BHARATHIDASAN UNIVERSITY

Tiruchirappalli- 620024, Tamil Nadu, India

Programme: M.Tech., GEOLOGICAL TECHNOLOGY AND GEOINFORMATICS

Course: Remote Sensing Application in Planetary Studies

Code : MTIGT1004

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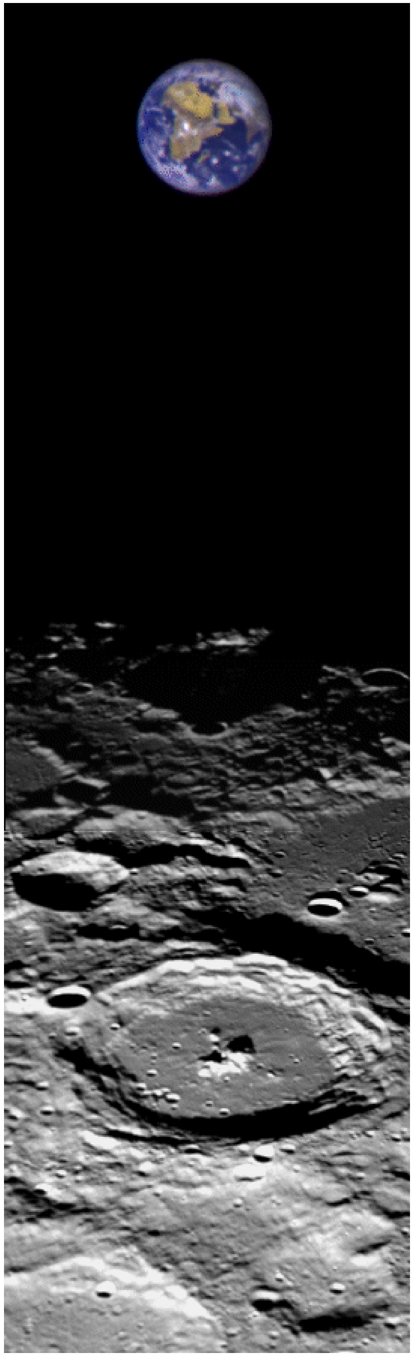
Unit-4 Moon. Introduction to Moon – Implication of Apollo missions – Origin of Moon – Evolution of Moon – Surface composition of Moon – spectral character major rock forming minerals of Moon - Polar region of the Moon – Evidences for the presence of Water in Moon - space weathering – Regolith, Volcanism on the Moon – Age and Lunar stratigraphy – Morphological features of Moon - Impact cratering processes: Morphology of simple craters and complex craters: Lunar Missions: Luna series, Apollo series, Clementine, Lunar Prospector, Kaguya (SELENE), Chang'e series, Chandrayaan-1&2, Lunar Reconnaissance Orbiter, The Lunar Crater Observation and Sensing Satellite (LCROSS), Gravity Recovery And Interior Laboratory (GRAIL) and various other missions.

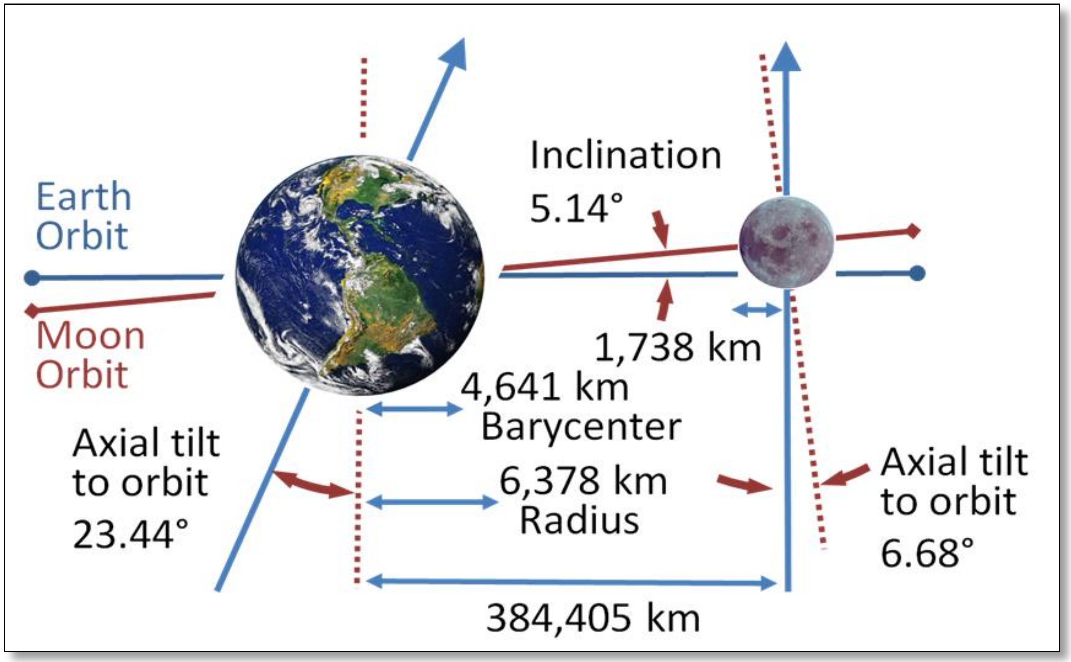
- The Moon is an astronomical body that orbits our mother planet Earth and being only natural satellite.
- As seen from the Earth, it is the second-brightest regularly visible celestial object in Earth's sky, after the Sun.
- About 384,000 km from Earth and 3,468 km in diameter (about ¼ the size of Earth).
- The Moon is in synchronous rotation with Earth, always showing the same face(Near Side).



Properties of The Moon

Mass	7.36 x 10^{22} kg	Gravitational acceleration	1.6 m/s^2
Volume	2.1958 x 10^{10} km^3	Atmosphere	No
Radius	1740 Km	Magnetic Field	No
Circumference	10,921 km (equatorial)	Escape Velocity	2.4 km/s
Mean density	3.34 g/cm^3	Sidereal rotation period	27.321661 days
Temperature	-103°C (Night) to 96°C (Day)	Equatorial rotation velocity	4.627 m/s
Axial tilt		1.5424° to ecliptic 6.687° to orbit plane	

Properties of Earth	
Mass	5.90 x 10^{24} kg
Radius	6370 km
Mean density	5.52 g/cm^3
Temperature	58°C to -88°C
Gravitational acceleration	9.8 m/s
Magnetic Field	Yes
Escape Velocity	11.9 km/s



Before and after Apollo

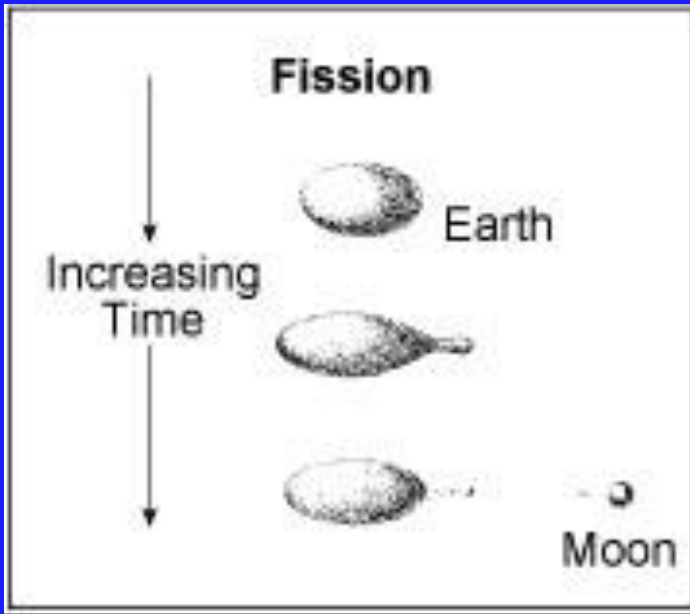
- Prior to the Apollo Missions, scientists believed the Moon formed in the early Solar System along with the other planets and had remained a primitive body.

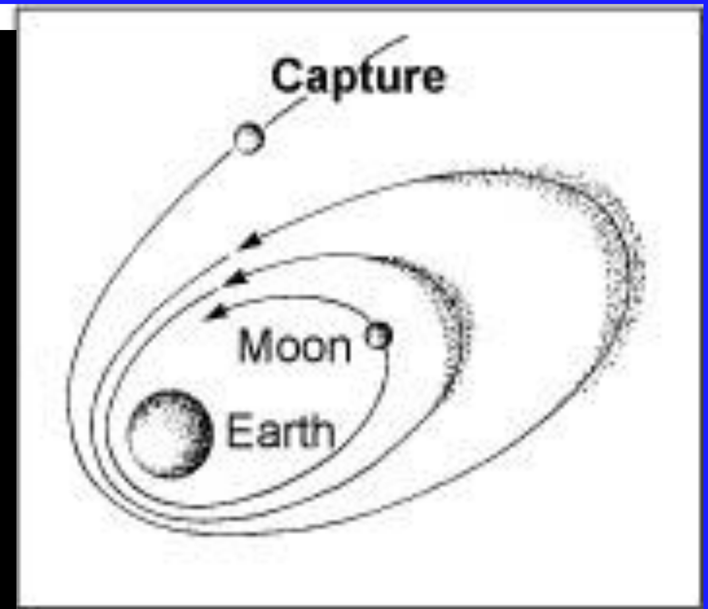
- Because of Apollo, we have learned this is not correct. In fact, the lunar samples brought back by Apollo, and subsequent remote sensing missions, have taught us a great deal about the geologic history of the Moon.

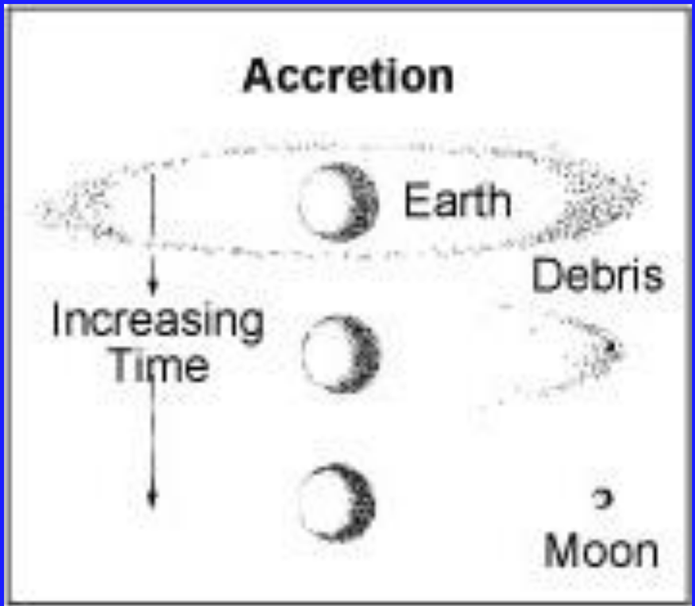
Implications for the origin and evolution of the Moon from Apollo missions?

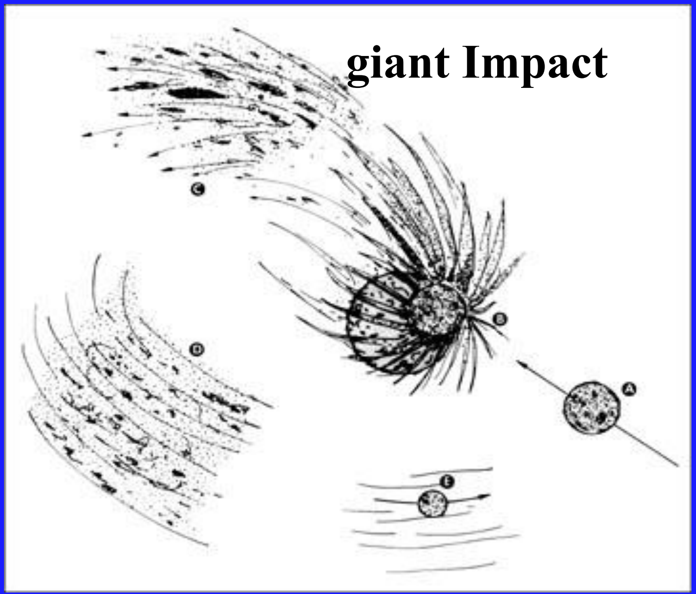
- Oldest Moon rocks are 4.3 billion years old
- Depletion of volatiles (H_2O, K, Na, etc)
- Enrichment of high temperature elements (Mg, Al, Si, Ca, Th, U, etc).
- Similar oxygen isotopic ratio as the Earth. whereas Mars rocks and meteorites from other parts of the solar system have different oxygen isotope compositions.
- Moon's orbit lies not in the equatorial plane of Earth or in the ecliptic plane.

Hypotheses of the origin of the Moon









Fission origin of the Moon, out of the Pacific Ocean (George Darwin)

Giant impact hypothesis

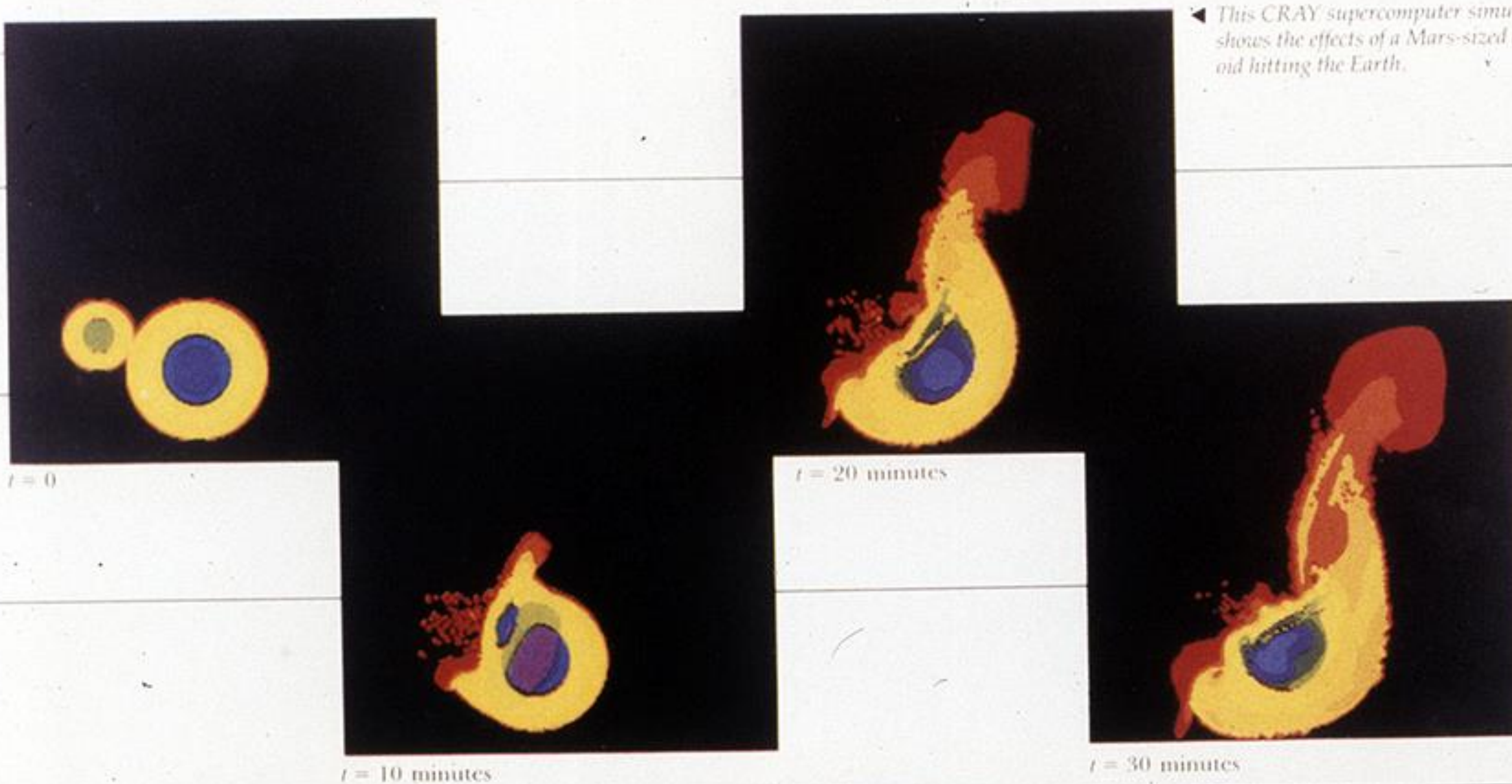
- A projectile about the size of Mars, struck the young, Earth in a catastrophic, glancing blow nearly 4.6 billion years ago.
- Material was jettisoned outward, and some fraction of this mass remained in Earth orbit and formed the Moon.
- The Moon may be mostly derived from the crust and mantle of the Earth and/or the impacting object.
- The giant impact and quick accumulation of material resulted in a hot, molten Moon, which accounts for the relative lack of water and other volatile elements.
- After the crust cooled, impacts into the Moon scarred the surface with numerous craters.

Artist's conception of the Giant Impact Hypothesis of the Moon

Artist's conception of the Giant Impact Hypothesis of the origin of the Moon.

CRAY supercomputer simulation of the origin of the Moon by a collision of Earth with a Mars-sized projectile.

Note: The Moon formed mostly from the silicate portions of the projectile and Earth's mantle, whereas the metal core of the impactor merged with Earth's metallic core. Hence, the Moon is depleted in metal and has a lower density than earth.



◀ *This CRAY supercomputer simulation shows the effects of a Mars-sized asteroid hitting the Earth.*

Origin of the Moon: Which hypothesis is correct?

Hypothesis	Volatiles	Isotopes	Orbit	Iron	Physics
Giant Impact	A	A	B+	A	B+
Fission	B	B	F	A	F
Capture	F	F	A	C	F
Co-accretion	F	A	F	F	B

A = v. good match; C = matches some data; F = doesn't match

Earth and Moon system

This prediction did not disagree with contemporary measurements of the chemical and isotopic composition of the lunar rocks, but as isotopic measurements have increased in precision.

than half of the Moon's material came from the impactor, how can the Moon's isotopes be nearly identical to the Earth's?

much larger fraction of Earth material would have reached orbit if the Earth was partially molten at the time of the giant impact.

The Moon's isotopic composition is mysteriously similar to Earth's.

This may be the signature of a magma ocean on Earth at the time of the Moon-forming giant impact, according to numerical simulations.

H. Jay Melosh

For the past three decades, the answer to the question "Where did Earth's moon come from?" was most likely to be "From the impact of a Mars-sized protoplanet".

The idea was shown to better explain the Moon's size, orbital angular momentum and overall composition than other hypotheses1.

All these simulations predicted that the Moon-forming material is mostly derived from the impactor, rather than directly from the Earth.

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With a solid Earth mantle, typically predicted that the orbiting disk from which the Moon condensed comprised about 40% Earth material.

Still many problems ?????????????

none have the near-identity of isotopes as an inevitable outcome.

Include: magma ocean phase

least part of the mantle melted due to the gravitational energy of accreting material.

Such melting partitions iron, in the form of FeO, preferentially into the liquid phase, so a magma ocean is expected to have contained more FeO than the bulk Earth.

Most of the material ejected - the giant impact - magma ocean ??????????

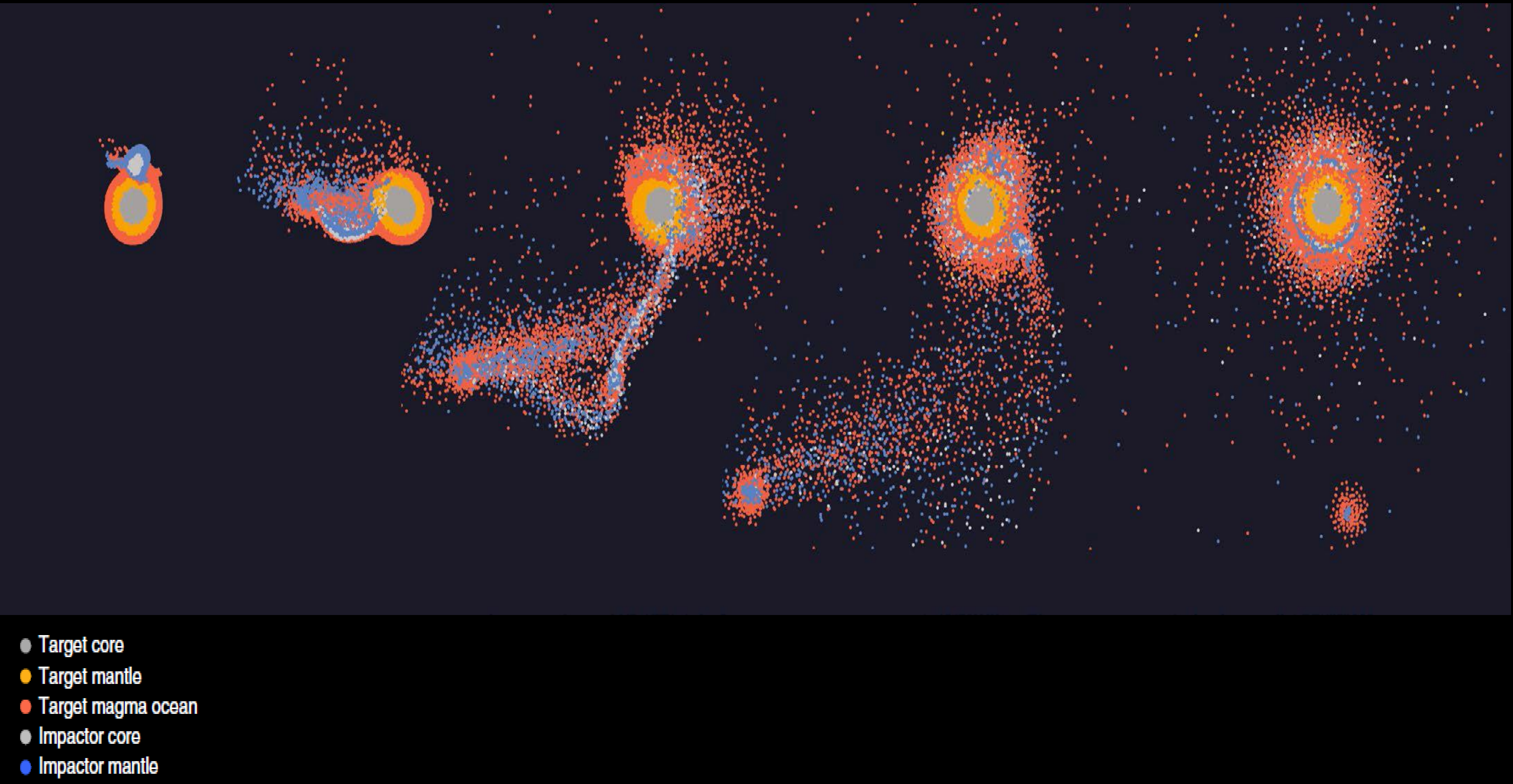
Resulting Moon would be expected to show an enrichment in FeO

This is exactly what is observed:

The major chemical difference between the bulk Moon and bulk Earth is a higher proportion of FeO in the Moon.

Perform simulations that suggest that when a magma ocean is present on the pre-impact Earth, the contribution of terrestrial material to the Moon is more than 70%, much greater than the approximately 40% in the canonical models.

The oxygen isotopic ratios of the Earth and Moon are so similar



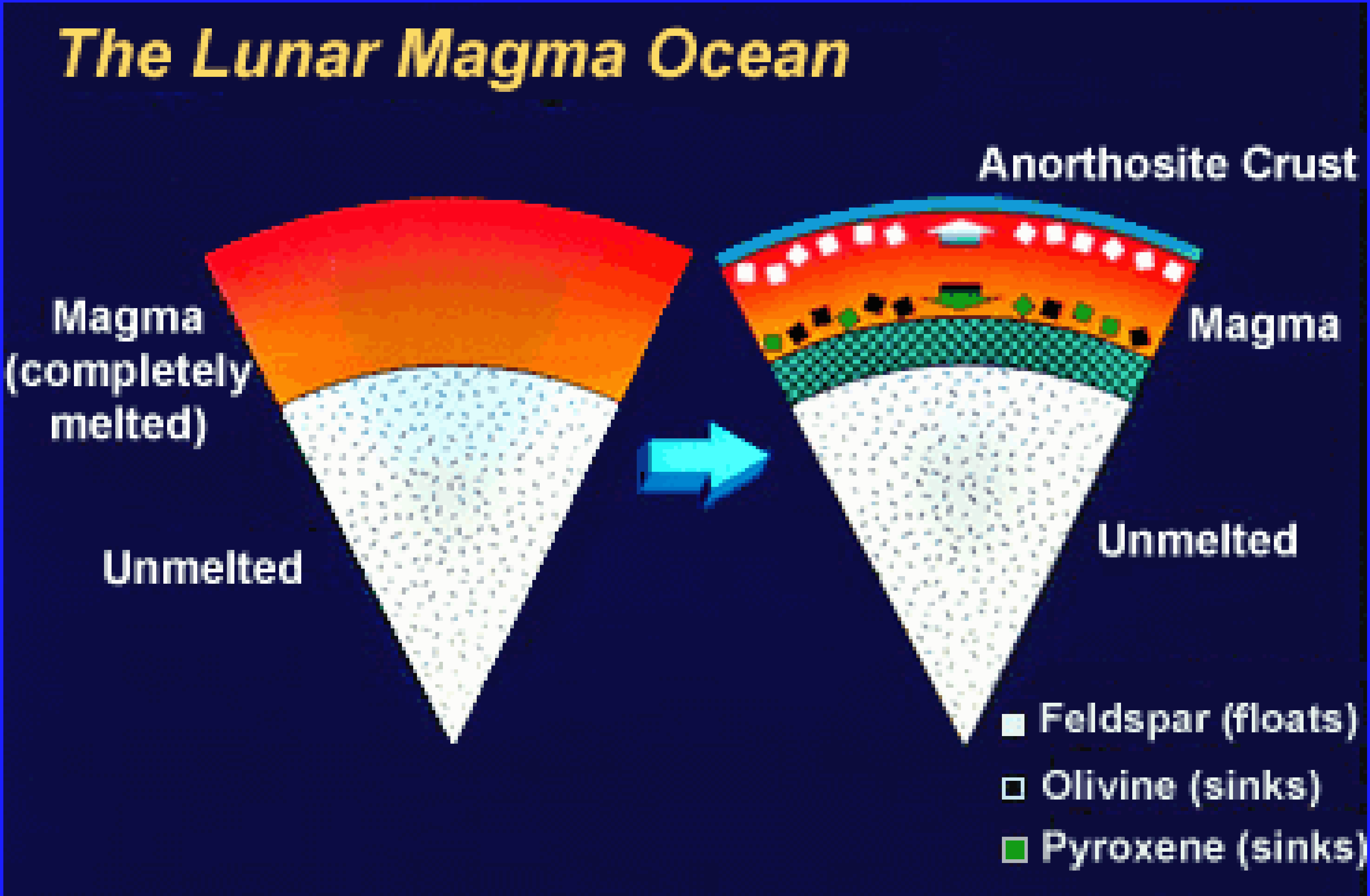
This simulation includes a terrestrial magma ocean, which results in a greater proportion of material from Earth forming the Moon than in canonical simulations (with a solid Earth mantle). Times are after the impactor first crosses Earth's Roche limit.

Evolution of the Moon

- Formation of Moon before 4.55 b.y ago
- Melting of entire Moon, formation of magma ocean, crystallization of Anorthosites crust with in first 100 m.y
- Large basin (mare) – forming impact from 4.5 to 4.1 b.y. ago and early epoch of volcanism
- Basaltic lava floods maria from 3.8 b.y to 3.2 ago
- Smaller impacts, regolith formation since 3.3 b.y ago to today

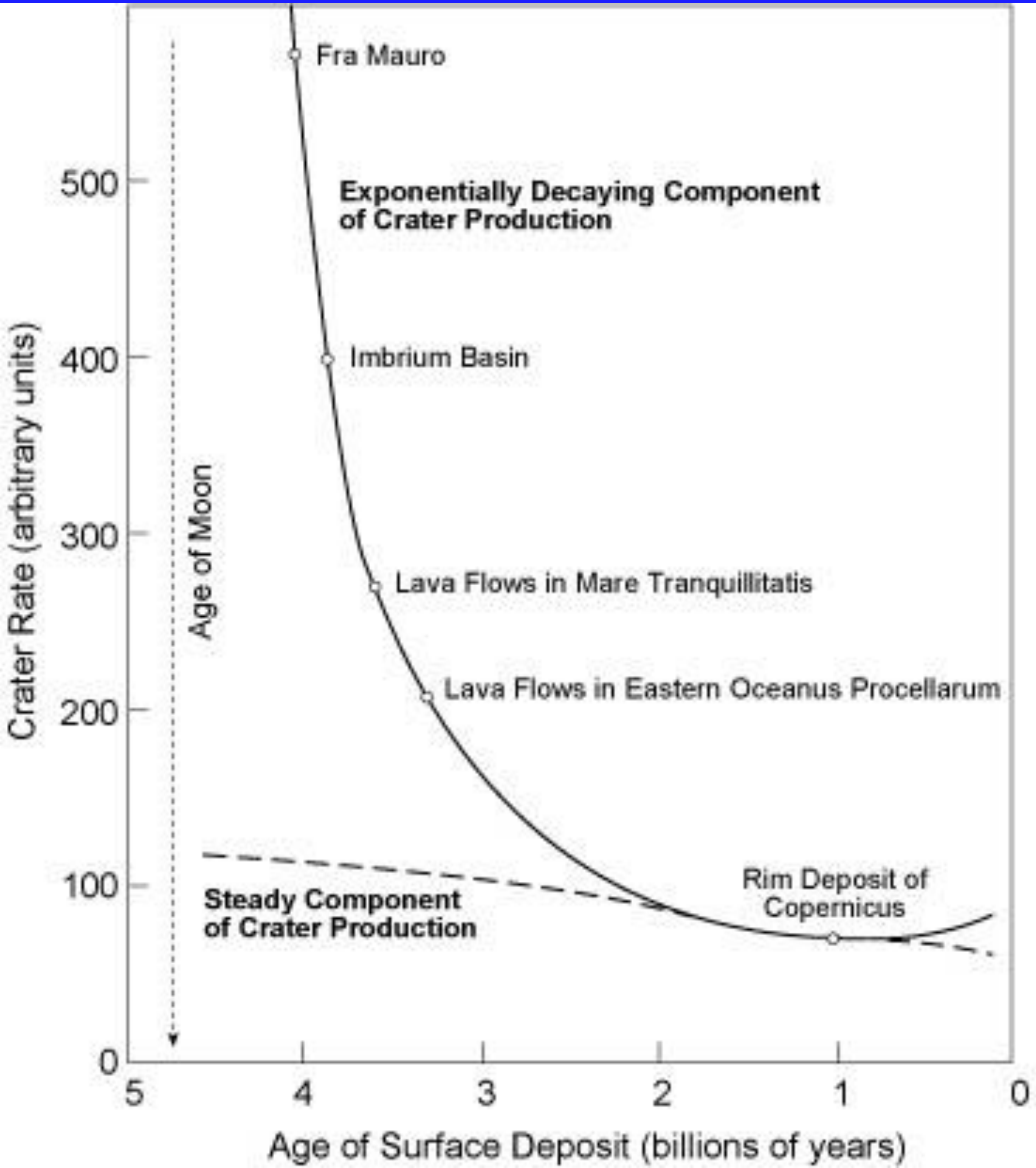
Magma Ocean hypothesis

- The Moon was molten after formation
- As the molten rock cooled, it crystallized
- Some crystals floated others sank



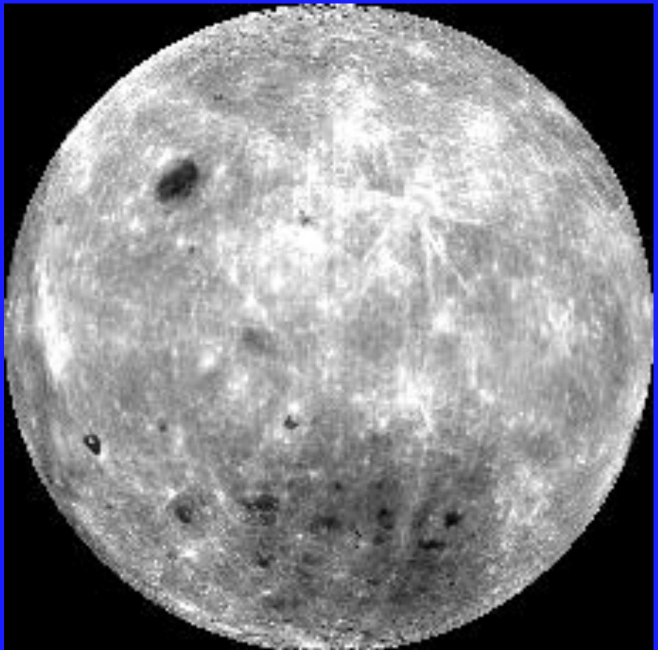
Impacts are the dominant surface process on the Moon

- Crater flux has decreased with time
- It would be hard to sustain life on Earth if flux was as high as during the early solar system.
- Impact erode the lunar surface
- Size range <1mm - >1,000km
- Age data from the Apollo landing sites allow an estimate of the number of craters formed over time.
- Scientist can then date surfaces by counting craters



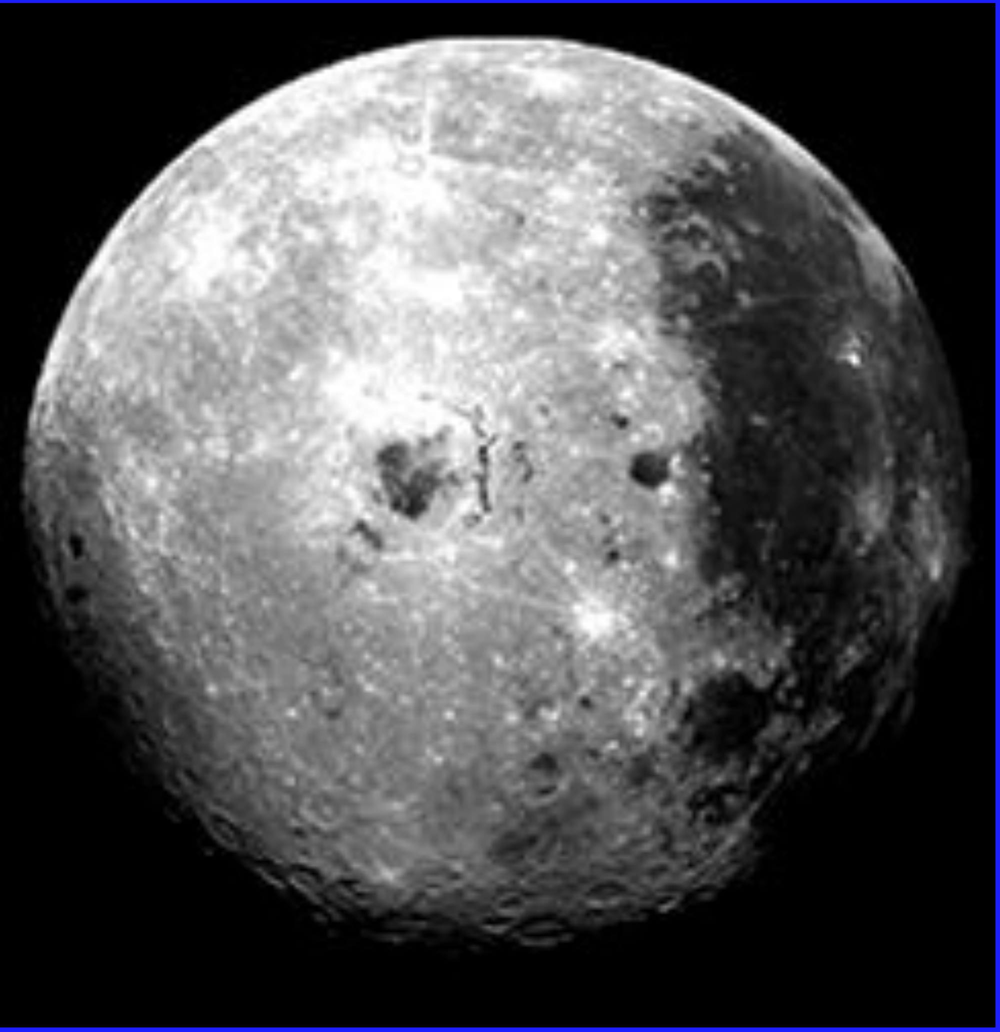
Differences: Near-side vs. Far-side

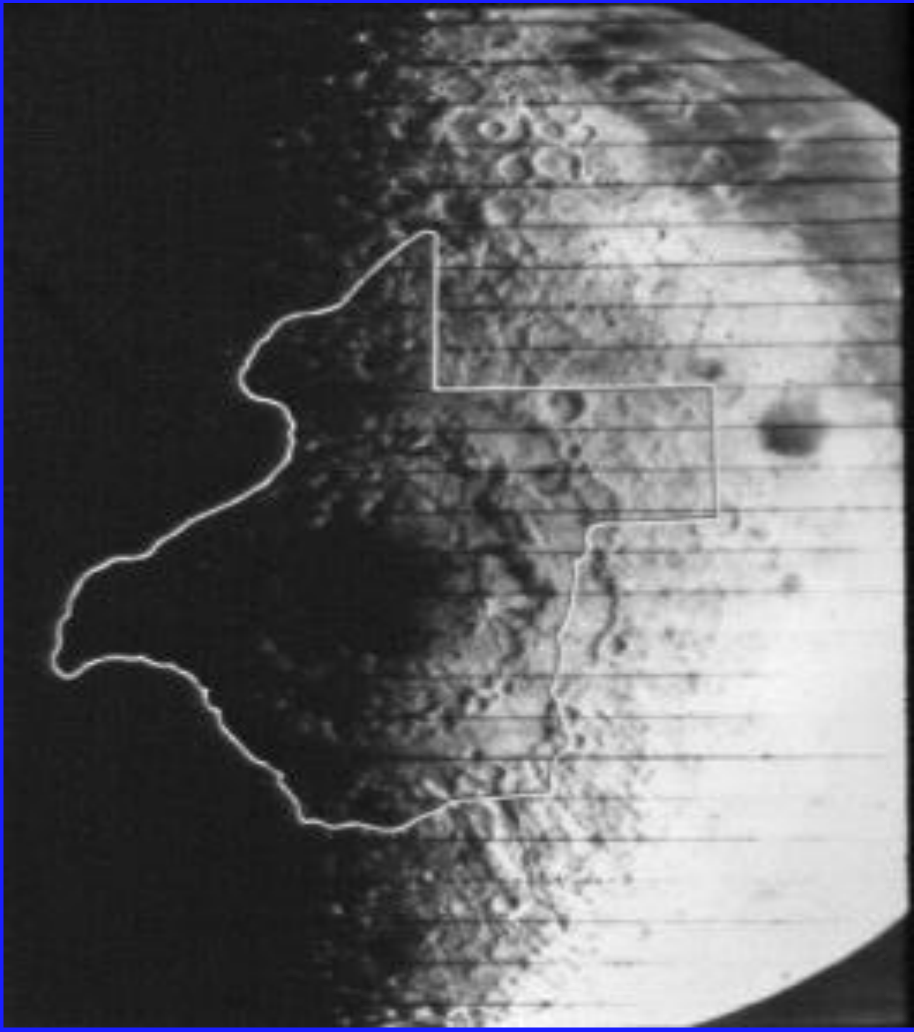
- **The Near side:**
  - Has more mare: 32% of its surface is mare covered compared with 2% of the far side (globally mare cover 17%).



- **The Far side:**
  - Large basins filled on near side, not filled on far side.

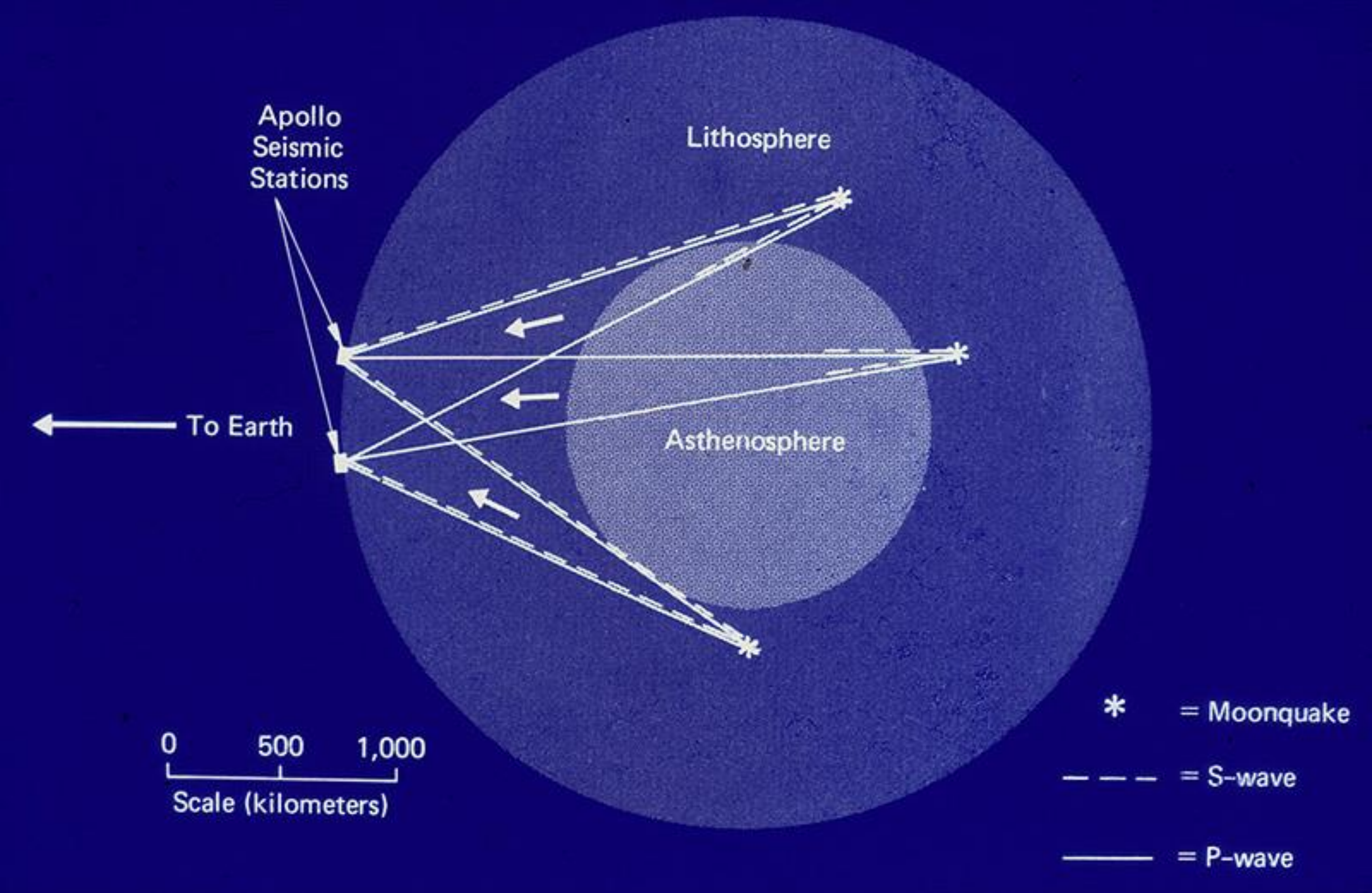
Gigantic impacts during the early history of the Moon caused formation of Multi Ring Basins



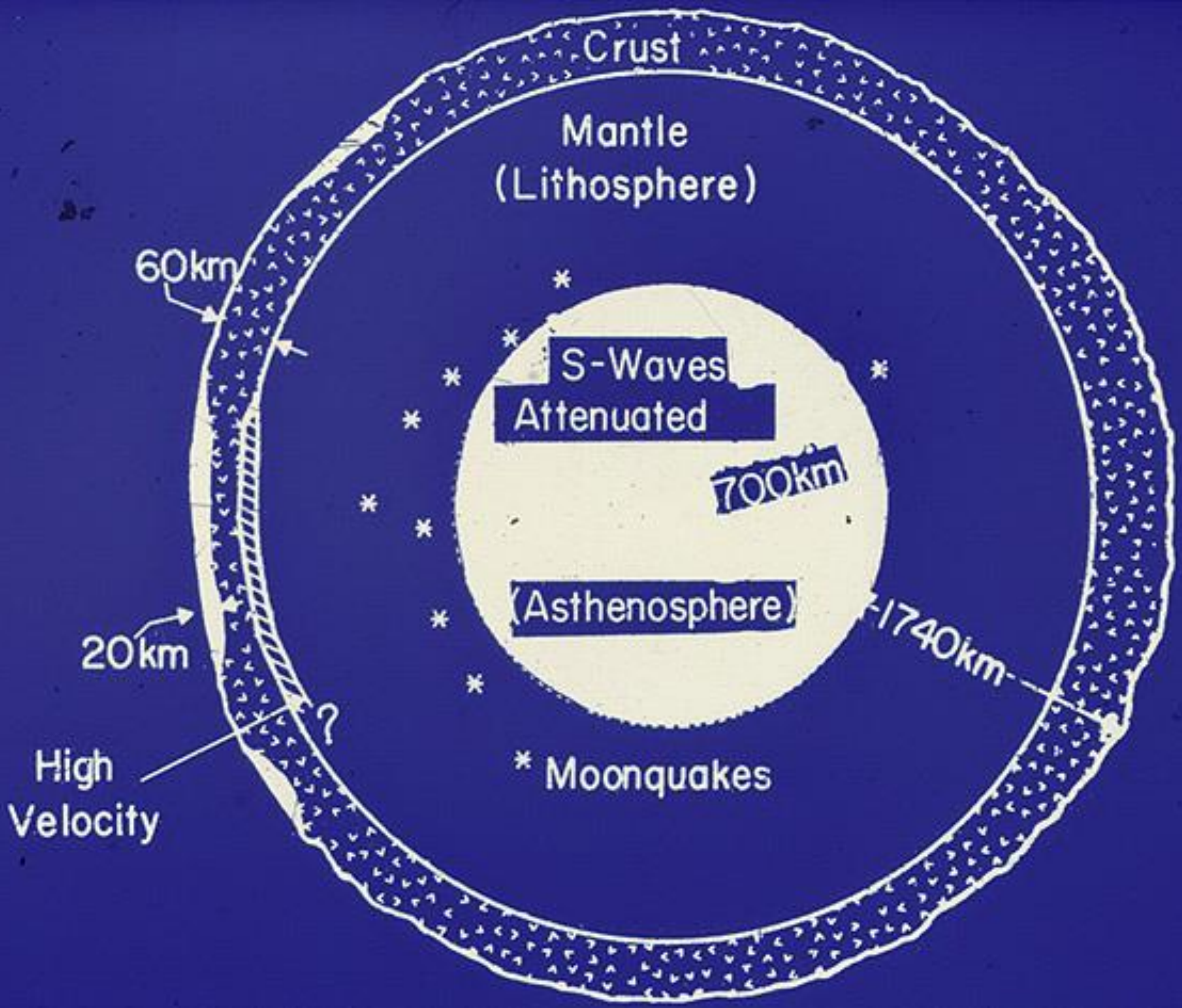


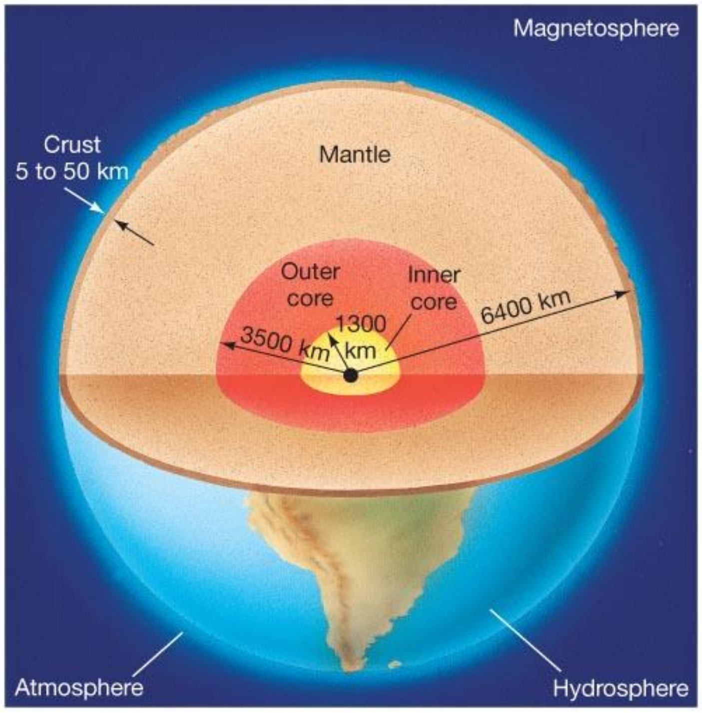
Interior of the Moon

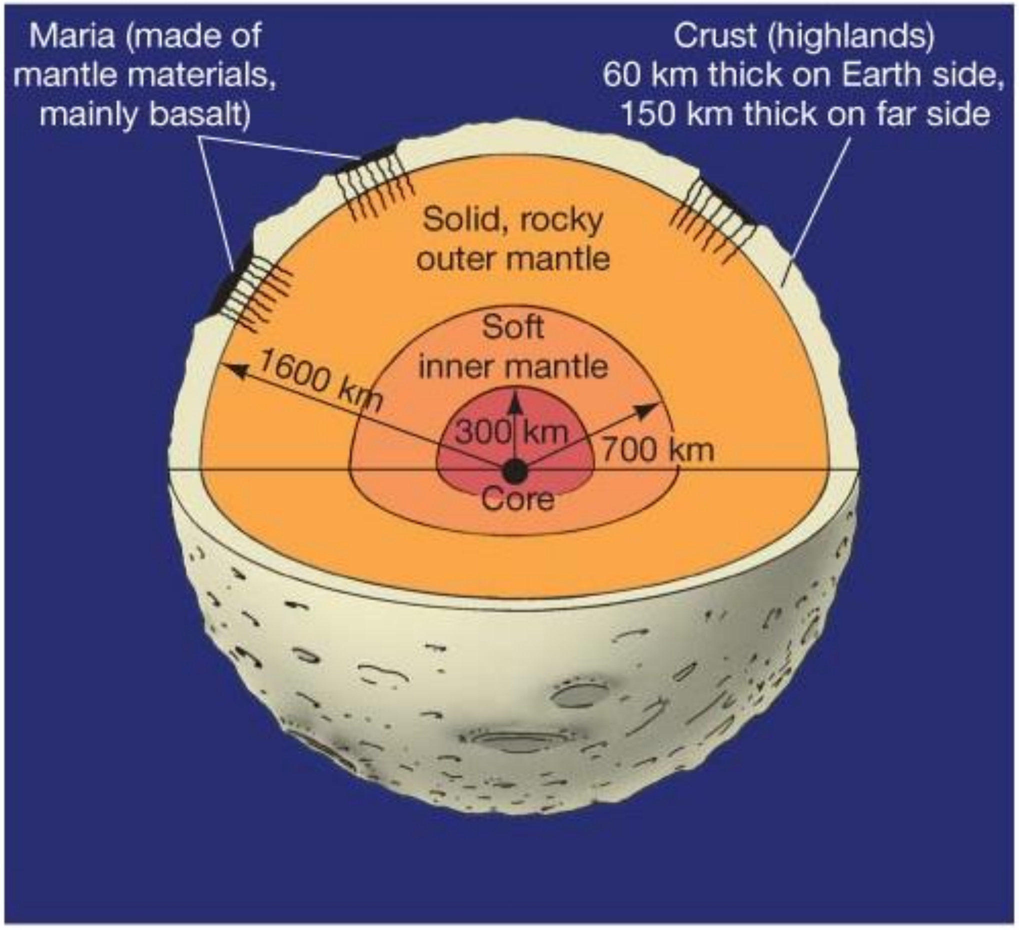
S-waves do not travel through “liquids”, hence, the Moon’s asthenosphere must be “plastic”.



Moon quakes originate at the boundary between the rigid lithosphere and the plastic asthenosphere, and on the side of the Moon facing Earth.




Magnetosphere
Crust
5 to 50 km
Mantle
Outer
core
Inner
core
1300
km
3500 km
6400 km
Atmosphere
Hydrosphere
(a)


Maria (made of
mantle materials,
mainly basalt)
Crust (highlands)
60 km thick on Earth side,
150 km thick on far side
Solid, rocky
outer mantle
Soft
inner mantle
1600 km
300 km
700 km
Core
(b)

The geochemical and petrological evidence:

The molten Moon floated – Anorthositic crust - 4.45 Ga – high albedo highland crust (60 to 100 km).

Initially hot, molten Moon cooled, the mantle (100 km) likely crystallized into a sequence of mineral zones by about 4.4 Ga.

Heavier elements sank to form a small metallic core (500 km).

Following the formation of the crust:

Major impacts on the surface produced many craters and multi-ring basins

South Pole-Aitken Basin – Oldest basin – 4.1 Ga – Far side

Orientale Basin – Multi ring basin – Near side –3.85 Ga

Mantle:

Beginning about 4.3 billion years ago, and peaking between 3.8 and 3.2 billion years ago, partial melting occurred in the lunar interior, and basaltic lavas flooded the low-lying basins on the surface.

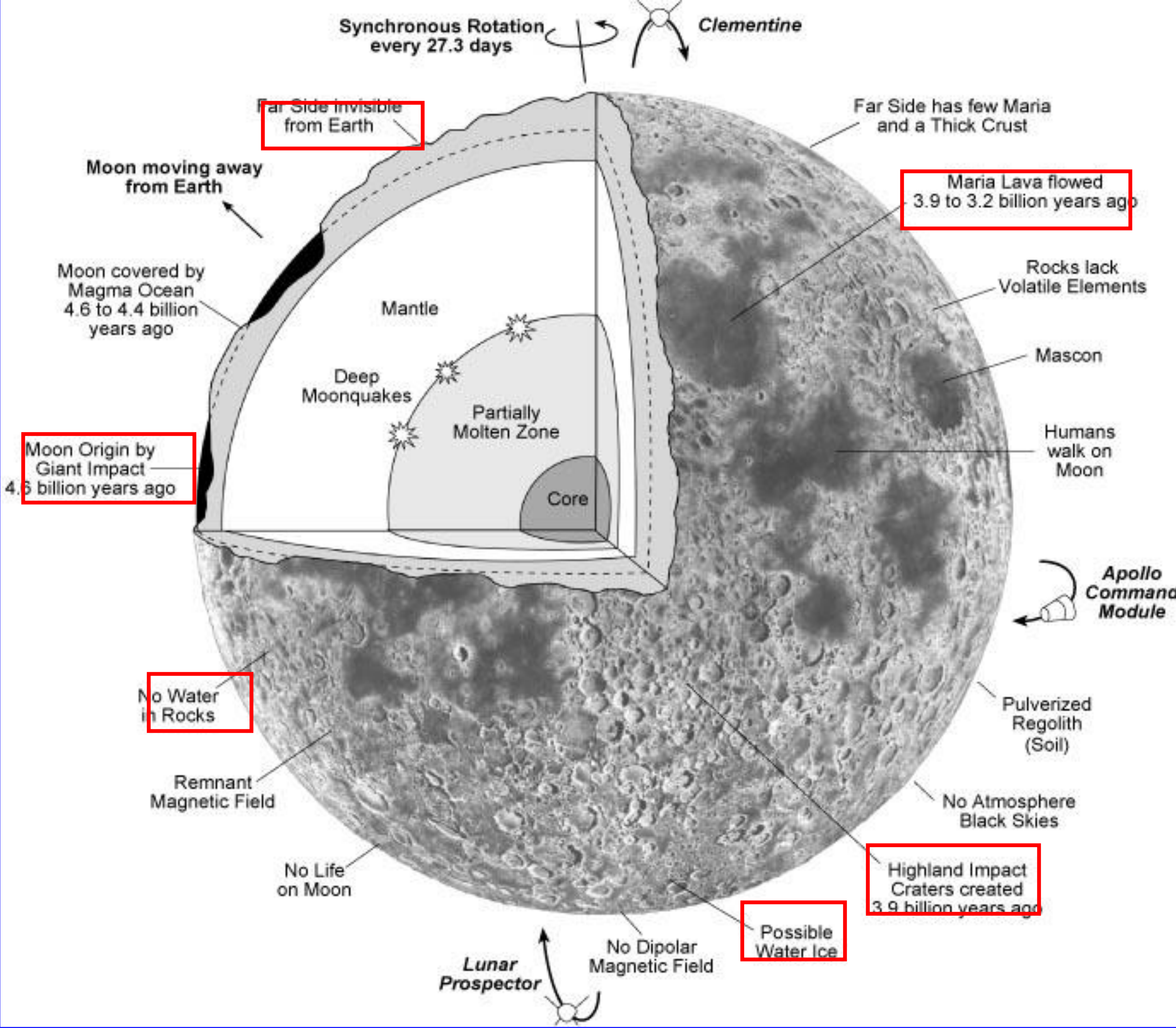
This occurred mostly on the nearside, where the crust is thinner, resulting in the low-albedo lunar mare.


Near Side
Far Side

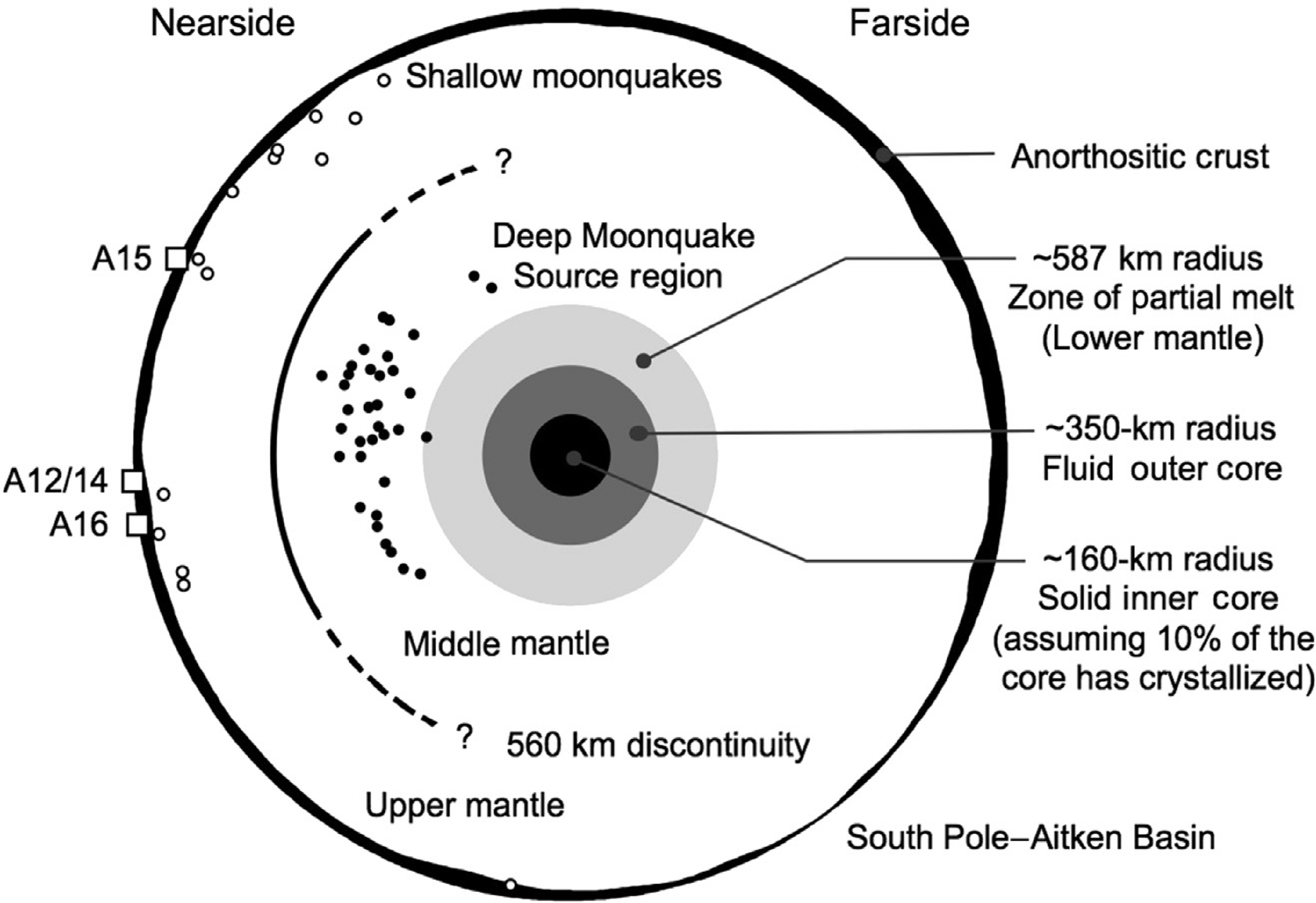
Major volcanic activity – Stopped - 3.0 Ga but??????
Minor activity - continued 1.0 to 1.3 billion years ago.

Something happening from inside some other thing must disturb from out side right???????????????

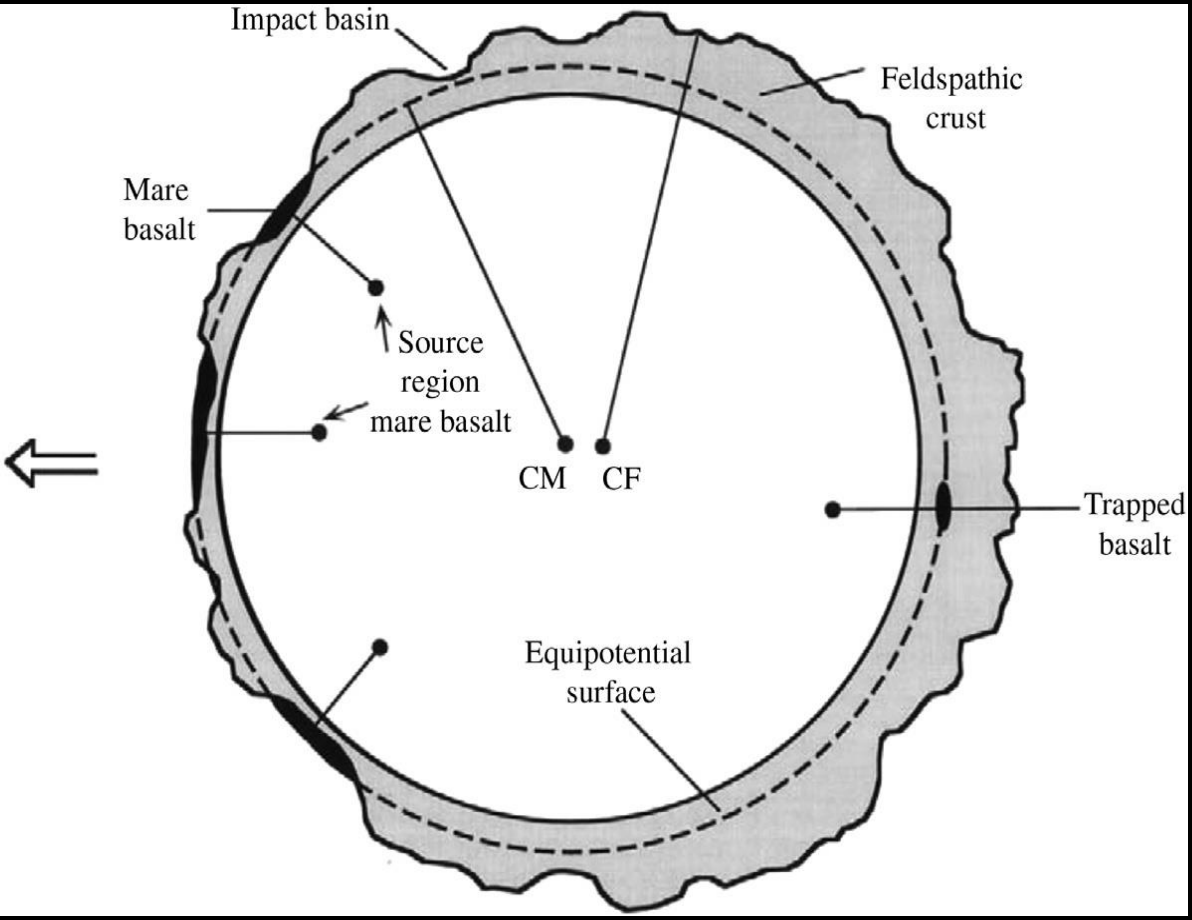
Few major impacts: The young rayed craters such as Copernicus and Tycho



Synchronous Rotation every 27.3 days
Clementine
Far Side invisible from Earth
Far Side has few Maria and a Thick Crust
Moon moving away from Earth
Maria Lava flowed 3.9 to 3.2 billion years ago
Moon covered by Magma Ocean 4.6 to 4.4 billion years ago
Mantle
Rocks lack Volatile Elements
Deep Moonquakes
Partially Molten Zone
Mascon
Humans walk on Moon
Moon Origin by Giant Impact 4.6 billion years ago
Core
Apollo Command Module
No Water in Rocks
Pulverized Regolith (Soil)
Remnant Magnetic Field
No Atmosphere Black Skies
No Life on Moon
Highland Impact Craters created 3.9 billion years ago
Possible Water Ice
Lunar Prospector
No Dipolar Magnetic Field



Nearside
Farside
Shallow moonquakes
Anorthositic crust
?
A15
Deep Moonquake
Source region
~587 km radius
Zone of partial melt
(Lower mantle)
~350-km radius
Fluid outer core
A12/14
A16
~160-km radius
Solid inner core
(assuming 10% of the
core has crystallized)
Middle mantle
?
560 km discontinuity
Upper mantle
South Pole–Aitken Basin



Schematic cross-section of the Moon in the equatorial plane showing the displacement of the Moon's center of mass toward Earth (figure left), due to the presence of a thicker farside crust (figure right).
The crustal thickness is exaggerated for clarity. An equipotential surface is indicated with a dashed line.

Mantle

The average P-wave velocity is 7.7 km/s and the average S-wave velocity is 4.45 km/s down to about 1200 km.

Pyroxene-rich upper mantle

Olivine-rich lower mantle beneath about a depth of 500 - 600 km.

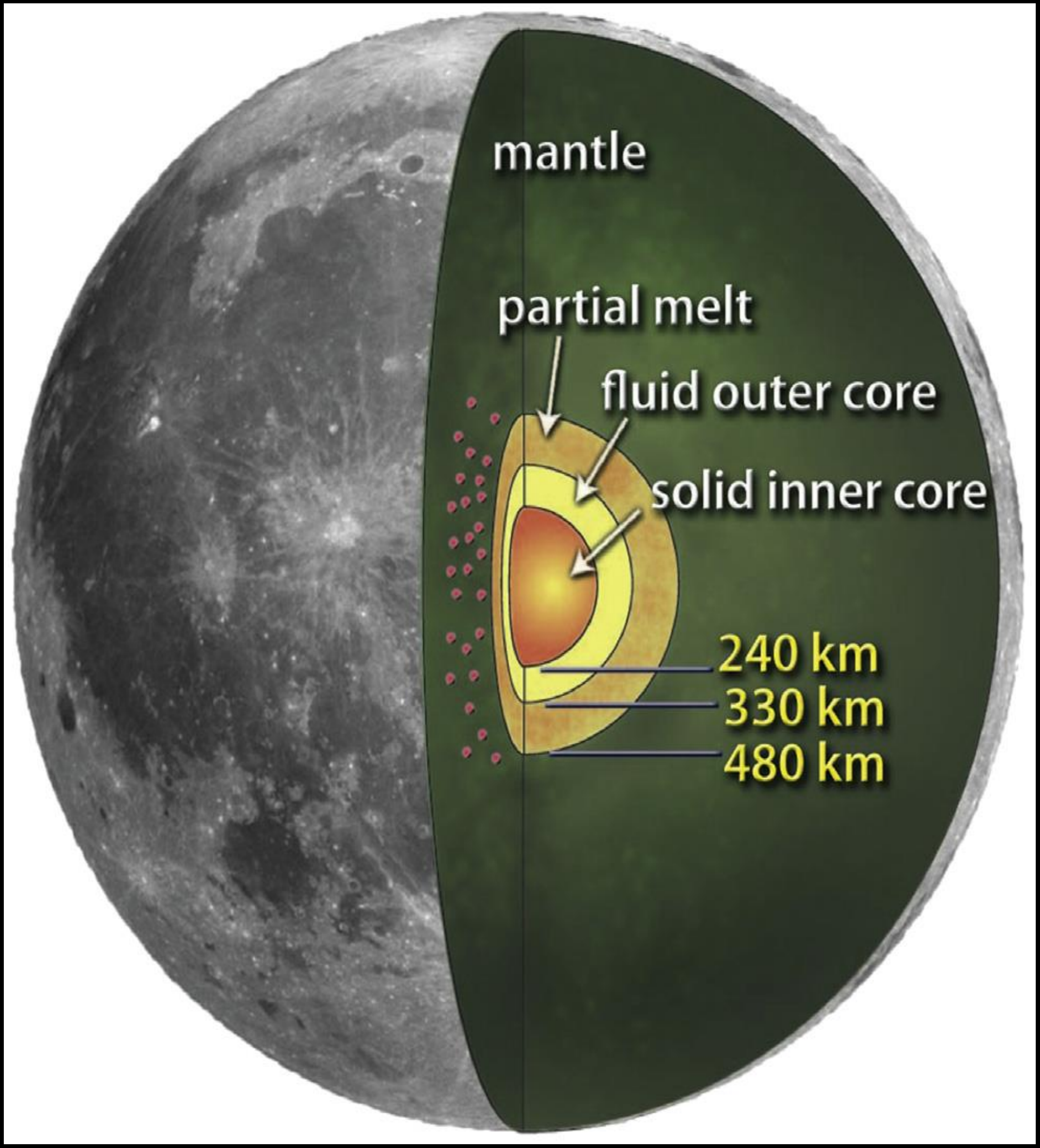
The seismically active deep moonquake zone lies deep within the lower mantle at about 800 - 1000 km depth.

P-waves are transmitted through the center of the Moon, but S-waves are missing, possibly suggesting the presence of a melt phase

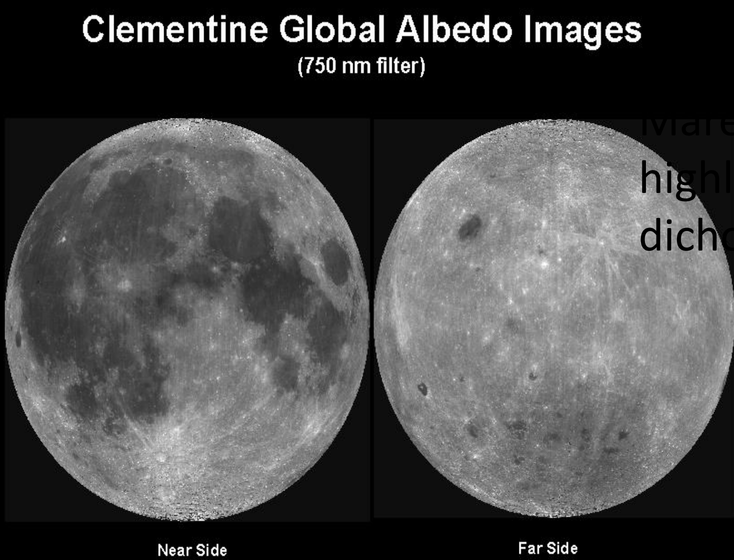
Core:

Apollo orbital magnetometers results in an upper limit of 400 to 500 km radius for a highly conducting (e.g. metallic).

Solid inner core, a fluid outer core, and a partial melt boundary layer that likely accounts for the lack of observed far side deep moonquake signals

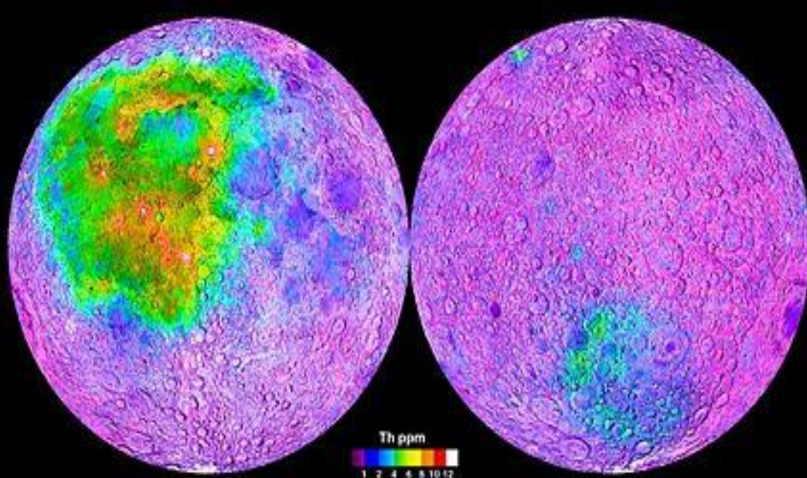

mantle
partial melt
fluid outer core
solid inner core
240 km
330 km
480 km

Lunar surface compos

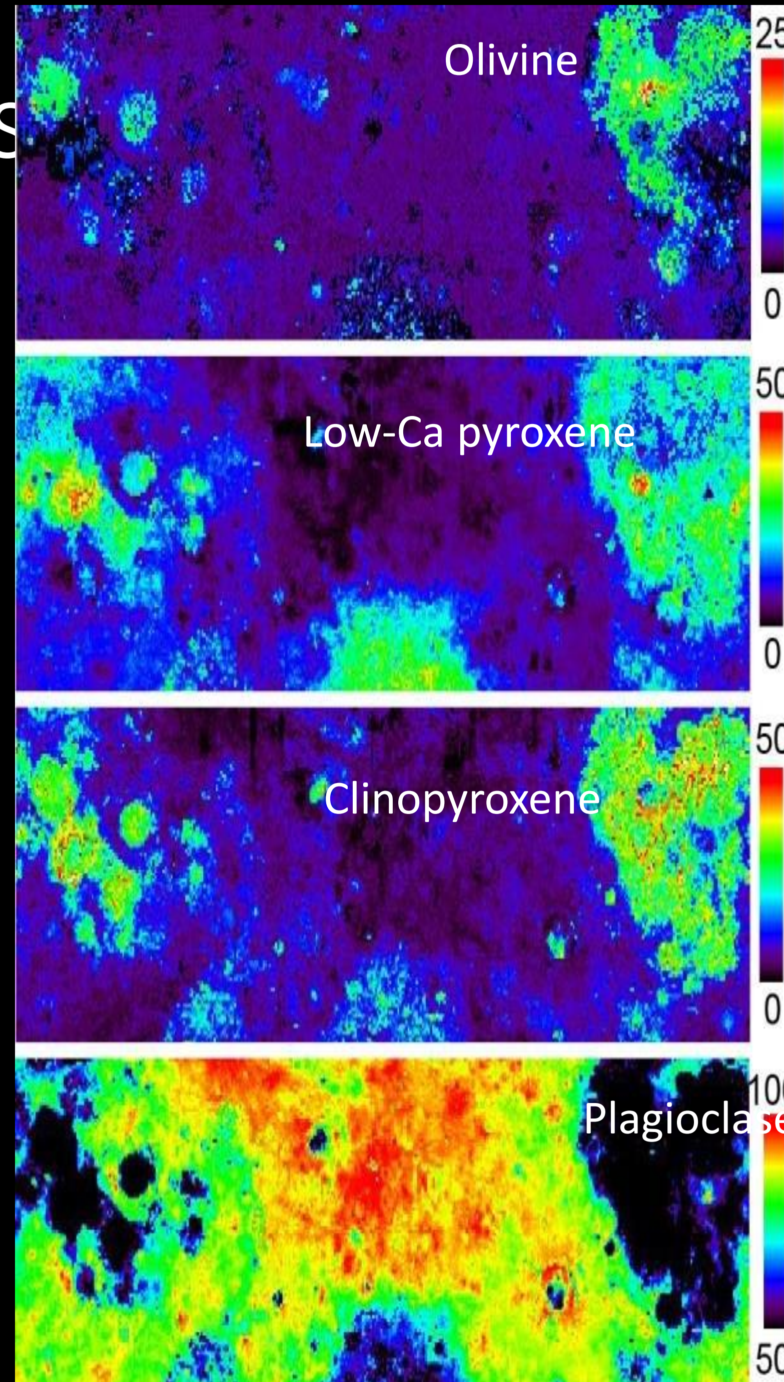


Mare
highl
dicho

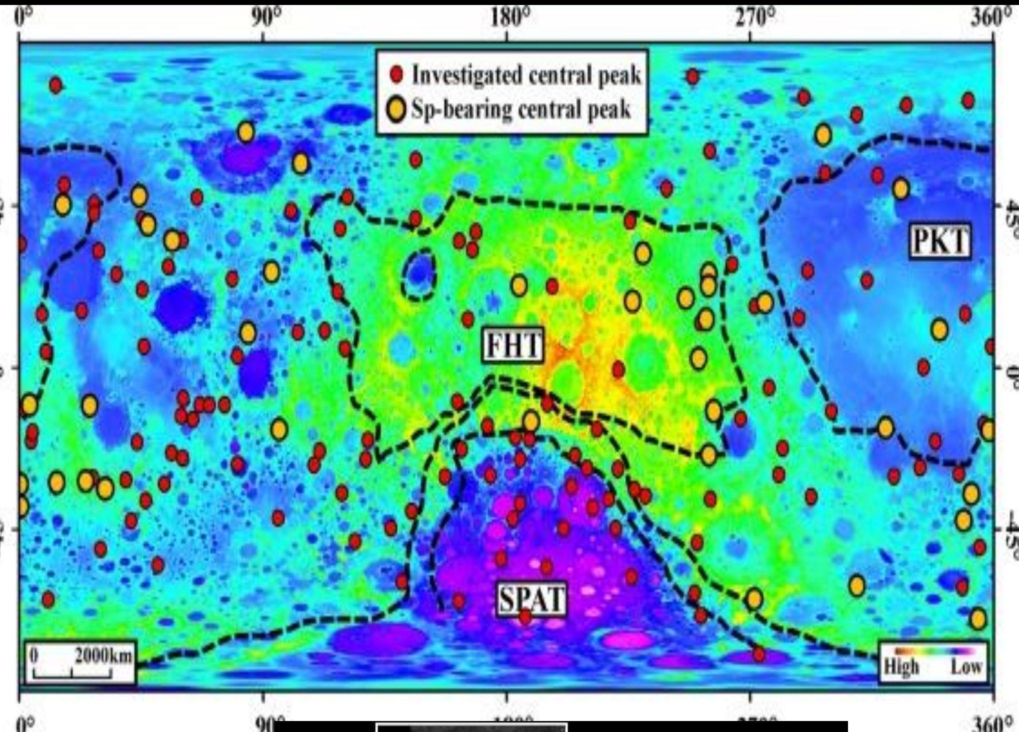
Th map from LP-GRS

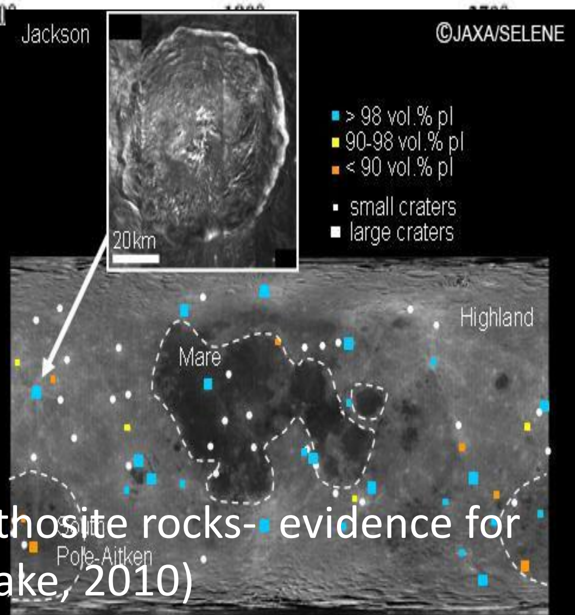


Kaguya Multi-band imager at 80m /pixel (Lemelin et

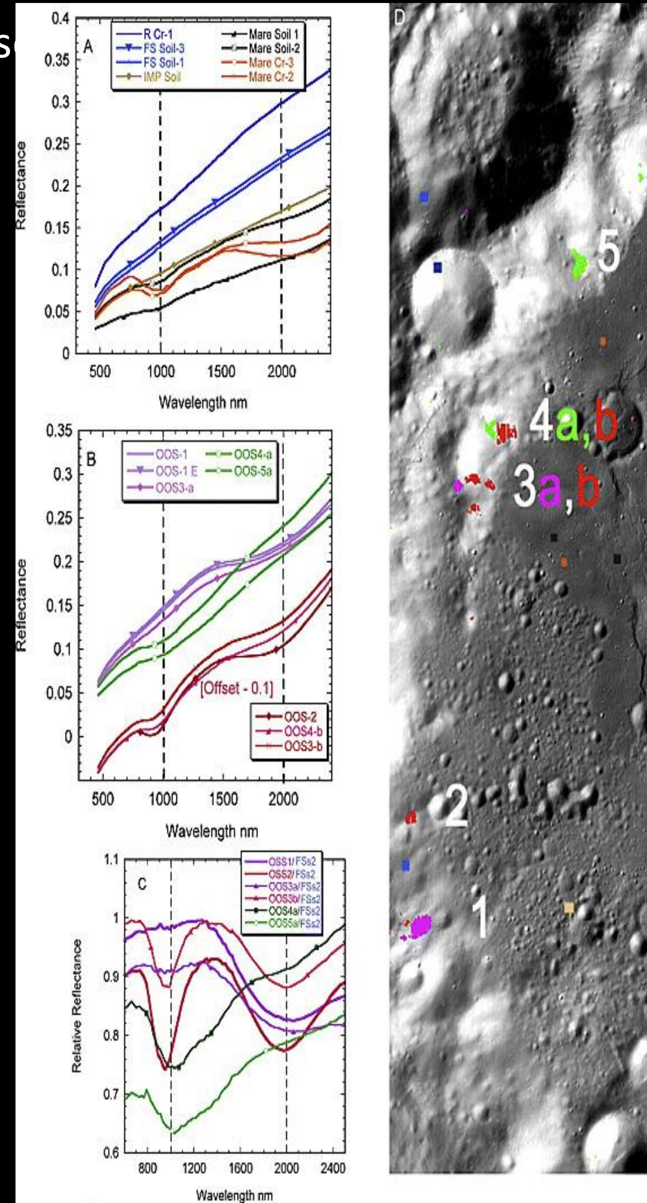


Mg spinel in the central peak of craters- petrogenesis (Priss





Pure anorthosite rocks- evidence for LMO (Ohtake, 2010)



New rock types termed ‘OOS’ at Moscoviense Basin on the lunar farside (Pieters, 2011)

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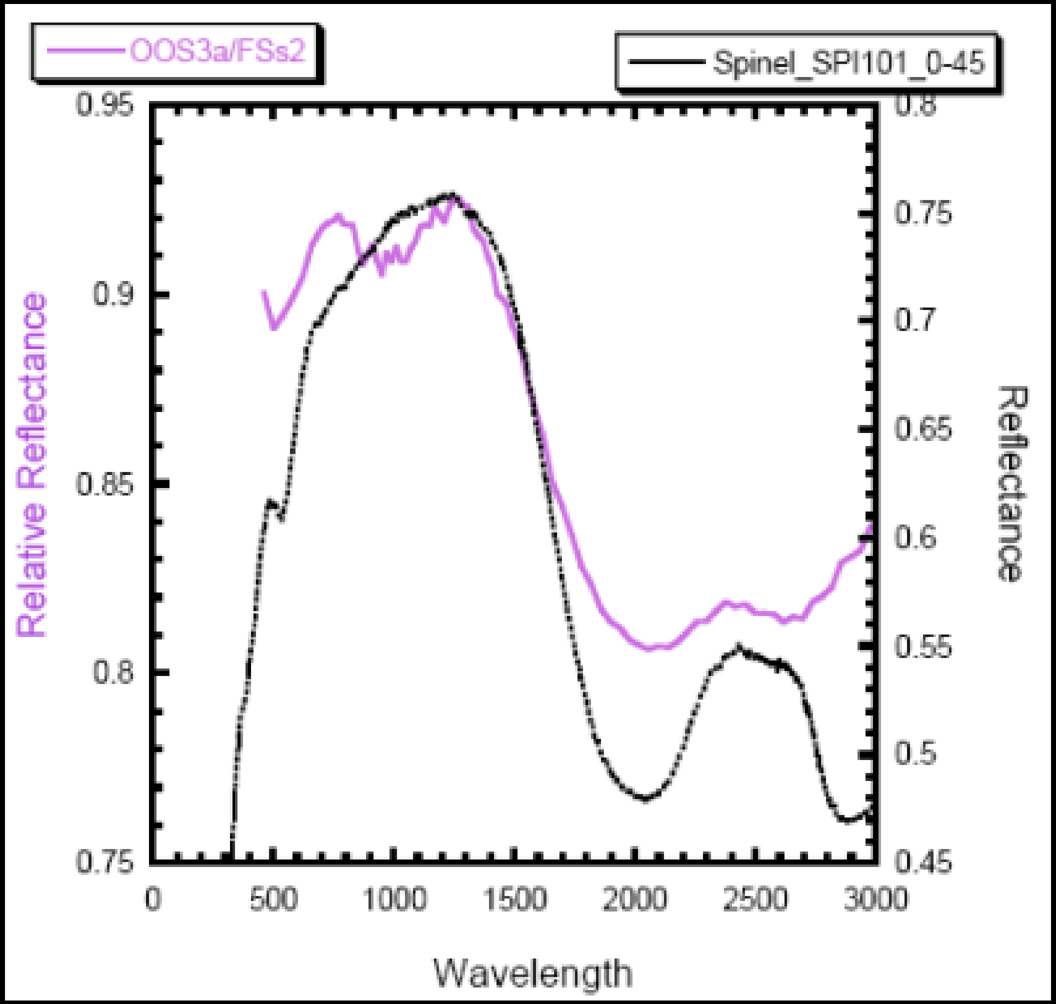


Reflectance spectrum of spinel-rich area OOS3a relative to featureless FS soil compared with a laboratory spectrum of Mg-rich spinel [7]

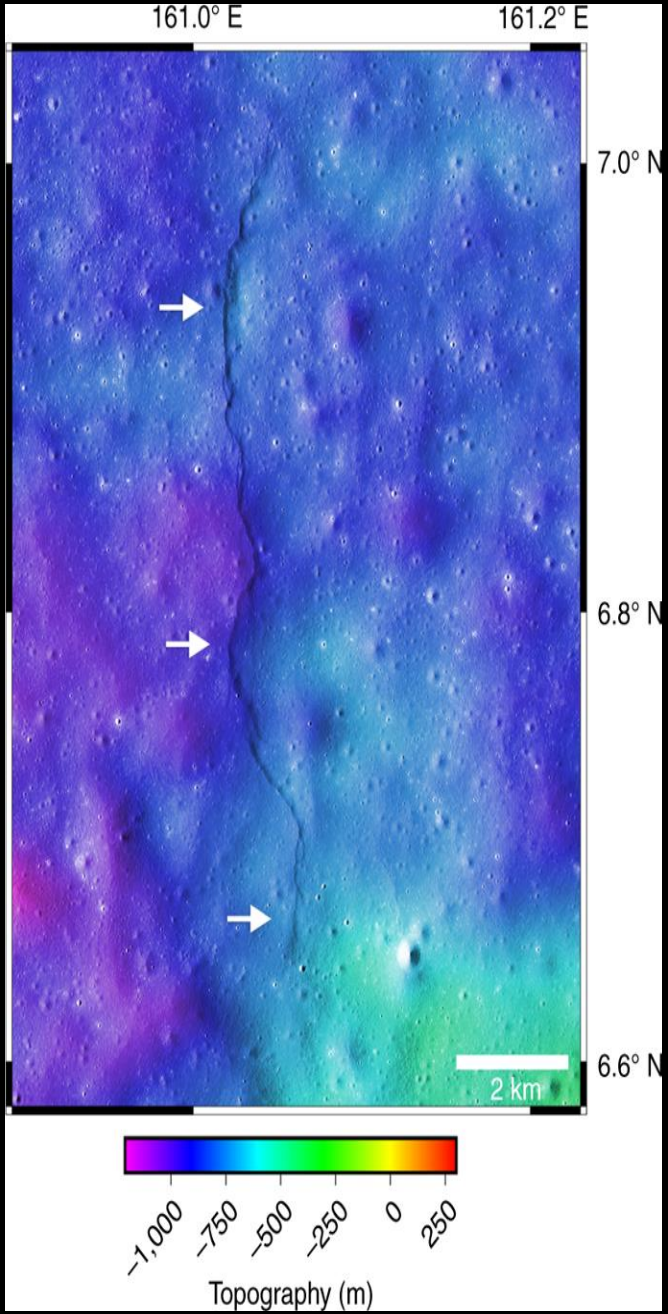
Moon quakes

Apollo missions detected 28 shallow moonquakes during 1969–1977.

Young faults discovered (Watters et al, Nature geoscience, 2019)

Tectonic features with linkage to the largest quake on 3 January 1975 (Senthil Kumar et al, GRL, 2019)

Moon is not geologically dead!



Watterson et al, 2019

Poles of the Moon

- **Large areas of permanently shadowed regions (PSRs) create cold traps holding volatiles stable for billions of years**
  - **Multiple observations show evidence for water ice**
  - **LCROSS impact in Cabeus crater : 5-7 wt% H_2O along with an array of volatiles as in comets- direct detection with no ambiguity**
  - **LAMP and LOLA measurements in South Polar PSRs show surface reflectance properties consistent with 0.1 to 10 wt% water frost**
  - **Water ice (∼30 wt % ice mixed with regolith suggested)**

Water ice does exist at the lunar poles

Quantity, state, distribution, time variation?

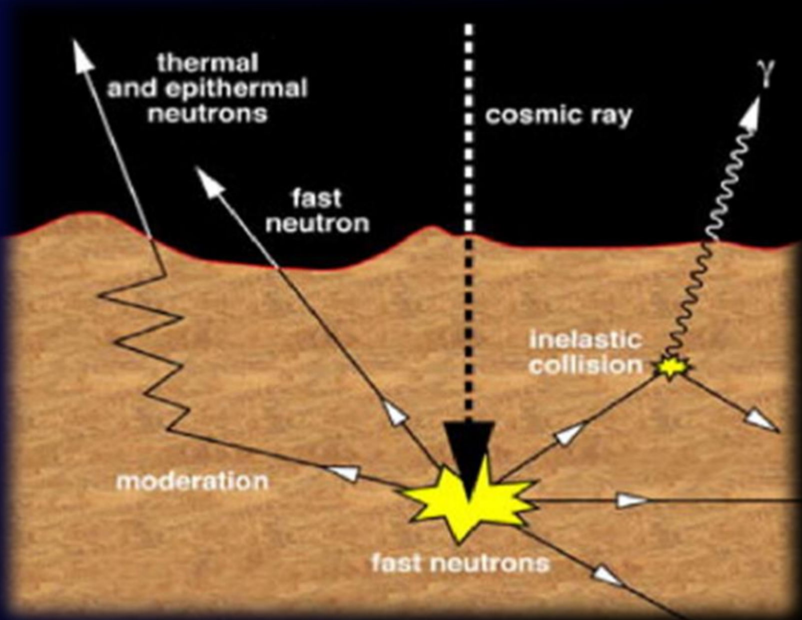
Water on the Moon: Remote Sensing from the Lunar Reconnaissance Orbiter

Michael Schaffner
Dr. William Boynton, LPL
Dr. Gerard Droege, LPL

19th Annual Arizona Space Grant Consortium Symposium

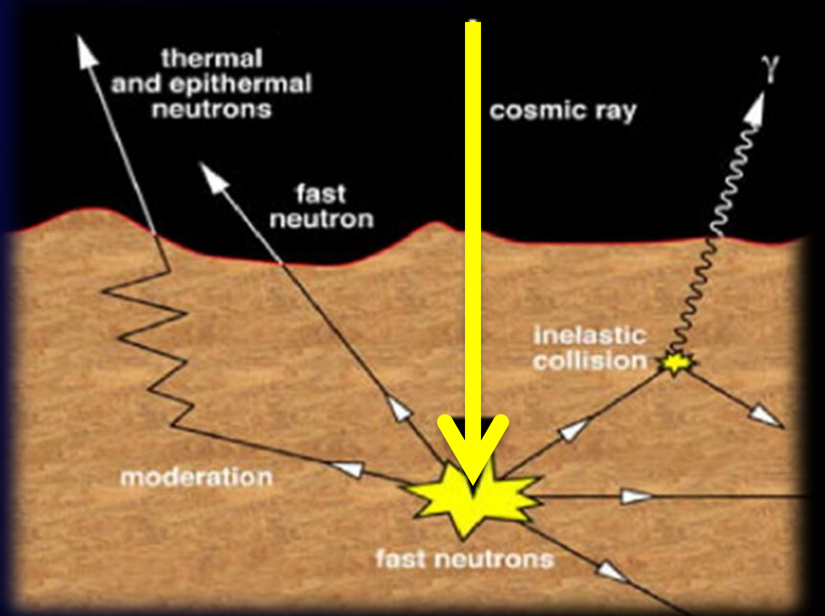
University of Arizona
April 21st, 2012

Intro to research with the Lunar Exploration Neutron Detector (LEND)



- Galactic cosmic rays (GCRs) regularly strike lunar atoms, and their energy knocks neutrons loose
- Neutrons' speeds are moderated best by similar-size hydrogen atoms
- LEND detects these slower (epithermal) neutrons

Intro to research with the Lunar Exploration Neutron Detector (LEND)



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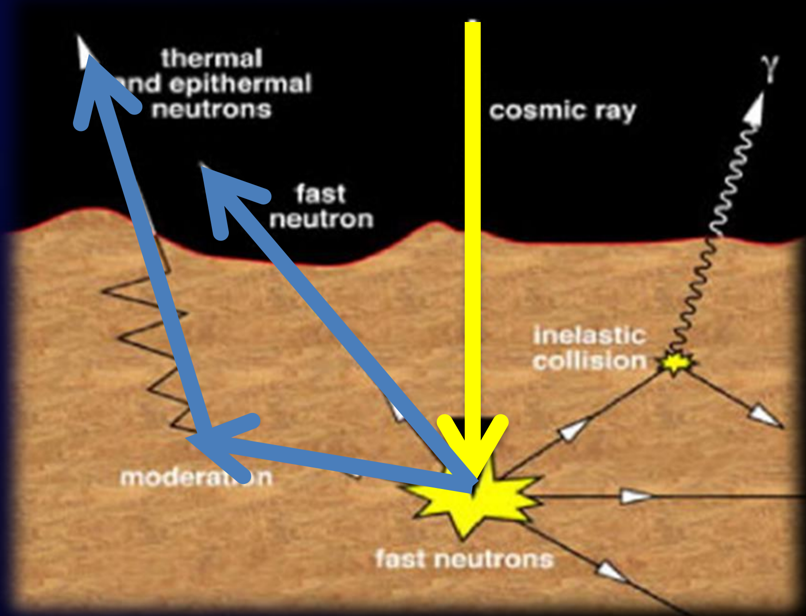

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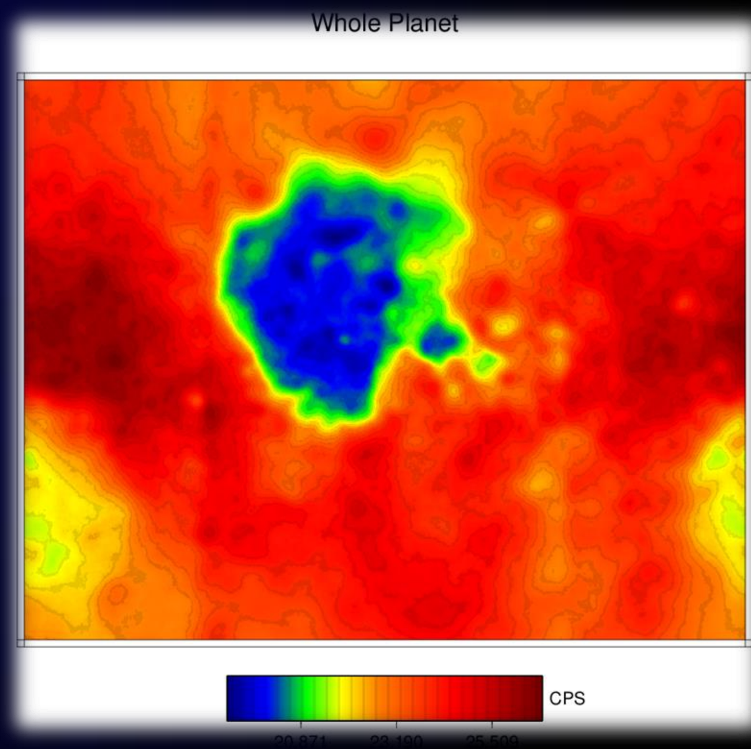
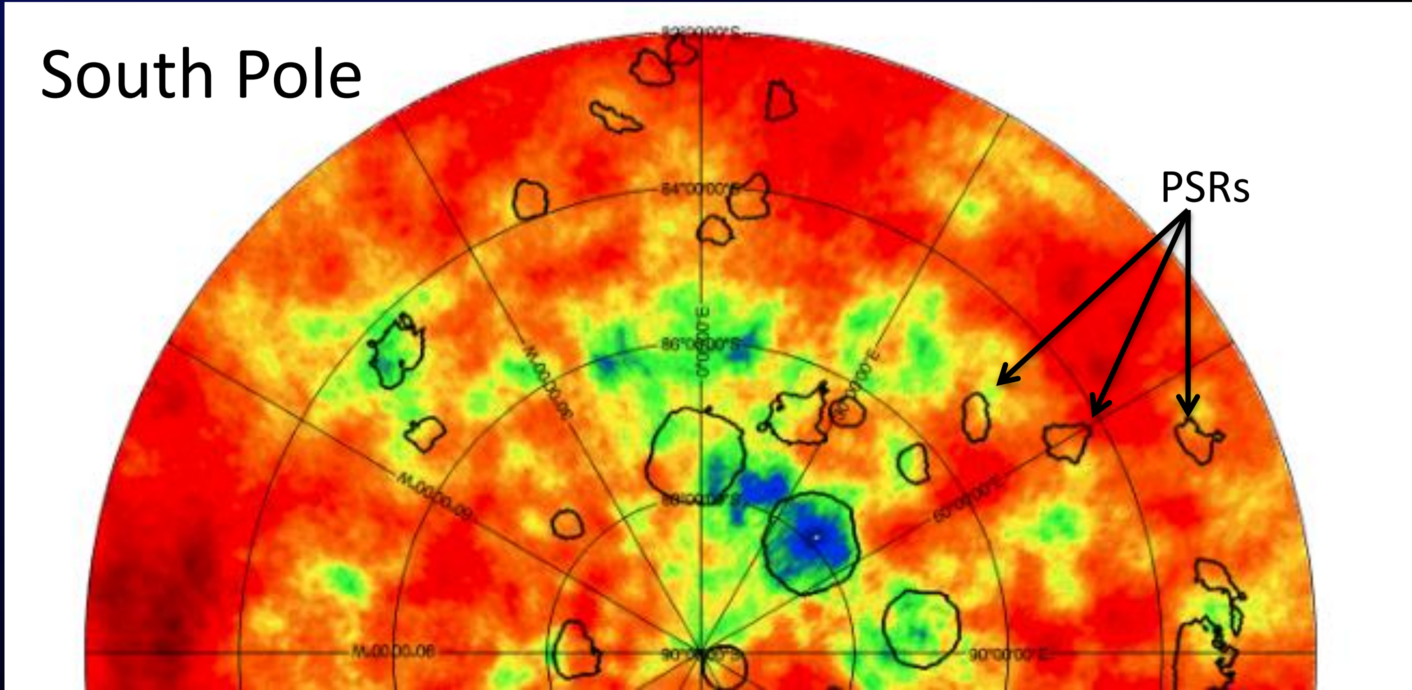
An introduction to LEND research, continued



- The LEND instrument records the number of neutrons detected each second, along with latitude, longitude, altitude, angle, and more.
- Using these data, scientists have mapped the surface of the moon to visually depict regions that deviate from the “normal” neutron counts.

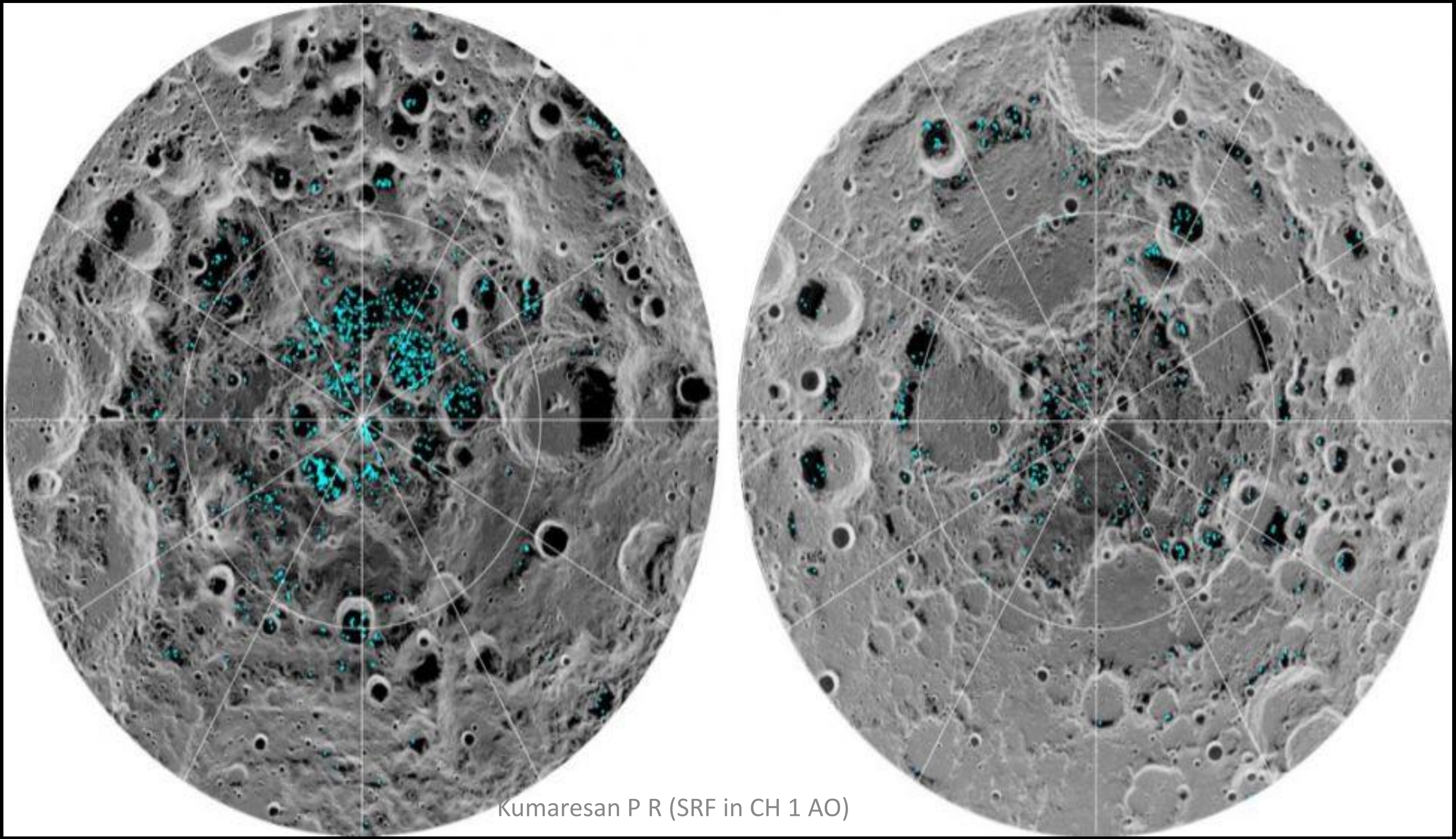
LEND Research Project
2011-2012

It had been previously theorized that lunar water would be found in the form of ice in Permanently Shadowed Regions (PSRs). LEND maps disagree:

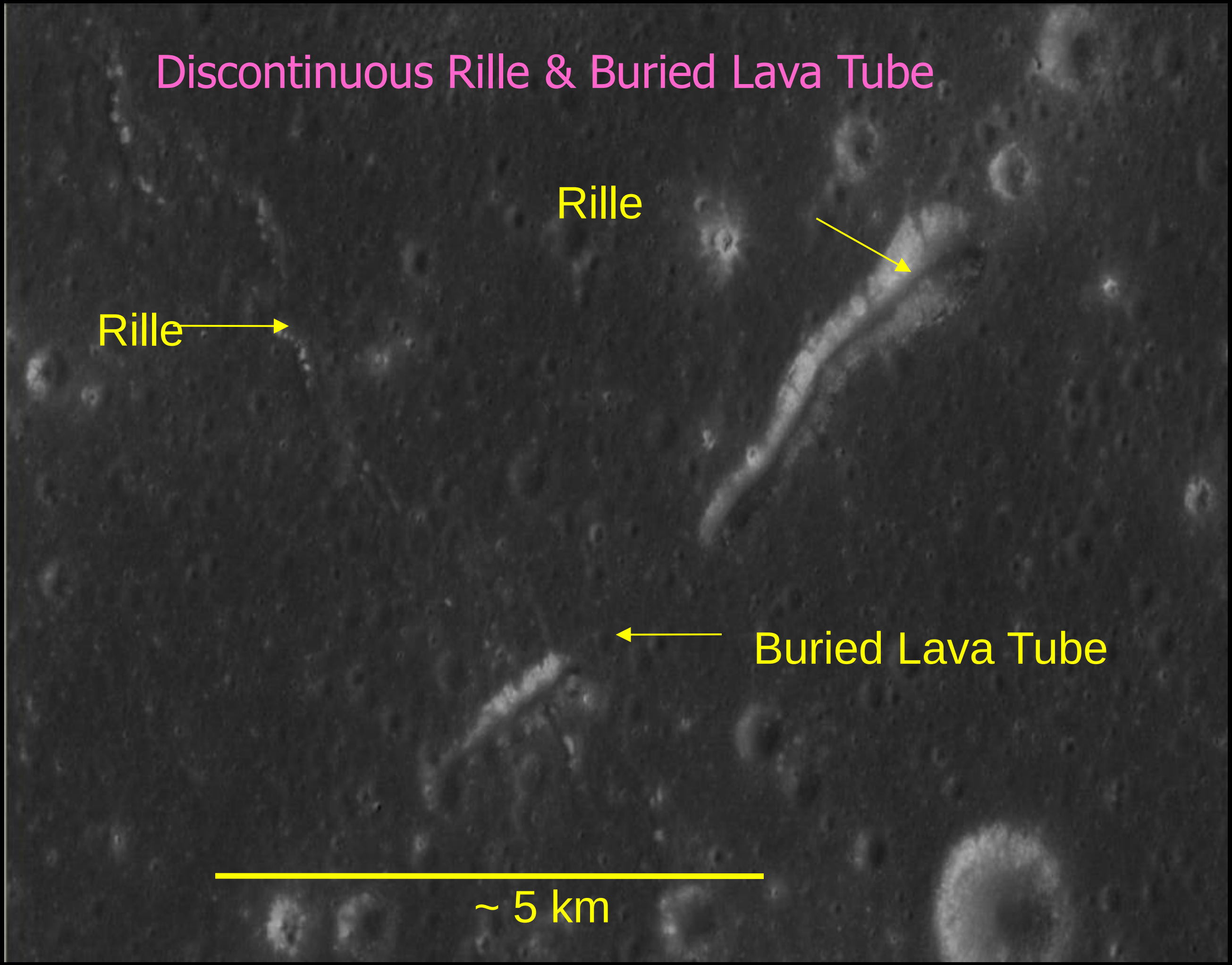


Water ice from M3

South Pole **North Pole**



Terrain mapping camera visible band



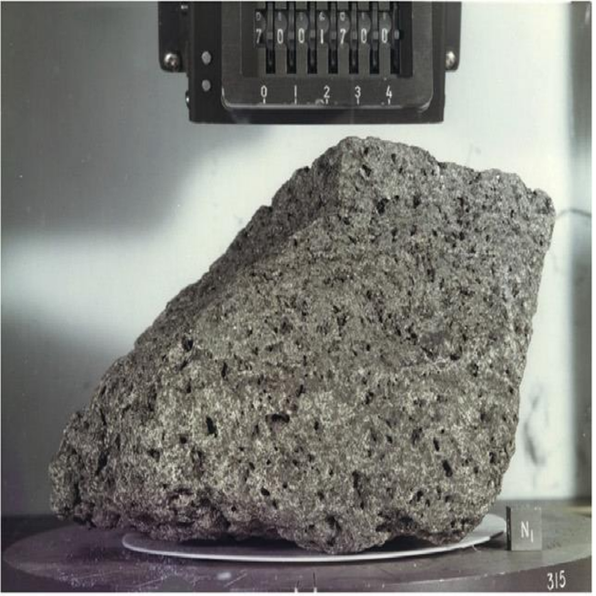
Chandrayaan-1, TMC Orbit 798 13 January, 2009
Location: Oceanus Procellarum
Longitude: 58.317 W / Latitude: 14.111 N

Volcanism on the Moon:

1. Dark maria, the low-lying smooth plains that make up large fractions of the near side.

2. 1949 book The Face of the Moon, astronomer Ralph Baldwin presented convincing evidence that the maria are made up of floods of basalt, a dark lava, rich in iron that is abundant on the Earth.

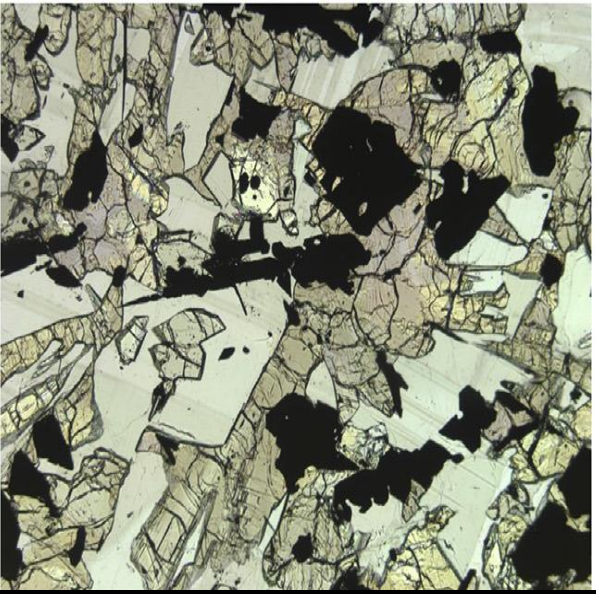
3. Most striking from the returned samples is the age of these lavas. The basalts returned by Apollo range in age from 4.3 to 3.1 Ga, as old as the very oldest rocks on the Earth.

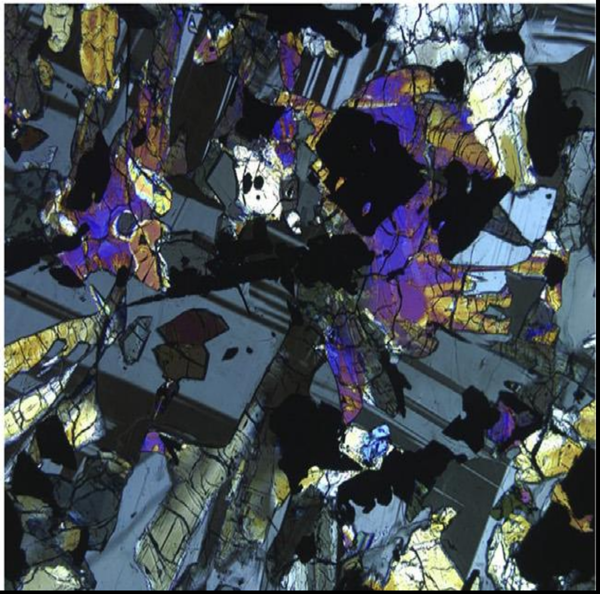


Apollo 17 high-Ti mare basalt
70017

Hand sample scale: 1 cm

Thin section FOV: 2 mm





Hand specimen (top left; markings in centimeters) and thin section (bottom, plane light and xpl; Field of view e 2 mm) of

Apollo 17
high-titanium mare basalt
70,017.

Lunar basalts are
made up predominantly of augite (Ca-rich pyroxene), olivine, plagioclase, and ilmenite;

They are
depleted in volatile elements and contain no
hydrous minerals.

But now science evidence show indigenous water

The Moon has a crust, formed early in it's history by global melting (the "magma ocean"). This differentiation produced the plagioclase-rich crust and the mantle source regions for the later mare basalts.

Thus, lunar volcanic rocks contain important information about the composition of the deep interior of the Moon.

Basalt: Iron-rich and magnesium-rich minerals olivine and pyroxene.

High density - Seismic velocity - lunar mantle – Mostly same mineral.

Blobs of silicate melt coagulate deep in a planet's interior and then slowly migrate upward, where they may force their way to the surface and be extruded onto a planetary surface as a lava flow.

Little evidence for the collection of large amounts of magma at shallow depths in the Moon's crust and

For its retention in subsurface "holding chambers".

Most magmas appear to have migrated upward through the mantle and crust and then erupted fairly quickly.

Example: lunar pyroclastic glasses – completely unfractionated, suggesting a rapid ascent from the mantle and violent, immediate eruption.

The chemistry of basaltic magmas tells us approximately where they formed within the Moon (at depths of 150 to 400 km) along with what processes subsequently affected them.

The mantle underwent melting episodes at several depths over a very long period of time, a period lasting at least 700 million years long and more likely over a time span of one to two billion years.

They came????????????????

Cracks that they themselves propagated or via fractures induced by the formation of the giant craters and basins of the highlands.

The maria appear prominent in areal extent, the lavas are relatively

It is estimated that the mare basalts cover about 16% of the Moon by area but probably account for less than about 1% of the total volume of the crust.

Apollo Mare Basalts:

Similar to Like terrestrial basalts, the lunar mare basalts are made mostly of the minerals pyroxene and plagioclase and are rich in iron and magnesium.

Grain size – very fine (usually <1 mm). (reason????????????????? rapid cooling)

Geomorphological evidences some lunar lavas have small, bubble-like holes in them (vesicles), indicating that the magmas contained gas during eruption.

As with basalts on Earth, mare basalts are formed by the partial melting of the lunar mantle, made of mostly pyroxene and olivine.

The first basalts - Apollo 11 landing site in Mare Tranquillitatis

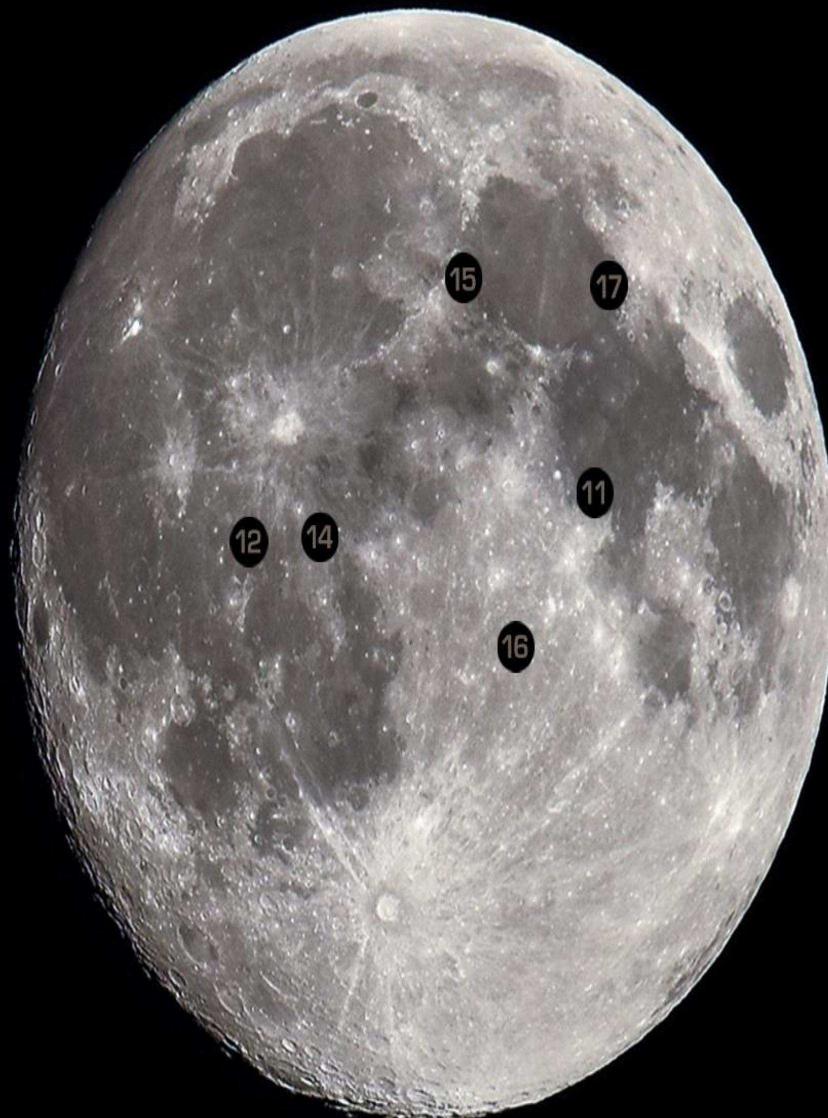
These rocks are remarkable in several respects. Mare basalts are not only devoid of water or any hydrous phase but they are also depleted in all the volatile elements.

These are rich in titanium (mineral ilmenite, an oxide of iron and titanium) whereas depletion in aluminum. the relative darkness (low albedo) of the maria as opposed to the terrae (lunar highlands).

Lavas from the Moon contain some minor minerals that are not found in Earth rocks. One of these, another iron titanium mineral, was given the name armalcolite.

APOLLO LANDING SITES

Apollo 11	Mare Tranquillitatis July 20, 1969
Apollo 12	Oceanus Procellarum November 19, 1969
Apollo 14	Fra Mauro February 5, 1971
Apollo 15	Hadley/Apennines July 30, 1971
Apollo 16	Descartes April 20, 1972
Apollo 17	Taurus-Littrow December 11, 1972



Moon photo captured June 18, 2016 by Jason Major
www.LightsInTheDark.com

Sources:
http://airandspace.si.edu/explore-and-learn/topics/apollo/apollo-program/landing-missions/sites.cfm
http://spaceflight.nasa.gov/gallery/images/apollo/apollo17/hires/s72-32719.jpg

The compositional properties of the lunar basalts reflect the unique chemical environment in which they formed:

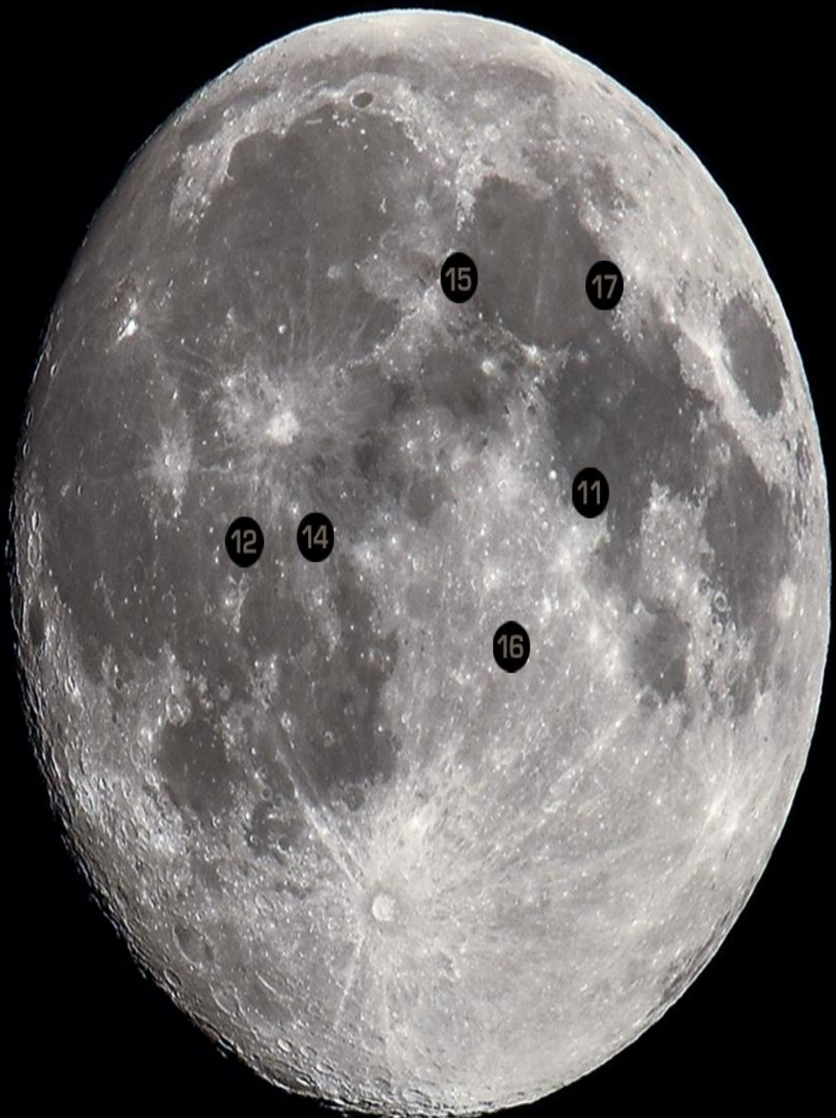
Inside a small planet (resulting in low interior pressures),
Depleted in volatile elements,
Containing little or no water (but see below), and
Erupted onto a low-gravity surface in a vacuum.

Next, Apollo 12 – similar inferences to Apollo 11 but comparatively low in titanium 600 to 700 million years younger (erupted about 3.1 Ga).

This differences say???????????????????????????????????

APOLLO LANDING SITES

Apollo 11	Mare Tranquillitatis	July 20, 1969
Apollo 12	Oceanus Procellarum	November 19, 1969
Apollo 14	Fra Mauro	February 5, 1971
Apollo 15	Hadley/Apennines	July 30, 1971
Apollo 16	Descartes	April 20, 1972
Apollo 17	Taurus-Littrow	December 11, 1972



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http://spaceflight.nasa.gov/gallery/images/apollo/apollo17/hires/s72-32719.jpg

The lower titanium and younger ages of the Apollo 12 basalts confirm that the maria were not erupted as a single, massive flood of lava across the surface all at one time but rather, the formation of the maria was an extended process
that involved different batches of magma erupted in different places at different times.

In short, the samples told us that the Moon had a complicated volcanic history and a protracted geological evolution.

Apollo 15 - inside the rim of the basin containing Mare Imbrium

Returned low-titanium basalts

Slightly older than those from Apollo 12 these lavas crystallized about 3300 million years ago.

Apollo 17, landing on the edge of Mare Serenitatis, returned very high in titanium basalts.

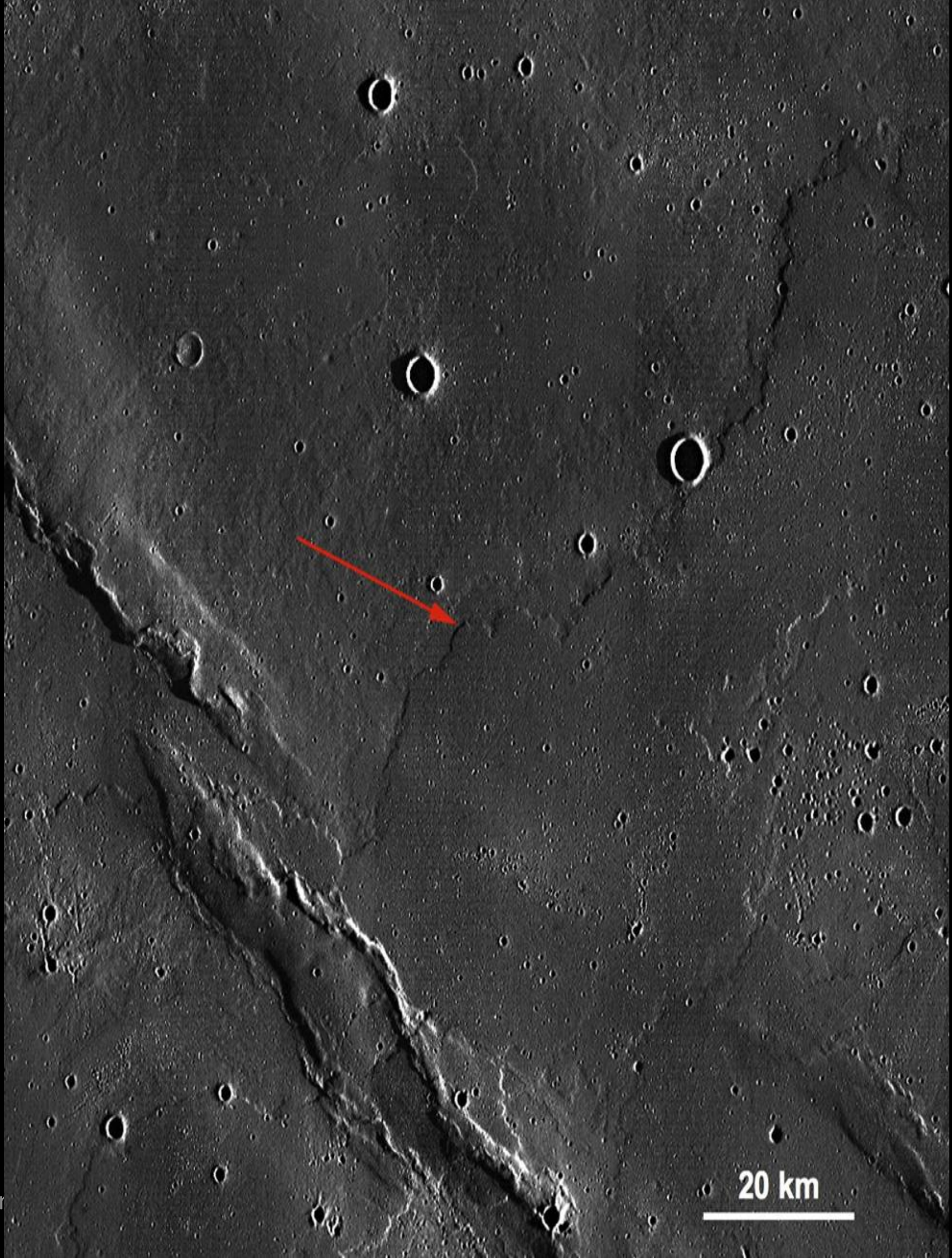
Similar to those from Apollo 11, but slightly younger, about 3700 million years old.

Happy in analyzing results

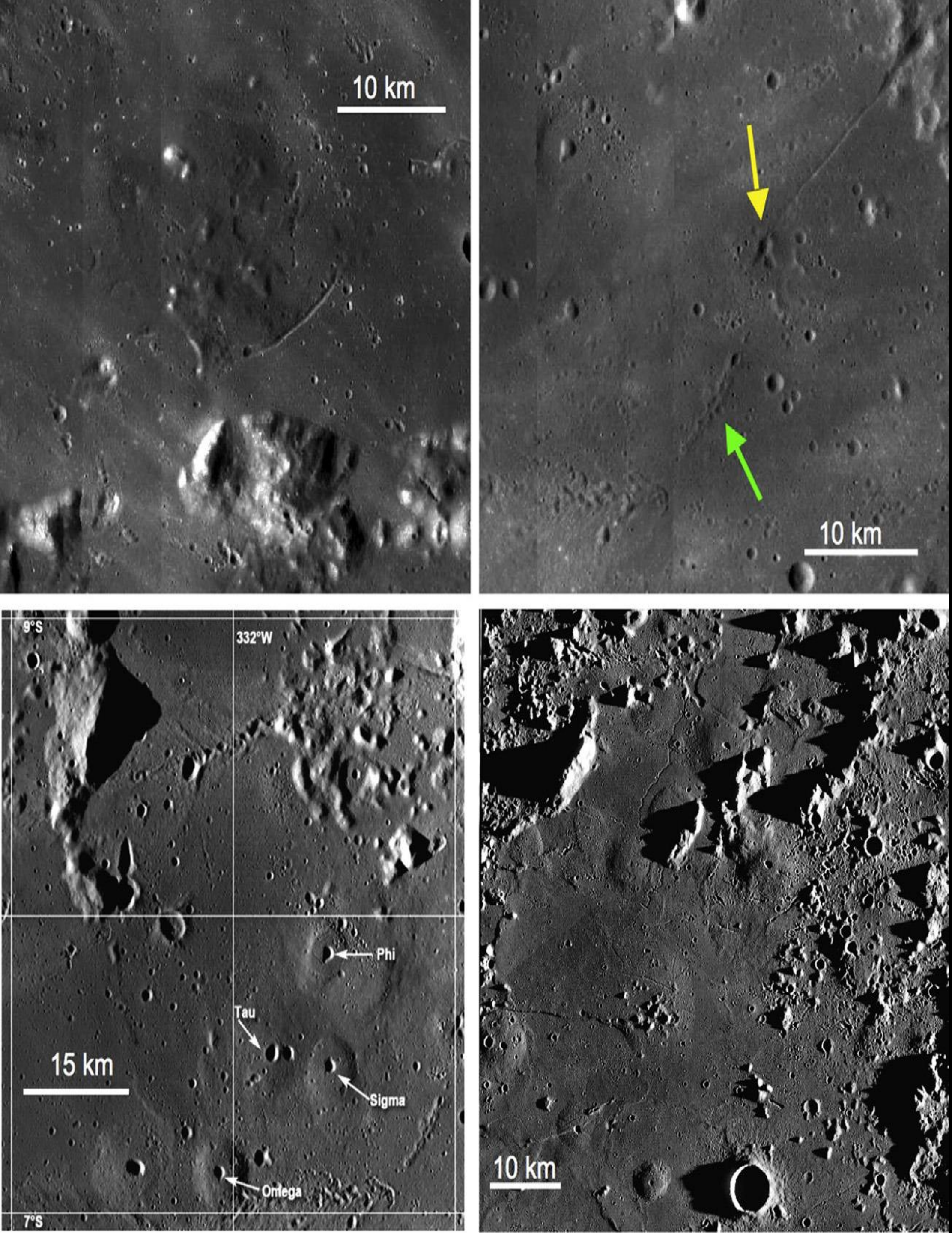
These results led some to conclude that the Moon had a fairly simple volcanic history, with early eruptions of
high-titanium lavas and late eruptions of low-titanium lava.

STYLES OF VOLCANISM AND ASSOCIATE
LANDFORMS

1. Lunar Lava Flows



Kumar



Small volcanic features of the lunar maria.

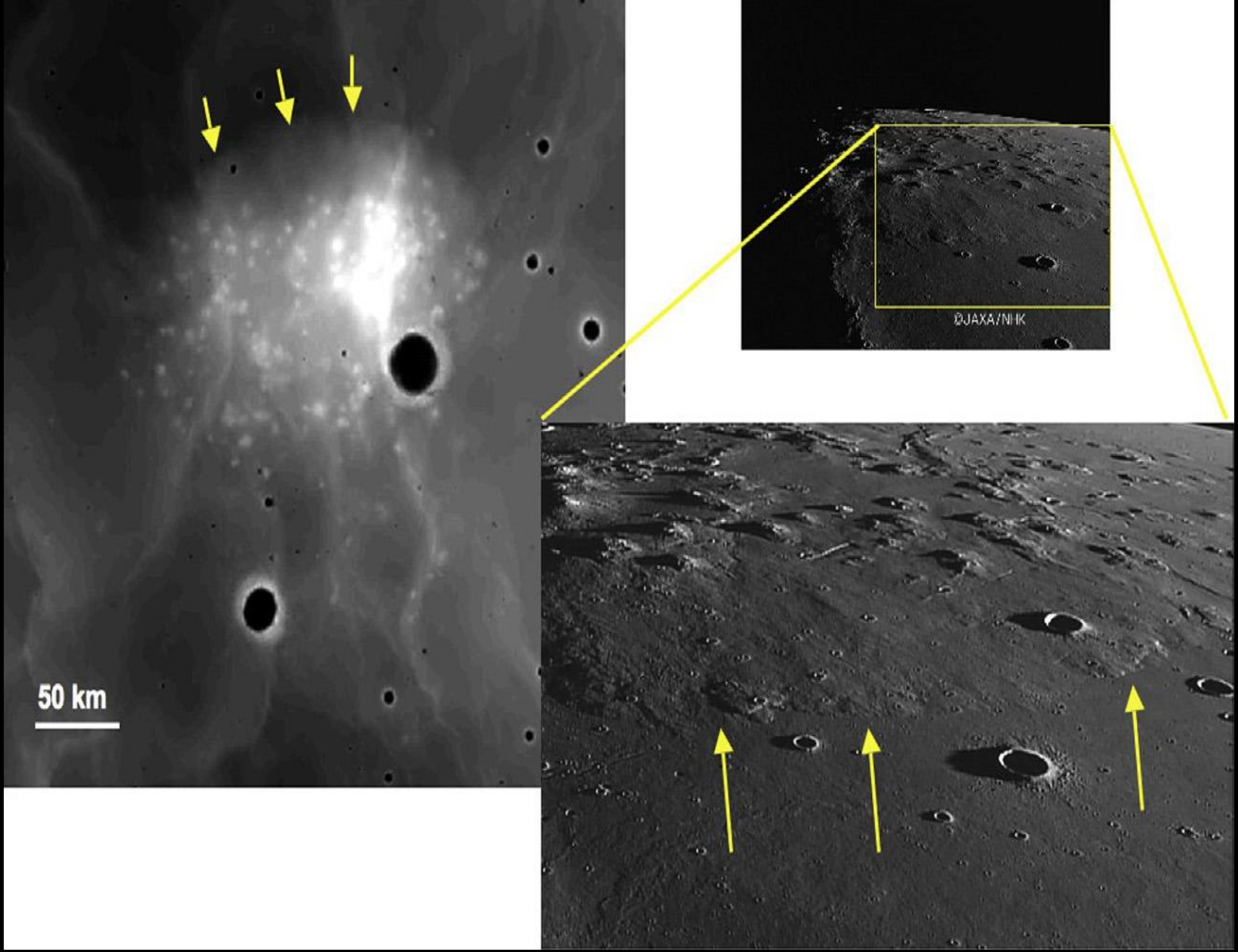
Top left: vent area of the late Imbrium flows
showing dark mantling and spatter constructs.

Bottom left: small shield volcanoes near Hortensius. These features are likely to
be small basaltic constructs, erupted from a single vent.

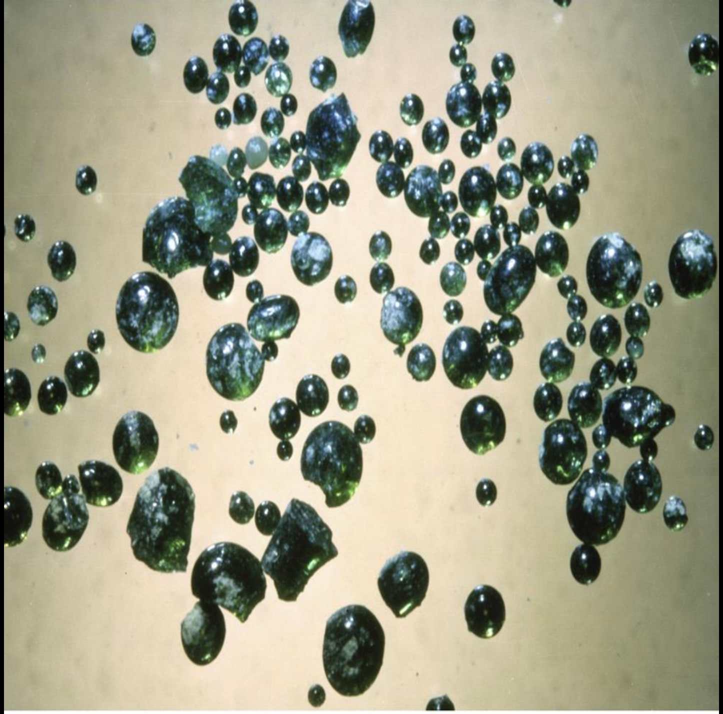
Top right: spatter cones aligned along a
fissure vent near Hortensius.

Bottom right: cones, rilles, and linear vents near the Hortensius volcanic complex.

AO



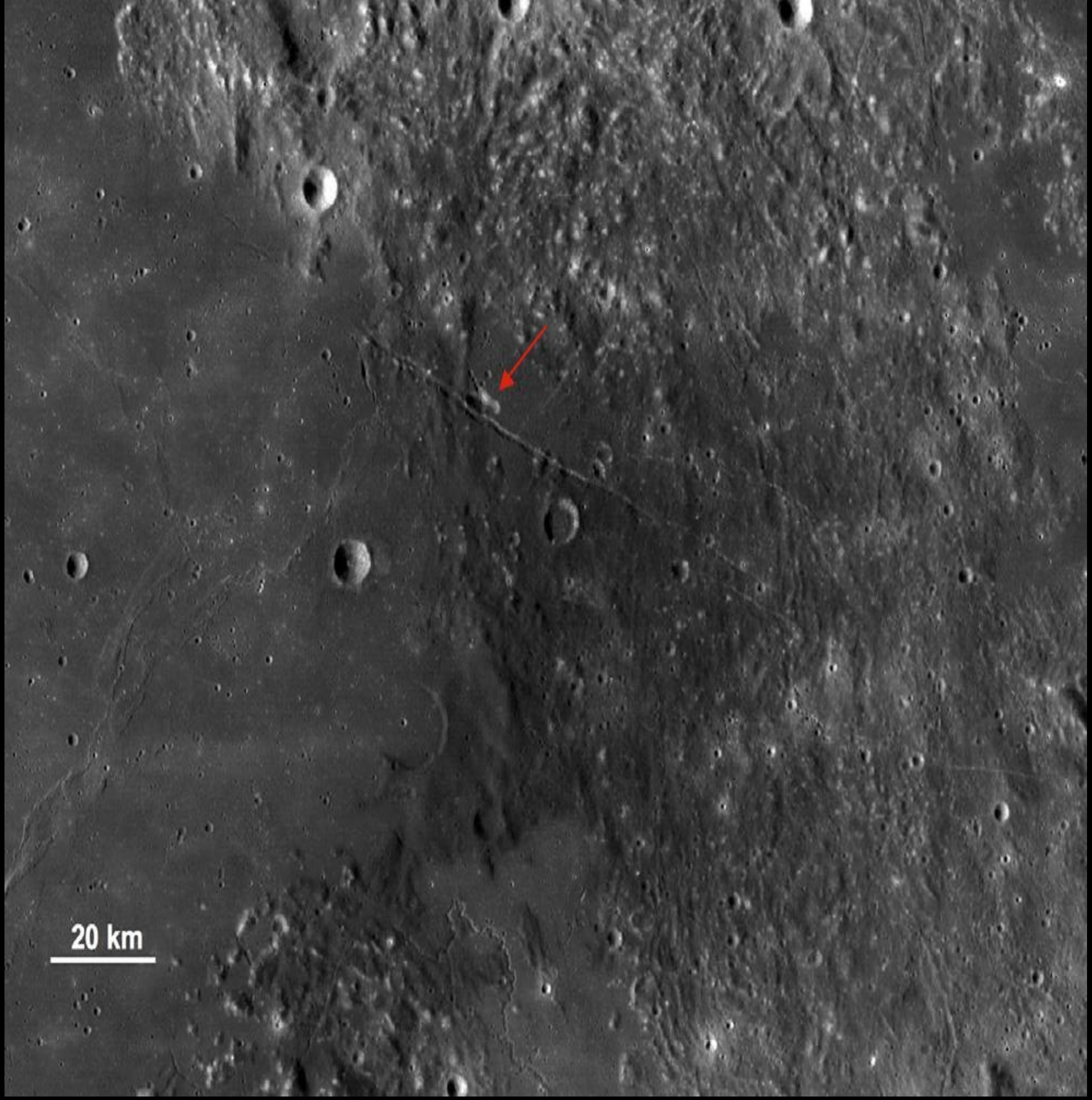
Marius Hills volcanic complex. Image on the left is the topographic map from stereo images and laser altimetry showing blister like shape. Image on the top right is from the Kaguya lunar orbiter, showing numerous small domes and cones occurring on up warped, shield like surface. Bottom right shows the flanks of the complex in Oceanus Procellarum. This feature has been proposed to be a lunar shield volcano.



Pyroclastic glasses (volcanic ash) from the Moon.

At the top is green glass (**very low titanium** and very high magnesium, age 3.3 Ga) from the Apollo 15 landing site; at

the bottom is orange-black glass (very high titanium and very high iron, age 3.7 Ga) from the Apollo 17 landing site. Both types of glass were erupted from deep mantle sources, driven by high volatile content. Glass fragments in each image are the sieved fraction from 90 to 150 mm.

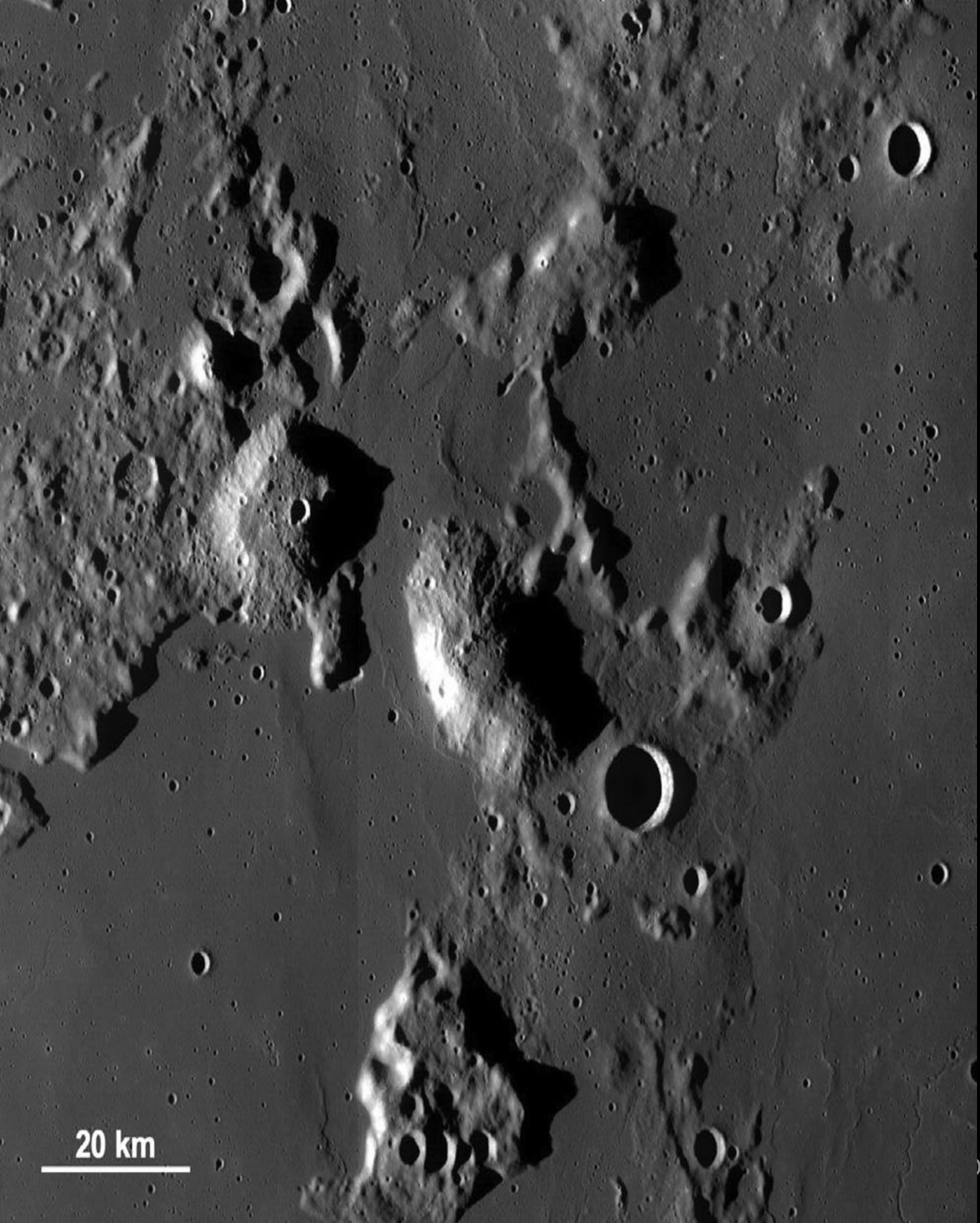


Regional view of dark mantling deposits near Rima Bode,
an irregular rille and vent system (arrow).

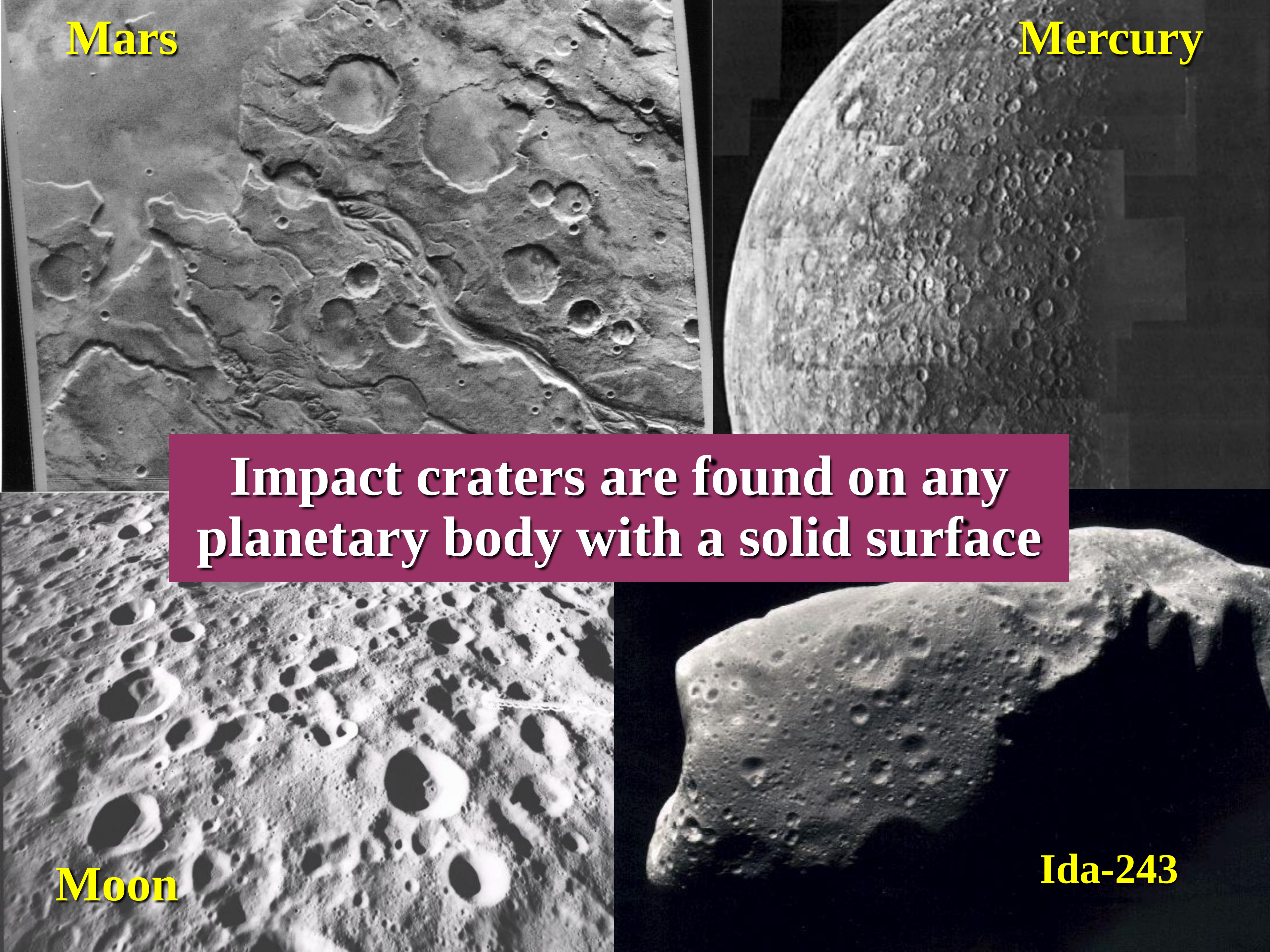
The Aristarchus volcanic plateau. This complex displays
numerous volcanic landforms, including large sinuous rilles (lava channels), small shields, pyroclastic dark mantling deposits, and flood lavas.
Studies have shown the lunar sinuous rilles are lava channels, in some
cases roofed over as lava tubes. LRO Wide Angle Camera mosaic.

Orbital view of the Apollo 15 landing site region. Hadley Rille is long sinuous rille (lava channel), striking mostly NEeSW along the base of the Montes Apenninus, the main rim of the Imbrium impact basin. Light plains on the left are the Apennine Bench Formation, a rare exposure of ancient (3.84 Ga) nonmare KREEP volcanism.

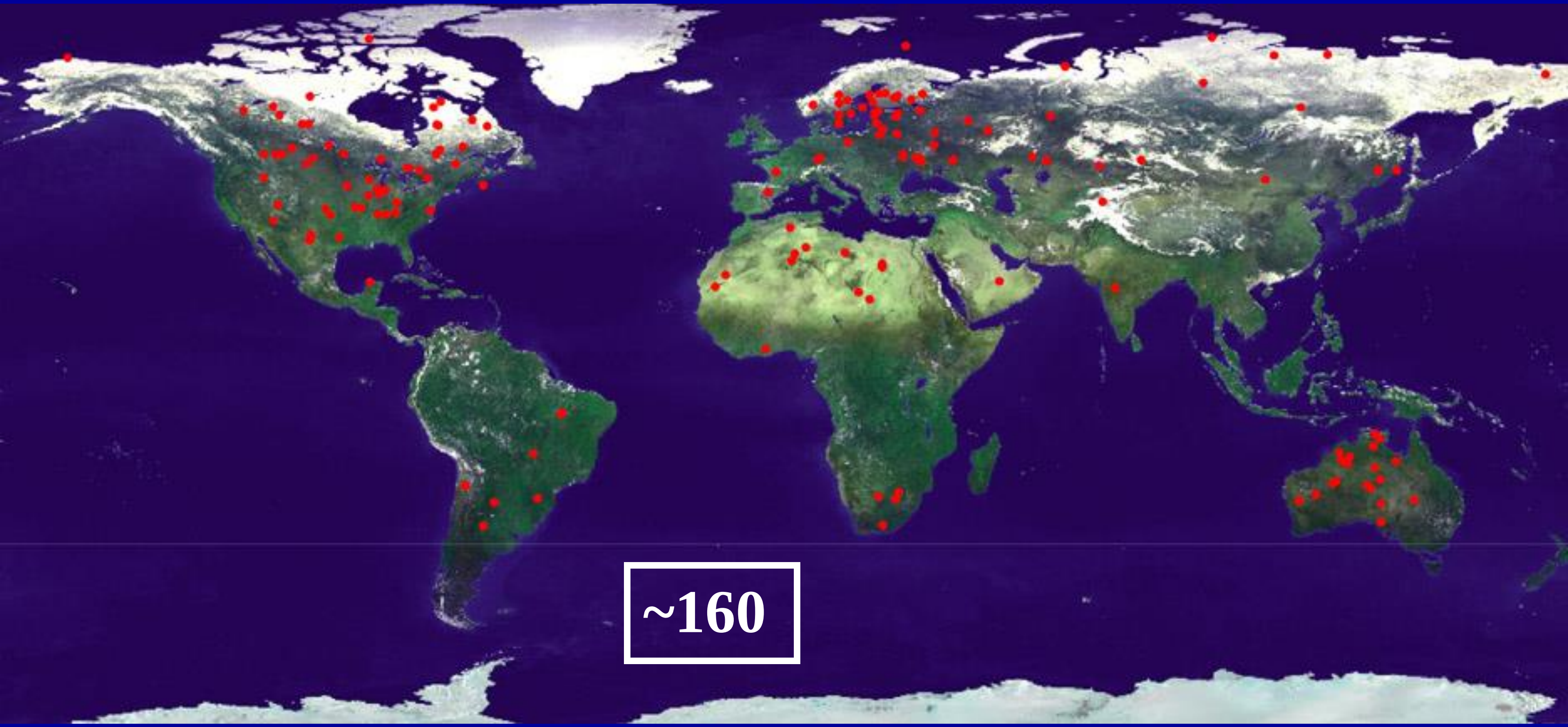
1 AO)



Gruithuisen Gamma (left) and Delta (right), two highland domes made up of silica-rich lavas. Several highland domes of
rhyolite-like material have now been documented, indicating the minor presence of highly differentiated volcanism on the Moon.


Mars
Mercury
Impact craters are found on any planetary body with a solid surface
Moon
Ida-243

Earth's Known Impact Structures



Earth retains the poorest record of impact craters amongst terrestrial planets

Why? Plate tectonics - Erosion – Sedimentation - Life
Oceans are relatively young and hard to explore

Many impact structures are covered by younger sediments, others are highly eroded or heavily modified by erosion. Few impact craters are well preserved on the surface


Roter Kamm, Namibia (1.6mi)
Spider, Australia (8.1mi)
Brent, Canada (2.4 mi)
Meteor Crater, AZ (0.75mi)
Wabar, Saudi Arabia (0.072mi)
Wolfe Creek, Australia (0.55m
Manicouagan, Canada (62mi)
Vredefort, South Africa
(125-185mi)
Popigai, Russia (62 mi)

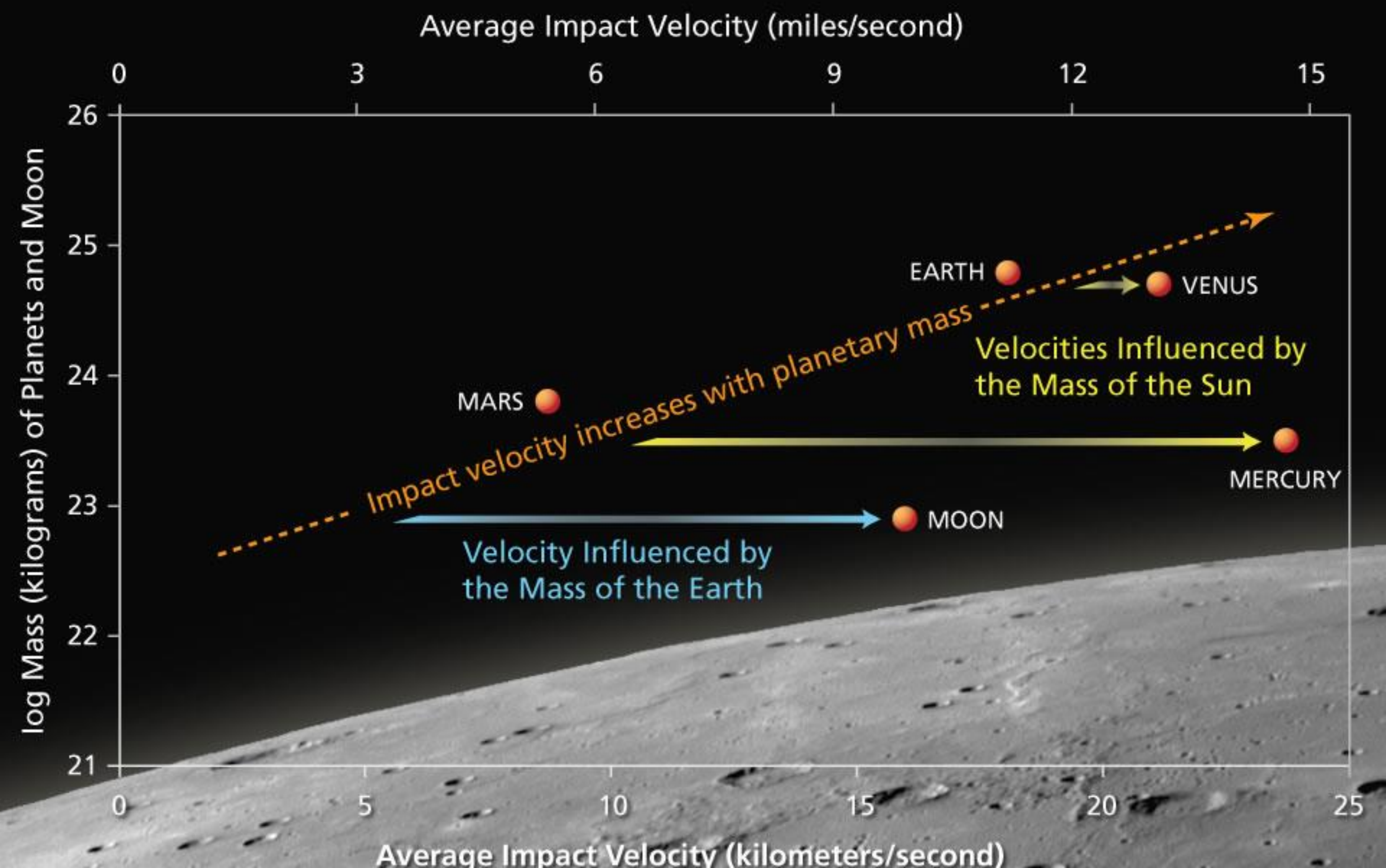
Impact Craters

- Impact cratering is the dominant geologic process that alters the solid surfaces of bodies throughout the solar system.
- Impact craters are approximately circular depressions in the surface of a planet, moon or other solid body in the Solar System, formed by the hypervelocity impact of a smaller body with the surface.


Barringer “Meteor” Crater, Arizona

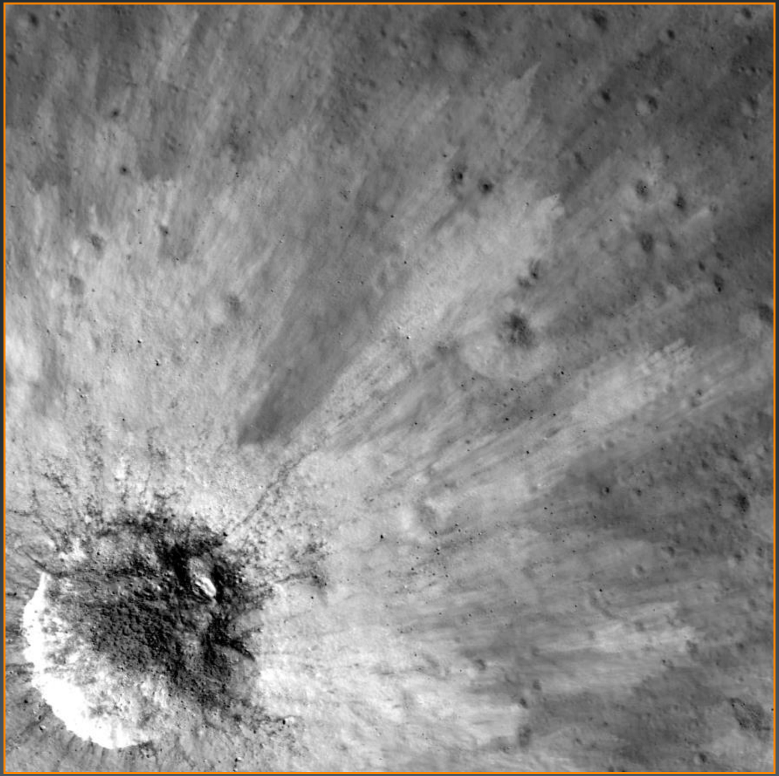
ASTEROID IMPACTS

Average Impact Velocities: Inner Solar System

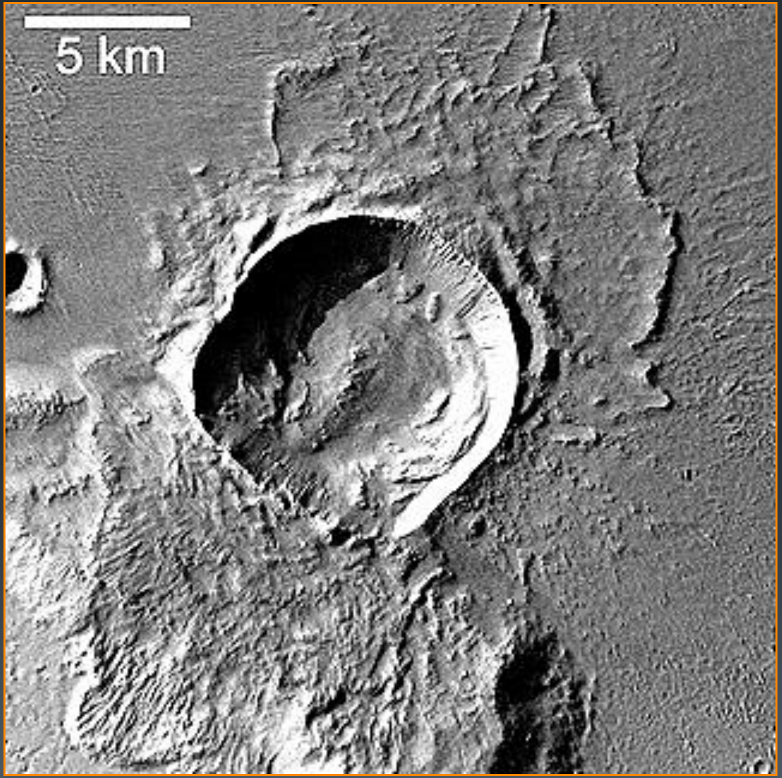


Impact Craters

- Characteristics
  - Rim is raised compared to the surrounding terrain
  - Floor is lower than the surrounding terrain
  - Inverted stratigraphy
- Ejecta

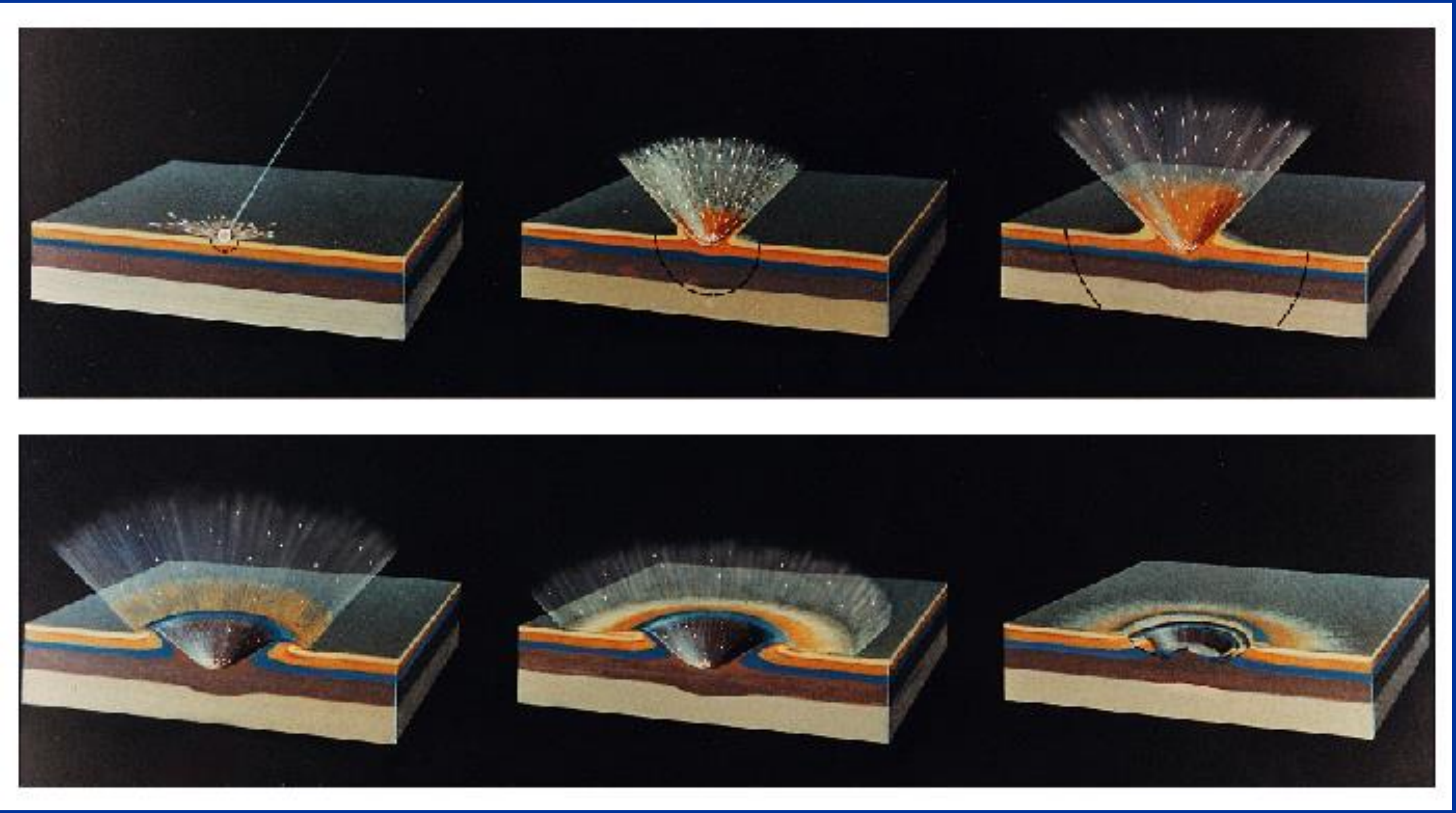


Radial ejecta surrounding a lunar crater.



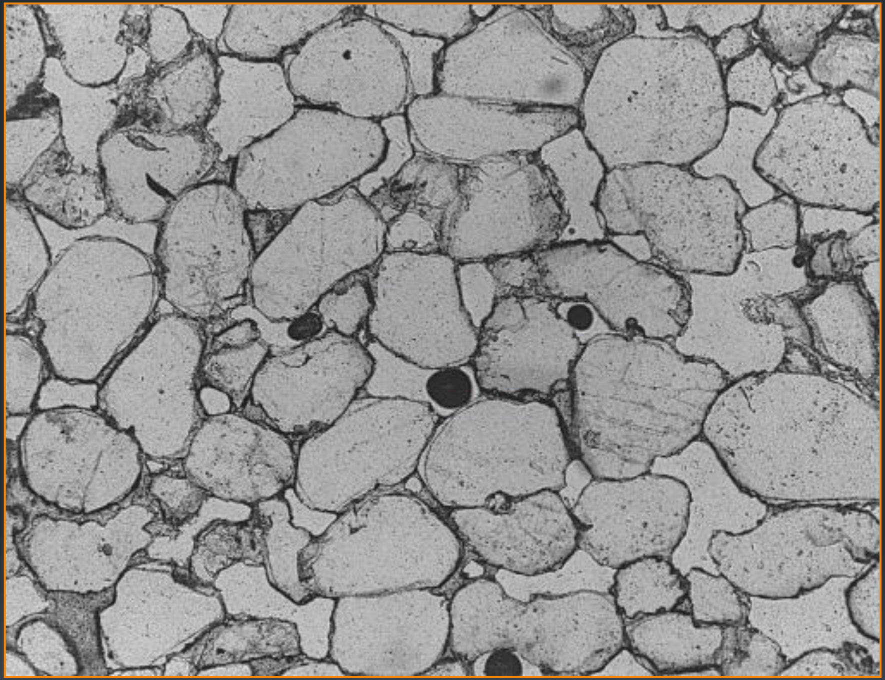
Lobate ejecta surrounding a Martian crater.

Impact processes

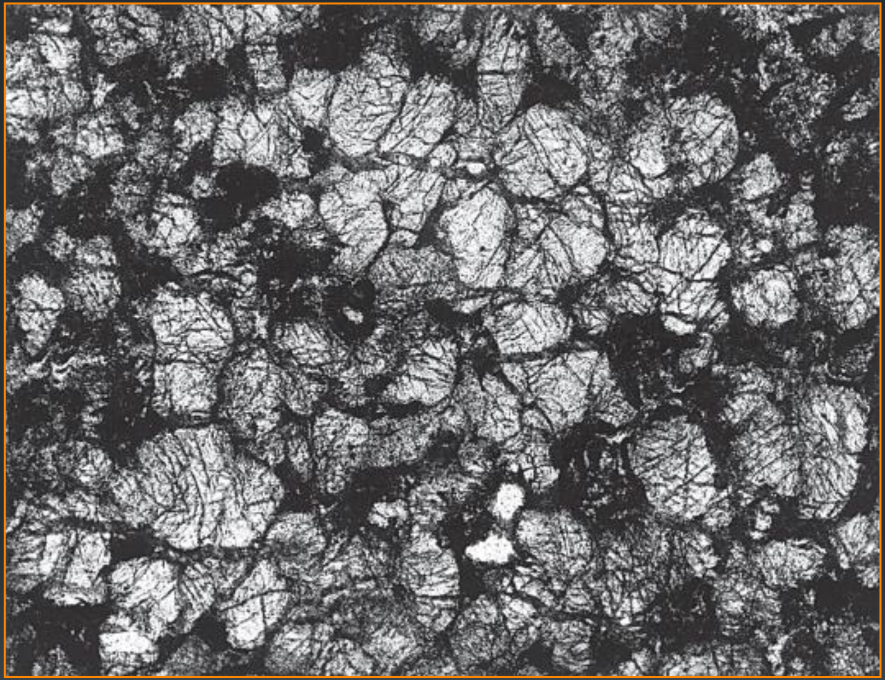


Impact Craters

Shock Metamorphism in Coconino Sandstone



Unshocked Coconino Sandstone



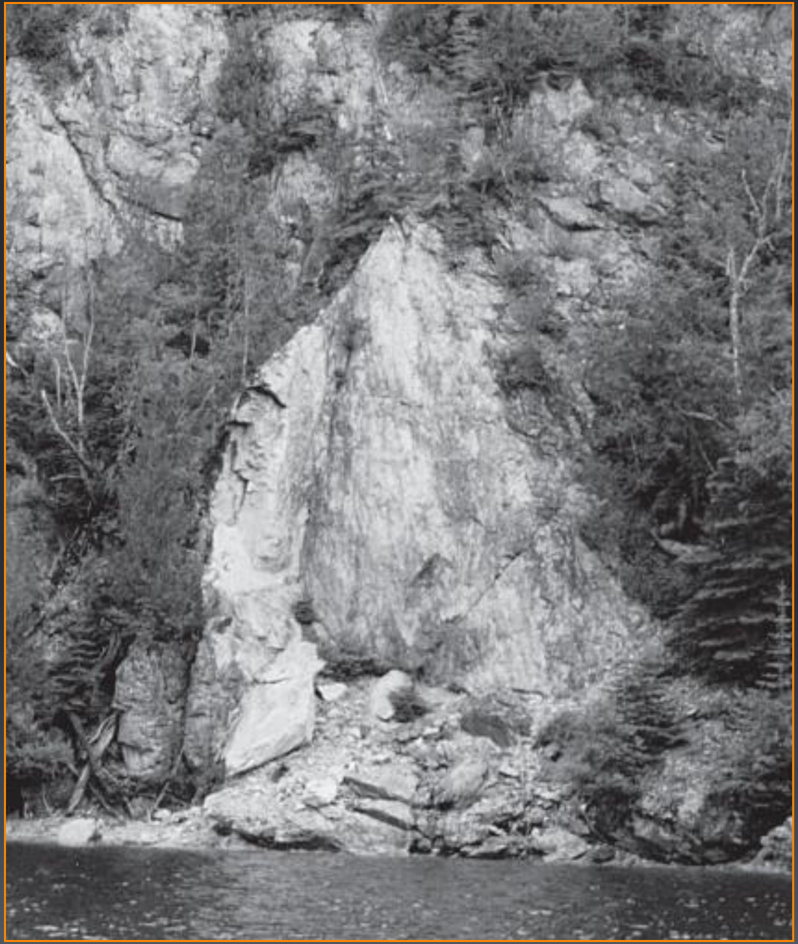
Shocked Coconino Sandstone

Images from *Traces of Catastrophe* by Bevan M. French, 1998

Impact Craters

Shatter Cones

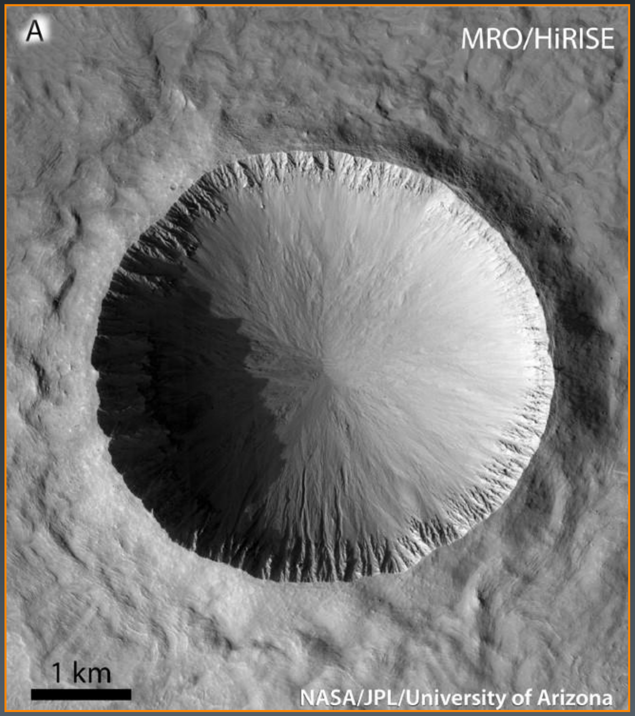
Image Credit: http://www.impact-structures.com/impact-rocks-impactites/

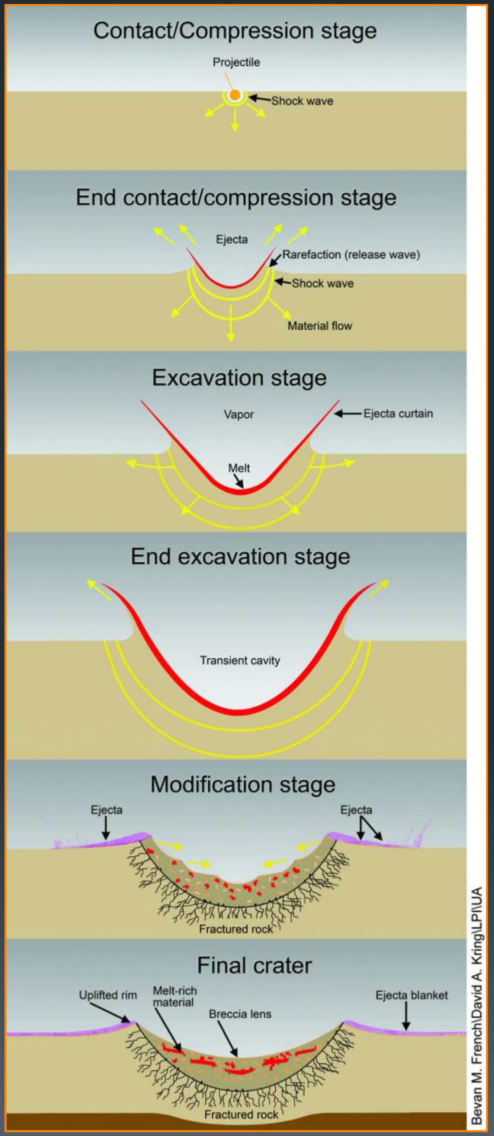


From *Traces of Catastrophe* by Bevan M. French, 1998, image courtesy of V.L. Sharpton

Impact Craters

- Simple Craters
  - Small (relatively) bowl-shaped depressions with no interior structure

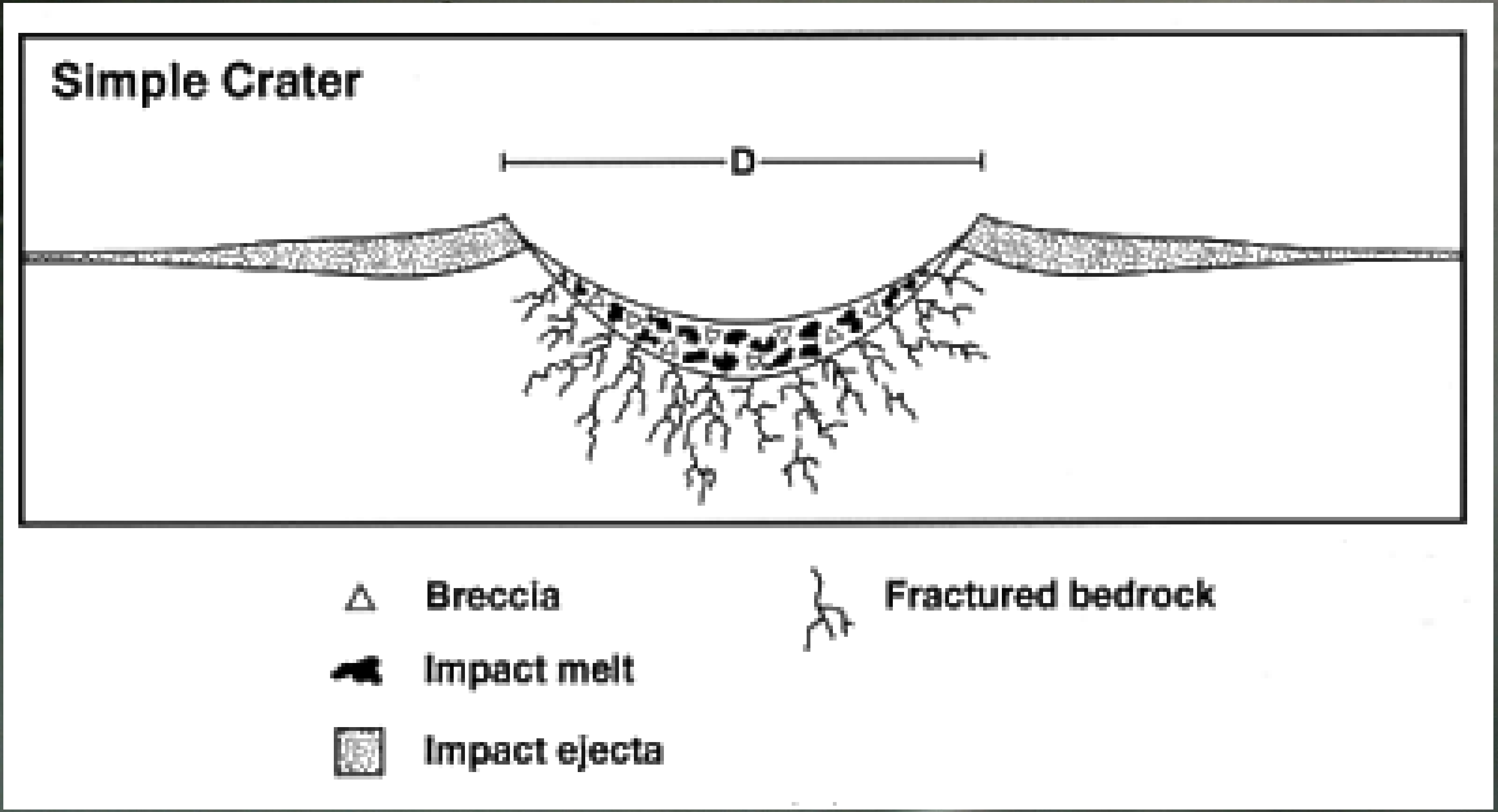




Simple Crater Facts

- Common at < 15 km rim-to-rim diameter, D, on moon
- Rim height 4% of D
- Rim-to-floor depth 1/5 of D
- Ejecta blanket extends one D from rim
- Secondary craters and bright ray ejecta
- Floor underlain by breccia
  - Contains shocked quartz i.e. coesite and stishovite
  - Floor typically 1/2 to 1/3 of rim-to-floor depth

Simple Craters Schematic



Simple Craters on Earth

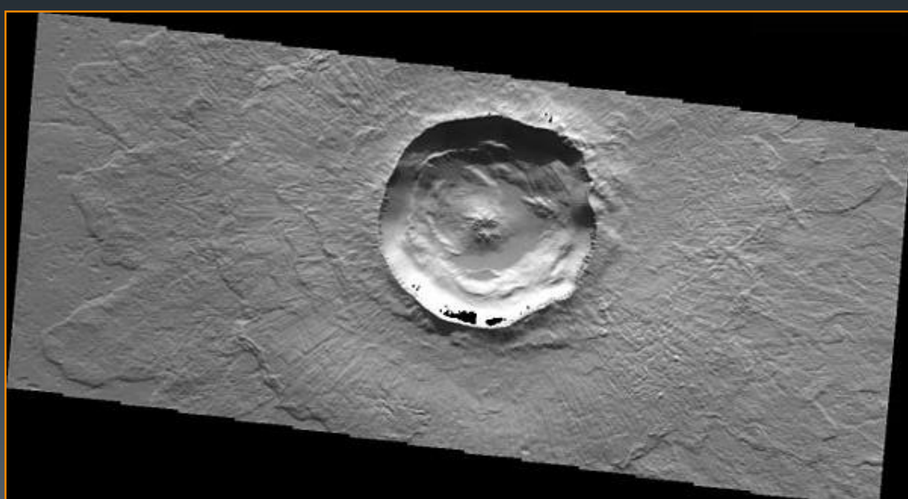
- First to be identified on Earth
- Not always completely circular
  - Faults
- Common at 3 km to 6 km diameter

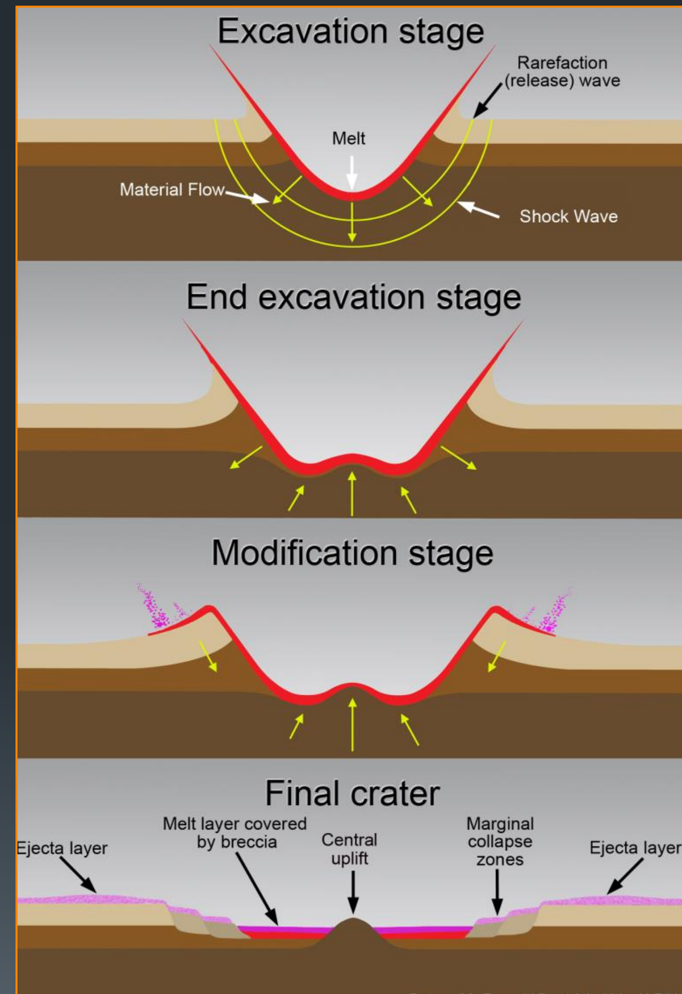
Simple Crater on Moon

- Moltke crater, a simple crater, was photographed by Apollo 10 astronauts in 1969. The depression, about 7 km (4.3 miles) in diameter.
- Common up to 15 km diameter

Impact Craters

- Complex Craters & Basins
  - Complex craters have interior terraces and flat floors surrounding central peaks.
  - Basins are craters >300km (~190 miles) in diameter.





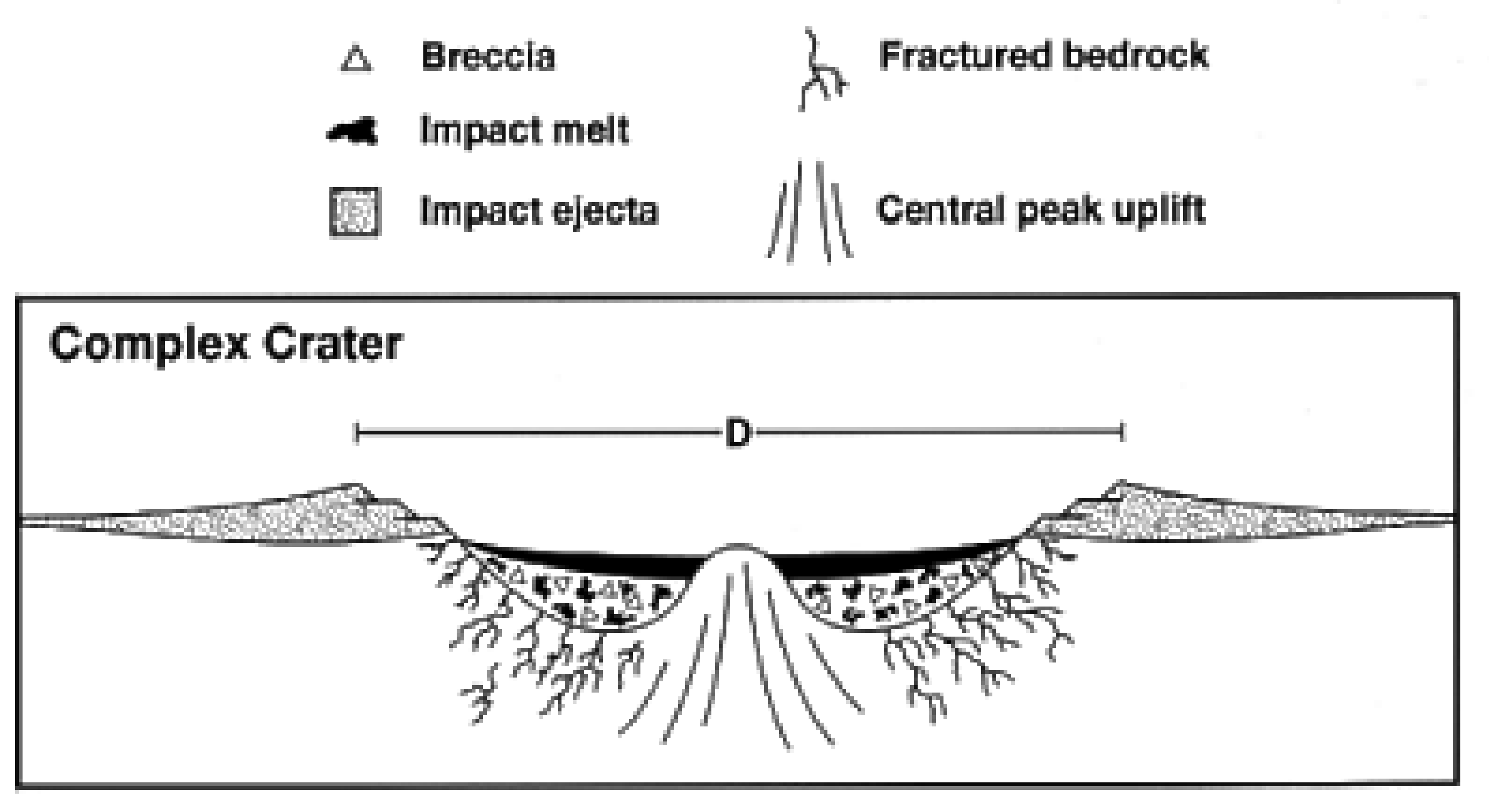
Complex Craters

- Formed by collapse of bowl-shaped crater
- Observed on Moon, Mars, Earth, and Mercury
- Uplift beneath centers
  - Structural uplift to crater diameter by

$$h_{su} = 0.06D^{1.1}$$

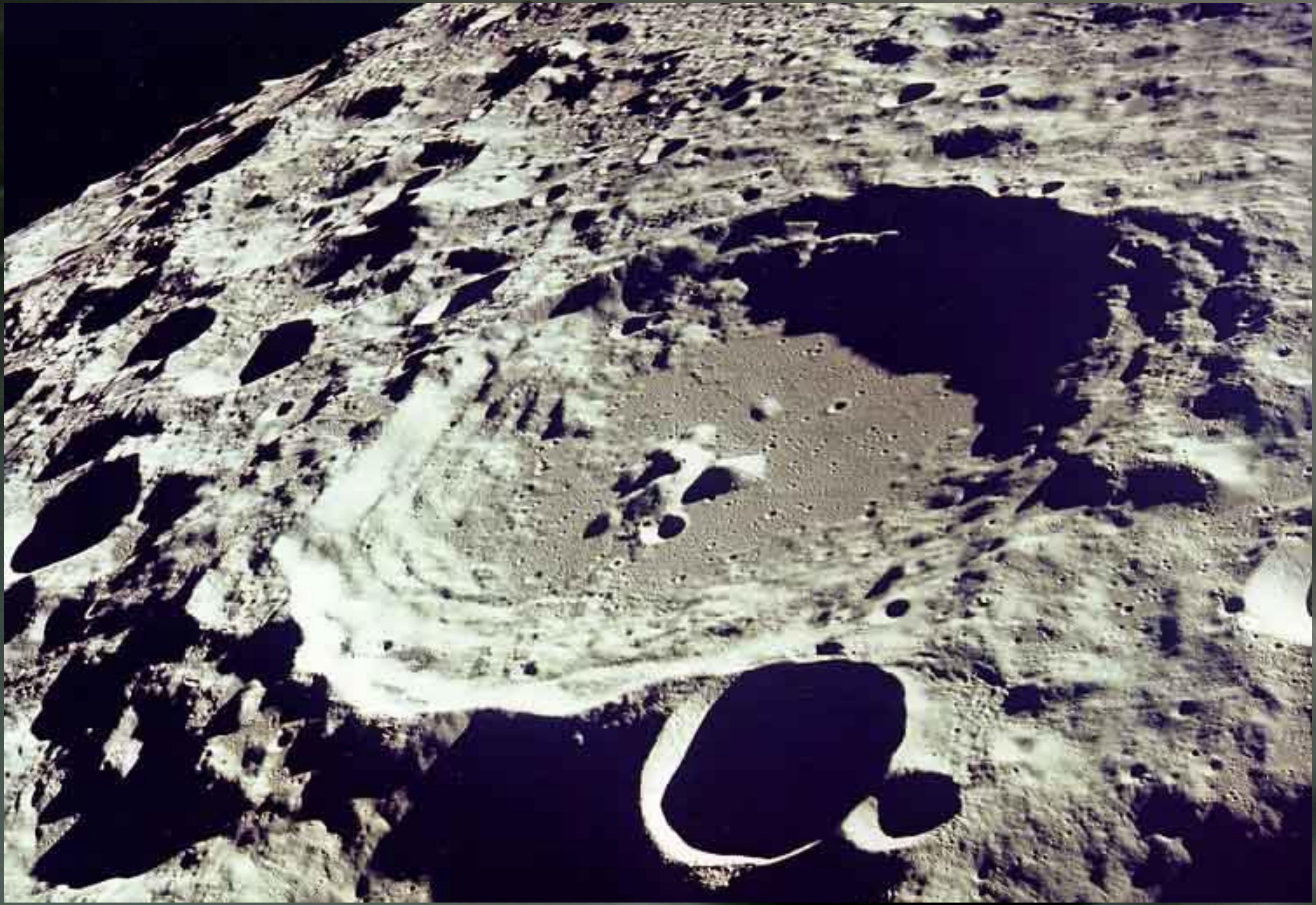
- Diameter of central peak approx 22% of rim-to-rim diameter on terrestrial planets
- Depth increases slowly
  - Depth from 3 - 6 km
  - Diameters from 20 - 400 km
- Diameter may increase as much as 60% during collapse

Complex Crater Schematic



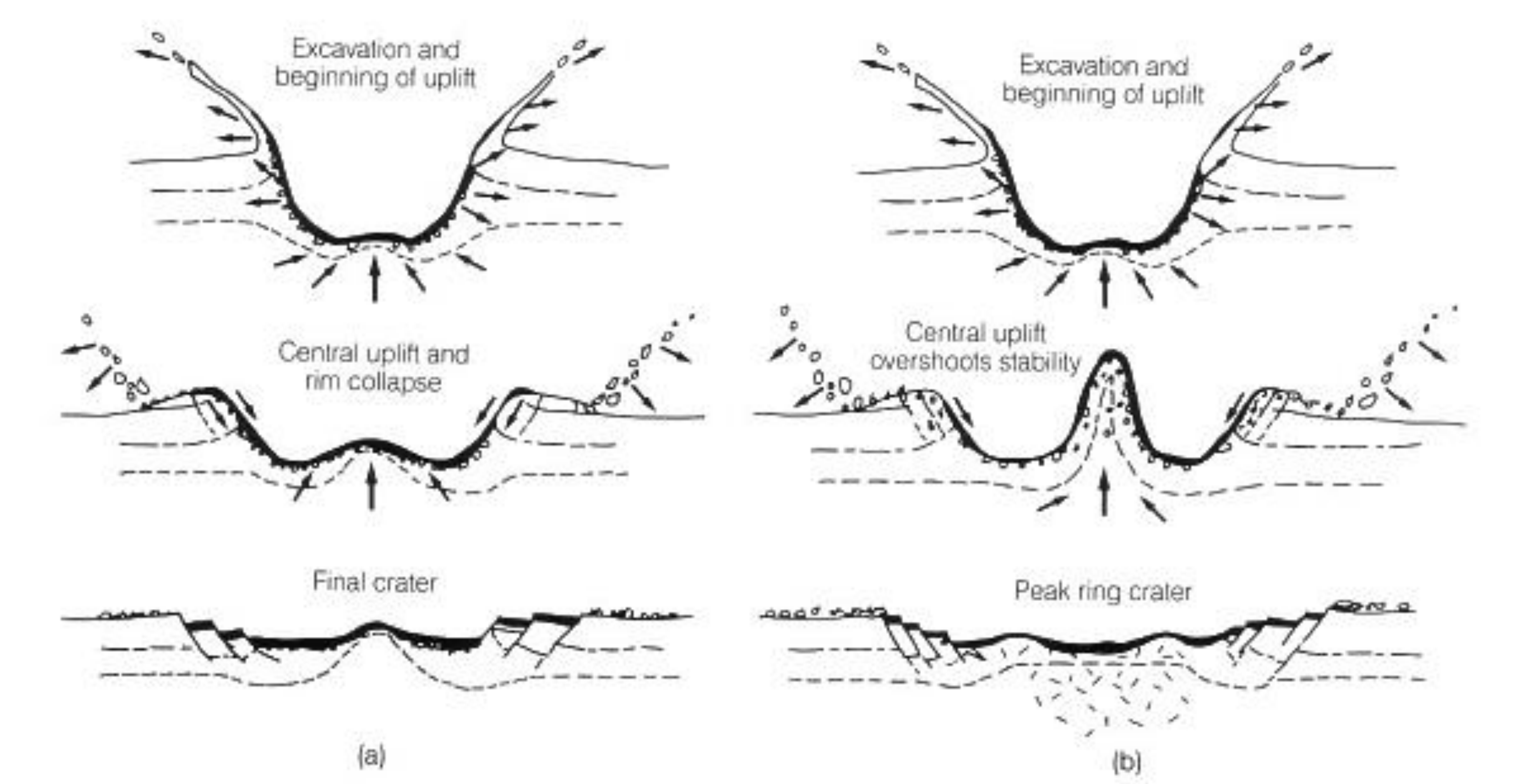
Complex Crater on Mercury

Complex Crater on Moon



The far side of Earth's Moon. Crater 308. It spans about 30 kilometers (19 miles) and was photographed by the crew of Apollo 11 as they circled the Moon in 1969

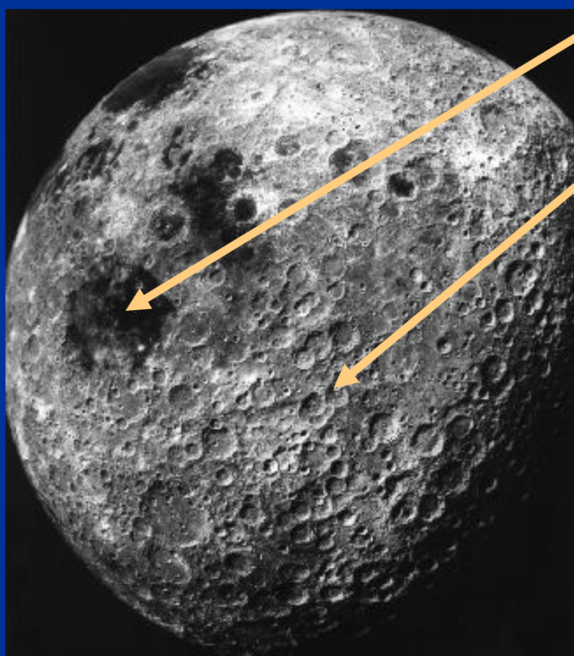
More Complex



Craters on Moon, Mars

Maria: impact basins filled in with lava

Highlands: ancient and heavily cratered



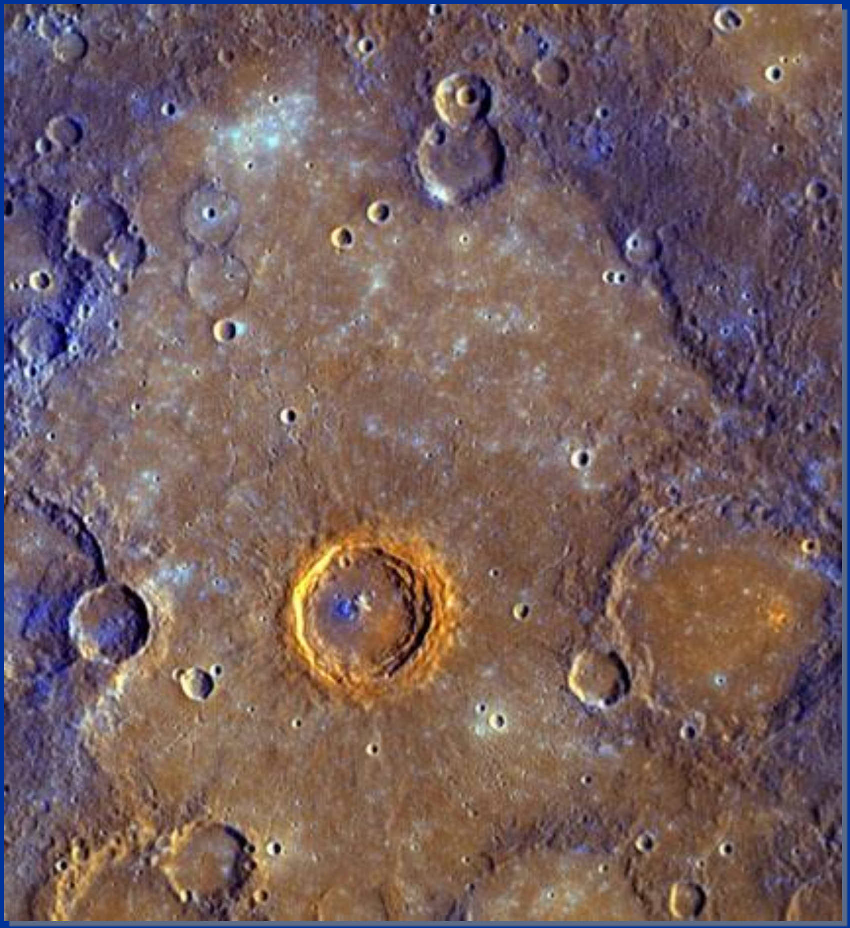
Moon craters

Impacts into icy ground may produce muddy ejecta

Mars craters

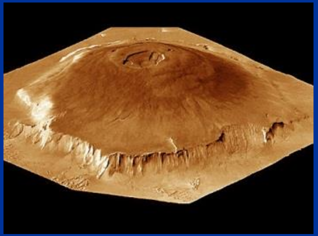
Craters on Venus, Mercury

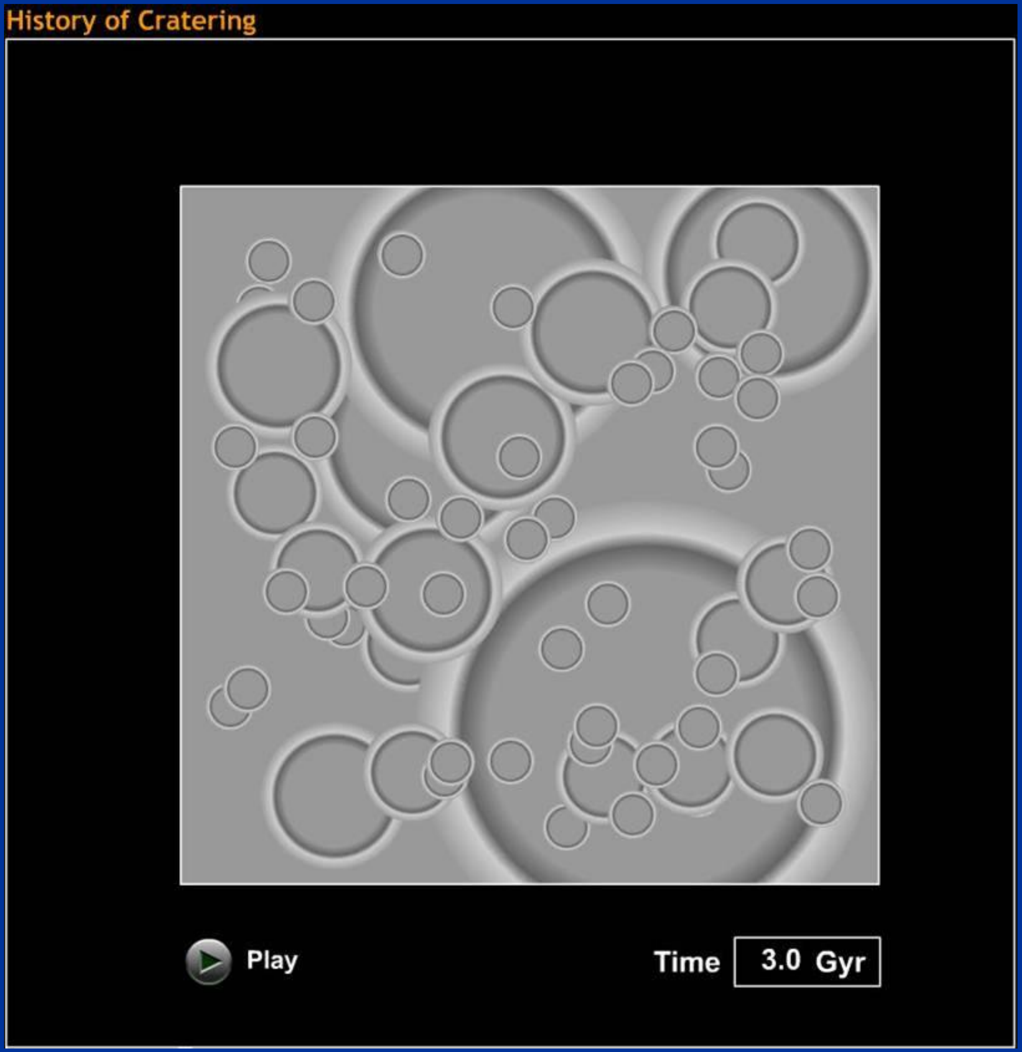
Venus
(from radar altimeter)



Mercury
(from MESSENGER spacecraft)

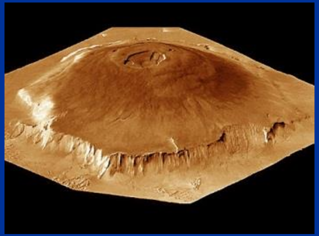
History of Cratering on the Moon





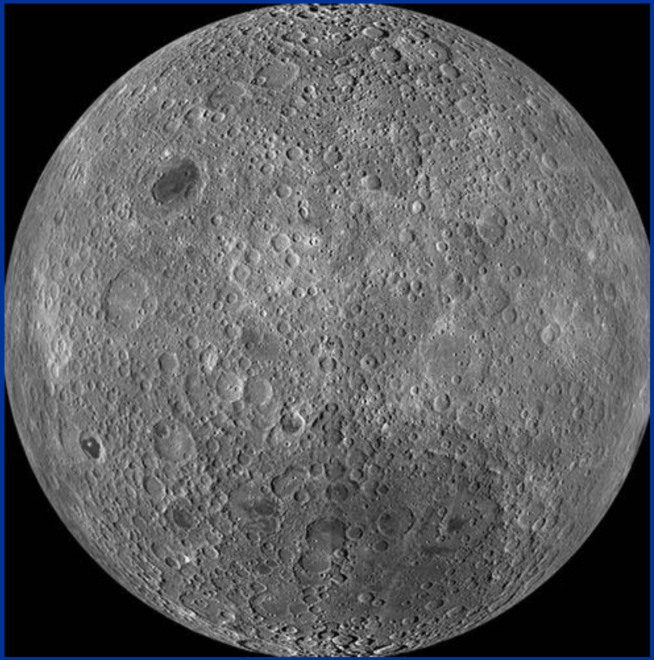
- Most cratering happened in the first billion years.
- A surface with many craters that has not changed much in 3 billion years.

Why are front and back sides of moon so different?



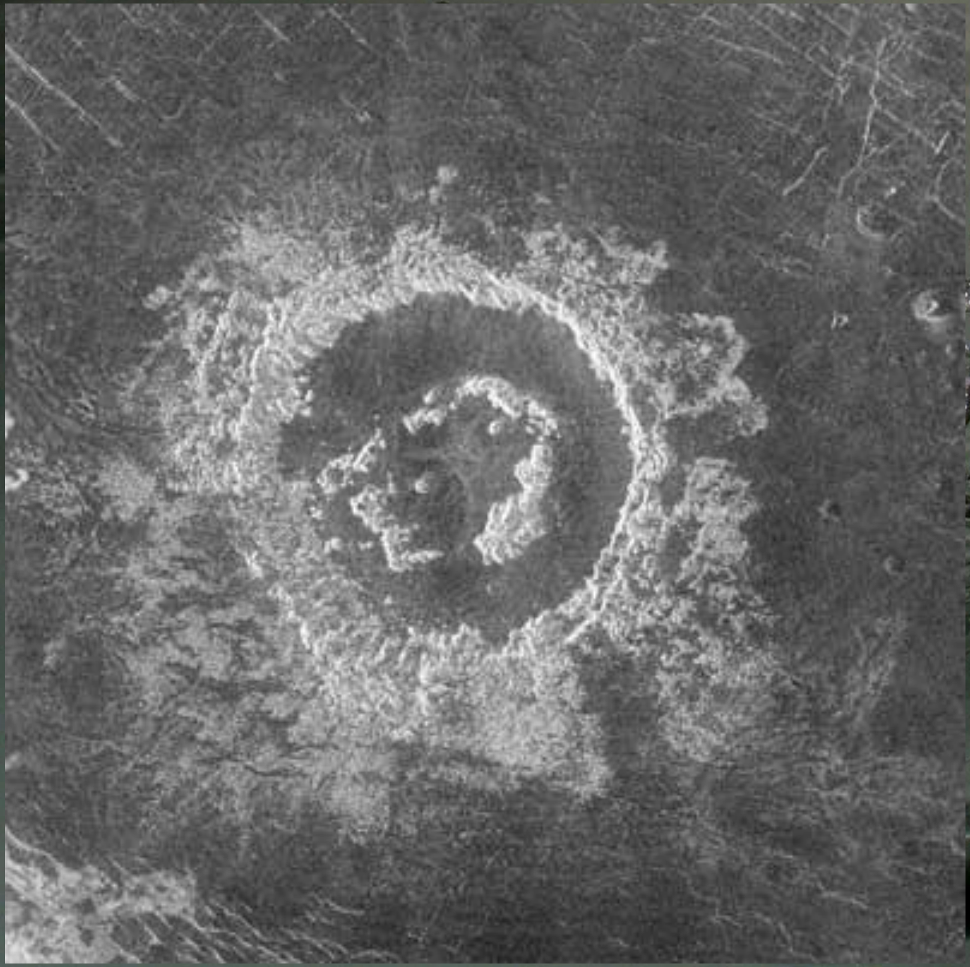
Front side

Back side



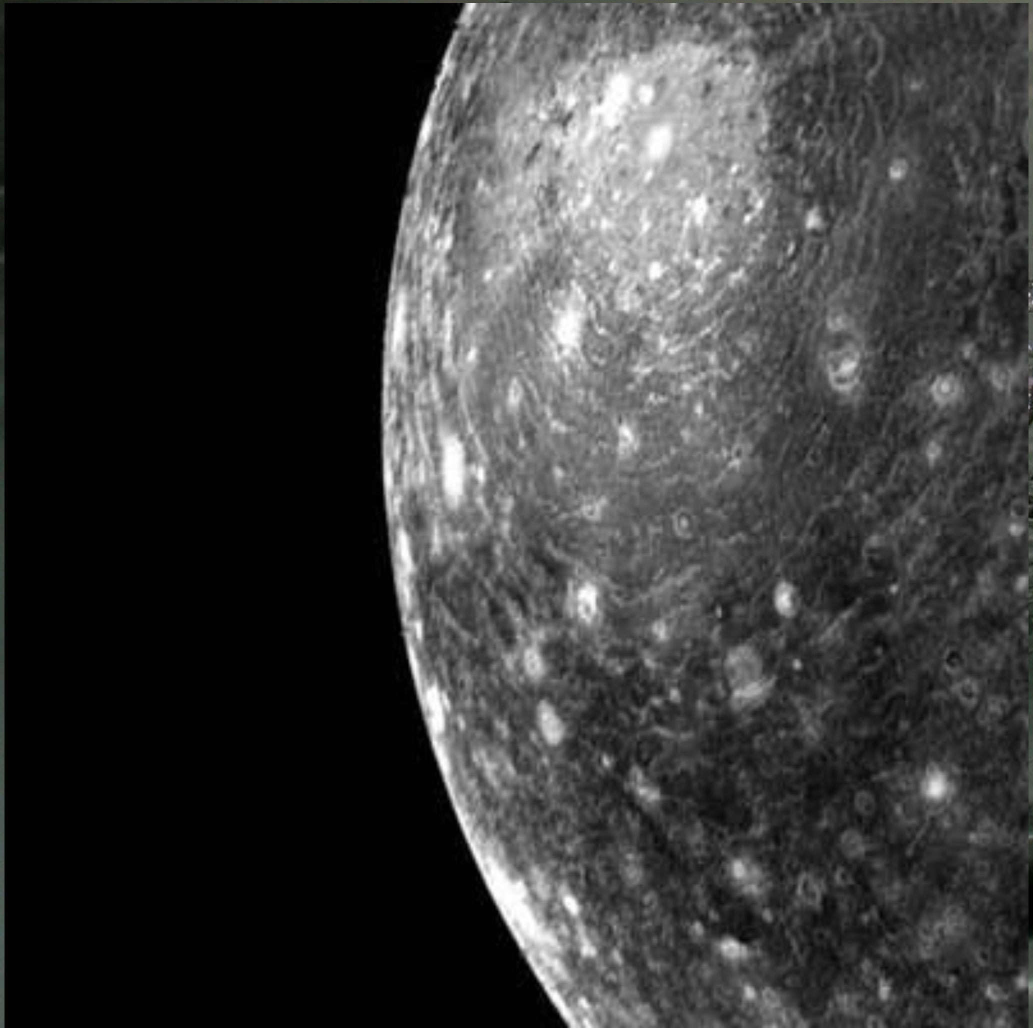
- Thicker far side crust may keep magma from surface.
- Heat released by radioactive decays is larger on near side; hot magma flows to surface more readily.

Central Ring Crater



- Barton crater on Venus
- Discontinuous central ring
- Very close to transition diameter
  - 50 km ring

Multiring basins



- Valhalla basin on Callisto
- 4000 km
  - Only central bright stop believed to be formed by impact
- Outward facing scarps

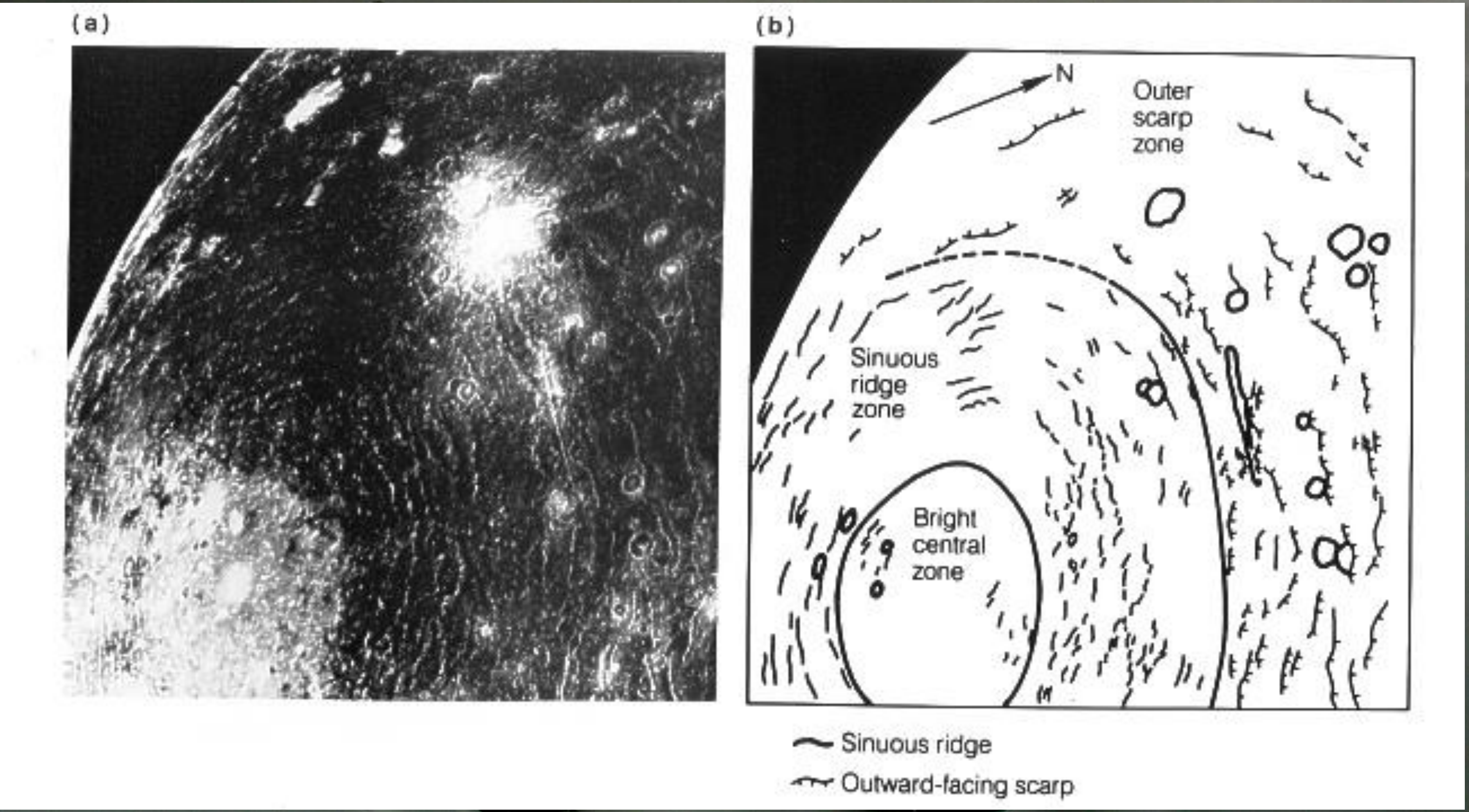
Multiring basins

- Orientale basin on Moon
- Youngest and best preserved
- Approx 930 km diameter
- 2 km depth
- Inward facing scarps

Characteristics of Multiring Basins

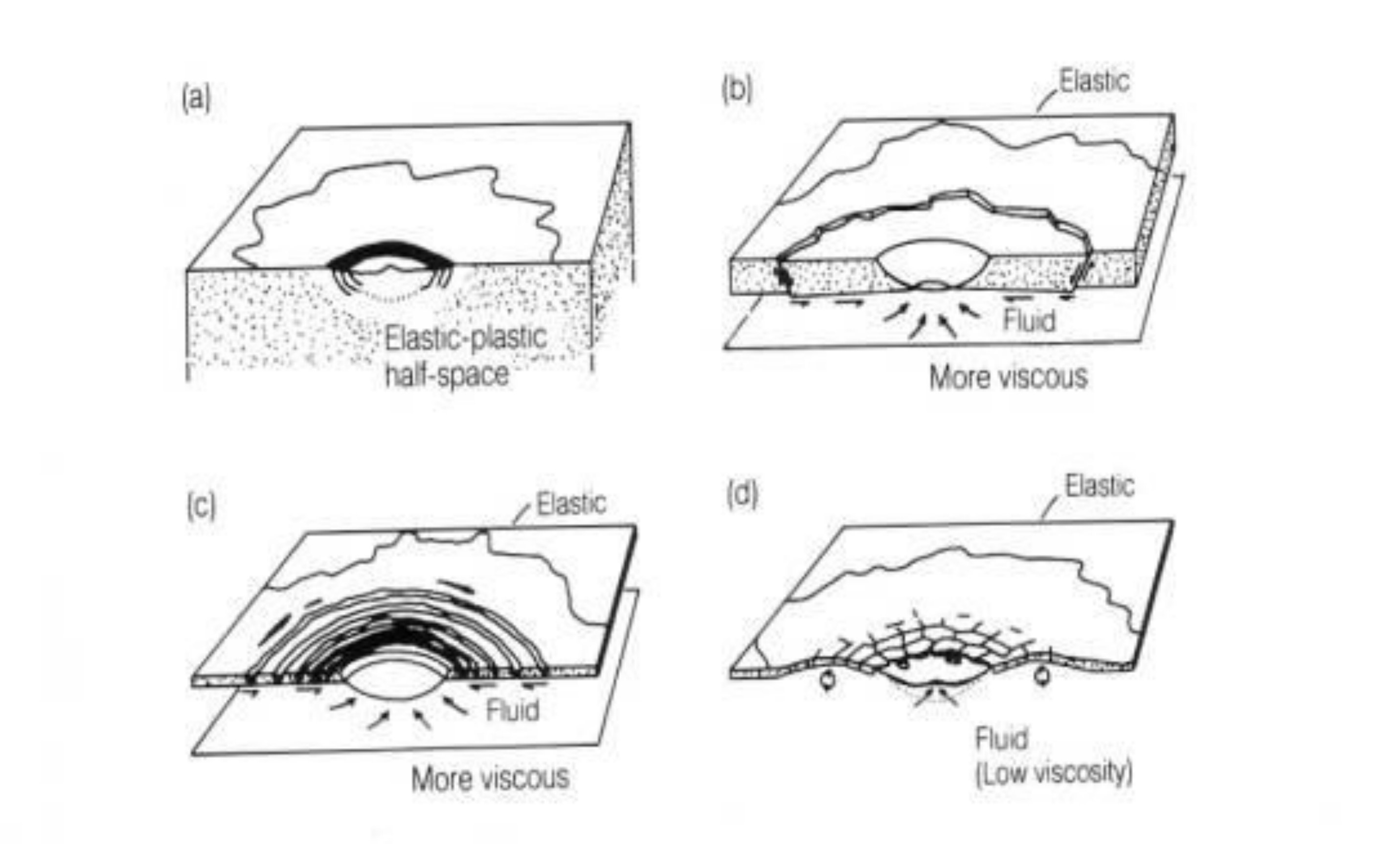
- Most likely caused by circular normal faults
  - Normal fault is result of crustal extension
- Ring diameter ratios of roughly $\sqrt{2}$
- No longer function of g^{-1}
- Possibly influenced by the internal structure of the planet

Valhalla



(a)
(b)
N
Outer scarp zone
Sinuous ridge zone
Bright central zone
Sinuous ridge
Outward-facing scarp

Multiring Schematic



The ring tectonic theory suggests that in layered media in which the strength decreases with increasing depth, one or more ring fractures arise outside the rim of the original crater (figure 5) (Melosh and McKinnon, 1978). This suggests that for the formation of multiring basins to occur there must be a high brittle-ductile thickness ratio in the impacted material i.e. where thick crust exists over a deeper ductile layer (Allemand and Thomas, 1999). **www.spacechariots.biz/ creaters.htm**

Aberrant Crater Types

- Unusual formation conditions
  - Either in impactor or planetary body
- Very low impact angles - 6° from horizontal
  - Circular crater with asymmetric ejecta blankets
  - Elliptical craters with butterfly eject patterns
- Smaller impactors on Earth and Venus tend to form clusters of craters, reflecting atmospheric breakup

Impact Observations

- **Physical:**
  shape, inverted stratigraphy, material displaced
- **Shock evidence from the rocks:**
  shatter cones, shocked materials, melt rocks, material disruption
- **Geophysical data:**
  gravity & magnetic anomalies

Table 3.3. **Criteria for the recognition of impact craters (modified from Dence 1972)**

Criterion	Characteristics	Reliability
Remote sensing		
Plan view	Distinctly circular; may be modified by slumping, tectonic patterns, or erosion	Fair, but can be attributed to other processes
Rim structure	Inverted stratigraphy	Definitive
Central zone	Floor lower than surrounding plain; may contain central uplift	Fair, but can be attributed to other processes
Geophysical observations		
Gravity anomaly	Generally negative	Supportive, but not conclusive
Magnetic field	Variable; may be distinct anomaly over melt rock	Supportive, but not conclusive
Seismic velocities	Generally lower in brecciated zones	Supportive, but not conclusive
Ground observations		
Presence of meteorites	Rare except in very young craters	Definitive
Shock metamorphism	Features such as high-pressure minerals, impact melt, planar shock features, and shatter cones	Definitive
Brecciation	Observed in ejecta, rim, and floor of craters	May be attributed to other processes

Observational: Physical

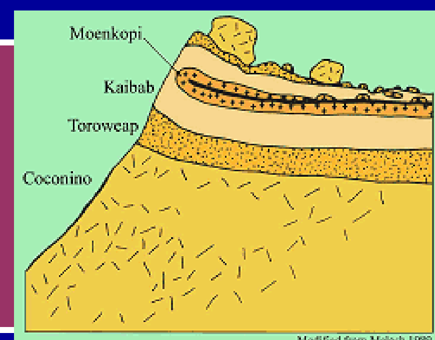
Shape:
circular features

Moltke
(2.7 mi)

Tycho
(53 mi)

Inverted Stratigraphy:

first recognized by Barringer
(only for well preserved craters)



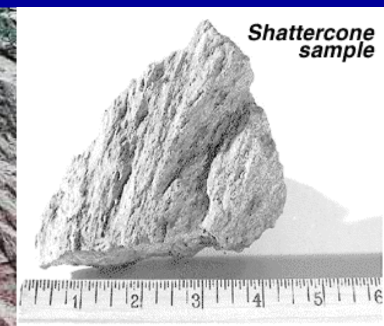
Meteor Crater

Material displaced:
Solid material broken up and ejected outside the crater: breccia, tektites

Observations: Shock Evidence

Shatter cones:

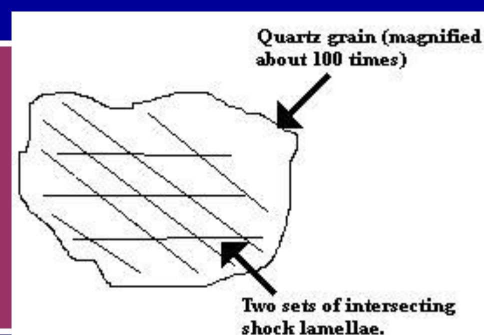
conical fractures with typical markings produced by shock waves

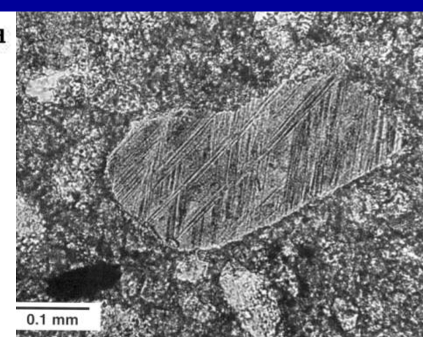


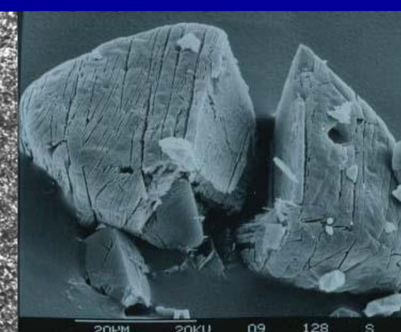
Shocked Material:

shocked quartz

high pressure minerals

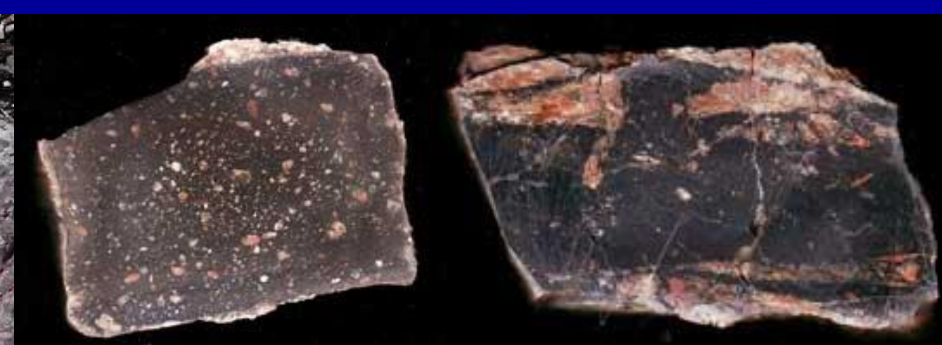






Melt Rocks:

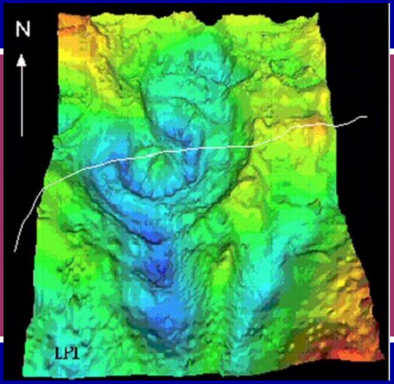
melt rocks may result from shock and friction

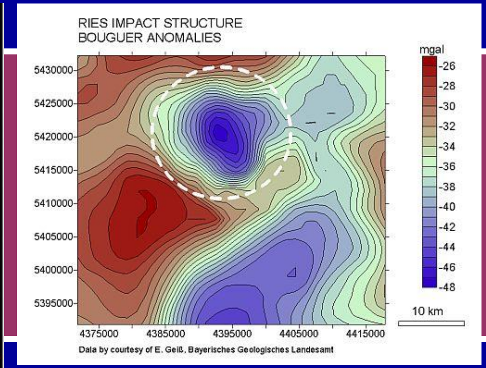


Observations: Geophysical data

Gravity anomaly:

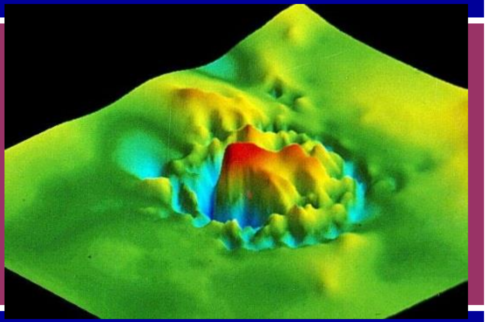
based on density variations of materials
Generally negative (mass deficit) for impact craters

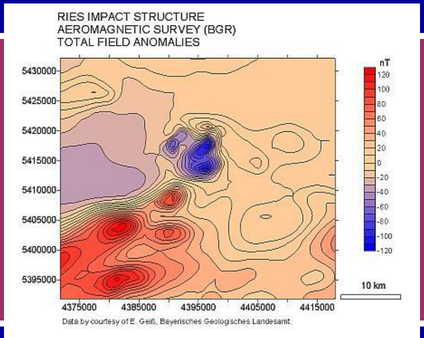




Magnetic:

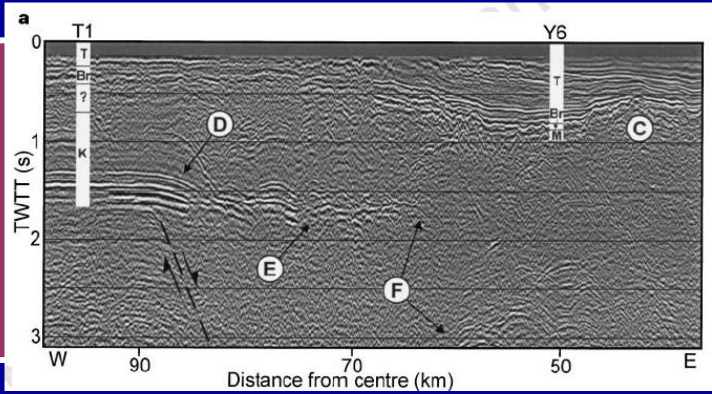
based on variation of magnetic properties of materials





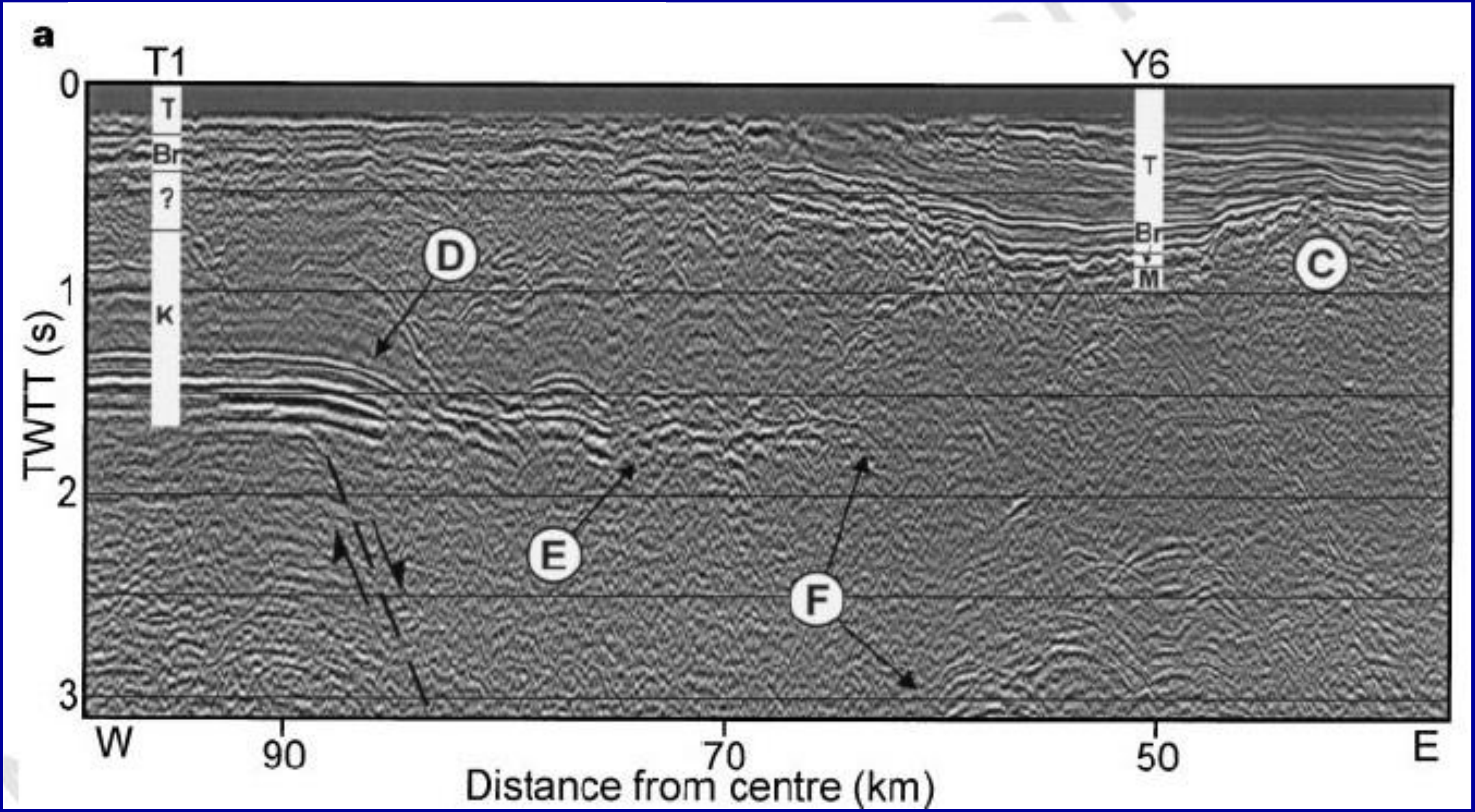
Seismic:

sound waves reflection and refraction from subsurface layers with different characteristics



Seismic Reflection and Refraction

Sound waves (pulses) are sent downward. They are reflected or refracted by layers with different properties in the crust. Different materials have very different sound speeds.



Age Determination

- Several decades of lunar exploration allowed accumulation of enough data to present an approximate lunar chronology based on the ages of returned samples.

- Impact craters yield footprints of small body evolution and Solar System chronology.

- The best statistics were for the range 4 km < D < 100 km, which give relatively straight lines on plots of 10gN (no. of craters per km2) vs. log D.

- These straight lines on plots of 10gN vs. log Dare power laws, and thus the earliest literature introduced the idea that power laws gave good fits to the cratering data.

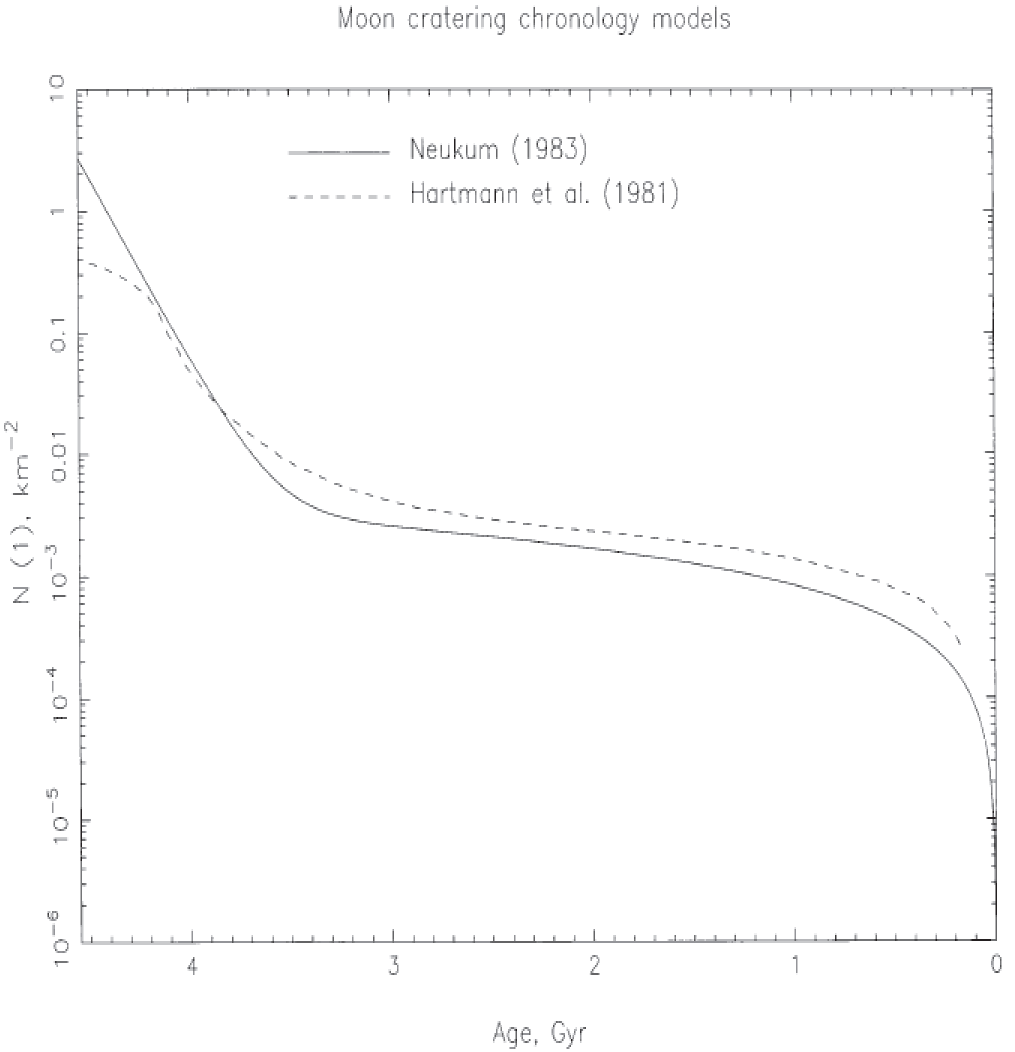


Figure 9. Comparison of two lunar cratering chronology models by Hartmann *et al.* (1981) and by Neukum (1983).

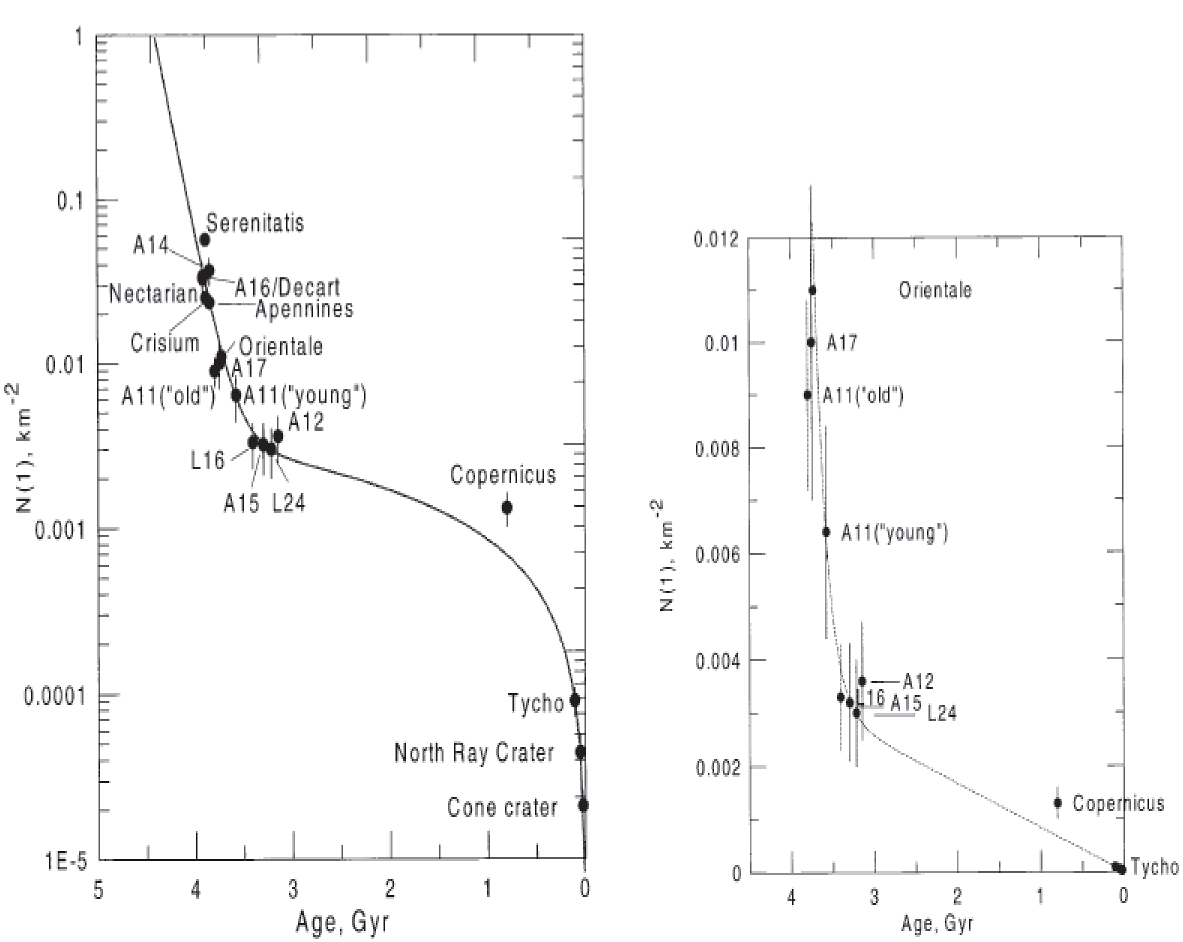


Figure 10. Left: Graphical representation of Equation (5) (lunar cratering chronology) in log-log format (see Table V of Stöffler and Ryder, 2001). *Right*: The part of the lunar cratering chronology in linear scale.

- There have been previously a number of attempts to combine crater frequency data and radiometric ages determined for the lunar landing sites and for other units on the moon for which a radiometric age could be derived indirectly from rock samples at the Apollo landing sites (e.g. for Tycho, sampling at the Apollo 17 landing site). The empirical relationship resulting from this kind of plotting crater frequency vs. radiometric age is called cratering chronology.

The lunar stratigraphy

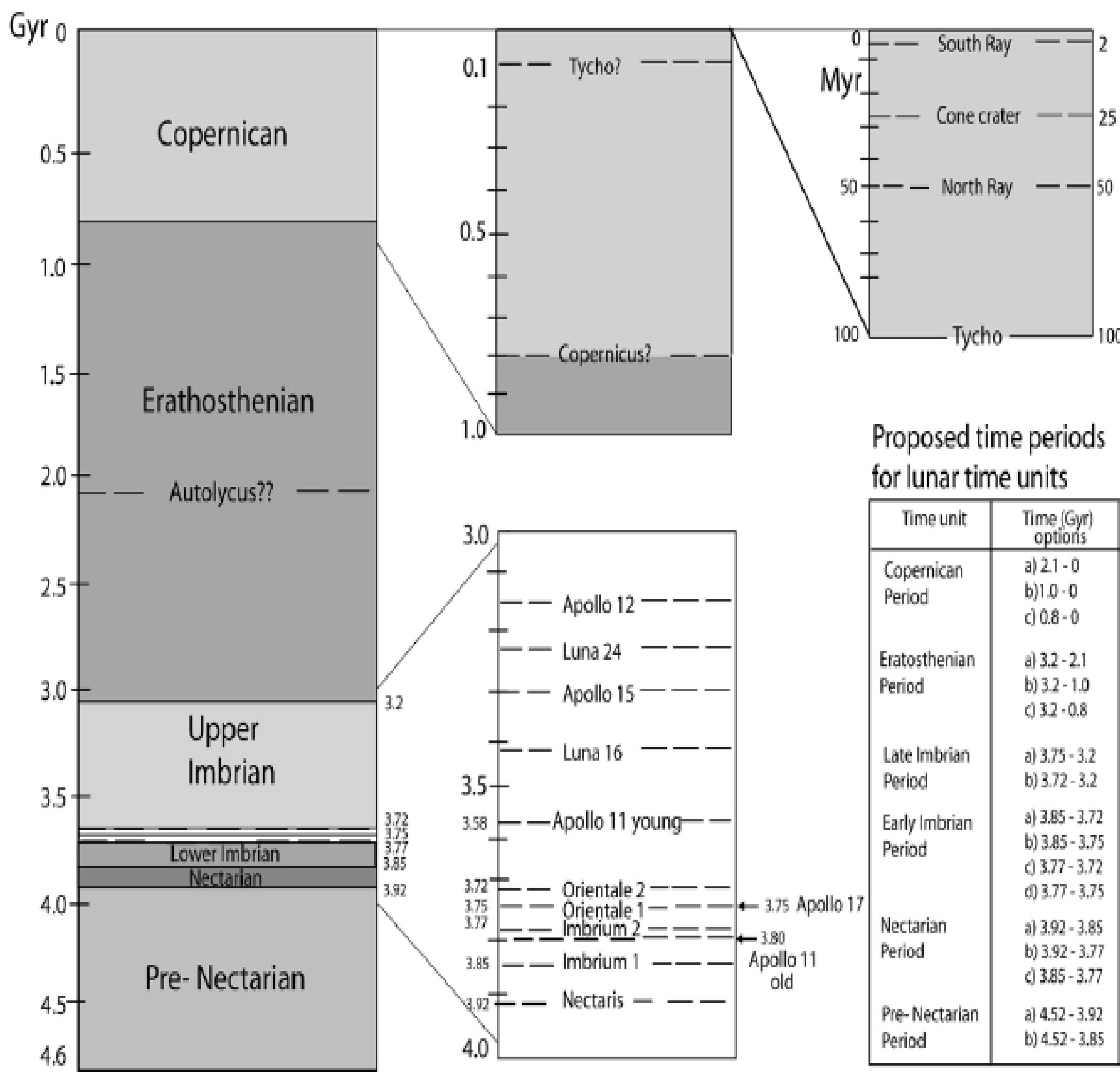
- Lunar stratigraphy establishes geologic units and arranges them into a relative time sequenced column of global significance.

✓ Pre-Nectarian System
✓ Nectarian system
✓ Lower Imbrian Series
✓ Upper Imbrian Series
✓ Eratosthenian System
✓ Copernican System

Table 5.8. Best estimates of crystallization ages of mare basalt flows at the Apollo and Luna landing sites.

Landing Site	Basalt Group	Absolute Age (Gyr)
Apollo 11	High-K basalts	**3.58 ± 0.01**
	High-Ti basalts, groups B1,3	3.70 ± 0.02
	High-Ti basalts, group B2	**3.80 ± 0.02**
	High-Ti basalts, group D	3.85 ± 0.01
Apollo 12	Olivine basalt	3.22 ± 0.04
	Pigeonite basalt	3.15 ± 0.04
	Ilmenite basalt	3.17 ± 0.02
	Feldspathic basalt	3.20 ± 0.08
Apollo 15	Ol-normative basalt	**3.30 ± 0.02**
	Qz-normative basalt	3.35 ± 0.01
	Picritic basalt	3.25 ± 0.05
	Ilmenite basalt (15388)	3.35 ± 0.04
	Green glass	~3.3 – 3.4
	Yellow glass	3.62 ± 0.07
Apollo 16	Feldspathic basalt	3.74 ± 0.05
Apollo 17	High-Ti basalt, group A	**3.75 ± 0.01**
	High-Ti basalt, group B1,2	3.70 ± 0.02
	High-Ti basalt, group C	**3.75 ± 0.07**
	High-Ti basalt, group D	3.85 ± 0.04
	Orange glass	~3.5 – 3.6
Luna 16	Aluminous basalt	3.41 ± 0.04
Luna 24	Very-low-Ti basalt (VLT)	**3.22 ± 0.02**
Lunar meteorite Asuka 881757	Basalt (gabbroic)	3.87 ± 0.06

Data compiled from various sources; see especially Snyder et al. (2000), Burgess and Turner (1998), Nyquist and Shih (1992); Dalrymple (1991), Spangler et al. (1984), and references therein. Proposed ages for surface flows (crater retention ages) are given in bold (see Table 5.10); from Stöffler and Ryder (2001).



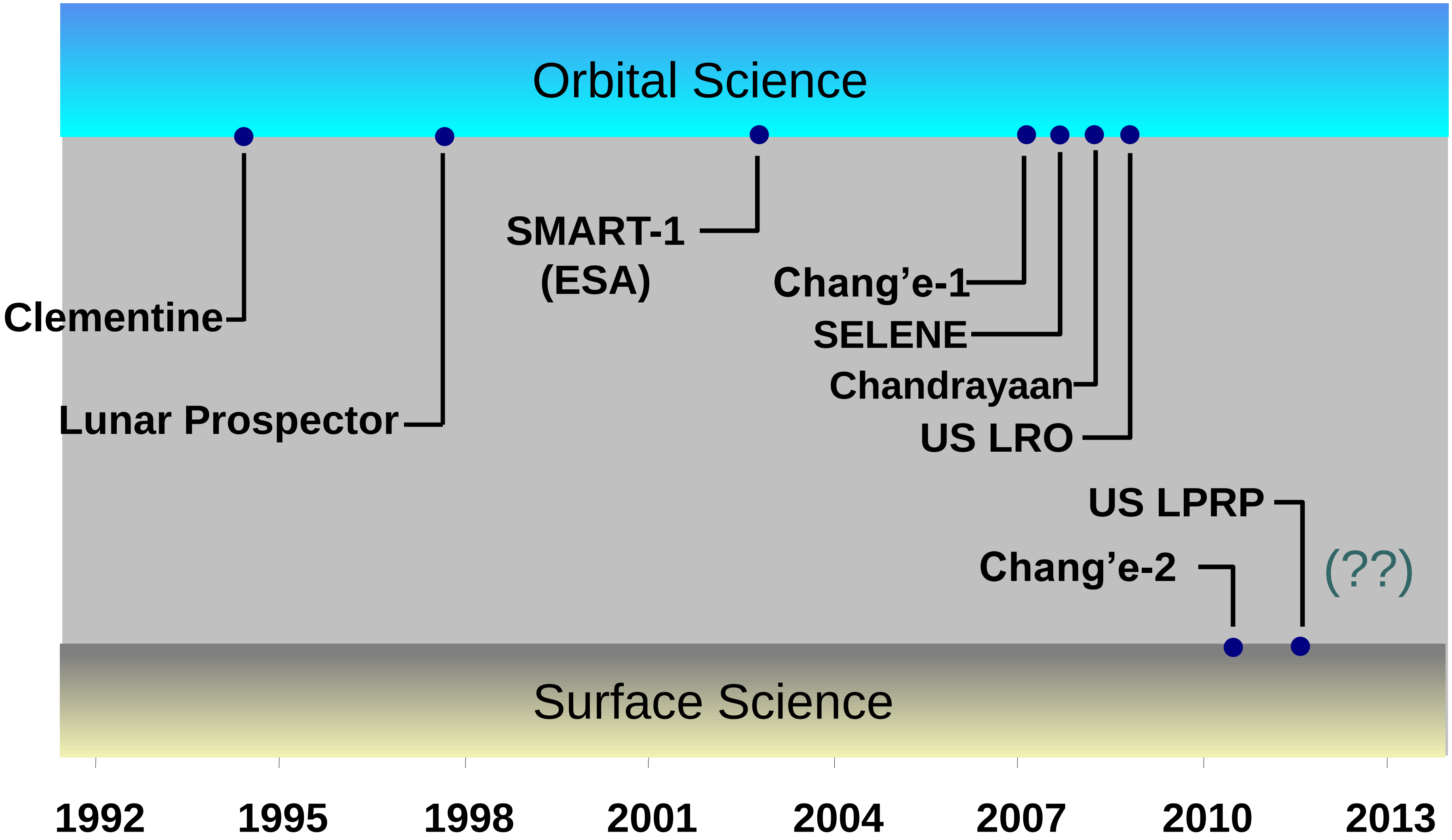
Time unit	Time (Gyr) options	Time (Gyr) adopted
Copernican Period	a) 2.1 - 0 b)1.0 - 0 c) 0.8 - 0	0.8 - 0
Eratosthenian Period	a) 3.2 - 2.1 b) 3.2 - 1.0 c) 3.2 - 0.8	3.2 - 0.8
Late Imbrian Period	a) 3.75 - 3.2 b) 3.72 - 3.2	3.75 - 3.2
Early Imbrian Period	a) 3.85 - 3.72 b) 3.85 - 3.75 c) 3.77 - 3.72 d) 3.77 - 3.75	a) 3.85 - 3.75 b) 3.77 - 3.75
Nectarian Period	a) 3.92 - 3.85 b) 3.92 - 3.77 c) 3.85 - 3.77	a) 3.92 - 3.85 b) 3.92 - 3.77
Pre- Nectarian Period	a) 4.52 - 3.92 b) 4.52 - 3.85	4.52 - 3.92

Figure 5.31. Proposal for a revised time-calibrated lunar stratigraphy based on data from Stöffler and Ryder (2001) and from references therein. The proposal differs from these authors regarding the age of the Eratosthenian-Copernican boundary. The data points for the lunar landing sites refer to ages of mare basalt surfaces. The optional age of 3.85 Ga for Nectaris basin is not shown here because the 3.92 Ga age is preferred.

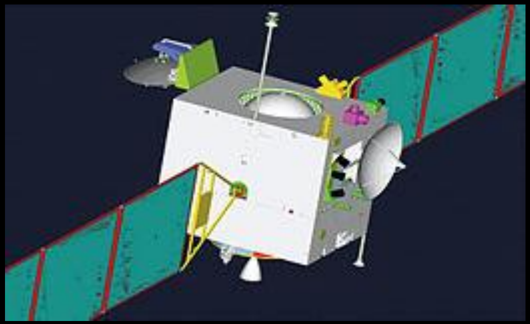
Proposed time periods for lunar time units

Time unit	Time (Gyr) options	Time (Gyr) adopted
Copernican Period	a) 2.1 - 0 b)1.0 - 0 c) 0.8 - 0	0.8 - 0
Eratosthenian Period	a) 3.2 - 2.1 b) 3.2 - 1.0 c) 3.2 - 0.8	3.2 - 0.8
Late Imbrian Period	a) 3.75 - 3.2 b) 3.72 - 3.2	3.75 - 3.2
Early Imbrian Period	a) 3.85 - 3.72 b) 3.85 - 3.75 c) 3.77 - 3.72 d) 3.77 - 3.75	a) 3.85 - 3.75 b) 3.77 - 3.75
Nectarian Period	a) 3.92 - 3.85 b) 3.92 - 3.77 c) 3.85 - 3.77	a) 3.92 - 3.85 b) 3.92 - 3.77
Pre- Nectarian Period	a) 4.52 - 3.92 b) 4.52 - 3.85	4.52 - 3.92

Lunar Missions, 1992-2014



Chang'e 1 Mission



Mission Facts:

- Launch—October 24, 2007
- Rocket—Chang Zheng 3A (Long March rocket)
- Launch site—Xichang LC-3, Sichuan Province
- Orbital insertion—November 5, 2007
- End of mission date—March 1, 2009 (impacted the surface of the Moon)

Mission objectives:

- To obtain three-dimensional imagery of the lunar surface
- To analyze the distribution of useful elements and materials on the lunar surface
- To probe the features of lunar soil and assess its depth
- To explore the space environment between the Moon and Earth and above the lunar surface

Return

Chang’e 2 Mission

Mission Facts:

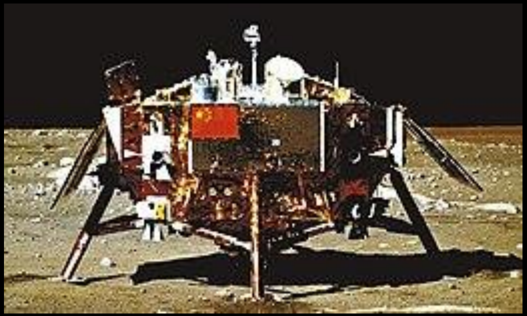
- Launch—October 1, 2010
- Rocket—Chang Zheng 3C (Long March rocket)
- Launch site—Xichang LC-2, Sichuan Province
- Orbital insertion—October 6, 2010
- Mission duration—planned 6 months; left lunar orbit June 8, 2011; mission on-going (2011 at Lagrange Point L2; 2012 flyby of asteroid 4179 Toutatis; now is conducting a long-term mission to verify China's deep-space tracking and control systems)

Mission objectives:

- To obtain three-dimensional images of the lunar surface with a spatial resolution < 10 meters
- To explore the composition of lunar surface material
- To observe the Earth-Moon and near-moon space environment

Return

Chang'e 3 Mission



Mission Facts:

- Launch—December 1, 2013
- Rocket—Chang Zheng 3B (Long March rocket)
- Launch site—Xichang LC-2, Sichuan Province
- Lunar landing—December 14, 2013 (Mare Imbrium)
- Status—Lander still transmitting as of June 2017

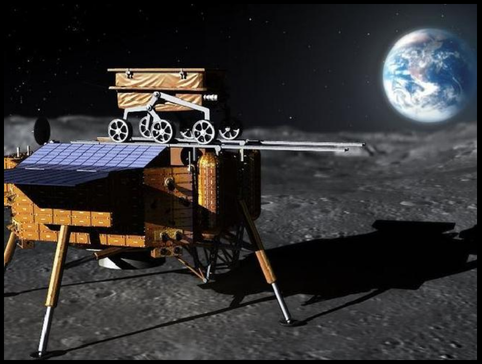
  Rover Yutu (Jade Rabbit) stopped transmitting August 2016 after 31 months

Mission objectives:

- To soft-land on the moon's surface and deploy an unmanned Lunar Rover to explore the areas surrounding the landing site
- Carry scientific payloads that are going to be used to study the Moon, other galaxies and stars as well as the near-Earth space environment
- Lunar surface topography and geology survey, lunar surface material composition and resource survey, Sun-Earth-Moon space environment detection, and lunar-based astronomical observation

Return

Chang'e 4 Mission



Mission Facts:

- Launch—May 20, 2018 (Queqiao orbiter)
  late 2018 (lander & rover)
- Rocket—Chang Zheng 4C (Long March rocket)
- Launch site—Xichang, Sichuan Province
- Lunar landing—end of 2018, on the far side of the Moon at the Von Karman crater in the South Pole-Aitken Basin

Mission objectives:

- While the orbiter will provide communications relay, the lander and rover will carry scientific payloads to study the geophysics of the landing zone
- The lander will carry a container with seeds and insect eggs to test whether plants and insects could hatch and grow together
- Will also carry international payloads from Sweden, Germany, the Netherlands and Saudi Arabia

Payload Return

CHANG’E Lunar Missions

Chang’e 5 Mission

Mission Facts:

- Launch—2019
- Rocket—Chang Zheng 5 (Long March rocket)
- Launch site—Wenchang Launch Site, Hainan, China
- Lunar landing—2019 (northwest area of the Moon in the Mons Rumker region)

Mission objectives:

- To land in the Mons Rumker region and return a 2 kg sample of lunar regolith, possibly from as deep as 2 meters
- Will consist of four modules: two will land on the Moon, one designed to collect samples and transfer them to the second module. The second module will ascend from the lunar surface into orbit, and dock with a third module, then transfer to the fourth module, also in lunar orbit. Fourth module will return samples to Earth
- Instruments: Panoramic Camera (PCAM), Lunar Regolith Penetrating Radar (LRPR) and Lunar Mineralogical Spectrometer (LMS)

Return

Chang'e 6 Mission

Mission Facts:

- Launch—2020
- Rocket—Chang Zheng 5 (Long March rocket)
- Launch site—Wenchang Launch Site, Hainan, China
- Lunar landing—2020

Mission objectives:

- Will be China's second sample return mission
- The mission is currently speculated to be under development

Return

Chang'e 4 Mission
Scientific payload:

Rover
- Panoramic camera
- Ground-penetrating radar
- Infrared spectrometer
- Active Source Hammer (ASH) for active source seismic experiments
- Energetic neutral atom analyzer: Advanced Small Analyzer for Neutrals (ASAN), provided by the Swedish Institute of Space Physics (IRF). It will reveal how solar wind interacts with the lunar surface and perhaps even the process behind the formation of lunar water.

Lander
- Lunar Dust Analyser (LDA)
- Electric Field Analyser (EFA)
- Plasma and Magnetic Field Observation Package (PMFOP)
- Lunar Seismometer (LS), for internal structure
- VLF Radio Interferometer (VRI), a type of radio telescope for astronomical observations[1]
- Neutron dosimeter: Lunar Lander Neutron Dosimetry (LND) project developed by Kiel University in Germany
- In addition, the lander will carry a container with seeds and insect eggs to test whether plants and insects could hatch and grow together

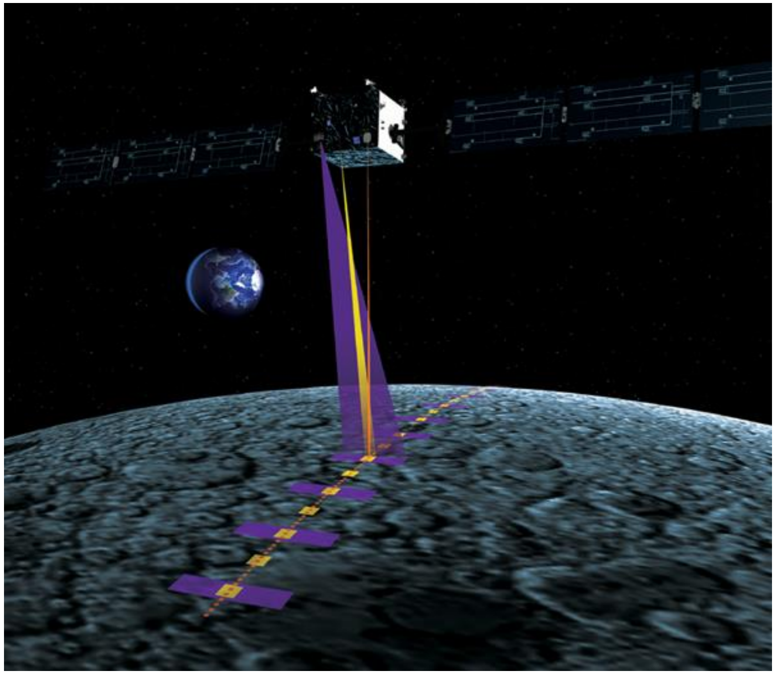
Return to Chang'e 4 Return

ESA SMART-1

ESA SMART-1 Orbiter, ongoing

Launched: 27 September 2003

Status: Arrived in lunar orbit, 15 November 2004. Nominal mission: 2-2.3 yrs.



Technology Demonstration:

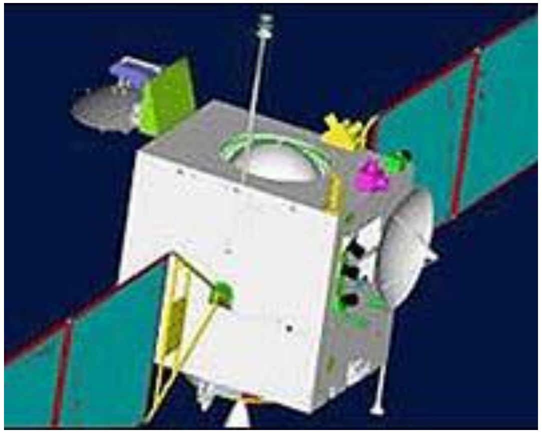
- Solar-electric Ion-propulsion
- Laser communications

Science Instruments:

- X-ray spectrometer (D-CIXS)
- VIS-NIR Camera (AMIE)
- Infrared Spectrometer (SIR)
- Radio Experiment (RSIS)

Will complete mission by attempting a controlled low-angle impact into a permanently shadowed crater.

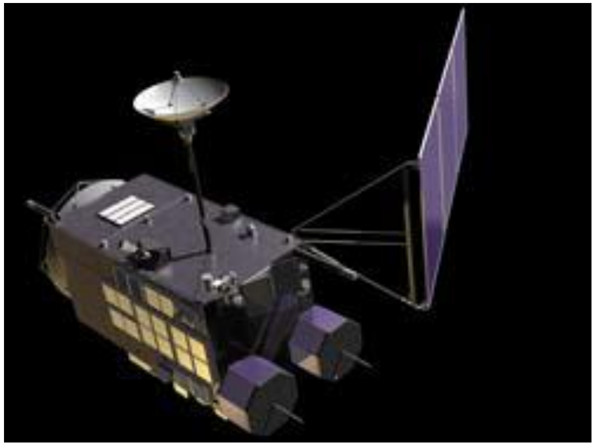
Chang'E-1

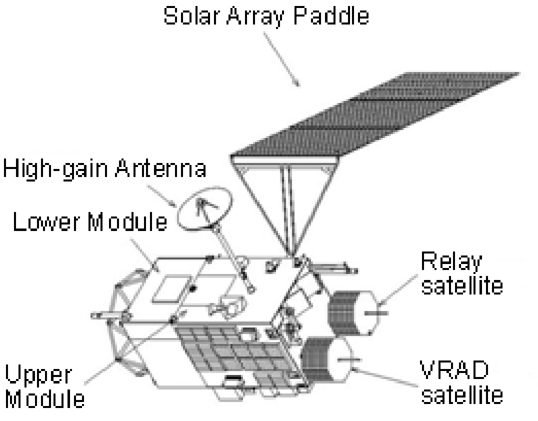


- The spacecraft will be tested in December. If tests go well, orbiter will be launched in April 2007.
- China's lunar probe project will be divided into three phases:
  - (1) satellite to orbit Moon by 2007
  - (2) landing an unmanned vehicle on the moon by 2010,
  - (3) collecting samples of lunar soil with an unmanned vehicle by 2020.
- The spacecraft carries 5 instruments
  - Altimeter: topography
  - Stereo Camera
  - Gamma ray spectrometer: determine radioactivity of lunar surface
  - X-ray spectrometer: determine composition of lunar surface
  - Microwave Radiometer: determine thickness of lunar regolith
  - Space environment monitor system: Map solar wind
  - Solar high-energy particles and solar wind ion detector

SELENE

- SELENE (SELenological and ENgineering Explorer) is targeting launch in summer of 2007.
- Nominal mission is 1 year in orbit.
- Mapping orbit will be 100 km altitude, circular, 3-axis stabilized.
- Expected data volume: ~10 Terabytes
- Data access: 1 year after end of nominal mission; planning for PDS compliant data formats.





SELENE Instrument suite (1)

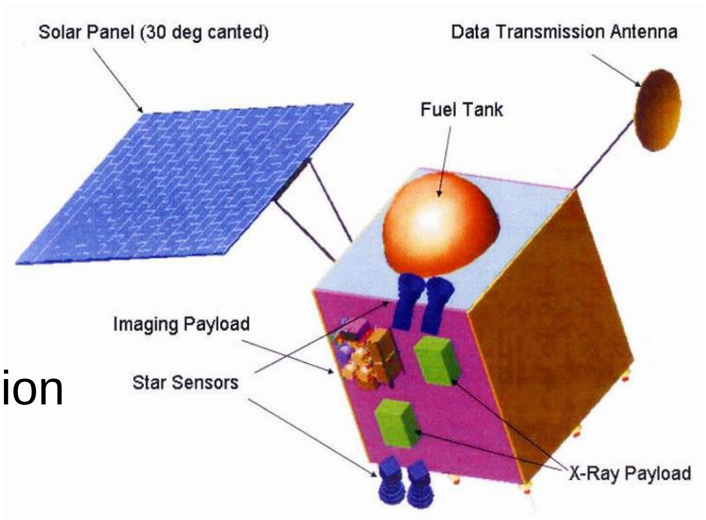
	Observation	Instrument and Characteristics
Main Orbiter	Chemical distribution	X-ray Spectrometer [XRS] (Surface distribution of major elements such as Mg, AI, Si, Fe, Na using X-ray CCD array, with spatial resolution of 20km) Gamma-ray Spectrometer [GRS] (Global mapping of K, U, Th etc. distributions using a highly pure Ge crystal, resolution 120km)
	Mineralogical distribution	Spectral Profiler [SP] (Continuous spectral profiling from 0.5 to 2.6µm, (Spectral resolution 6 to 8nm), spatial resolution 500m) Multiband Imager [MI] (UV-VIS-NIR imager, spectral coverage ranging from 0.4 to 1.6µm, 9 bands(Spectral resolution 20 to 50nm), spatial resolution 20m)
	Surface Structure	Terrain Camera [TC] (High-resolution stereo camera, spatial resolution 10m) Lunar Radar Sounder [LRS] (HF radar sounding of subsurface structure of the Moon and observation of natural radio and plasma waves) Laser Altimeter [LALT] (Nd:YAG laser altimeter, height resolution 5m, pulse rate 1Hz)

SELENE Instrument suite (2)

	Observation	Instrument and Characteristics
Main Orbiter	Surface environment & Imaging	Lunar Magnetometer[LMAG] (Mag. field measurement w/ flux-gate magnetometers, accuracy 0.5 nT) Upper atmosphere and Plasma Imager[UPI] (Imaging of the Earth's magnetosphere and aurora from lunar orbit) Charged Particle Spectrometer[CPS] (Mapping Rn and Po using the ARD(4 to 6.5 MeV for alpha), Measurement of high energy particles using the PS instruments (e: 0.3 to 1MeV, p:0.1 to 60MeV, Heavy ion: 2.5 to 370MeV/n)) Plasma energy Angle and Composition Experiment[PACE] (Charged particle energy and composition measurement 5eV/q to 28keV/q(Ion),5eV to 17keV(Electron)) Radio Science[RS] (Detection of lunar ionosphere using S- and X-band carriers)
	Imaging	High Definition Television [HDTV] (Photos and movies of the Earth and the Moon)
Relay satellite	Gravitational field distribution	Four way Doppler measurements by relay satellite and main orbiter transponder[RSAT-1,2] (Far-side gravity using four-way Doppler measurement from the ground station to Orbiter via Relay Satellite, 2400 x 100 km alt., elliptical orbit)
VRAD satellite Relay satellite	Gravitational field distribution	Differential VLBI Radio source-1,2[VRAD-1,2] (Differential VLBI observation of radio sources on Relay Satellite and VRAD Satellite from ground radio telescopes. 100 x 800 km, alt, elliptical)

Chandrayaan-1

- Indian Space Research Organization (ISRO) plans to launch Chandrayaan-1 in late 2007 or early 2008.
- Initially the spacecraft will circle Earth in a geosynchronous transfer orbit (GTO). From there, it will transit to a polar orbit of the Moon at an altitude of ~100 km above the lunar surface.
- Instruments will include:
  - XRF (ESA CIXS)
  - Gamma ray spectrometer
  - M3 (Moon Mineralogy Mapper, Brown/JPL)
  - Laser altimeter
  - Miniature synthetic aperture radar (APL)
- Chandrayaan is nominally a two-year mission
- Chandrayaan is Hindi for "Moon Craft"



Chandrayaan-1 Payload, detail

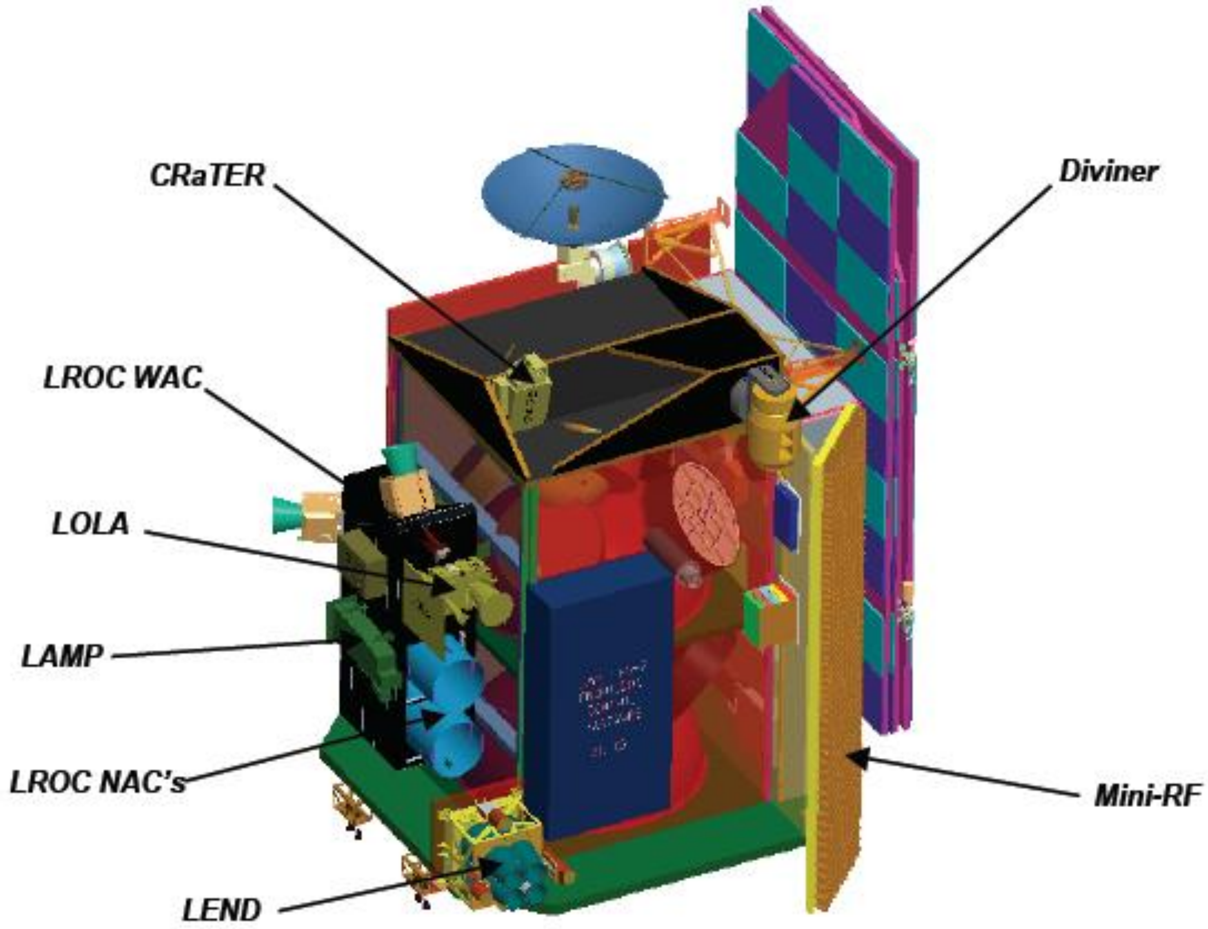
- **Terrain Mapping Camera (TMC)**: 5 meter resolution and a 40 km swath in the panchromatic band and will be used to produce a high-res map of the Moon. (Indian)
- **Hyper Spectral Imager (HySI)**: mineralogical mapping in the 400-900 nm band with a spectral resolution of 15 nm and a spatial resolution of 80 m.
- **Lunar Laser Ranging Instrument (LLRI)**: determine surface topography.
- **X-ray fluorescence spectrometer**:
  - Imaging X-ray Spectrometer (CIXS) covering 1-10 keV with a ground resolution of 10 km; will map Si, Al, Mg, Ca, Fe, and Ti at the surface
  - High Energy X-ray/gamma ray spectrometer (HEX) for 10-200 keV measurements with ground resolution of about 20 km; will measure K, U, Th, Pb(210), Rn(222)
  - Solar X-ray Monitor (SXM) to detect solar flux in the 2-10 keV range. SXM will monitor the solar flux to normalize the results of CIXS and HEX.
- **Sub-keV Atom Reflecting Analyzer (SARA)**: will map composition using low energy neutral atoms sputtered from the surface.
- **Moon Mineralogy Mapper (M3)**: imaging spectrometer designed to map the surface mineral composition.
- A **near-infrared spectrometer (SIR-2)**: will also map the mineral composition using an infrared grating spectrometer.
- **Miniature Synthetic Aperture Radar (Mini-SAR)**: will perform radar scattering and imaging investigations at the poles in a search for water ice.

Lunar Reconnaissance Orbiter (LRO)

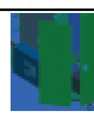
- **Launch planned for October, 2008**
- **Provides knowledge required for safe landing-site selection and in-situ resource utilization.**
- **Planned: 50 km altitude circular orbit**
- **Focus on lunar poles**

LRO Instrument Payload

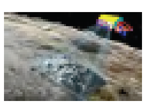
- **Payload includes 8 scientific instruments**
- **Nominal mission is one year**
- **Extended mission:**
  6 months at 50 km <u>or</u> several years at high, stable orbit



LRO Instrument Suite

Instrument	Navigation/ Landing Site Safety	Locate Resources	Life in Space Environment	New Technology
CRaTER Cosmic Ray Telescope for the Effects of Radiation 			• High Energy Radiation • Radiation effects on human tissue	
DLRE Diviner Lunar Radiometer Experiment 	• Rock abundance	• Temperature • Mineralogy		
LAMP Lyman Alpha Mapping Project 		• Surface Ice • Image Dark Craters		
LEND Lunar Exploration Neutron Detector 		• Subsurface Hydrogen Enhancement • Localization of Hydrogen Enhancement	• Neutron Radiation Environment	
LOLA Lunar Orbiter Laser Altimeter 	• Slopes • Topography/Rock Abundance • Geodesy	• Simulation of Lighting Conditions • Crater Topography • Surface Ice Reflectivity		
LROC Lunar Reconnaissance Orbiter Camera 	• Rock hazards • Small craters	• Polar Illumination Movies • Mineralogy		
Mini-RF *Technology Demonstration* 				• S-band and X-band SAR demonstration

LRO Instrument Suite

INSTRUMENT	Key Data Products	Exploration Benefits	Science Benefits
CRaTER Cosmic Ray Telescope for the Effects of Radiation 	Lunar and deep space radiation environment and tissue equivalent plastic response to radiation	Safe, lighter weight space vehicles. Radiation environment for human presence at the Moon and journeys to Mars and beyond.	Radiation boundary conditions for biological response . Map radiation reflected from lunar surface
DLRE Diviner Lunar Radiometer Experiment 	500 m scale maps of surface temperature, albedo, rock abundance, and ice stability	Measures thermal environment in permanent shadow and permanent light, ice depth map	Source, history, migration and deposition of polar volatiles
LAMP Lyman Alpha Mapping Project 	Maps of frosts and landforms in permanently shadowed regions (PSRs).	Locate potential water-ice on the surface, image shadowed areas, and map potential landing areas in PSRs	
LEND Lunar Exploration Neutron Detector 	Maps of hydrogen in upper 1 m of Moon at 10 km scales, neutron albedo	Locate potential water-ice in lunar soil or concentrations of implanted hydrogen	
LOLA Lunar Orbiter Laser Altimeter 	~25 m scale polar topography at < 10 cm vertical, global topography, surface slopes and roughness	Identify safe landing sites, image shadowed regions, map potential surface ice, improve gravity field model	Global topography and gravity for interior structure and geological evolution
LROC Lunar Reconnaissance Orbiter Camera 	1000's of 50cm/pixel images, and entire Moon at 100m in UV, Visible. Illumination conditions of the poles.	Surface landing hazards and some resource identification including locations of near constant solar illumination	Tectonic, impact and volcanic processes, resource evaluation, and crustal evolution
Mini-RF *Technology Demonstration* 	X and S-band radar imaging and interferometry	Demonstrate new lightweight SAR and communication technologies, locate potential water-ice	Source, history, deposition of polar volatiles