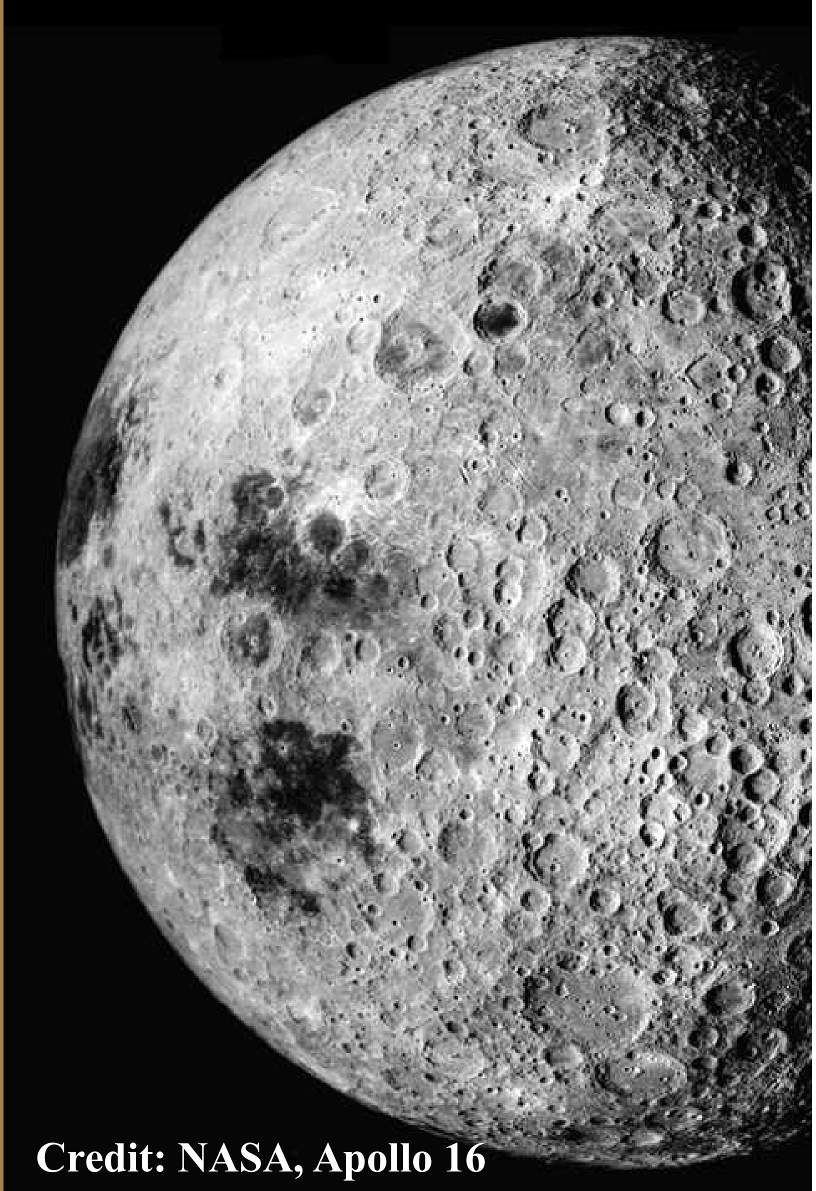
Cratered Worlds

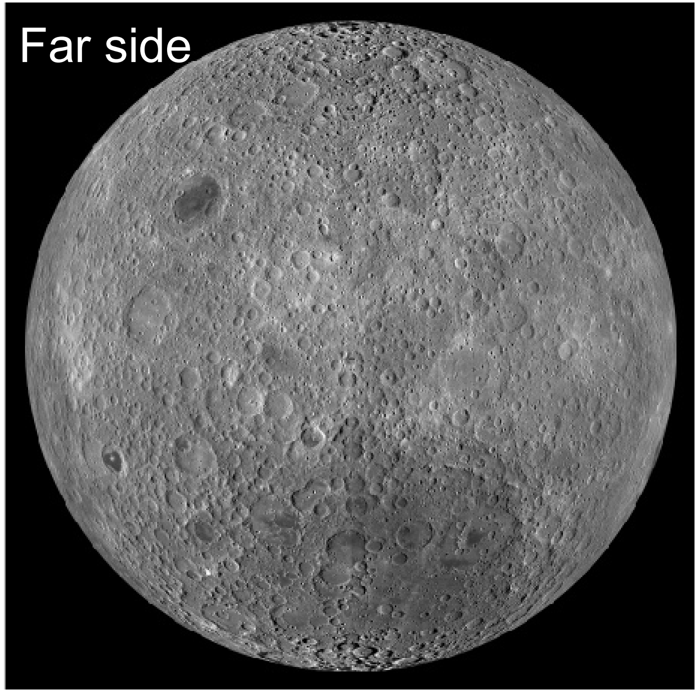
DR. FABIEN BARON



Credit: NASA, Apollo 16

The Lunar Surface

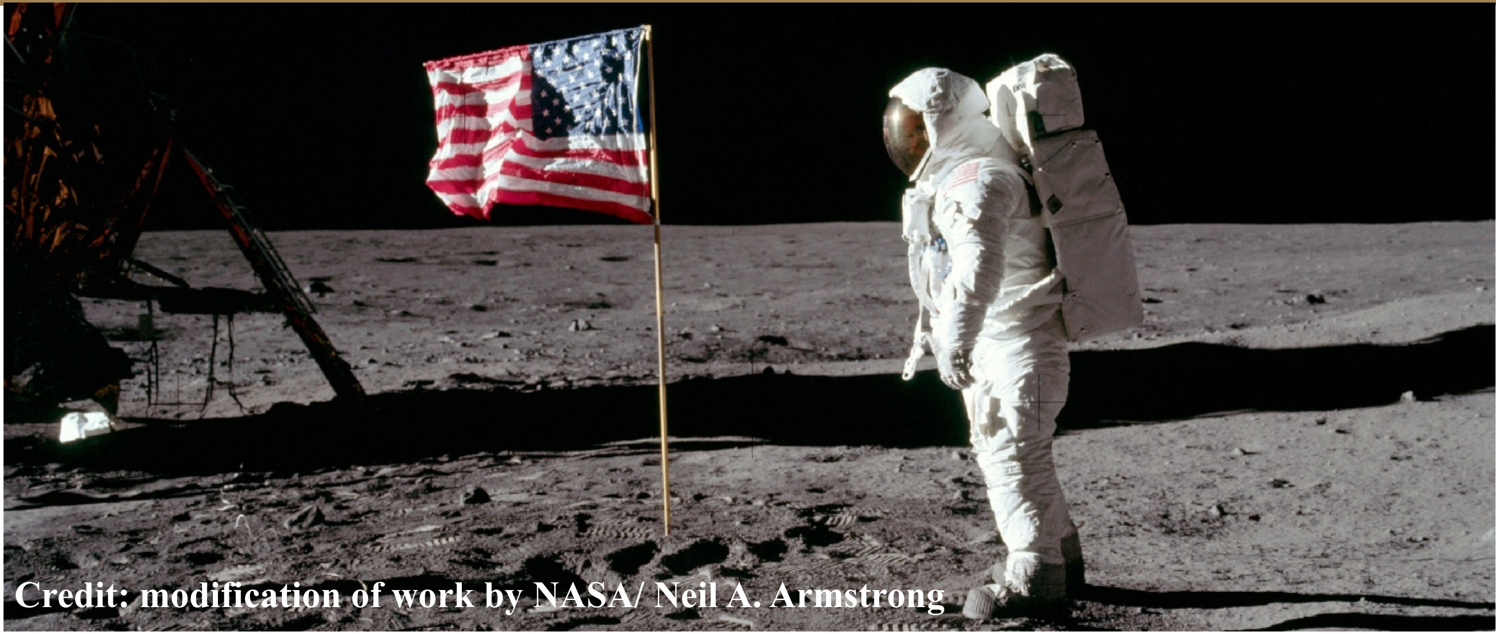
- $1/8^{th}$ the mass of Earth, $1/6^{th}$ Earth gravity: no atmosphere
- Some areas of Moon are more heavily cratered than others (ex. back side)
- Younger regions were flooded by lava after most cratering finished



The resolution of these images is several kilometers, similar to that of high-powered binoculars or a small telescope.

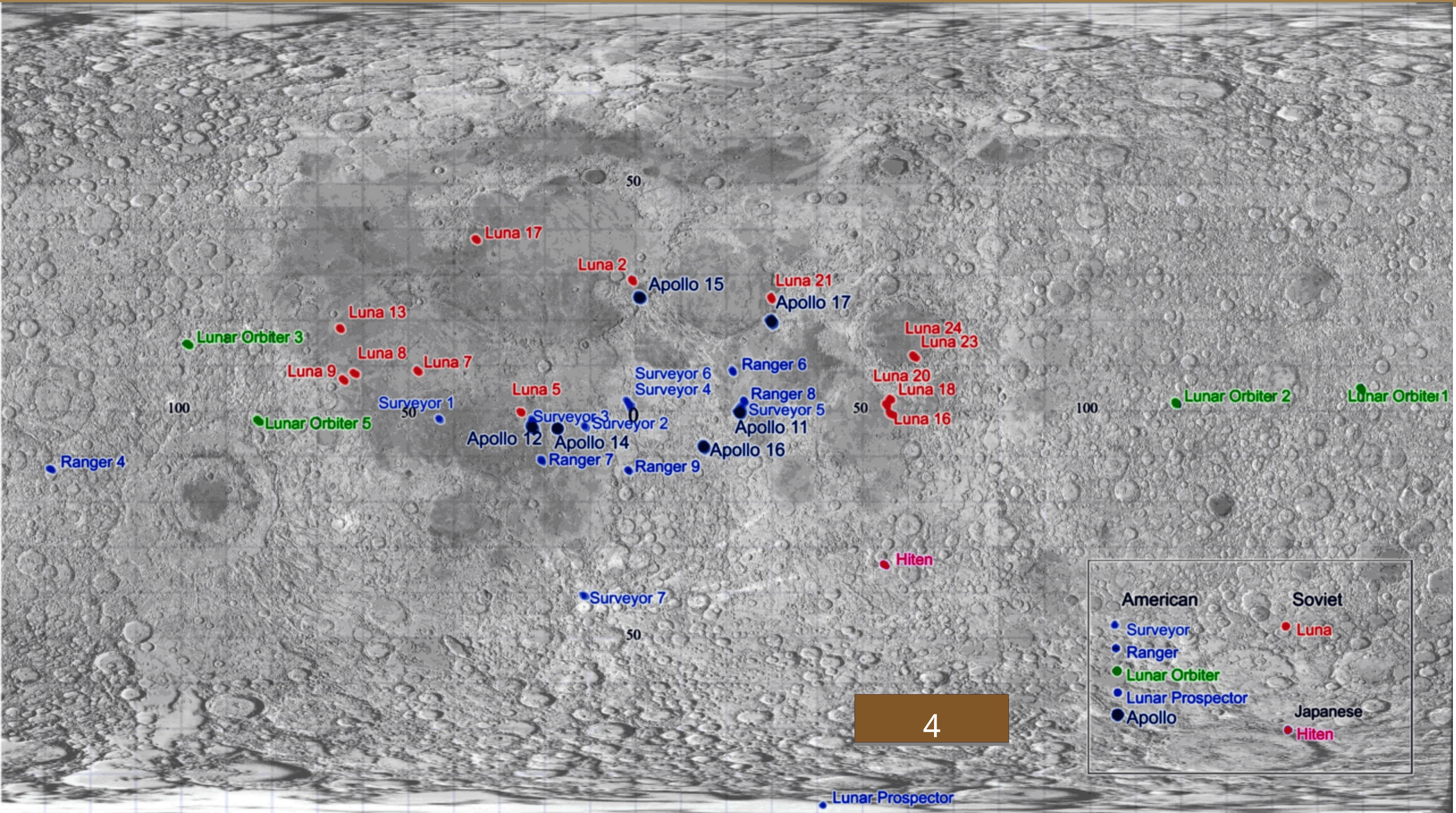
Exploration of the Moon: first steps

- Russian Luna missions mapped most of the Moon in the 50s/60s
- US Apollo program: 9 piloted spacecrafts (1968-1972), twelve astronauts on the surface
- July 20, 1969: the first American astronauts set foot on the Moon



Apollo 11 Astronaut Edwin "Buzz" Aldrin on the Surface of the Moon. Because there is no atmosphere, ocean, or geological activity on the Moon today, the footprints you see in the image will likely be preserved in the lunar soil for millions of years

Exploration of the Moon: landers



Locations of major spacecraft on the Moon superimposed on data from the Clementine mission in equirectangular projection.

Exploration of the Moon: geology

Credits:NASA/JSC

Lunar landscape from Apollo 17

Geologist (and later US senator) Harrison "Jack" Schmitt in front of a large boulder in the Littrow Valley at the edge of the lunar highlands.

Astronaut collecting lunar soil sample.

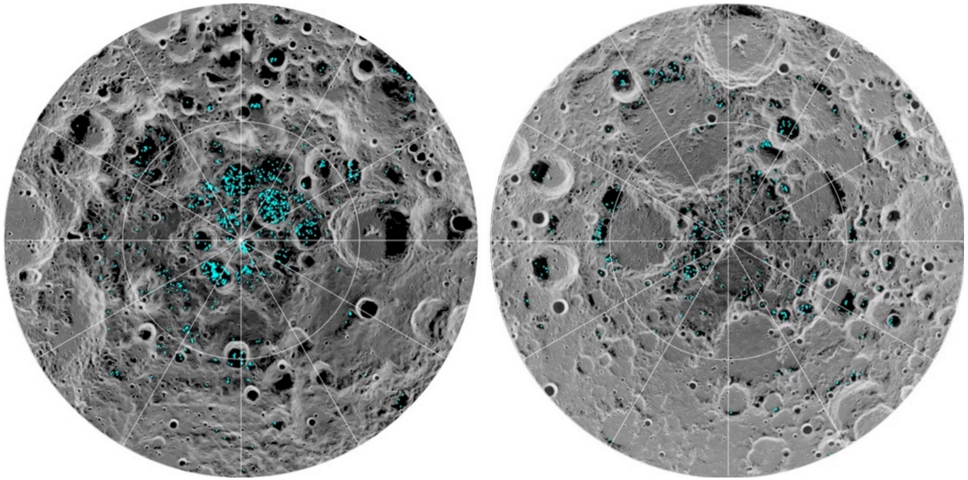
Exploration of the Moon: geology

"Big Muley", is a 11.7 kg (26 lb) lunar sample discovered and collected on the Apollo 16 mission in 1972 in the Descartes Highlands. It is the largest sample returned from the Moon as part of the Apollo program.

Lunar samples collected in the Apollo Project are analyzed and stored in NASA facilities at the Johnson Space Center in Houston, Texas. Here, a technician examines a rock sample using gloves in a sealed environment to avoid contaminating the sample.

Composition of the Moon

- An average density of only 3.3 g/cm^3 (Earth: 5.51 g/cm^3). Moon must be made almost entirely of silicate rock!
- Compared to Earth, it is depleted in iron and other metals, as well as of volatiles
- Water ice has been detected in permanently shadowed craters near the lunar poles. It was probably carried to the Moon by comets and asteroids that hit its surface, and ice stayed in a few cold traps where the Sun never shines, such as the bottom of deep craters at the Moon's poles.
- Water molecules are also present on the sunlit surface (SOFIA, October 2020)

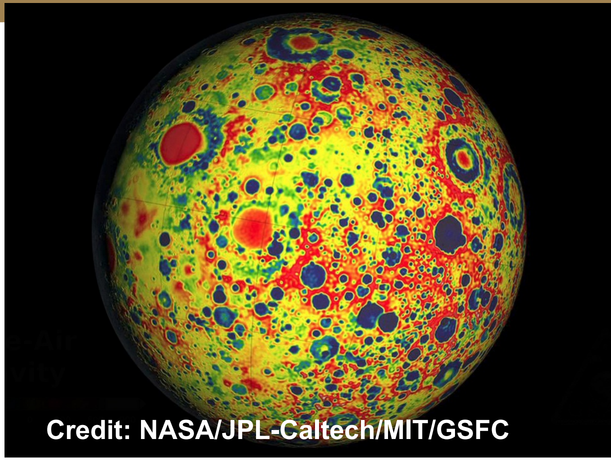


Distribution of surface ice at the Moon's south pole (left) and north pole (right), detected by NASA's Moon Mineralogy Mapper instrument. Credit: NASA.

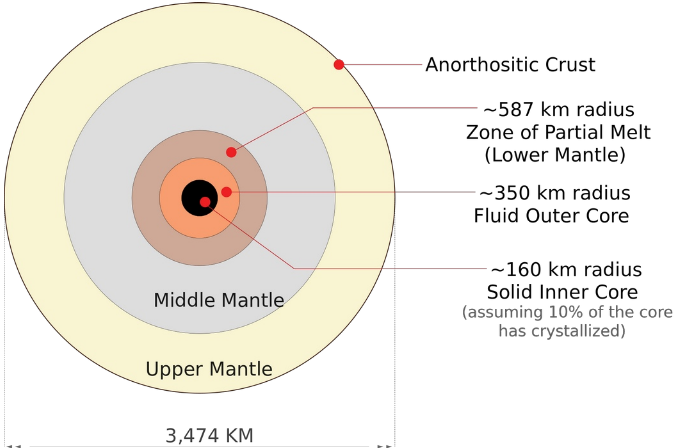
Structure of the Moon

- Seismometers placed on the Moon by the Apollo 12, 14, 15 and 16 missions studied moonquakes
- Gravity Recovery and Interior Laboratory (GRAIL) spacecrafts carried gravitometers
- Lunar core is small, with a radius of about ~350 km (20% the size of the Moon)

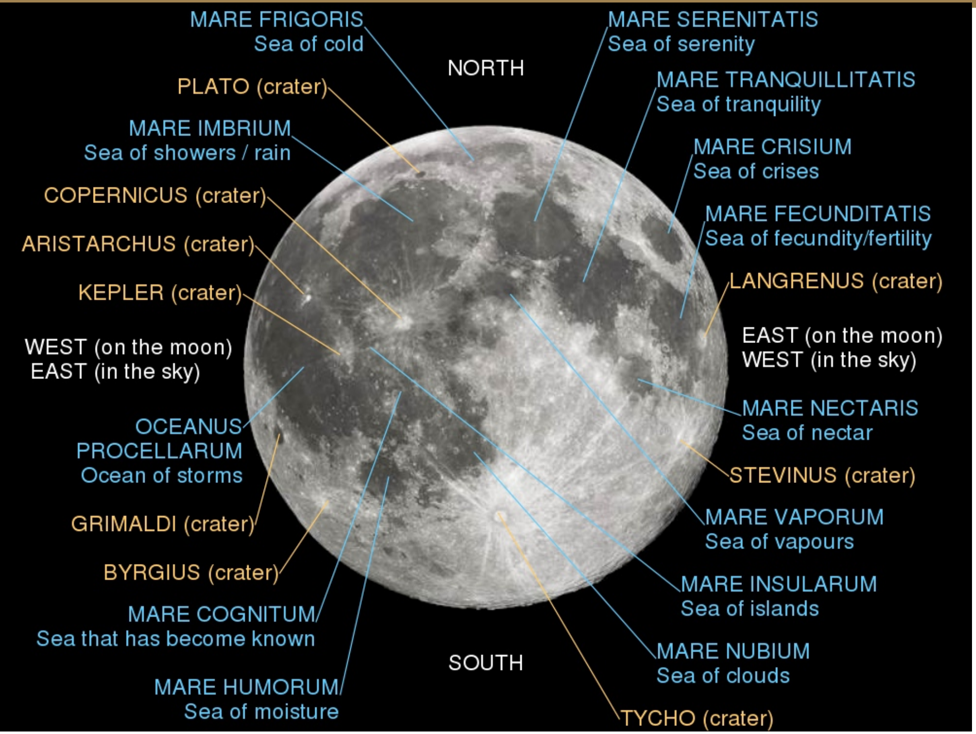
Gravity map of the Moon by GRAIL



Schematic illustration of the internal structure of the Moon



Maria, Highlands and Craters



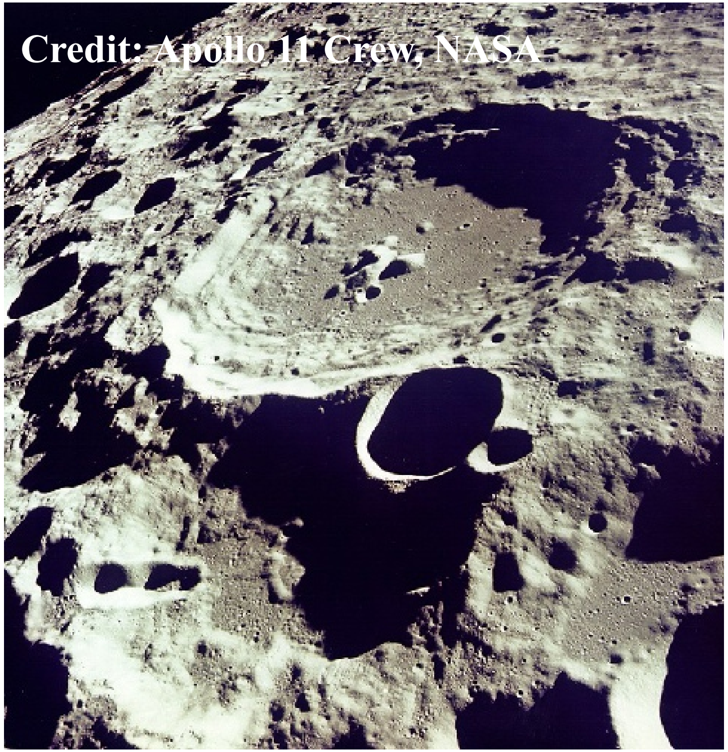
Lunar nearside with major maria and craters labeled – Credit: Peter Freiman Cmglee, background photograph by Gregory H. Revera

- The dark areas – thought by ancient astronomers to be “seas” – are called **maria** (**mare** in the singular) and represent 17% of the surface.
- Heavily cratered lunar **highlands** make up 83% of the Moon’s surface. “Land” areas between the maria are not named.
- Around 9,200 craters, the largest ones have been named after great scientists and philosophers

Highlands and maria

A cylindrical projection of the surface of the Moon obtained from the Clementine mission. The dark regions are the lunar maria (17% of the surface), whereas the lighter regions are the highlands (83% of the surface).

Highlands



The old, heavily cratered lunar highlands make up 83% of the Moon's surface.

- Highlands are made of silicate rocks called anorthosites. They formed early in lunar history (4.1-4.4 billion years ago).
- Relatively low-density rock that solidified on the cooling Moon like "slag floating on the top of a smelter"
- Erosion mostly due to impact cratering from meteorites

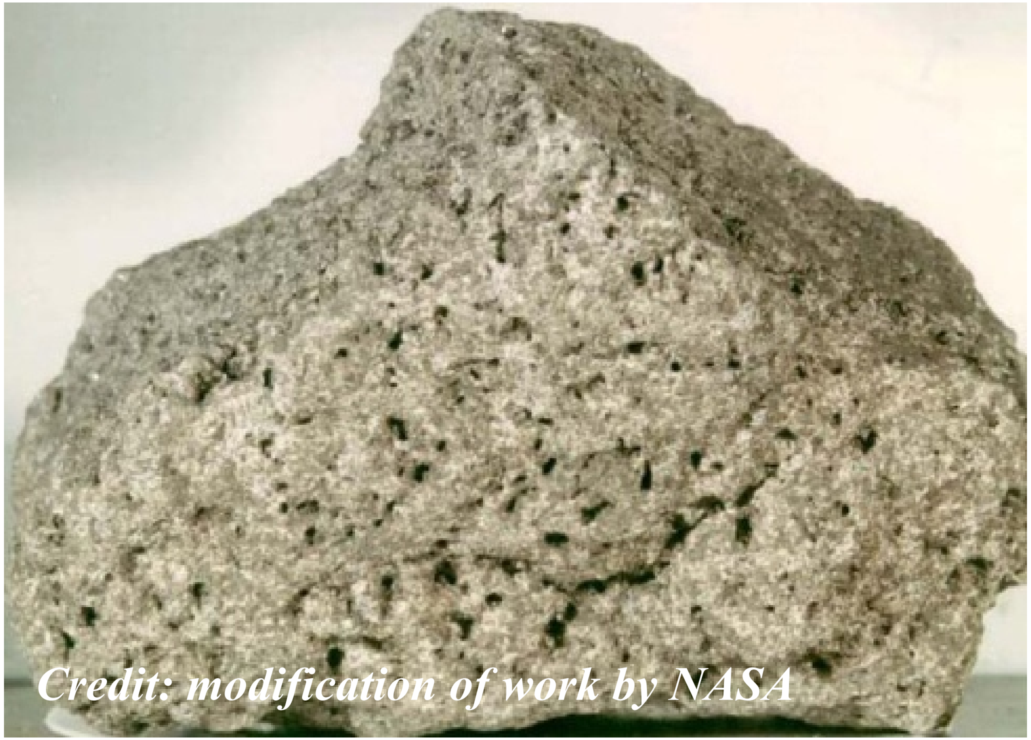
Maria

- Maria are flat plains of dark-colored basalt (volcanic lava) laid down in volcanic eruptions billions of years ago.
- Eventually, these lava flows partly filled the huge depressions called impact basins, which had been produced by collisions of large chunks of material with the Moon relatively early in its history. The basalt on the Moon is very similar in composition to the crust under the oceans of Earth or to the lavas erupted by many terrestrial volcanoes.
- Major mare volcanism mostly ended about 3.3 billion years ago.

This view of Mare Imbrium also shows numerous secondary craters and evidence of material ejected from the large crater Copernicus on the upper horizon.

Rock from a Lunar Mare

In this sample of basalt from the mare surface, you can see the holes left by gas bubbles, which are characteristic of rock formed from lava. All lunar rocks are chemically distinct from terrestrial rocks, a fact that has allowed scientists to identify a few lunar samples among the thousands of meteorites that reach Earth.


Credit: modification of work by NASA

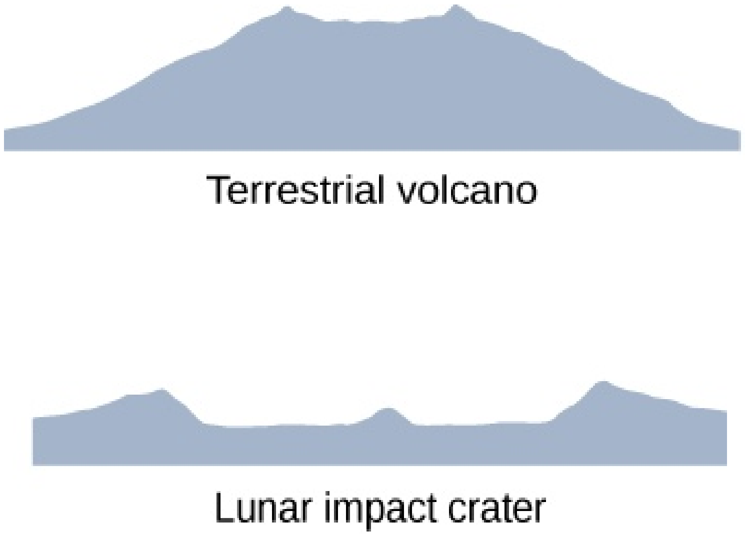
Lunar surface material

- Lunar soil/regolith is generally from 4 to 5 m thick in mare areas and from 10 to 15 m in the older highland regions.
- Results from disintegration of basaltic and anorthositic rock, caused by continual meteoric impacts and bombardment by solar and interstellar charged atomic particles over years.

Footprint on Moon Dust. Apollo photo of an astronaut's boot print in the lunar soil.

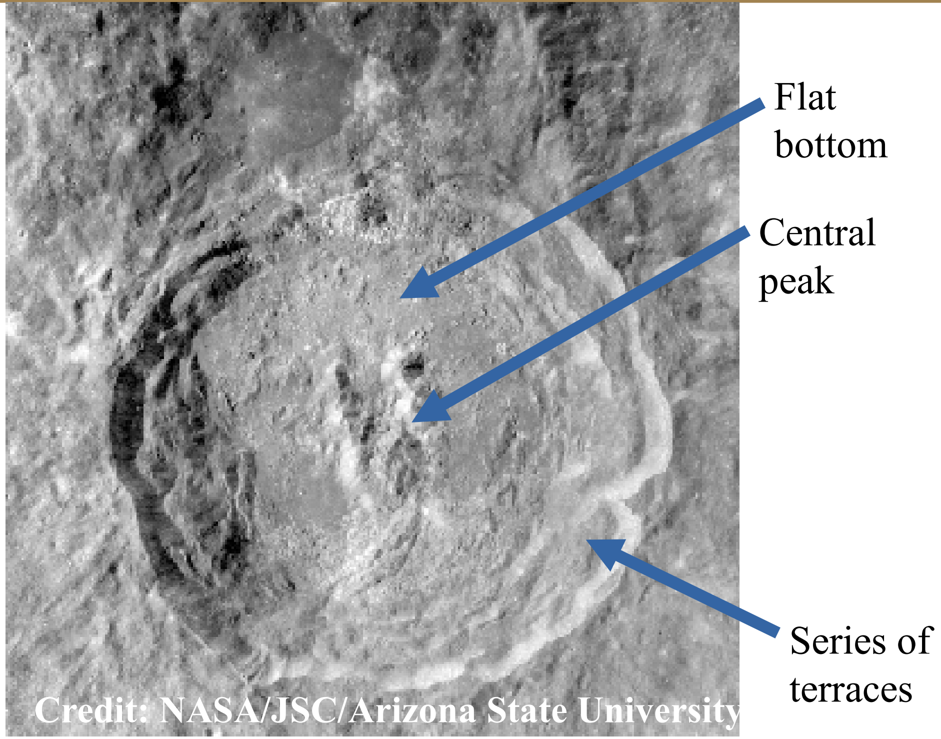
Impact craters

- Until the middle of the 20th century, craters on the Moon were hypothesized to result from volcanism.
- Grove K. Gilbert in the 1890s suggested they may be impact craters.
- The circular (rather than elliptical) shape of craters support a high velocity impact origin.

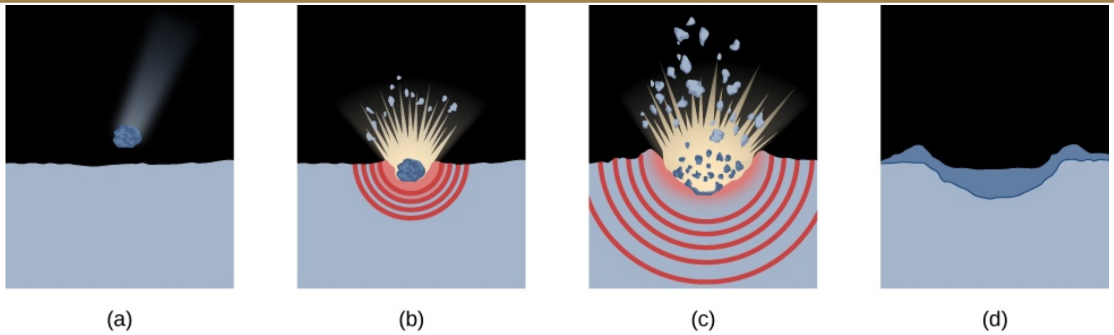


The profiles of a typical terrestrial volcanic crater and a typical lunar impact crater are quite different.

Stages of the Formation of Impact Craters



King Crater on the far side of the Moon, a fairly recent lunar crater 75 kilometers in diameter, shows most of the features associated with large impact structures.



Stages in the Formation of an Impact Crater.

a) The impact occurs.

b) The projectile vaporizes and a shock wave spreads through the lunar rock.

c) Ejecta are thrown out of the crater.

d) Most of the ejected material falls back to fill the crater, forming an ejecta blanket.

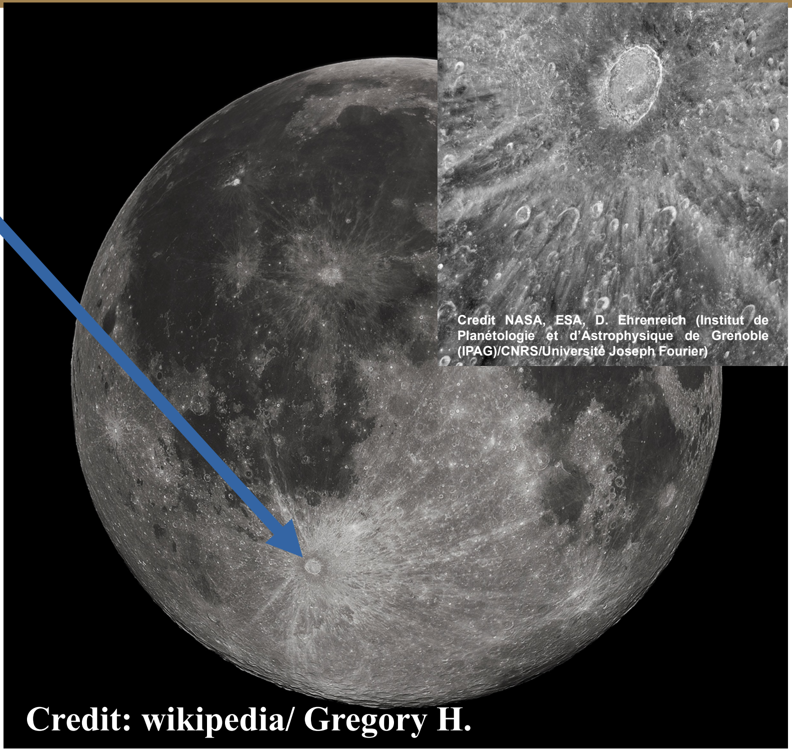
The size of the excavated crater depends primarily on the speed of impact, but generally is 10 to 15 times the diameter of the projectile.

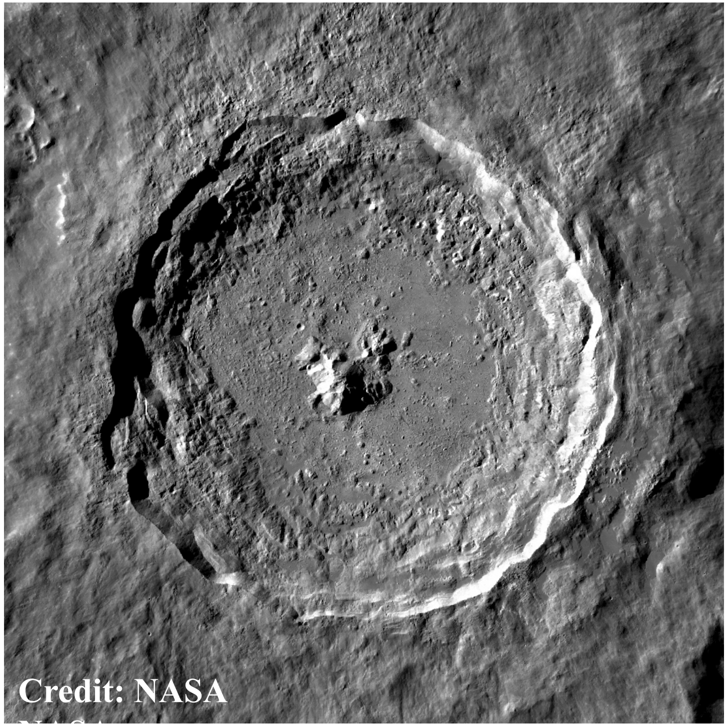
The Tycho crater

Tycho crater and rays

The young and large (108 million years old, 82 km wide) Tycho crater is located on bright highlands.

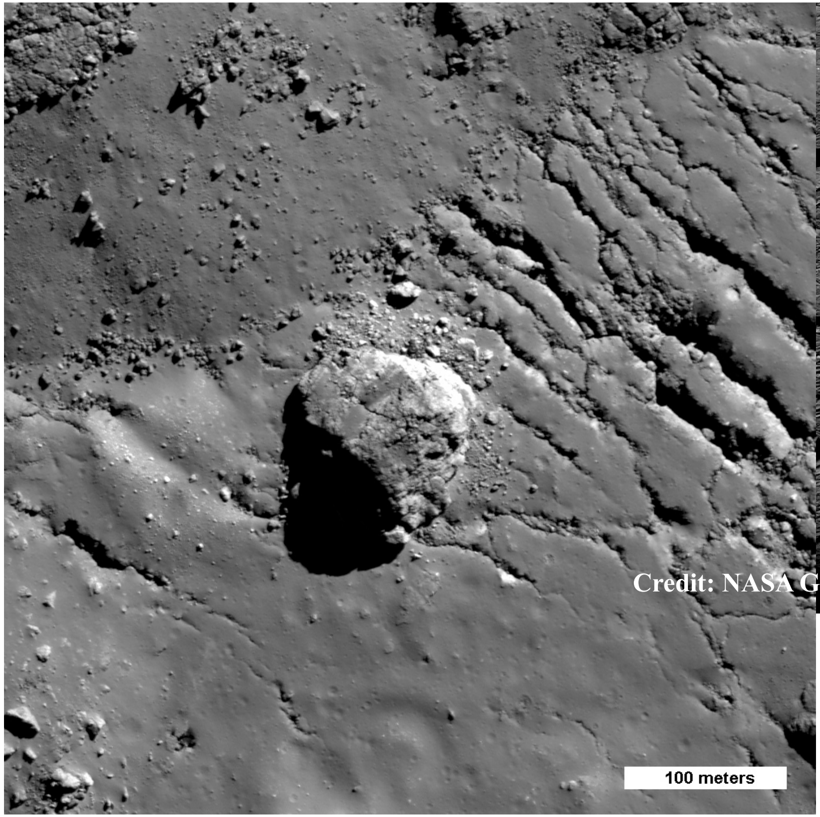
A crater ray system comprises radial streaks of fine ejecta thrown out during the formation of an impact crater.

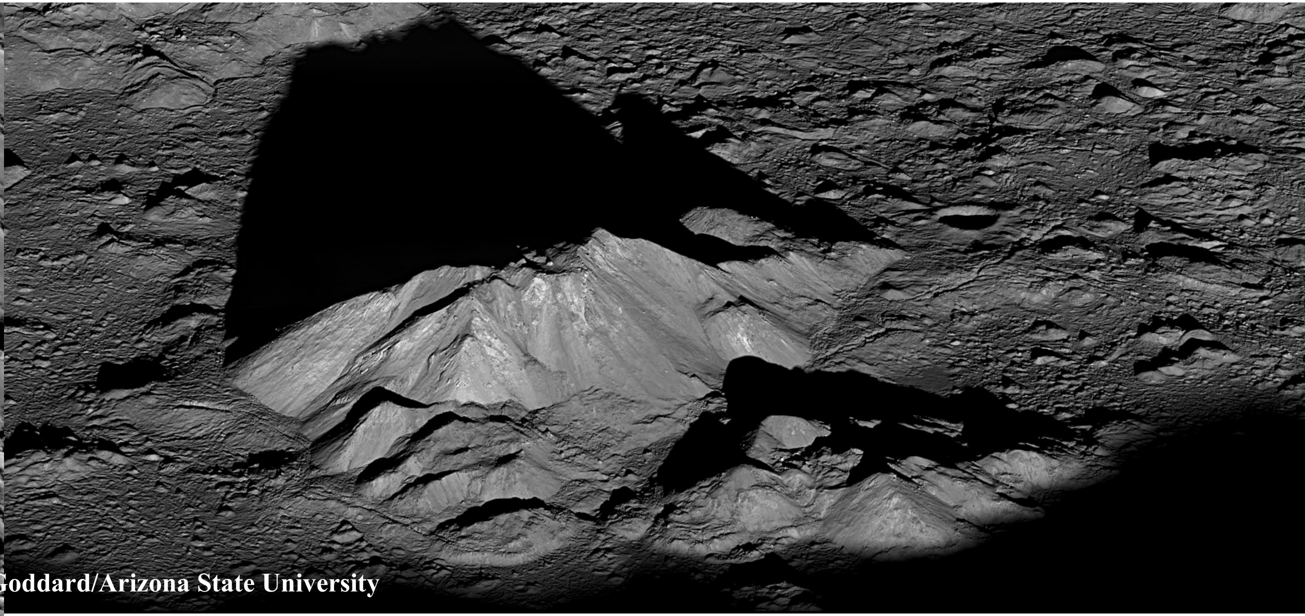




Tycho crater on the Moon: mosaic of images, made by Lunar Reconnaissance Orbiter (Wide Angle Camera). Width of the image is 120 km.

Tycho's central peak

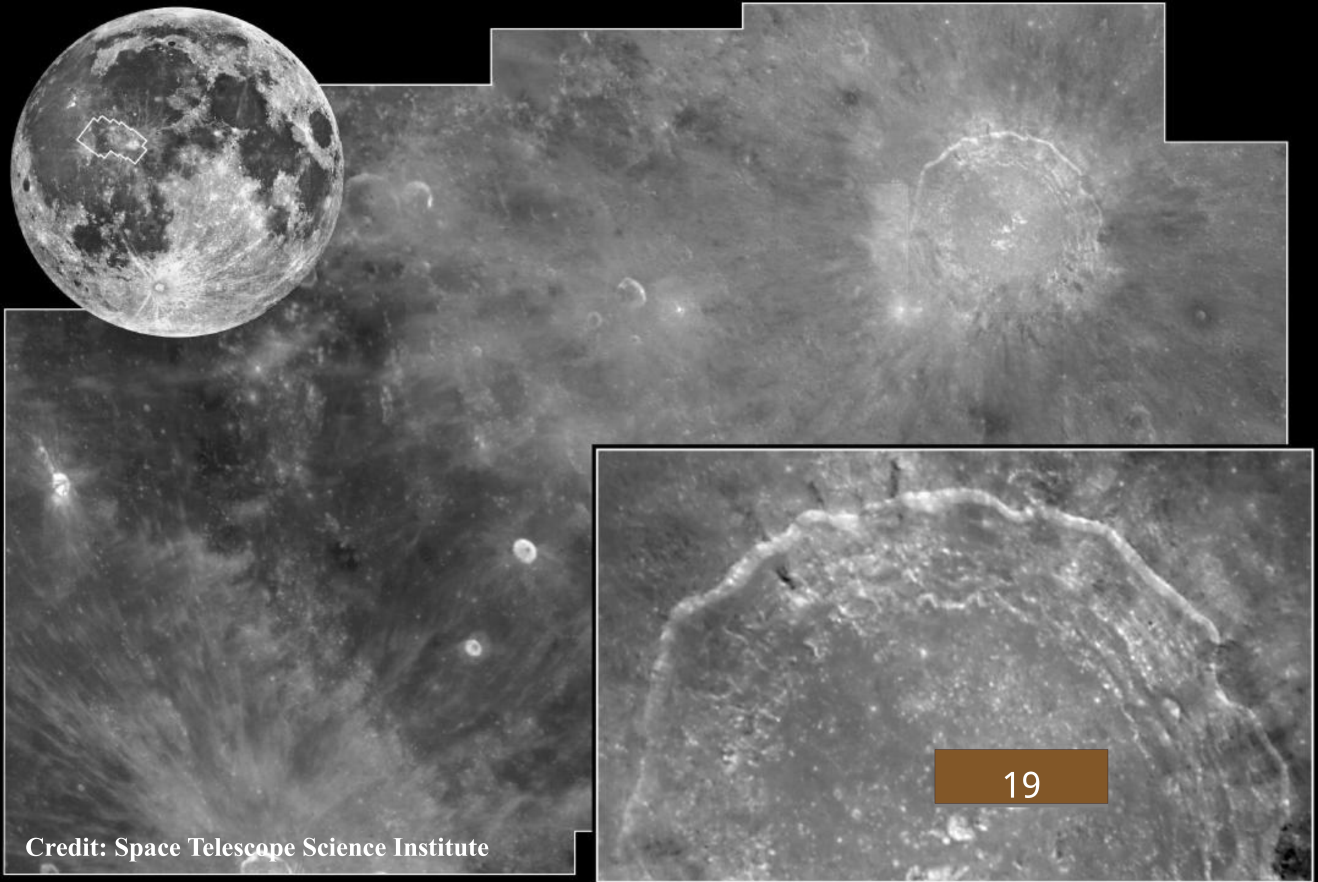




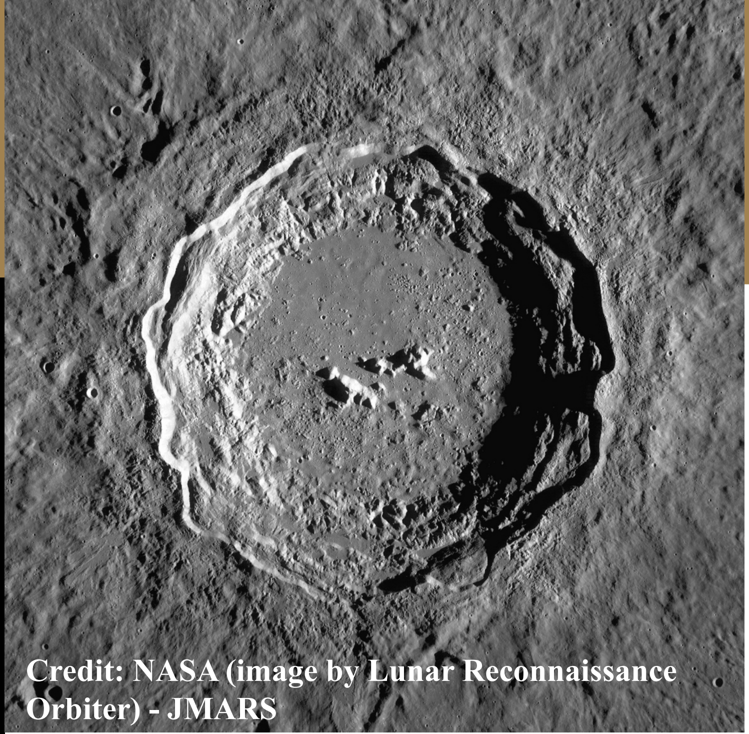
Credit: NASA Goddard/Arizona State University

Sunrise on the Central Mountain Peaks of Tycho Crater, as Imaged by the NASA Lunar Reconnaissance Orbiter. The central mountain rises 2 kilometers above the crater floor.

The Copernicus Crater



Credit: Space Telescope Science Institute

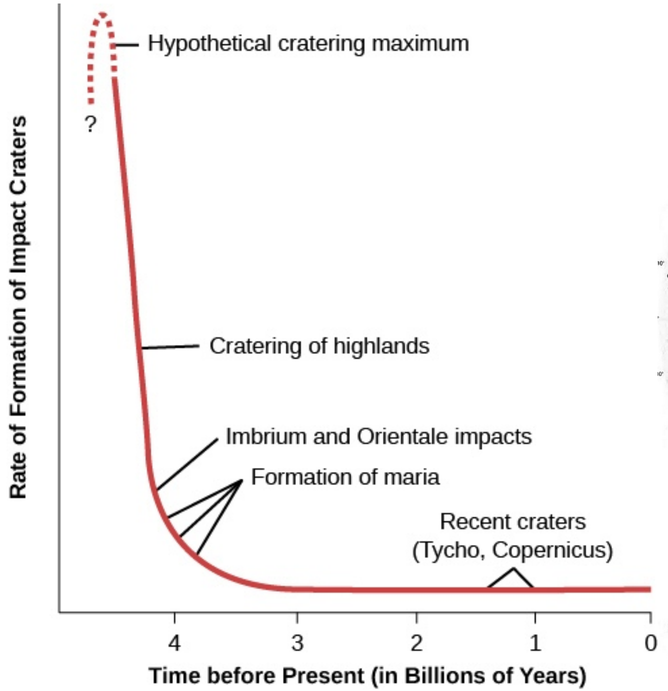


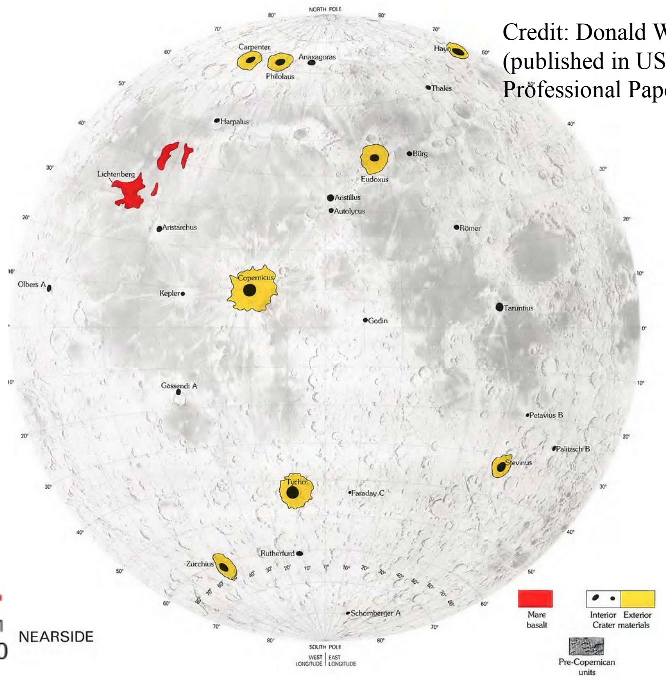
Credit: NASA (image by Lunar Reconnaissance Orbiter) - JMARS

Hubble views of Copernicus crater (inset), showing its location on the near side.

Impact Craters: cratering rate over time

- The number of craters being made on the Moon's surface has varied with time over the past 4.3 billion years.
- Most cratering happened in the first billion years, hence the Moon has not changed a lot in 3 billion years.
- Maria can be roughly dated by counting the number of craters on their surfaces





Credit: Donald Wilhelms (published in USGS Professional Paper)

In yellow, craters formed within the last 1.1. billion years.

Origin of the Moon: Early Hypotheses

- Early hypotheses
  - The fission theory: the Moon was once part of Earth, but somehow separated from it early in their history.
  - The capture theory: the Moon formed elsewhere in the solar system and was captured by Earth.
  - The sister theory: the Moon formed together with (but independent of) Earth, as we believe many moons of the outer planets formed.

Objections

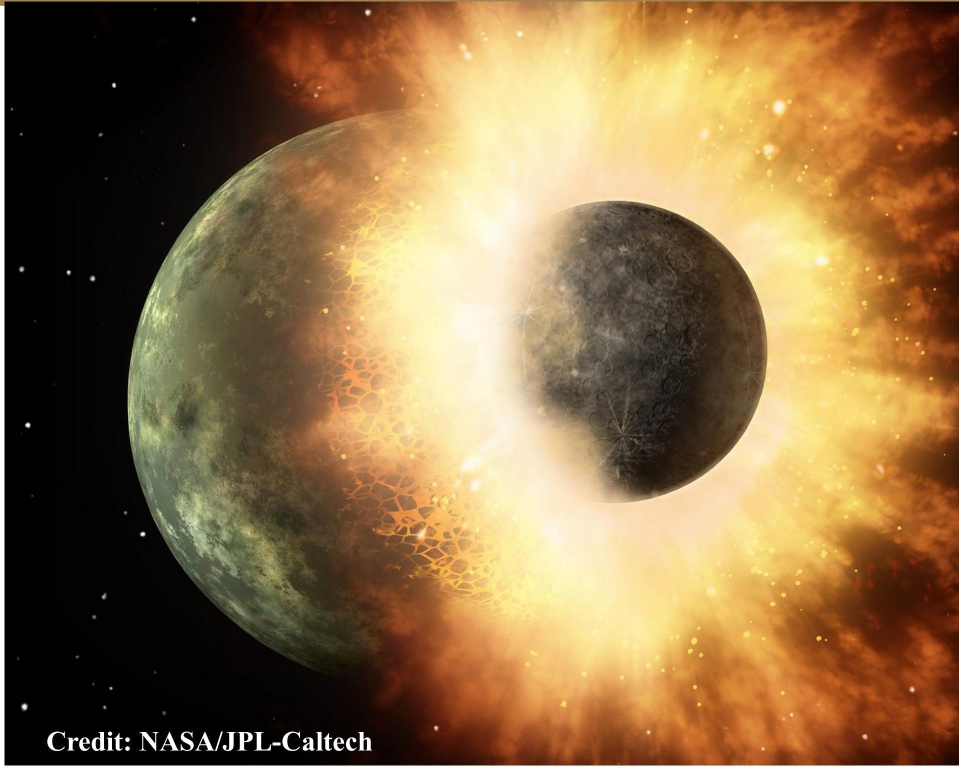
→ spontaneous fission or splitting is impossible
composition should then be identical

→ capture process improbable
would not result in circular orbit
does not explain the compositional similarities between Earth and the Moon

→ does not explain why the Moon does not have a substantial iron core

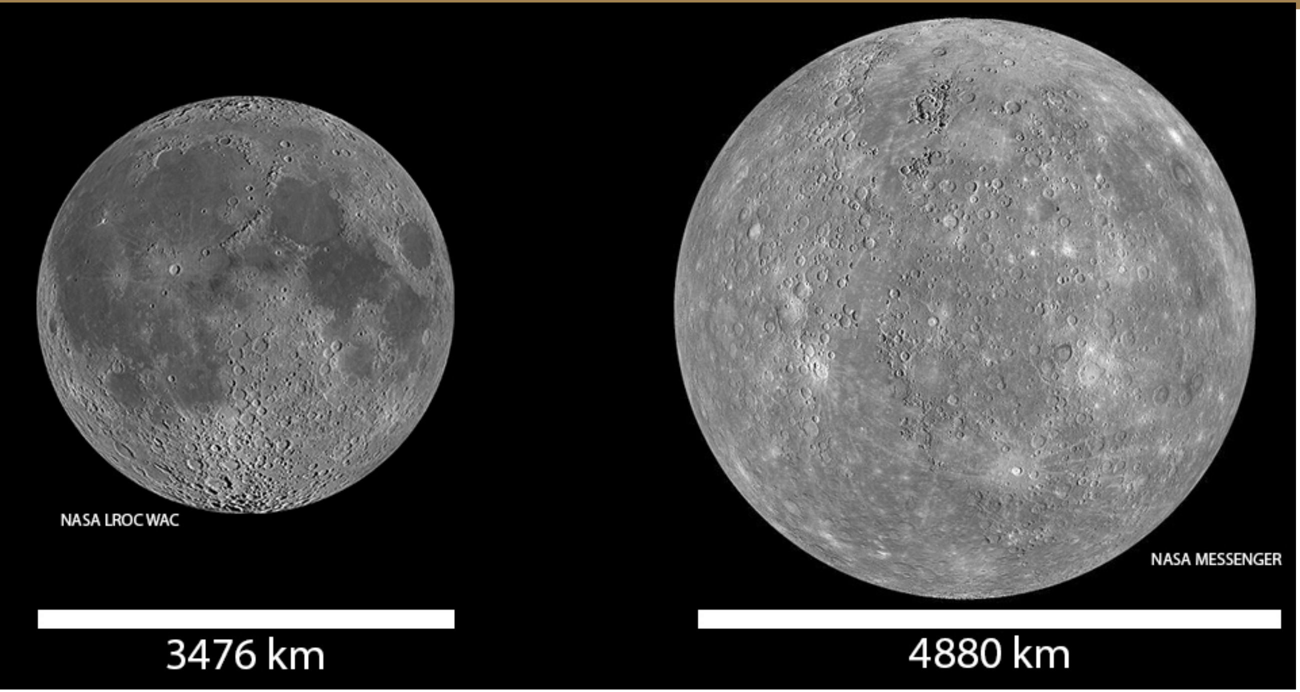
Origin of the Moon: the Giant Impact Hypothesis

- Theia may have been a planet of the early solar system, the size of Mars
- Collided with the early Earth around 4.5 billion years ago, with some of the resulting ejected debris gathering to form the Moon
- The Moon would be made mostly from the stony mantles of Earth and Theia
- The metal core of Theia merged with that of the Earth
- May not be correct but regarded as the current best explanation (explains similarities and differences in composition)



An artist's depiction of the hypothetical impact of a planet like Theia and the Earth

Mercury

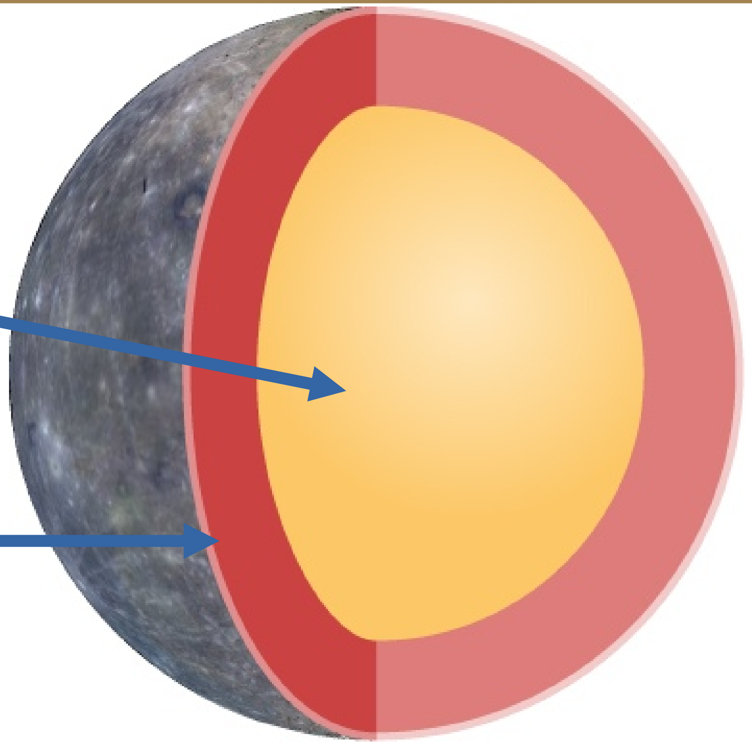


A comparison of the Moon (left) and Mercury (right) show their surfaces to be similar.

Image: data used is LRO WAC (NASA/GSFC/ASU) of lunar nearside and MESSENGER (NASA/JHU-APL) of Mercury.

Mercury's Composition and Structure

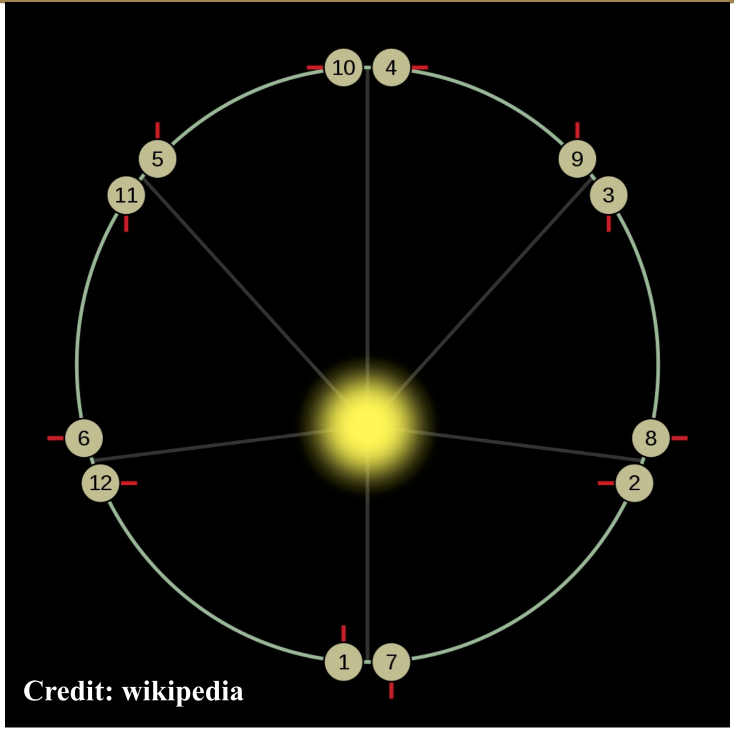
- Density of 5.4 g/cm^3, close to that of Earth
- Metallic iron-nickel core amounting to 60% of the total mass, 3500 km diameter
- Weak magnetic field, hence part of the core must be liquid
- Rocky crust, 700 kilometers thick



The interior of Mercury is dominated by a metallic core about the same size as our Moon.

Mercury's Strange Rotation

- Long-thought to have one side fixed facing the Sun, until radar observations showed otherwise in the 1960s
- Rotation period 59 days, Revolution period of 88 days, a stable 2:3 spin-orbit resonance.
- The length of the day on Mercury (sunrise to sunrise) is 176 Earth days
- No significant atmosphere
- Extreme temperature contrast of 600 K: 700 K at noontime, 100 K during the night or even colder in sunless craters.



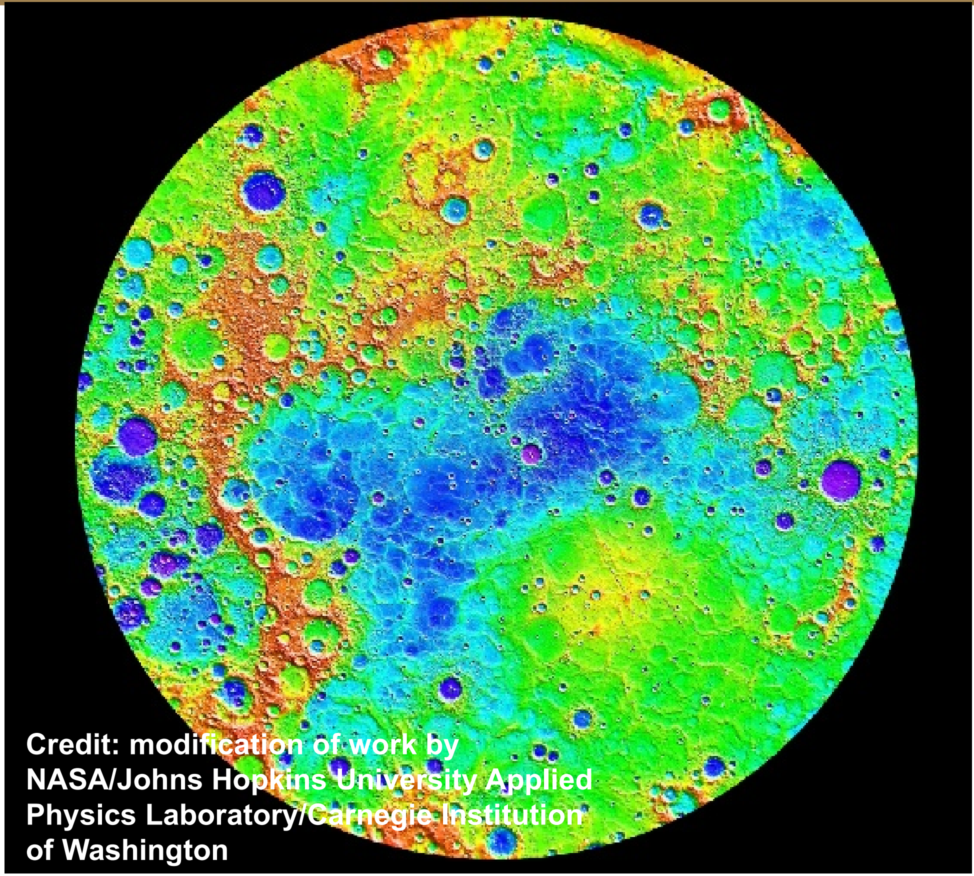
After one orbit, Mercury has rotated 1.5 times, so after two complete orbits the same hemisphere is again illuminated.

Topography of Mercury

The topography of Mercury's northern hemisphere was mapped by MESSENGER in 2011-2015.

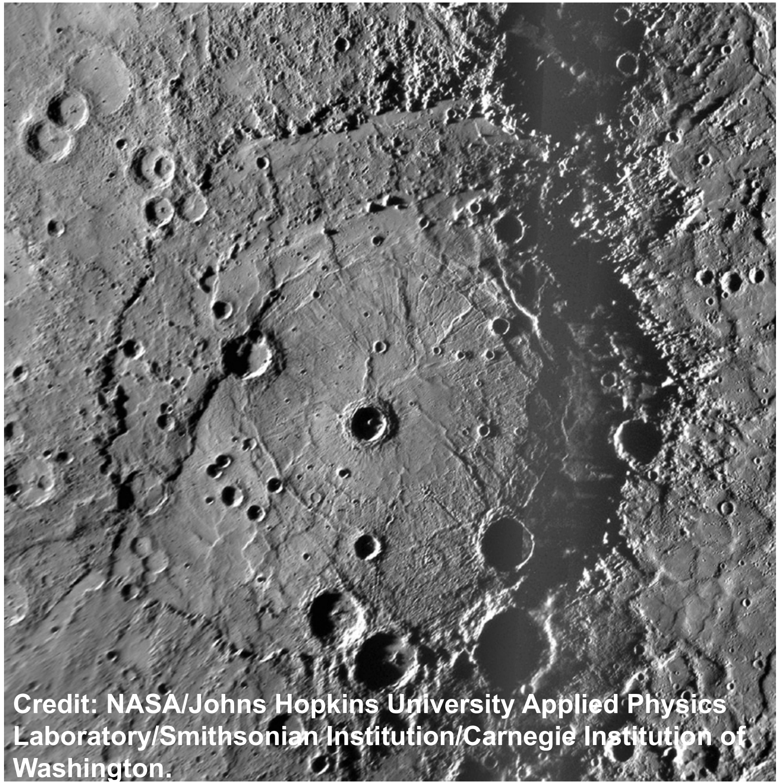
The lowest regions are shown in purple and blue, and the highest regions are shown in red. The difference in elevation between the lowest and highest regions shown here is roughly 10 kilometers. The permanently shadowed low-lying craters near the north pole contain radar-bright water ice.

763 craters have been identified.



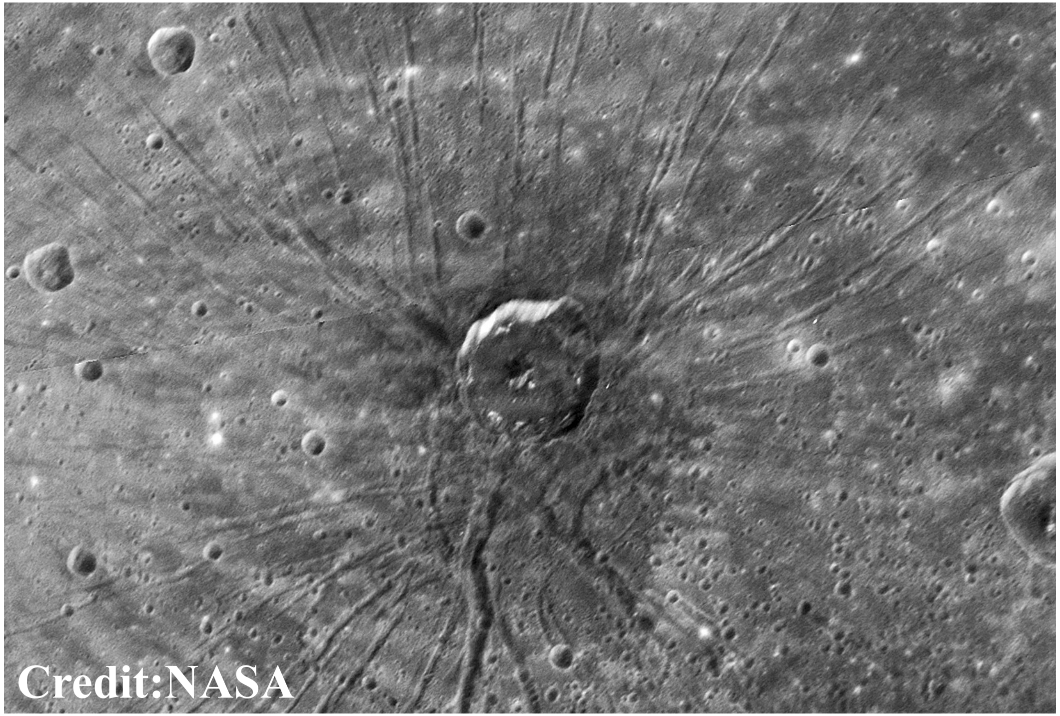
Credit: modification of work by NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington

Cratering of Mercury



Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Smithsonian Institution/Carnegie Institution of Washington.

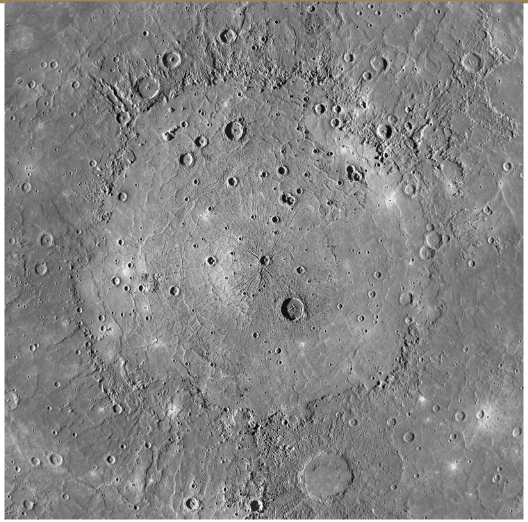
- *The Rembrandt Basin is a large and young impact crater on Mercury.*



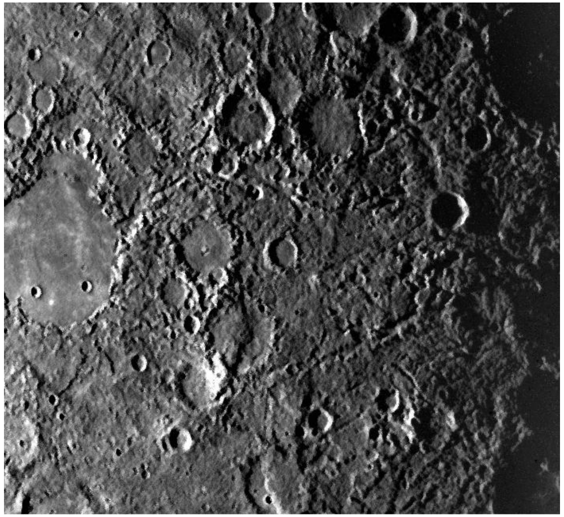
Credit:NASA

Apollodorus is an impact crater on Mercury. Its unusual appearance, with radiating dark troughs, led to a nickname of "the Spider".

The Caloris basin and its antipode



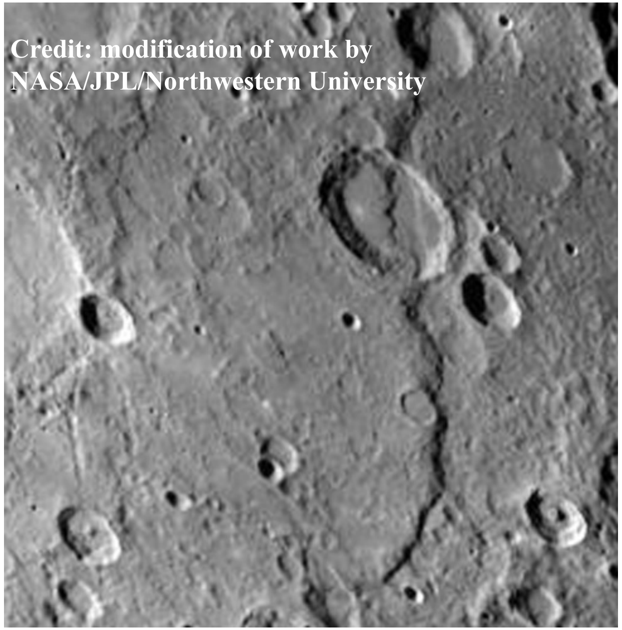
Mosaic of the mighty **Caloris basin**, Mercury's youngest large impact basin. Caloris has been filled by volcanic plains that are distinctive in color from the surrounding terrain. The basin interior has a complex tectonic history. The interior smooth plains have an area of 1.72 million km2, approximately the area of Alaska.



At the exact antipode of the Caloris basin is a large area of hilly, grooved terrain, with few small impact craters that are known as chaotic terrain (also "weird terrain"). It is thought by some to have been created as seismic waves from the impact converged on the opposite side of the planet.

Compressional tectonic features

- Large fault scarps (cliffs), up to 1000 km and heights of 3 km indicate that Mercury shrank early in its history, by about 1-7 km in radius
- Compression of the interior and consequent surface geological activity continue to the present
- The Moon presents similar structures
- Both the Moon and Mercury are small bodies and have cooled down significantly faster than the Earth.



Discovery Scarp on Mercury. This long cliff, nearly 1 kilometer high and more than 100 kilometers long, cuts across several craters. Astronomers conclude that the compression that made "wrinkles" like this in the plank's surface must have taken place after the craters were formed.