T) is only a few hundred million years old. Notice that we can see much fine detail in Tycho. Older craters have less detail because the ejecta of younger craters cover them. The very old Crater Orontius (Or) has been covered so much that it is hardly seen anymore. The middle aged craters Pictet and Saussure are easier to see than Orontius but obviously are not as distinctive as the youngster Tycho.

(continued on next page)

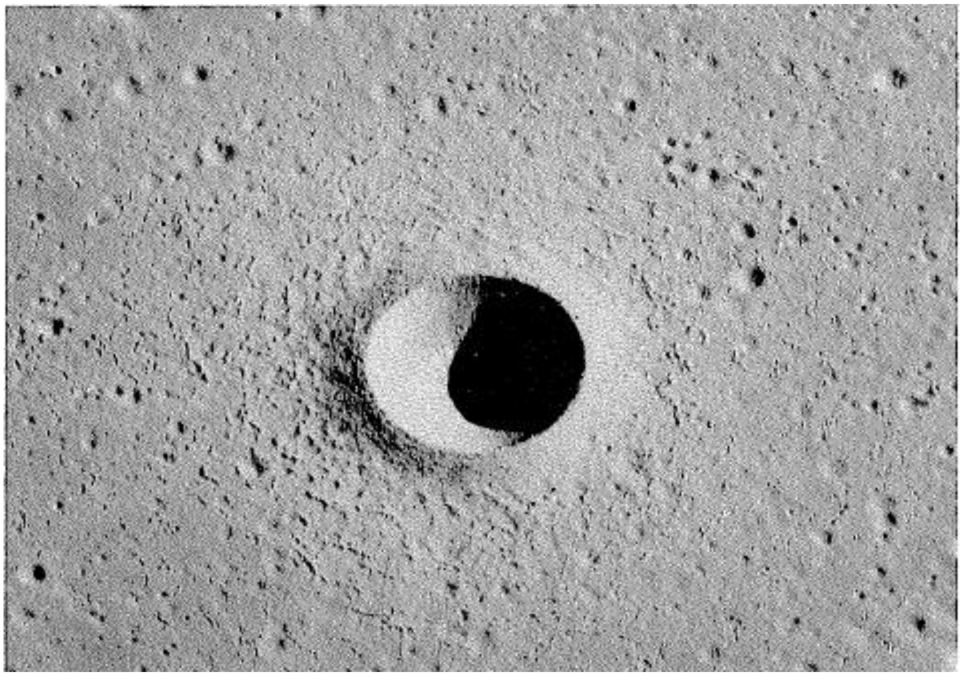


Figure 7 A simple crater named Linné (2.5 kilometers diameter). The inside is smooth except for minor rubble. Apollo 15 photo

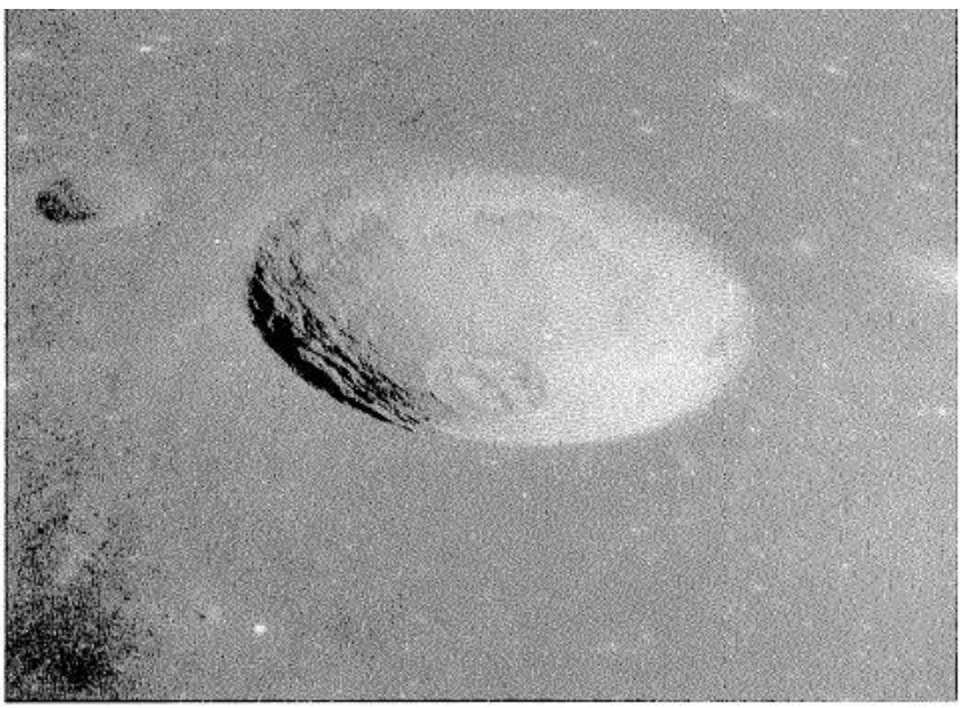


Figure 8 simple crater named Taruntius H (8.5 kilometers diameter). Profile is smooth except for level floor in center. Apollo 10 photo

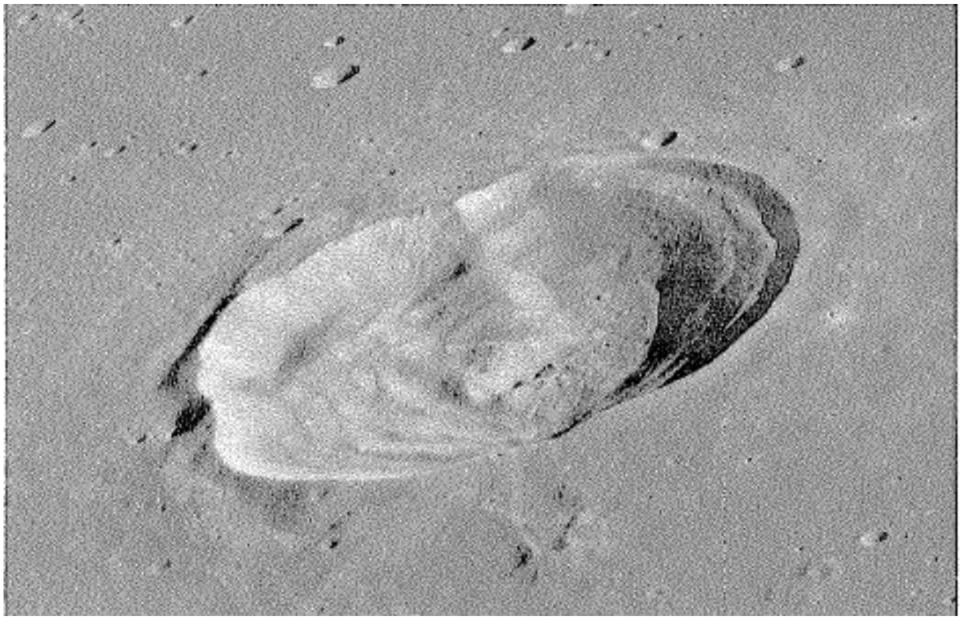


Figure 9 crater Arago (26 kilometers diameter). Large interior wall terraces, evidently formed by slumping; peak in the center is merged with the inside wall. Apollo 10 photo

(continued next page)

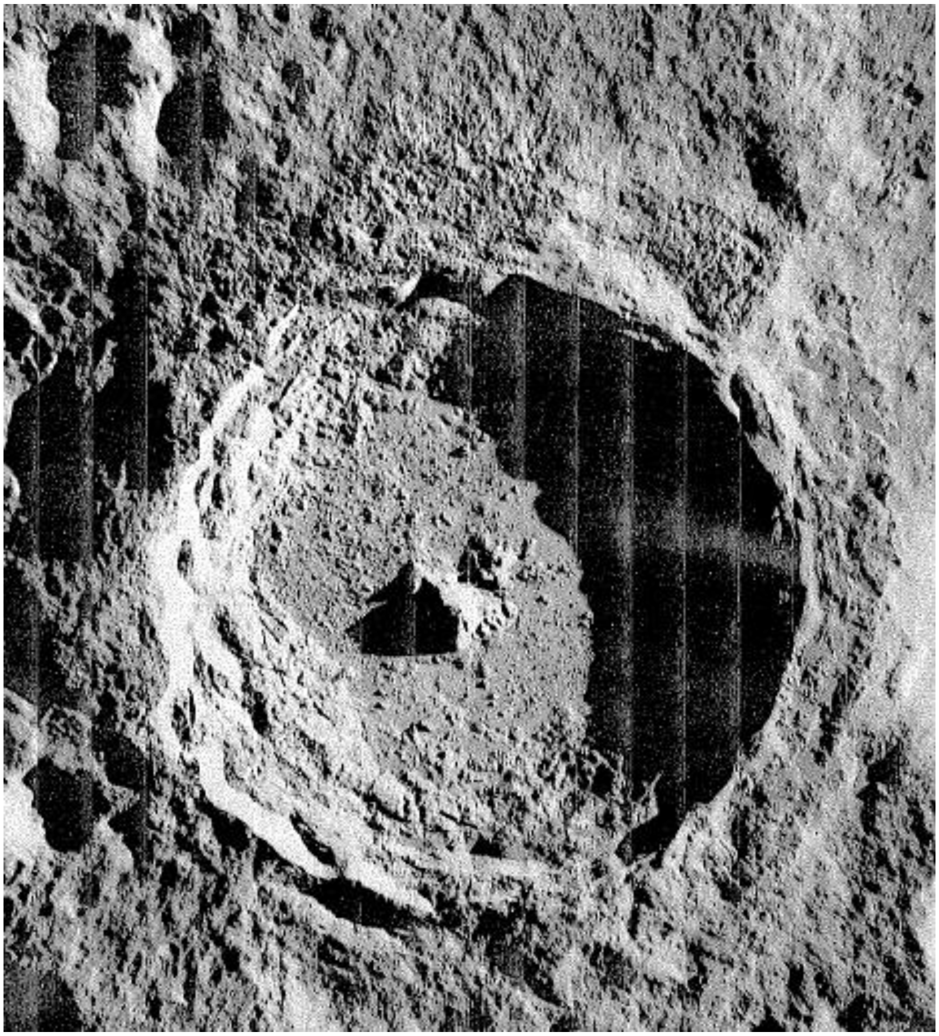


Figure 10 crater Tycho (85 km). Characterized by very crisp, fresh-appearing topography much more complex than that of Arago. Floor mounds are fissured. Pools of impact melt are superposed on terraces and rim flank.

(continued next page)

Figure 11 crater Hausen (167 km). Floor is broader relative to diameter than in Tycho; peak is relatively smaller, though large absolutely. Possible ring-like pattern of smaller peaks is visible. Terraces and rough wall masses are conspicuous. Secondary craters and herringbone pattern are conspicuous north and southeast of crater. Lunar Orbiter 4 photo.

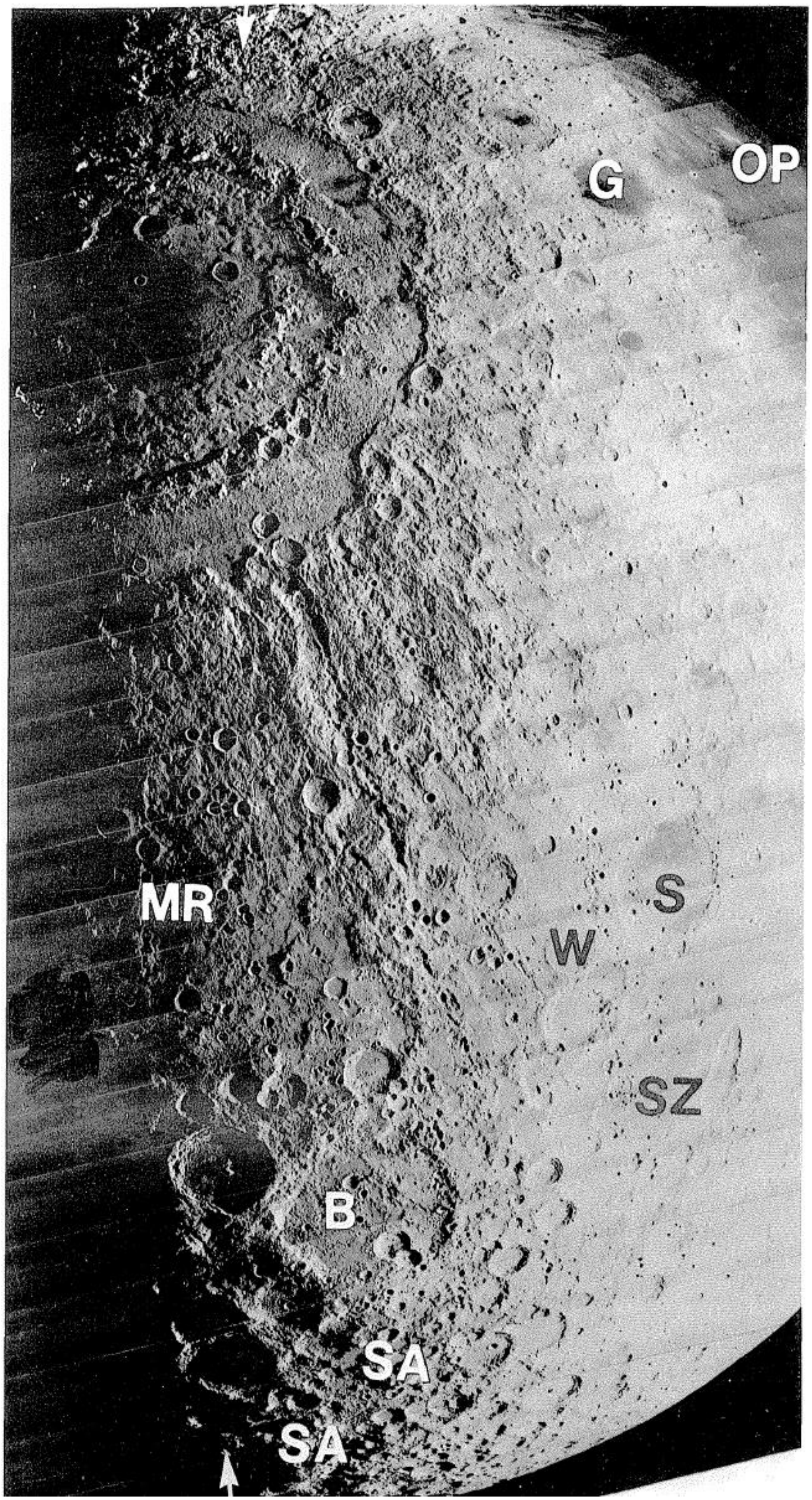


Figure 12 Southwest edge of Moon (lower left as seen from northern hemisphere of Earth).

In Figure 12, arrows indicate longitude 90 degrees West (on average, this is the limiting line of what we can see from Earth, from this line and to the right); upper arrow on equator and lower on south pole. The largest craters on the Moon are called basins. On the near side, nearly all of the basins were filled with lava a very long time ago. In this photo you can see the large Orientale basin (upper left part of photo). You can't see this view from Earth because this basin is right on the west edge of the Moon. Conspicuous lineations are radial to Mare Orientale (the mare is in the center of the basin, note its darker color) and ringed Orientale basin. Light-colored plains form part of terrain outside Orientale radials, for example, in Schiller-Zucchius basin (SZ), in central part of crater Schickard (S; 227 km), and in and near crater Wargentin (W; 84 km). Other basins: Bailly (B;

300 km) Grimaldi (G; partly mare-filled), Mendel-Rydberg (MR, barely visible), and South Pole-Aitken (SA, mountainous massifs); OP, part of Oceanus Procellarum in Procellarum basin. Footprint-shaped crater is Schiller (180 km). Lunar Orbiter 4 photo.

Surface of Moon

The uppermost layer of maria and terrae is called **regolith** and is generally thinner than 5 or 6 meters on maria, thicker than that on terrae.

The bedrock underneath the regolith of the maria is basaltic (a type of volcanic rock) with a density of 3.3 to 3.4 grams per cubic centimeter. The basalt typically extends hundreds of meters below the surface and can go as deep as 5 kilometers.

Terra bedrock is feldspathic (a type of rock) with a density of 2.90 to 3.05 grams per cubic centimeter and 45 to 60 kilometers thick in the west-central nearside. The thickness was determined by a seismic method.

Where measured, average elevations are higher, relative to the Moon's center of mass, on the far side than on the near side; the crust may be as thick as 120 kilometers under some elevated terra on the far side.

It is not known if the core of the Moon is in the liquid state.

Stratigraphic approach

Stratigraphy is the study of geological layers. By the study of layers, we can learn more about the geology of the Moon. The younger layers are usually on top except when something happens to fold layers over, so that a lower layer becomes placed on top.

A small crater inside a larger crater must be younger (any smaller crater would be destroyed by a younger, larger crater, at the time of the larger crater formation). A crater that cuts the rim of another is younger. Craters on maria are younger than the maria (remember that maria were formed by lava that flowed out of the interior of the Moon and when the lava cooled and solidified, it produced a smooth surface, so any craters on the maria must have been formed after the lava cooled and solidified).

The exogenic-endogenic controversy over the source of lunar topography was not settled until the end of the 1960s. Huh??? Until the end of the 1960s, scientists were not sure how craters were formed on the Moon. Figure 13 on the next page is a photo of Crater Lake in Oregon. The crater was formed by the collapse of a volcano. If volcanos on Earth could collapse to form craters, then maybe that is what formed craters on the Moon (an endogenic process, *i.e.*, from the inside). However, after careful study, scientists concluded that nearly all of the craters on the Moon were formed by objects striking the surface of the Moon (exogenic, or formed on the outside).

Figure 13 Crater Lake, Oregon

Formation of Craters on the Moon

Scientists now know that almost all craters on the Moon were created by objects that collided with the Moon. The majority of these collisions occurred early in the Moon's history. As our solar system was forming, there were a great number of rocky objects orbiting around the Sun. Over millions of years these rocky objects collided with each other and formed the protoplanets (the objects that became the planets). Some of these rocky objects collided with our Moon and caused the craters we can see today.

The objects that collided with the Moon were traveling at very high speeds (between 2.4 and 70 kilometers per second, with most traveling in the range of 16 to 20 kilometers per second – 20 km per second is the same as 45,000 miles per hour!). Due to the high speed, a great amount of energy was released each time an object struck the Moon. The energy was released in an explosion. The explosion removed material from the surface of the Moon, directly underneath the colliding object. The material removed was thrown out to the side, forming a rim around the depression created in the surface of the Moon. Some of the material could be thrown more than a thousand miles from the site of the explosion!

The material excavated from the crater ranged in size from dust particles to objects as large as small asteroids. The larger objects thrown from the explosion produced secondary craters when they landed on the surface. Thus, we can see a collection of smaller secondary craters surrounding the primary crater. The objects thrown from the site of the primary crater did not travel at speeds as high as the initial impacting object. Therefore, when they landed again on the surface of the Moon, the collisions were not explosive. That is why almost all primary craters are circular, but secondary craters can be of different shapes (oval for example). An explosion produces a circular crater. Objects thrown from the site of the primary crater can skid along the surface of the Moon when they land, creating an elongated crater or a series of craters if the object bounces.

On a given terrain, small craters are always more abundant than larger ones. The reason for this is that the number of small objects colliding with the Moon were far greater in number than large objects.

Near maria borders crater numbers decrease because the older craters were covered over by ejecta from the basin impact event.

Overwhelming evidence is that almost all lunar craters are of impact origin according to rock analysis of samples returned from the Moon.

We can apply relative ages to structures on the Moon by the study of stratigraphy. An object which is on the top of all other objects is the youngest.   Let us take Mare Serenitatis as an example. The Serenitatis basin is underneath the Imbrium rim (see Figure 15), but the Mare Serenitatis is unaffected by the Imbrium deposits (that is, the Mare Serenitatis lava flowed around the mountains that form the rim of the Imbrium basin), thus the Imbrium impact occurred before the Serenitatis impact, but the filling of the Serenitatis basin with maria lava happened after the Imbrium impact – thus this shows that there was a span of time between the impact that formed the Serenitatis basin and the volcanic activity that filled it.

(continued on next page)

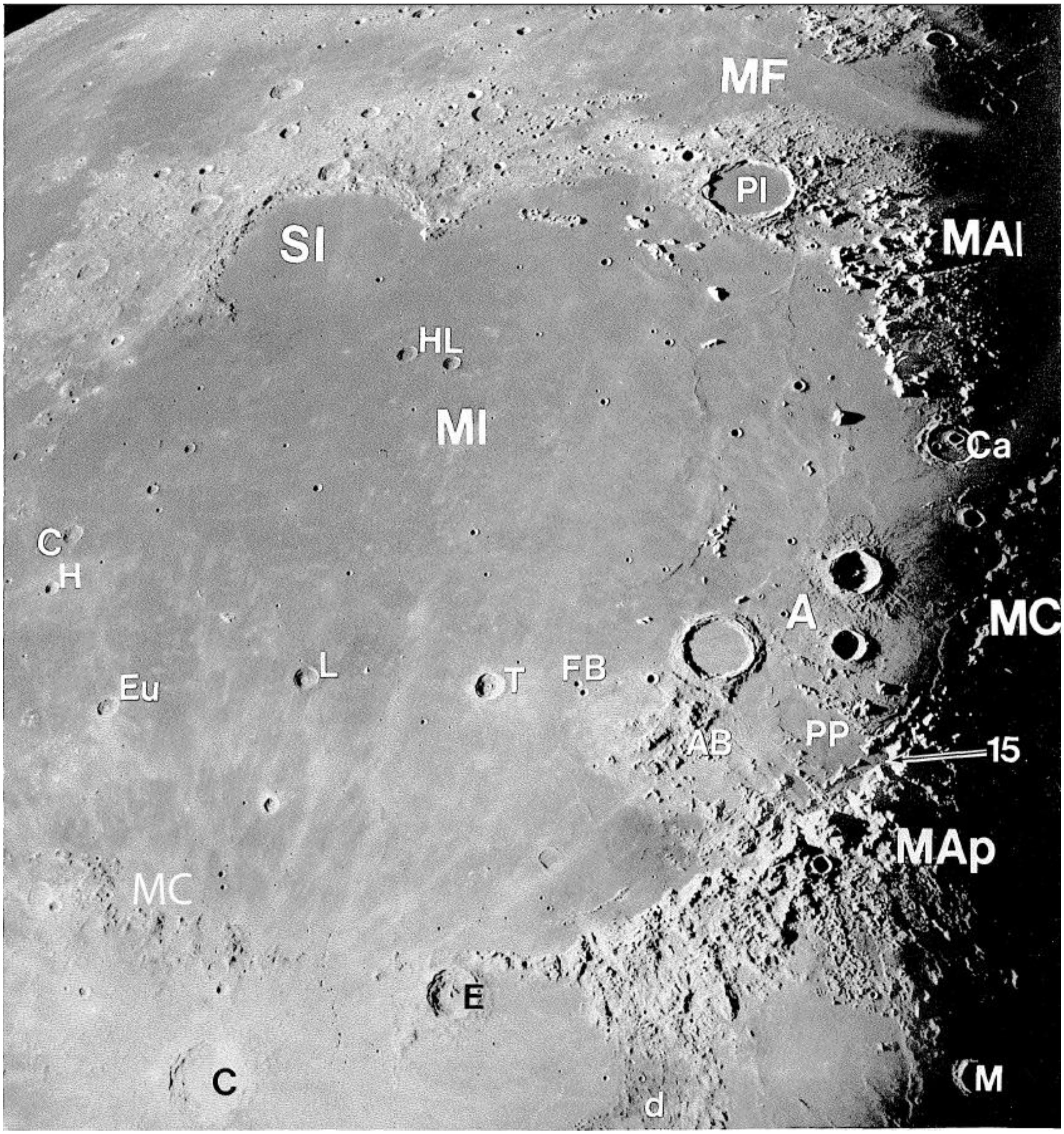


Figure 14

Figure 14 - Mare Imbrium (MI) and Imbrium basin. Mare Frigoris (MF), Palus Putredinis (PP), arrow is Apollo 15 landing site. Imbrium-basin rim is composed of Montes Alpes (MAl), Montes Apenninus (MAp), Montes Caucasus (MC), and terra occupied by Iridum crater bounding mare feature Sinus Iridum (SI). Lunar stratigraphic scheme of Shoemaker and Hackman (1962) is based on relations among Imbrium basin, planar material of Apennine Bench (AB), Archimedes (left of A), mare material, Eratosthenes (E), and Copernicus (C; 95 km). "Wrinkle ridges" (dorsa) are above A; rilles are below PP. Crater pairs include Aristillus and Autolycus (right of A), Caroline Herschel and Heis (CH), Feuillée and

Beer (FB), and Helicon and Leverrier (HL). Other features: Cassini (Ca), Euler (Eu), Lambert (L), Manilius (M), Plato (PL), and Tiomocharis (T); many irregular craters north of Mare Frigoris; d, dark-mantled terra surface. Mount Wilson Observatory photo.

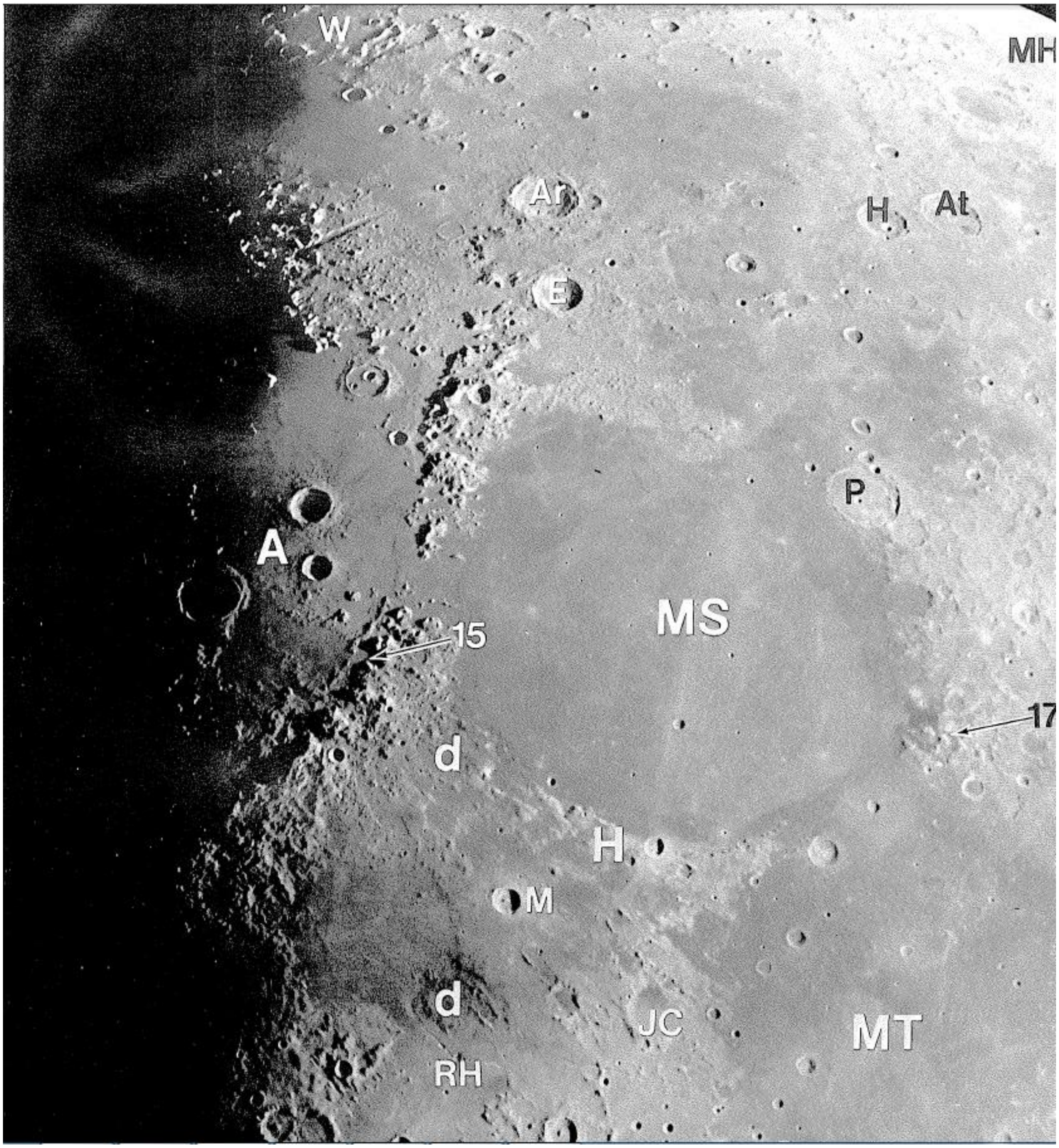


Figure 15

Figure 15 – this image overlaps Figure 14. Mare Serenitatis (MS), - Lineations in Montes Haemus (H) on southern part of Serenitatis rim are radial to Montes Apenninus (mountains that arrow 15 cross); nonlineate hummocky terrain adjoins Montes Caucasus and Montes Alpes. Terrain east of Mare

Serenitatis consists of irregular craters and massifs. Other features: Ar, Aristoteles (87 km), At, Atlas (87 km), E, Eudoxus; H, Hercules, JC, Juiius Caesar; M, Manilius; MH, Mare Humboldtinanum; MT, Mare Tranquillitatis; P, Posidonius, R, Ritter (29 km); RH Rima Hyginus; densely cratered northern terrain including W. Bond (W; 158 km), d, dark mantling material. Arrows, Apollo 15 and 17 landing sites. Mount Wilson Observatory photo.

Only kinetic energies of asteroidal masses impacting at cosmic velocities could supply the requisite energies for basin formation. Huh??? In looking at the largest craters on the Moon (the basins) scientists tried to find an explanation for their formation. These huge craters could not have formed from volcanos as the energy required to form such large craters is much greater than the energy that can be produced by volcanos. The only way to explain the large craters is by the collision of objects the size of asteroids, traveling at very high speed.

Apollo 15 returned samples with radiometric ages of a gap of 500 million years between Imbrium basin formation and the mare basalt that it contains. Huh??? There are certain elements in Moon rocks (or any rocks for that matter) that are radioactive. Over time those radioactive elements decay into different kinds of elements. By measuring the amounts of specific radioactive elements in Moon rocks, scientists were able to determine the age of the rocks. The site for the landing of the Apollo 15 mission was selected in part so that the astronauts could take samples of rock from Mare Imbrium and also from the rim of the Imbrium basin. Back on Earth, scientists determined the age of both kinds of rocks and found that the rocks of the rim of the basin were 500 million years older than the mare rocks. Therefore, the impact event that formed the giant crater we call the Imbrium basin happened 500 million years before the basin was filled with lava, forming the mare. Without sending space probes to the Moon to sample the rocks there, we could not have determined the age of the Imbrium mare material or rim material. It is important to know the ages of various rocks on the Moon if we want to assemble a geological history of the Moon.

Types of Craters

Craters less than 16 to 21 km diameter are simple, smooth interior profiles, smooth and highly circular rim crests, depth/diameter (d/D) ratios about 1/5., floors commonly flat or gently sloping, many ejecta blankets of younger craters of simple type display radial textures and some have subconcentric dunelike forms.

Larger craters more complex characterized commonly by broad floor generally level but interrupted by various hills and mounds, a centrally disposed hill, peak or peak complex; single or multiple blocks or slices of material slumped from the walls; continuous terraces on the wall that represent wholesale circumferential failure of the rim, as opposed to the blocks or slumps or to the minor debris wasting seen in simple craters; d/D ratio 1/5 for small complex craters to 1/40 for the largest, rims scalloped or irregular, but more or less radially symmetrical; rim topography adjacent to the crest and out to about half a crater radius is elevated, rugged, and commonly concentrically structures, then lower and more radially structured beyond this rugged collar; between one and 2 radii from the crest, the radial pattern passes into a zone dominated by negative landforms, the secondary craters

Secondary Impact Craters

Secondary-impact craters differ in most respects from their parents. Sizes are controlled not by the nearly unrestricted masses and kinetic energies of cosmic fragments but by the size of the primary crater and the 2.4-km/s lunar escape velocity, above which the ejected fragments would leave the Moon. Because of the lower impact velocities, rim-crest circularity is less commonly developed than in hypervelocity primaries (fig. 16).

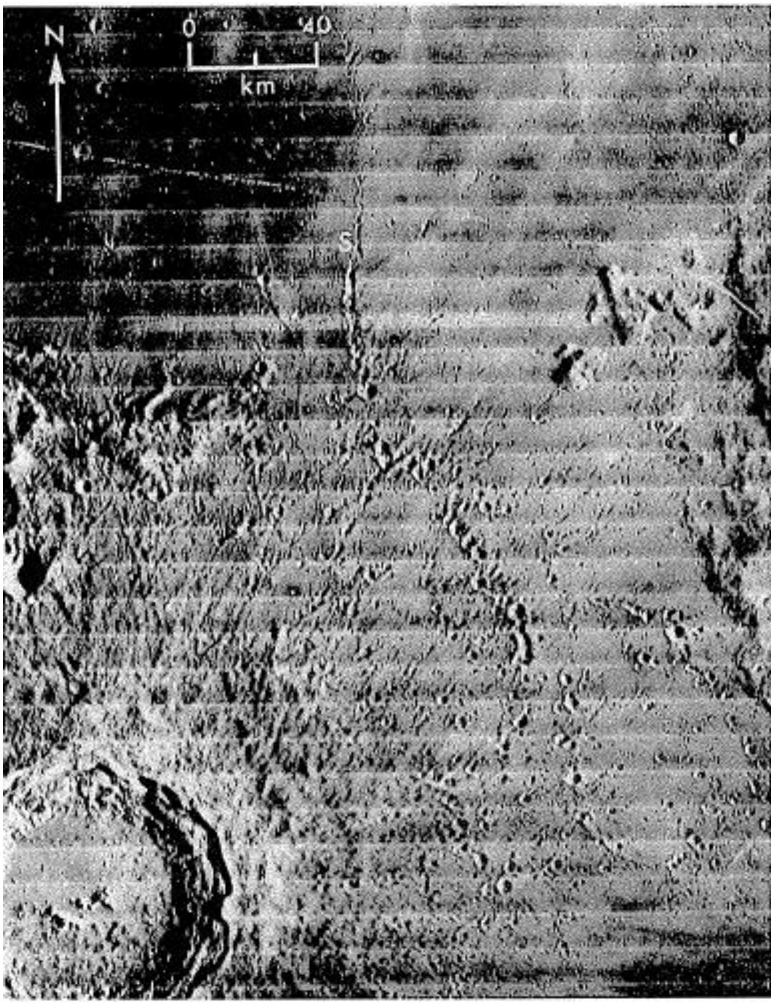


Figure 16 crater Copernicus

Figure 16 - crater Copernicus and northeast exterior, showing rays and subconcentric chains of secondary craters (Rimae Stadius labeled with an S) - Lunar Orbiter photo

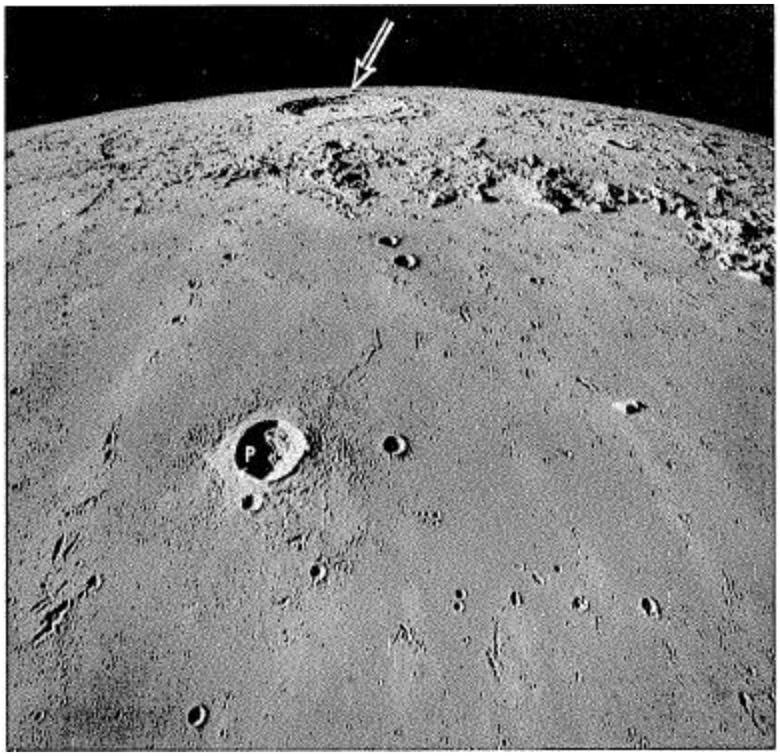


Figure 17 crater Copernicus on horizon

Figure 17 - Crater Copernicus on horizon (arrow), secondaries of Copernicus superposed on Mare Imbrium near crater Pytheas (labeled P, north of Copernicus, diameter 20 km,), Carpathian Mountains between Copernicus and Pytheas – Apollo 17 photo

Figure 18

Figure 18 - Detail of Rima Stadius I, showing V-shaped herringbone pattern – Lunar Orbiter photo

However, circular secondaries do form at large distances from their sources and are difficult to distinguish from primaries if not clustered. Because the ejecta projectiles that form secondaries are larger relative to crater size than the hypervelocity cosmic projectiles, irregularities in projectile shape are more manifest in secondaries than in primaries.

Most interior profiles of secondaries are as smooth as or smoother than those of small primaries, but shallower.

Spatial grouping is the main difference from primary craters and is the main diagnostic characteristic of secondary-impact craters (in other words, it can be difficult to determine if a crater is primary or secondary if you just look at one crater – you must look for the grouping of craters – secondary craters occur in groups, they are not randomly scattered). Secondaries generally occur in linear or curving chains or in patches and clusters. Only a few of the farflung projectiles may separate enough to form seemingly randomly scattered secondaries. Chains, loops, and clusters were probably excavated by secondary impacts of ejecta derived from certain structures in the bedrock struck by the Copernicus primary impact.

Atypical craters

Although high velocity impacts normally create circular craters, impacts at angles less than 10 degrees in weak materials or about 30 degrees for certain combinations of target material, projectile material, and velocity may generate noncircular craters. Elongate craters, such as Messier and Schiller (figures 19 and 20), have been interpreted as volcanic or volcanotectonic. However, craters formed by artificial oblique impacts mimic their shapes. The Messier ejecta possesses such typical impact characteristics as radial ridges, secondary craters, and rays. The position of Schiller along a basin ring (figure 20) was considered as supporting the endogenic origin. Schiller, however, consists of overlapping elliptical craters that could have been created by oblique, nearly simultaneous impact of a fragmented projectile or by a very low-angle. Two primary-impact mechanisms have been proposed to explain the lunar groupings. First, Sekiguchi (1970) showed that tidal forces may break up weak approaching bodies before they impact. Second, small bodies may orbit mutually in space.

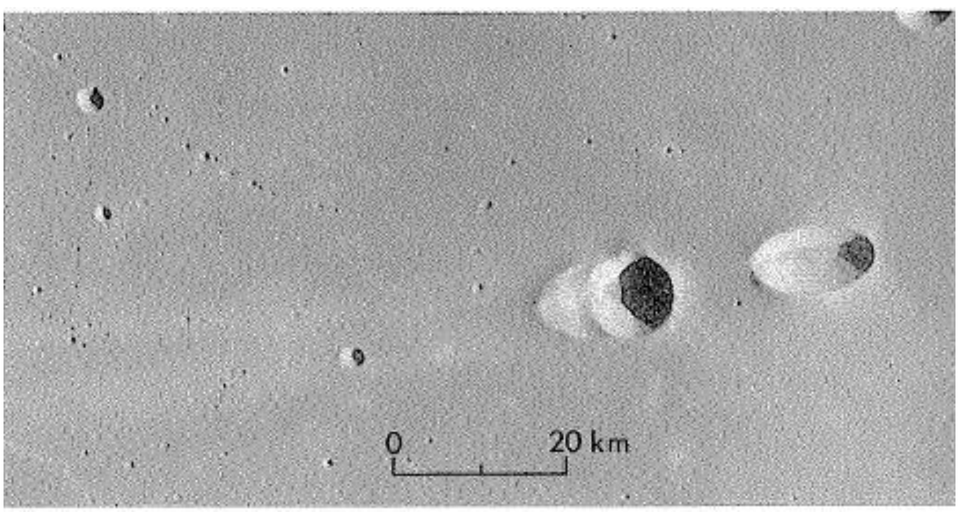


Figure 19

Figure 19 - irregular primary-impact craters Messier (right) and Messier A. Radial ejecta and rays are north and south of Messier, and long double rays to west (down trajectory). Apollo photo.

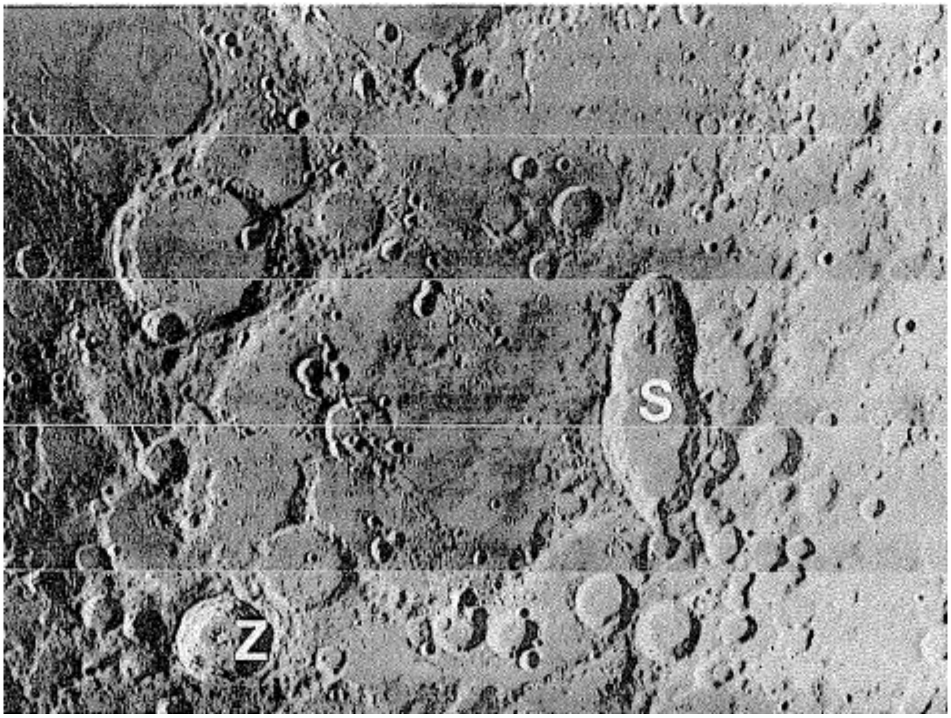


Figure 20

Figure 20 irregular primary-impact crtater Schiller (S, 180 km long), superposed on ring of double-ringed Schiller-Zucchius basin. Lunar Orbiter 4 photo.

Shock Compression

An impact crater results from the meeting of an irresistible force with an immovable object. A hypervelocity collision generates intense high-pressure shock waves that propagate into both the target and the projectile. As the shock front moves downward and outward into the target, masses are set into motion with particle velocities much greater than the speed of sound in the various materials. Pressures and energies within the shock wave are commonly so great that parts of both the target and projectile are melted and vaporized around the impact zone. More significantly for the ultimate crater, the shock wave strongly compresses and energizes a mass of target material much greater than that of the projectile.

Cavity excavation and growth

Very early in the sequence of events, even before the shock wave reaches the projectile's trailing edge, small amounts of both the projectile and target material may be jetted from the sides of the impact zone at velocities that may exceed the initial velocity of the projectile (figure 3.17A). Most ejection, however, takes place at velocities first comparable to and then much lower than the initial projectile velocity. Particles of material are deflected from the initially radial motions induced by the shock wave into upward and outward trajectories curving back toward the surface on the heels of the expanding shock wave. Subsequently, expanding concentric zones that include more moderately shocked materials from increasingly deep target materials are successively ejected. The ejecta forms an upward- and outward-flaring curtain of debris in the shape of an inverted lampshade (a frustum).

Decompression and not the direct, intense shock compression excavates most of the cavity.

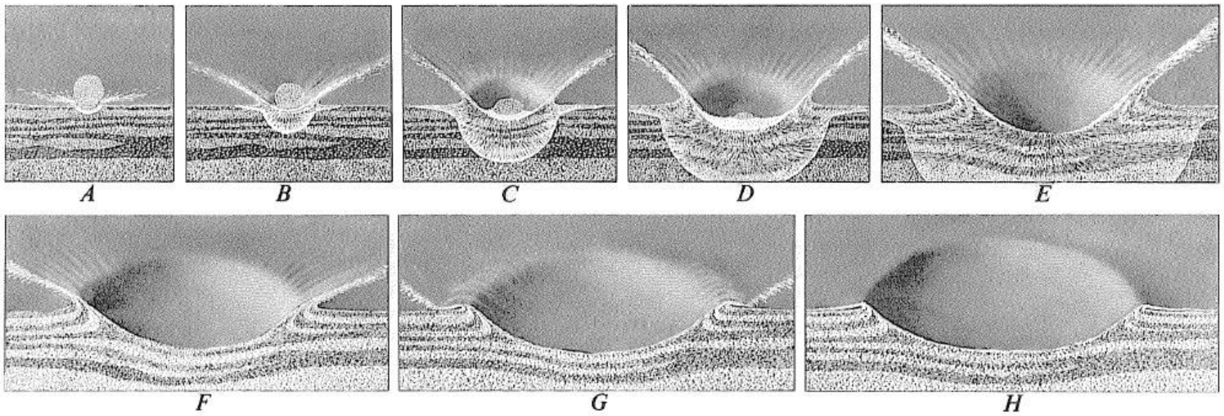


FIGURE 3.17.—Stages in formation of a simple impact crater. Drawing by Donald E. Davis, courtesy of the artist.
A. Initial contact and jetting.
B, C, D. Compressional shock wave propagates outward, and cavity grows by rarefaction behind shock wave while projectile is consumed.
E. Cavity continues growth after projectile has been consumed.
F. Maximum crater size.
G. Frustum-shaped curtain of ejected debris continues outward expansion after cavity ceases growth and overturned ejecta flap comes to rest.
H. Final crater configuration.

The cavity of a typical small simple crater ceases to expand downward when it has acquired depths of 1/5 to 1/2 of the diameter.

As a result of the velocity distribution in the curtain, ejecta deposition occurs in approximately the reverse order of excavation. The first material to be deposited, from the base of the ejecta curtain, is the last to have been engulfed by the shock wave and to be sheared from the crater walls (figs. 3.17). That material is lofted or barely pushed over the rim at low velocities and soon lands near the crater rim. In simple craters, the near-rim material may form a more or less coherent overturned flap

Secondary cratering and ground surge

With increasing distance from the crater, the ejecta that strikes the surface forms secondary craters rather than building up a deposit. At some distance, the curtain separates into filaments of debris, whose impact creates loops and chains of secondary craters and rays. Circular secondaries are formed by the last material to impact the surface, that which was launched first at the highest velocities and in the longest, highest trajectories from sources high in the target near the impact zone. The general picture, then, around craters as well as ringed basins is one of outward-thinning deposits of primary ejecta grading into increasingly conspicuous secondary craters and their ejecta deposits.

Deformation and nonballistic ejection

Beyond the sphere of shocked material that is launched into ballistic flight, other target material is less highly shocked but is deformed and sheared. Some of this material is pressed downward and outward along the crater floor and walls in curving paths that resemble those that precede the ballistic ejection. Part of this peripheral material may surge over the walls and exit the crater at very low velocities without leaving the surface. Additional shock-damaged material is not permanently ejected. Some may be lofted above the crater and fall back inside; other material is mildly brecciated or fractured in place without significant dislocation. Both the fallback and the inplace material form a breccia lens in the bottom of the crater that grades downward and outward into a zone of fractured rock.

Peak and terrace formation

The most conspicuous indicator of internal deformation in craters is the presence of central peaks and wall terraces in complex craters. Diameters of complex craters are generally larger than 16 km in the maria and 21 km in the terrae. Peaks increase in size and complexity in proportion to crater size up to crater diameters of about 40 or 50 km, but diminish in relative size in larger craters.

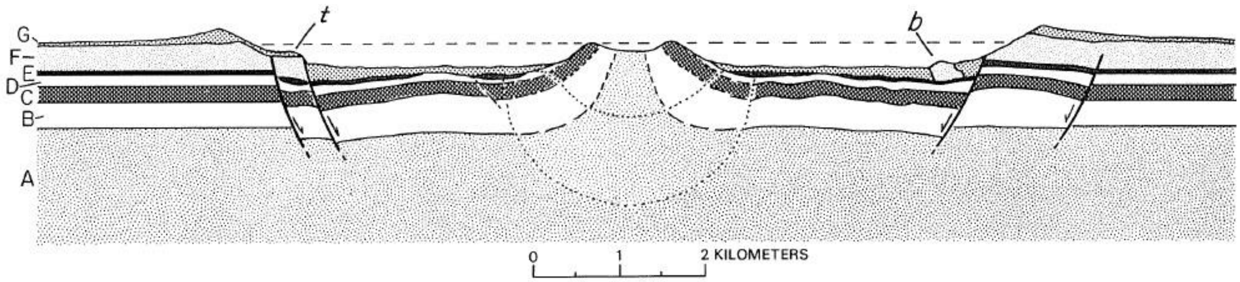


Figure 21

Figure 21 - Model of formation of features of complex crater. Only layers A, B, and C are exposed in central uplift, where they dip vertically or steeply. Layer F has been stripped from crater, although it forms a slump block (b). Layer G is composed of ejecta and intracrater breccia. Faults creating terraces (t) pinch out at shallow depths. Arcuate dotted lines indicate zones of deformation in center. Modeled after four complex craters on Earth; scale applies to average horizontal and vertical dimensions of those craters.

All lunar scientists agree that cavities larger than 300 km in diameter that have concentric rings instead of central peaks are basins. The origin of rings in basins is among the most important unsolved problems of lunar geology.
(continued next page)

.

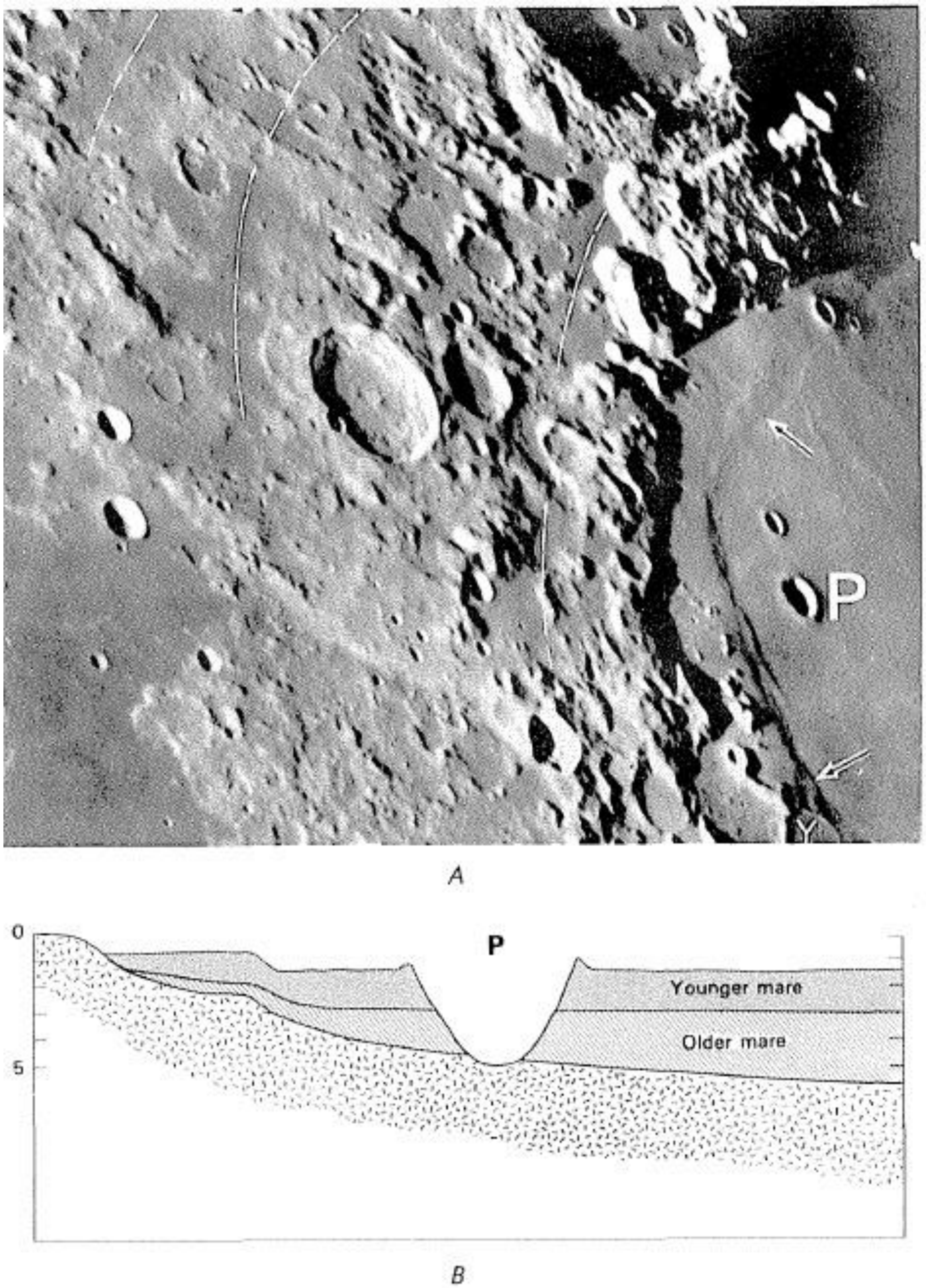


Figure 5.23 - Thickness of mare-basalt flows in Mare Crisium
A. Western Mare Crisium and part of Crisium basin, showing difference in elevation (arrows) between mare shelf and depressed center. P, crater Peirce (19 km). Dashed lines indicate basin-concentric troughs, as interpreted by Wilhelms.

B. Diagrammatic cross section of Mare Crisium, based on radar-sounder profile. Arrow denotes shelf indicated by arrows in A. Crater P (Peirce; also Picard) penetrates younger mare unit and excavates older mare unit and, possibly, terra underlying the mare section. Scales are diagrammatic, exaggerated vertically.

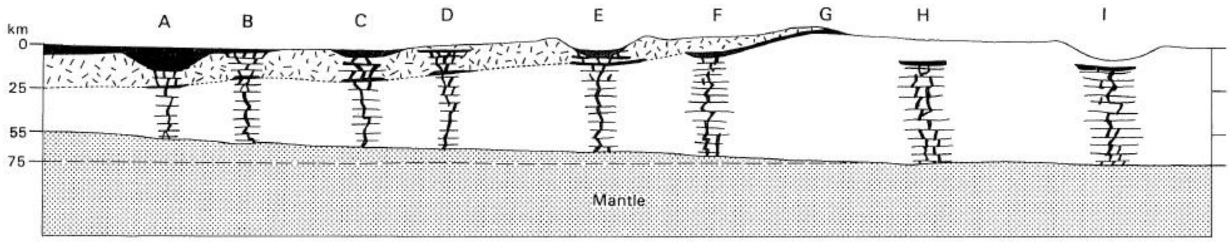
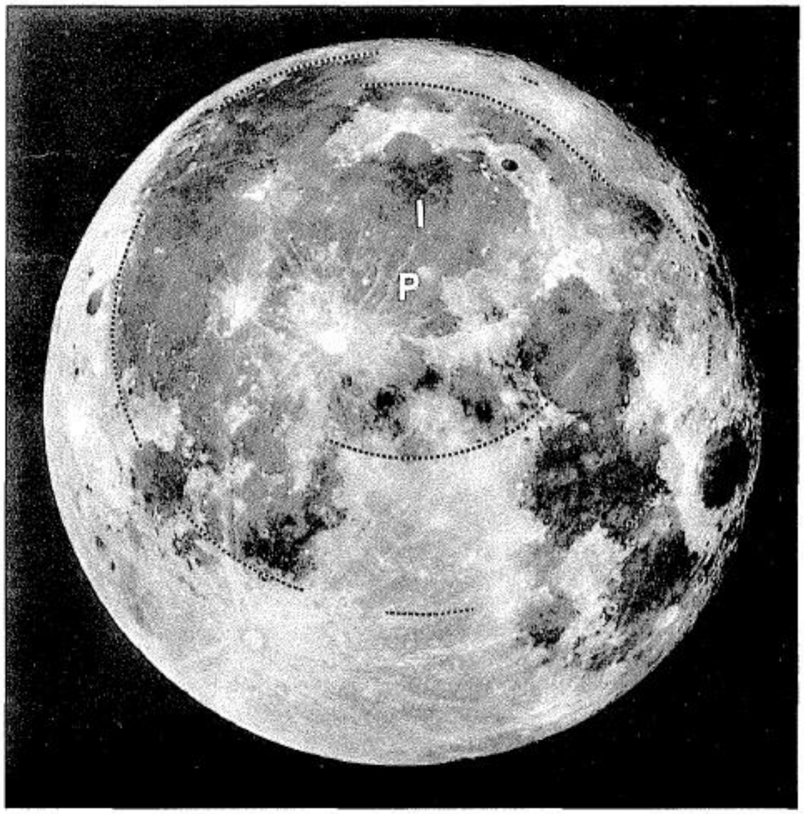
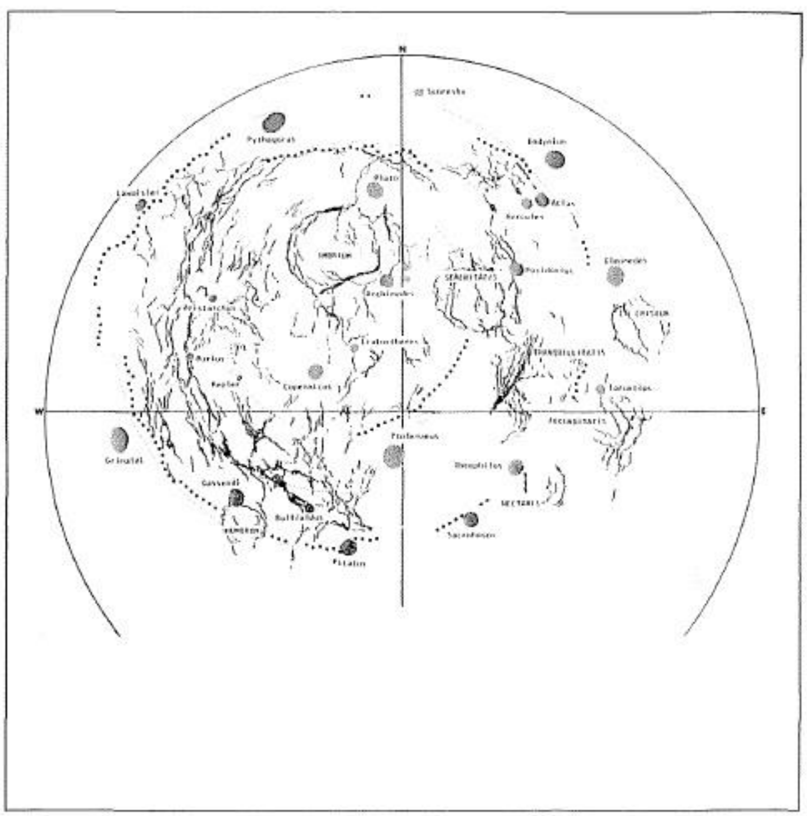


Figure 5.24 Diagrammatic cross section of typical basin 1,000 km in diameter; no vertical exaggeration. Crust is about 75 km thick outside basin and is estimated at 55 km thick beneath basin center; deformed zone (above dotted line) is estimated at 25 km thick, and mantle uplift at 20 km. Magma-ascent paths, 60 km high above mantle surface, are indicated diagrammatically in nine places (A - I) as systems of dikes and sills. At A, lava was extruded onto floor of a crater superposed on the basin, and spilled beyond crater rim; at B, lava was extruded directly onto basin floor; extrusions A and B combined to flood basin center. At C, lava was extruded onto trough but did not overtop trough edges. At D, crust was too thick to allow an equal column of magma to be extruded. At E, floor of superposed crater decreased magma-ascent path by amount necessary to allow extrusion; crater interior was flooded. At F, contact of deformed zone and less severely deformed crust afforded path for lateral migration of lava, which was extruded high on basin flank at G. Crust at H and I outside basin was too thick to allow extrusion, even beneath a crater (I) equal in depth to the flooded craters inside basin.

(continued next page)



A



B

Figure 5.26 - Procellarum basin as drawn by E. A. Whitaker (1981)

A. Telescopic full-Moon photograph of nearside, showing center (P) and parts of three rings of Procellarum basin. In much early work, an asymmetry in basin distribution was thought to cause the hemispheric dichotomy in mare distribution, but basins are distributed randomly; Procellarum may account for most of the dichotomy.

B. Observed scarps and terra margins concentric with basin (large dots), complete rings that best fit the topography (small dots), mare ridges (lines), and major landmarks.