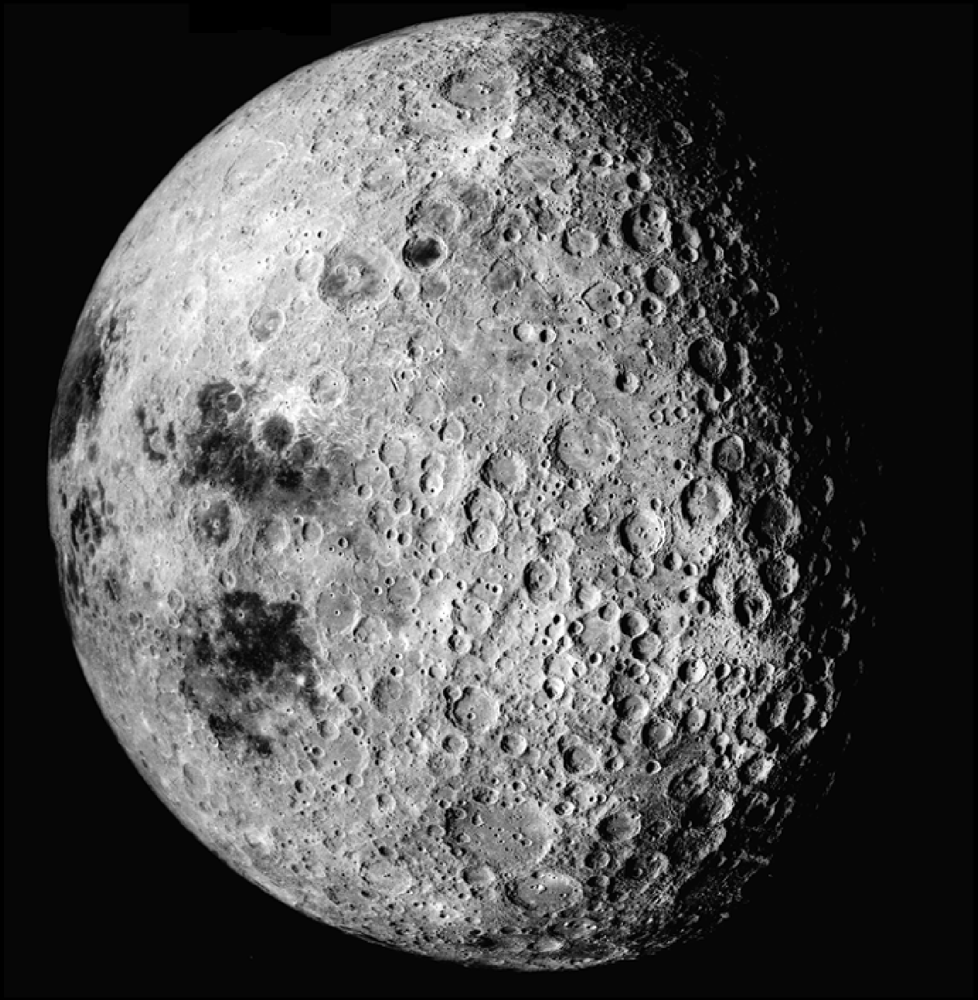
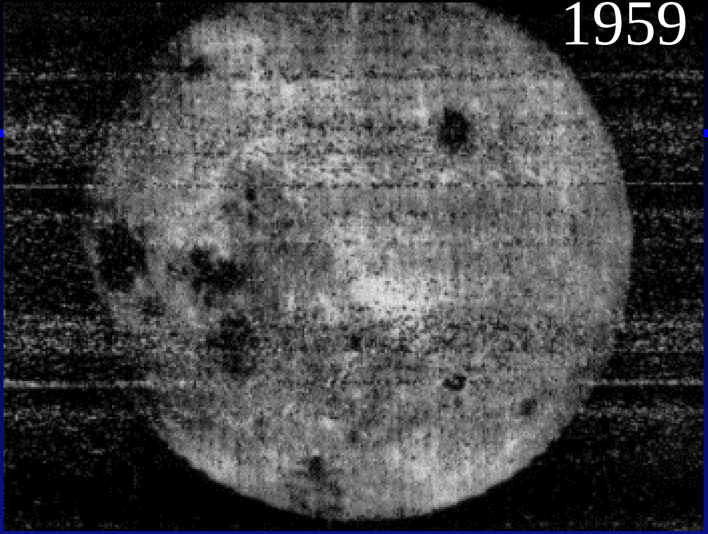
Exploration and Science of the Moon

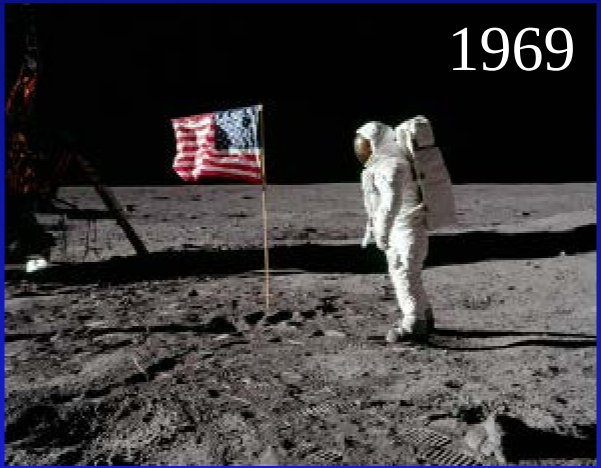


Caleb Fassett
NASA Marshall Space Flight Center
March 23, 2019

The Moon: Exploration

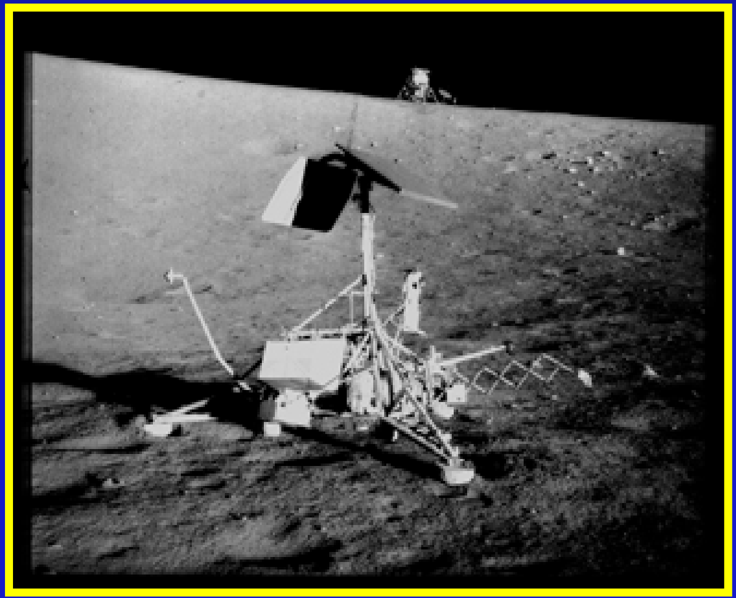


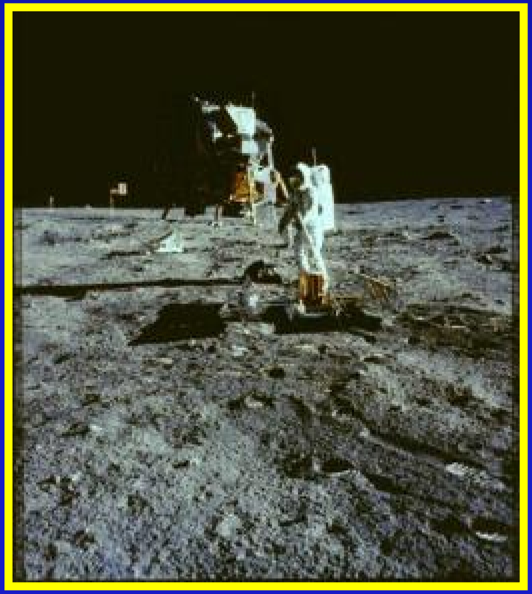
- Telescopic Phase: Galileo, Huygens, etc.
- Photography: Mid-1800's
- Robotic Orbiter (Earth): Sputnik - 1957
- Human Orbiting (Earth): Gagarin - 1961
- Kennedy's National Goal
- Space Missions: The US-USSR Space Race
  - 1959 Luna 3 (Farside)
  - 1964 Ranger 7, 8, 9
  - 1966 Luna 9 (Soft Lander)
  - 1966 Surveyor I, III, V, VI, VII
  - 1966-1967 Lunar Orbiter I-V
  - 1969-1972 Apollo 11-17
  - 1970-1976 Luna 16, 20, 24
  - 1970 Lunakhod I, II, Zond spacecraft
  - 1990's Galileo, Clementine, Lunar Prospector
  - 2000-2019 USA, Japanese, Indian, Chinese, and Israeli missions



- Next steps: Commercial landed missions, return of humans?

The Moon: Exploration





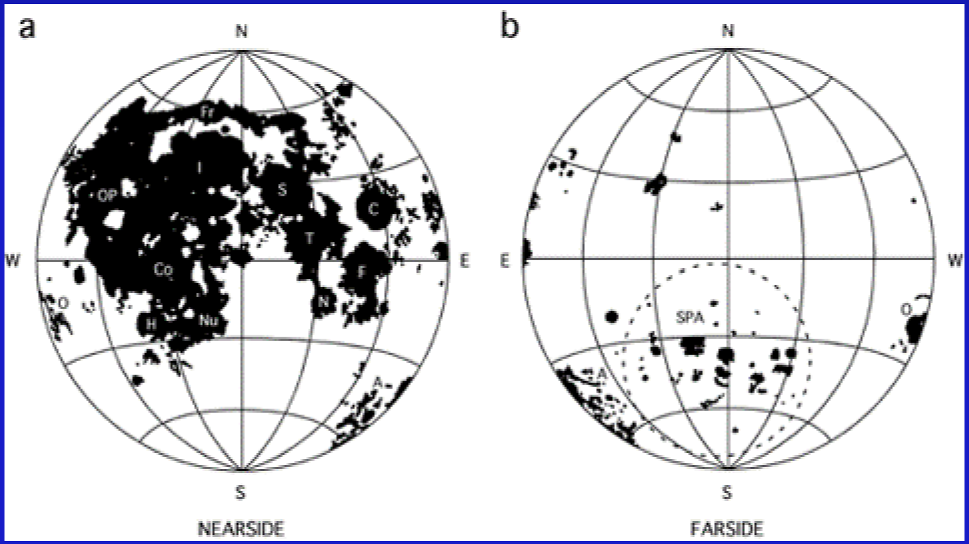
The Moon: Exploration

- After Apollo 17 (1972) and Lunar 24 (1976), *no* scientific missions to the Moon (human or robotic) again until 1994.
- Recent years have seen an uptick in activity:
  - Clementine: 1994
  - Lunar Prospector: 1998
  - Smart-1 (Europe): 2003
  - SELENE / Kaguya (Japan): 2007
  - Chandrayaan-1 (India): 2008
  - Lunar Recon Orbiter: 2009
  - LCROSS: 2009
  - Chang'e 2 (China): 2010
  - GRAIL: 2011
  - LADEE: 2013
  - Yutu/Chang'e 3 (China) 2014
  - Yutu 2/Chang'e 4 (China) 2019
  - Beresheet (Israel) 2019

Coming Soon:
- CLPS landers 2019-
- Mid-sized landers [notional] (2022)
- Human-class lander [notional](2028)

The Moon: A User's Guide

- *Two Major Provinces:*
  - Highlands, Maria
- Maria:
  - ~20% of surface (mostly on near-side)
  - Basaltic (volcanic)
  - Albedo: 8-10%
  - 'Young'/Lightly-cratered
- Highlands (or Terra)
  - ~80% of surface
  - Anorthositic
  - Albedo: 12-25%
  - 'Old'/Heavily-Cratered



The Moon: A User's Guide

- *Most Important Processes on the Moon:*
  - Formation, Differentiation, Magma Ocean
  - Impact Cratering
  - Volcanism

The Moon: Formation

Prior to the Apollo Missions, many scientists believed the Moon formed in the early Solar System by direct accretion from a primordial disk similar to other planets:

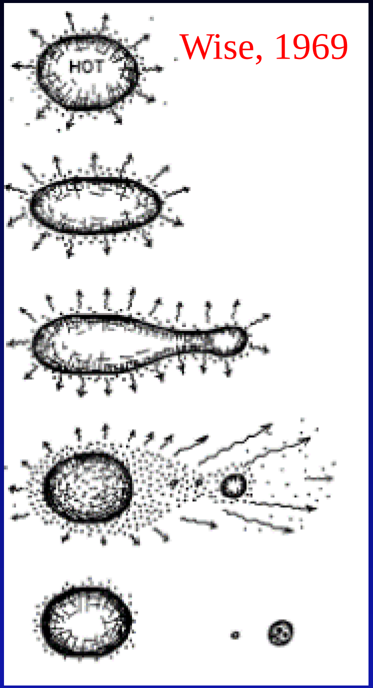
- Co-accretion **(sibling)**
  - ⊕ and ☾ formed together

Other ideas:

- Fission **(child)**
  - Fast-spinning ⊕, a blob tore away
- Capture **(cousin)**
  - ☾ made a close pass to ⊕, captured into orbit
- Giant impact **(angry cousin)**
  - **Proto-**⊕ struck by Mars- sized impactor then Moon forms from debris

George H. Darwin

Fission origin of the Moon



"[People] will always aspire to peer into the remote past to the utmost of their power and the fact that their success or failure cannot appreciably influence their life on Earth will never deter them from such endeavors."

Fission Origin of the Moon

Likely Problems:

- Classical fission mechanism requires **too much** total angular momentum in the Earth-Moon system

  [Think about it: the Earth would have had to be spinning fast enough to tear itself apart! Where does the angular momentum go?]

- Cannot easily account for the fact that the Moon revolves around the Earth in an orbit slightly off the Earth's plane of rotation

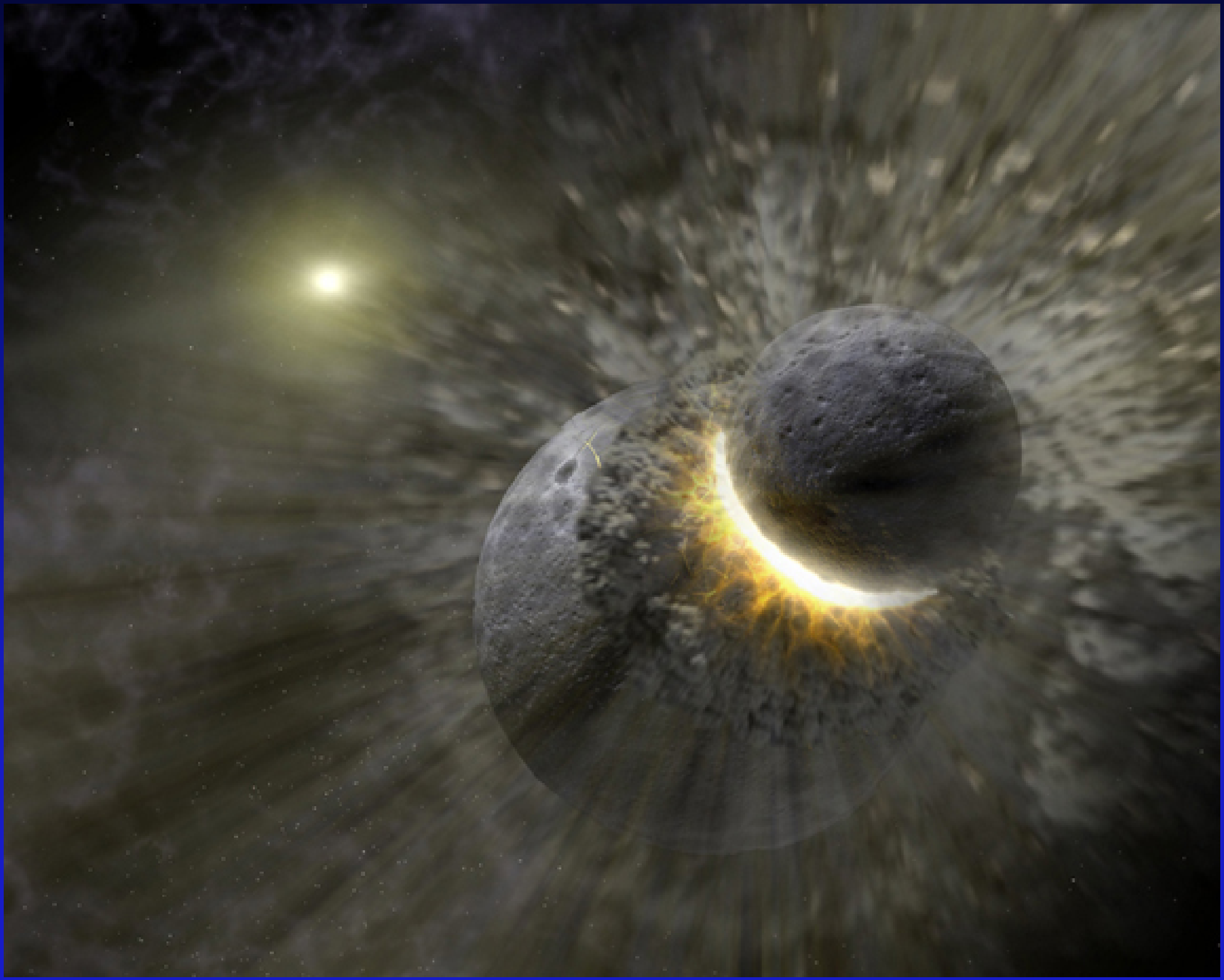
Prior to 2010, most scientists settled on a Giant Impact as the most likely Moon origin hypothesis…

Giant Impact Hypothesis

Canonical model:

A projectile about the size of Mars ($1/10^{th}$ the M_{Earth}) struck Earth ~4.5-4.55 Gy.

First proposed by four scientists (1974-1977): Hartmann, Davis, Cameron, Ward

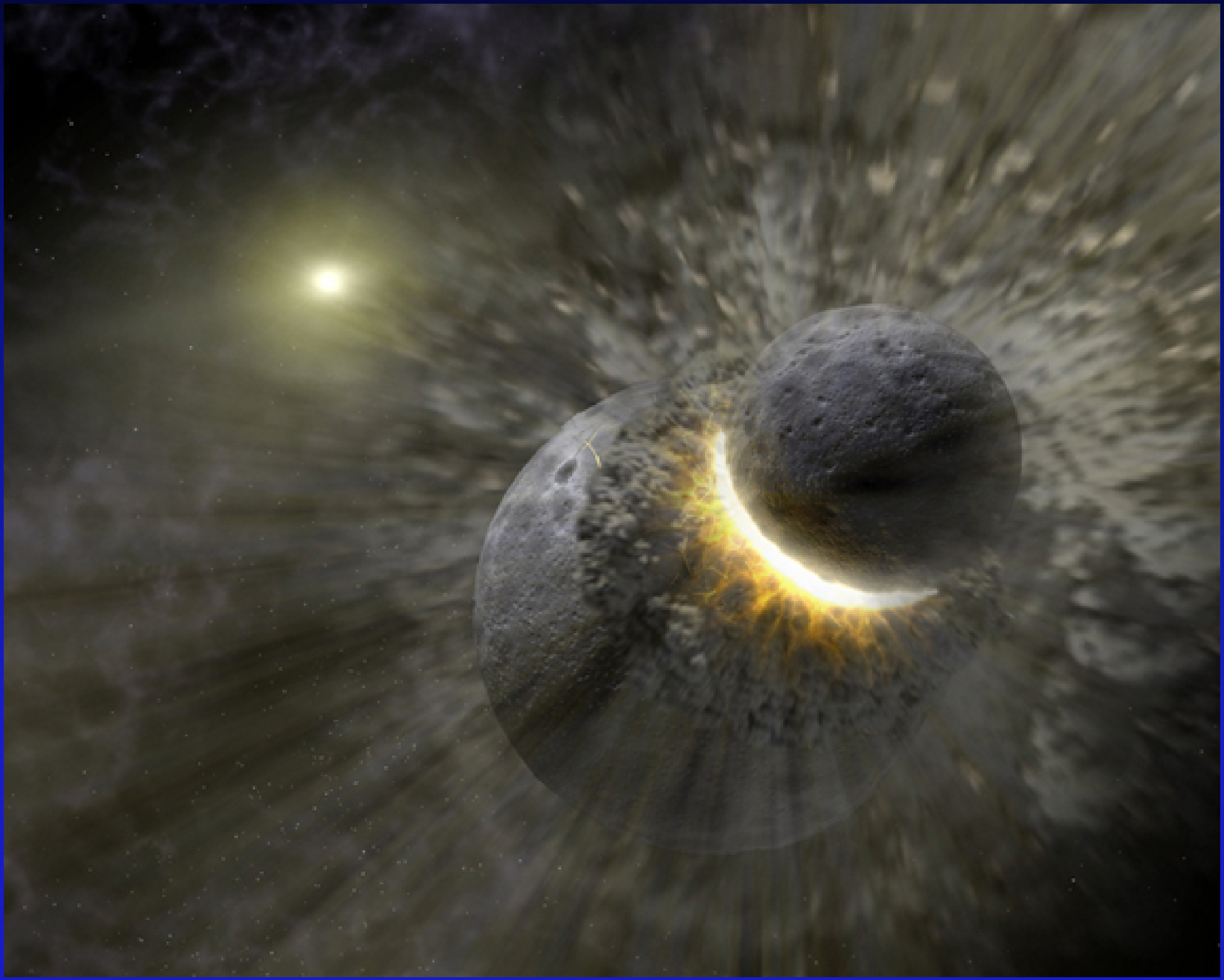


NASA/Artist’s Conception

Giant Impact Hypothesis

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.



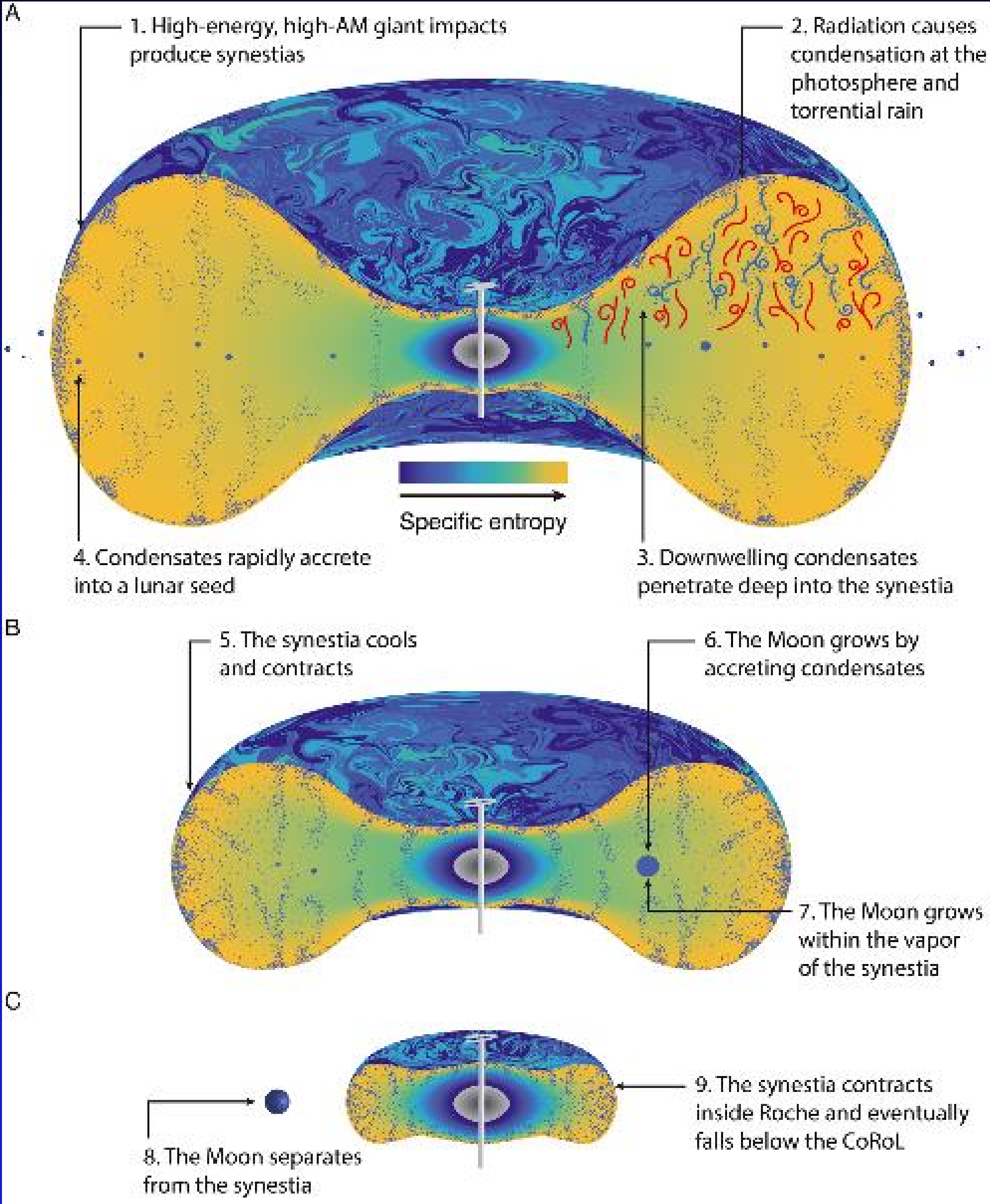
NASA/Artist's Conception

The Earth-Moon Donut: "Synestia"

A new 2017-2018 idea:

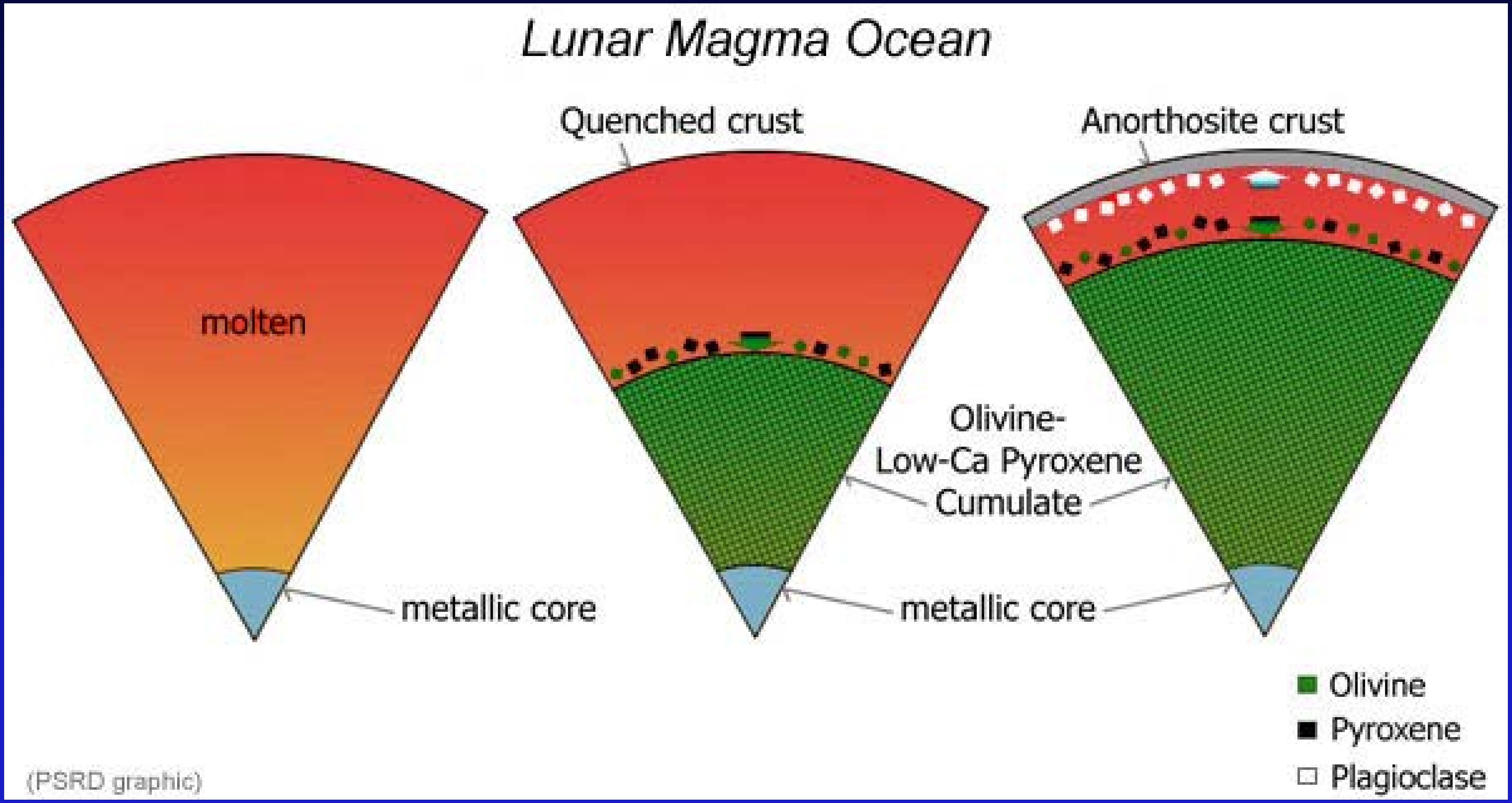
A higher energy, high angular momentum impact produces a fast-rotating, donut-shaped disk of silicate vapor, and the Moon condenses out.

A nice feature of this model is that a wide range of giant impact parameters can end in this state (as long as the impact is big enough).



(Lock and Stewart, 2017; Lock et al., 2018)

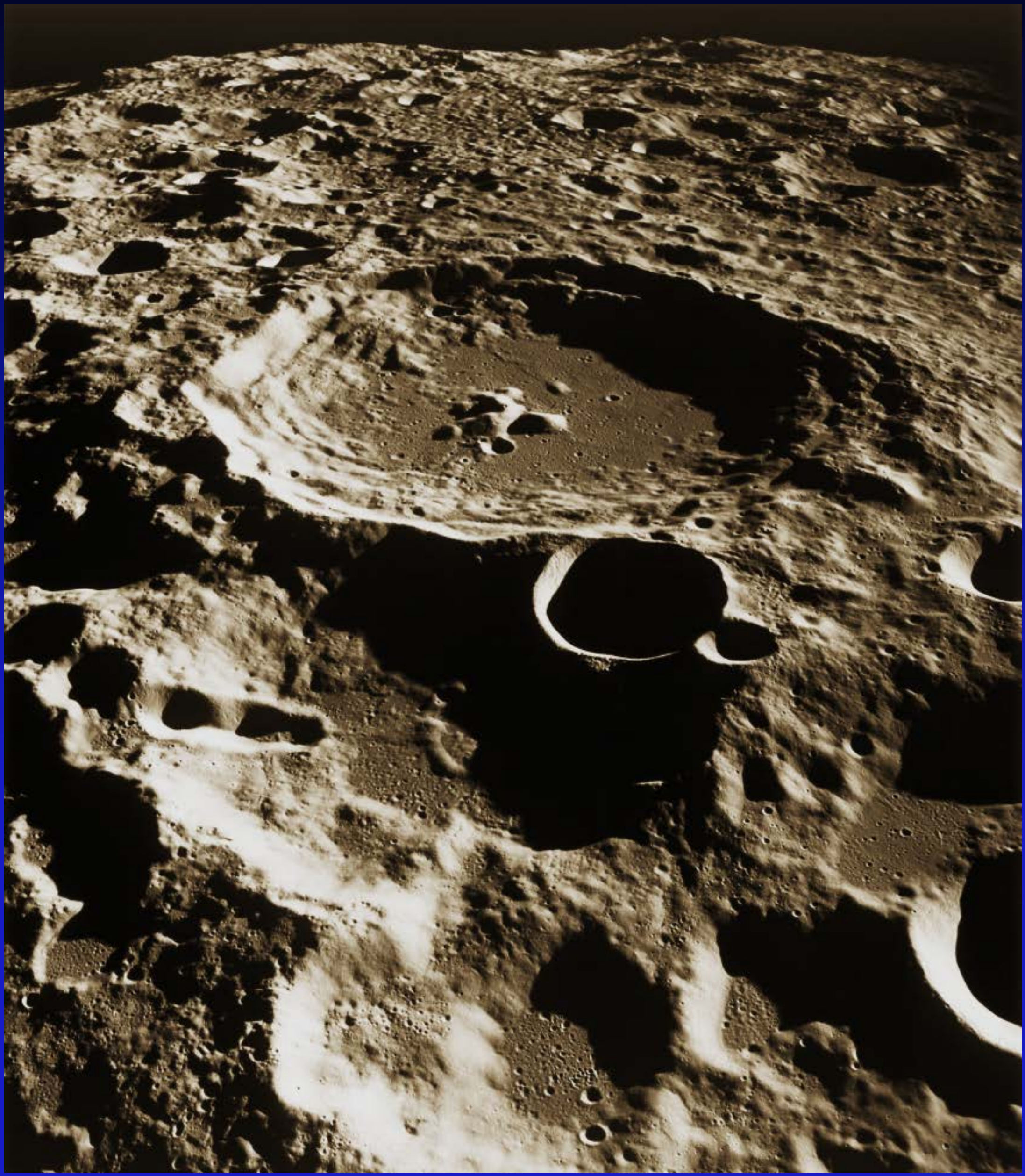
The Moon after Giant Impact: Magma Ocean



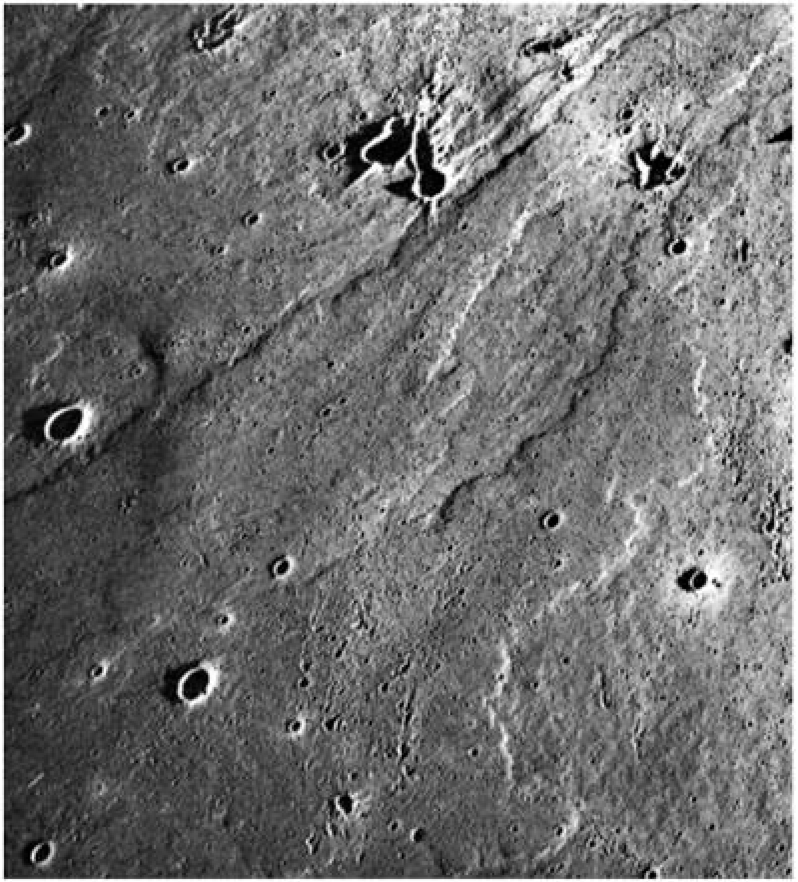
Heavy (High Density) Minerals Sink, Light (Low Density) Minerals Float

The Moon: Lunar highlands

- Highlands:
  - *'Primordial Crust'*
  - Composition: dominated by anorthosite
  - Geology: most influenced by impact cratering



Volcanism and the Maria: Effusive Volcanism



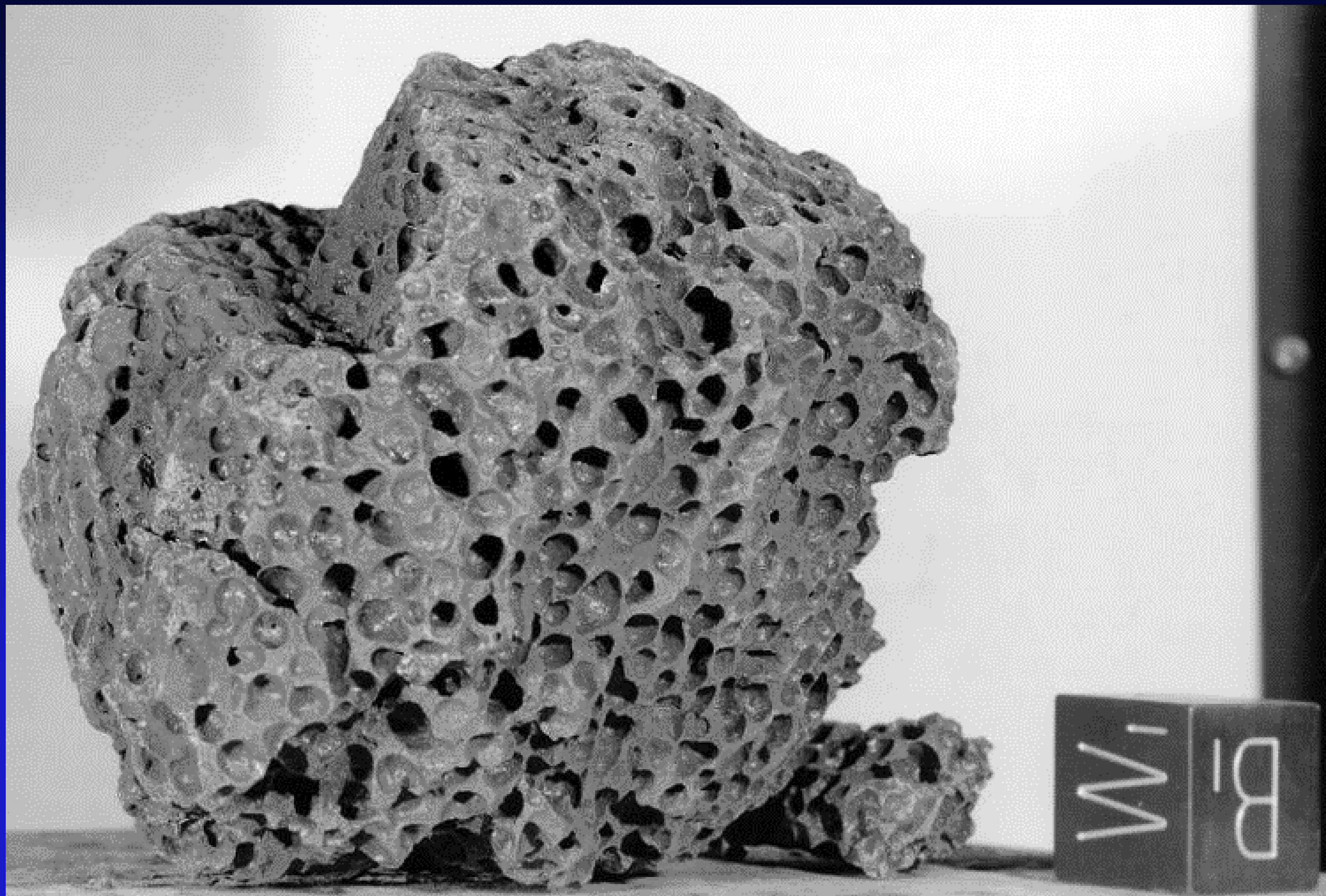
Mare Imbrium

Rimae Prinz

Mare Lava Flows: Similar to those on Earth

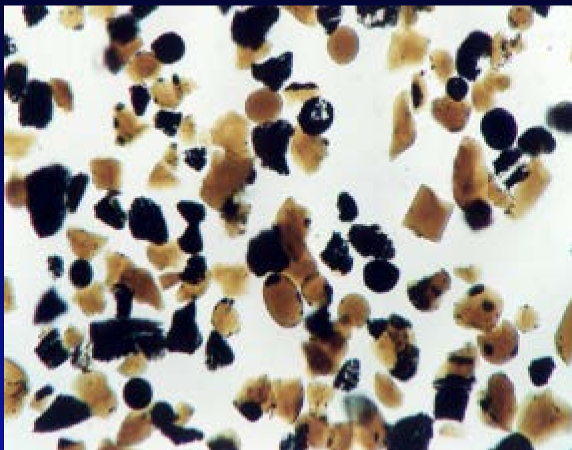
Sinuous Rilles: High Eruption Rates; Potentially High Enough to Erode Rock?

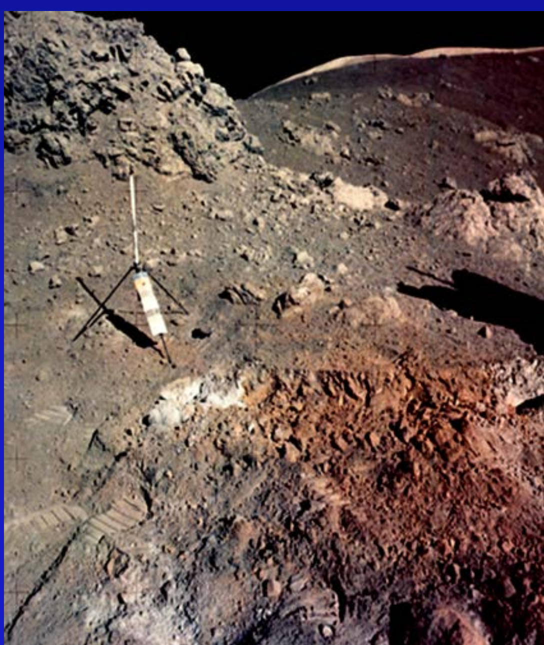
Volcanism and the Maria: Effusive Volcanism



Vesicular Basalt, Apollo 15
Sample 15556

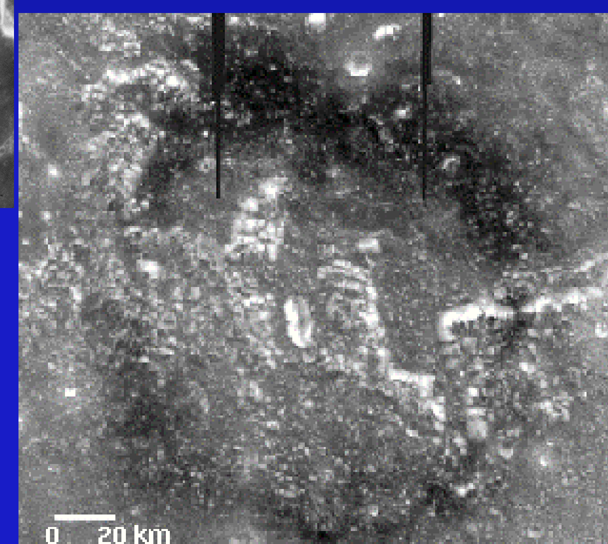
Volcanism and the Maria: Explosive Volcanism



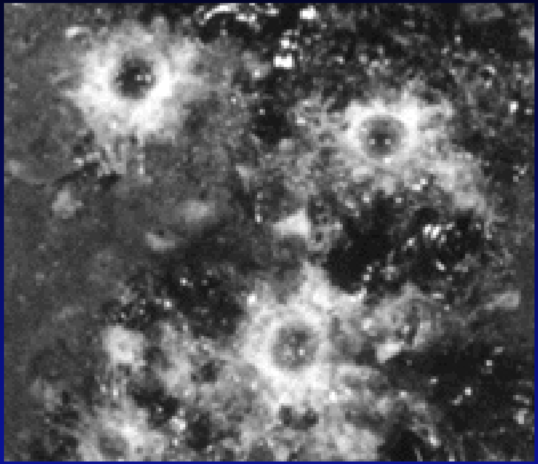


Apollo 17 Landing Site

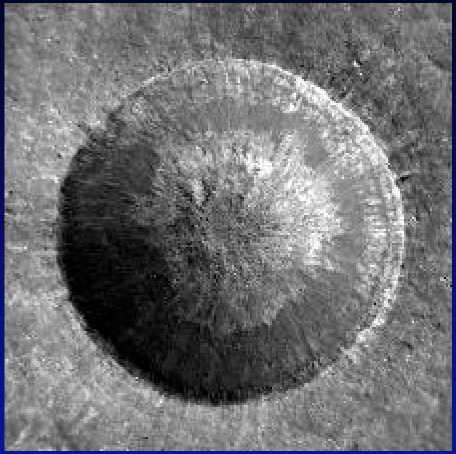
Dark Pyroclastic Ring in Orientale Basin



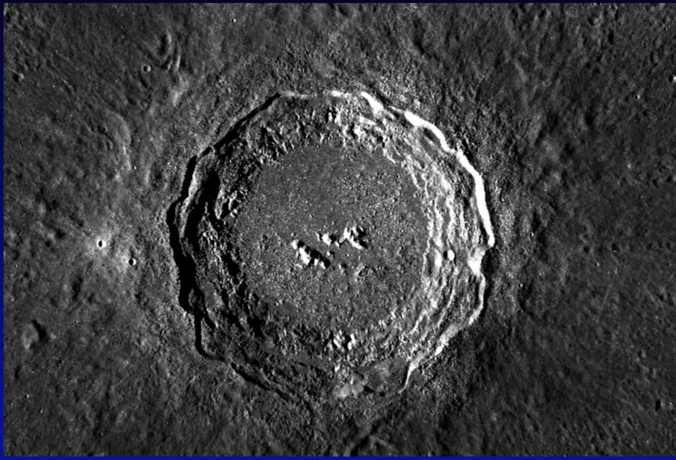
Craters at all scales on the Moon



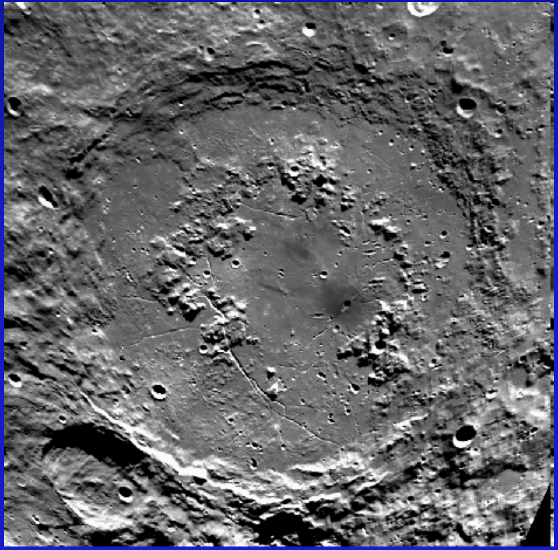
'Zap pits' D~1 mm
(Apollo sample 64455)



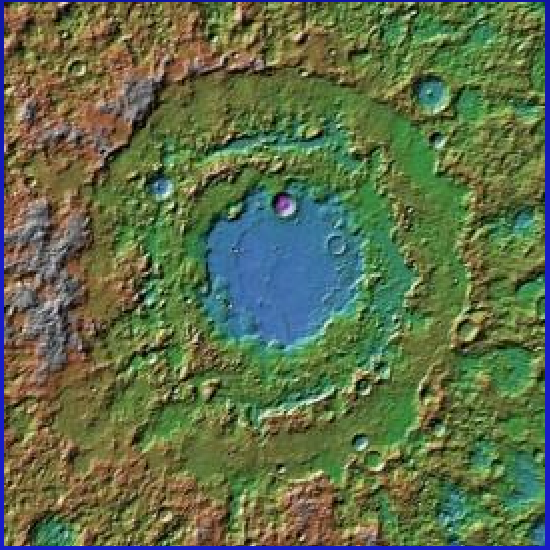
Linne Crater D=2.5 km
(LROC NAC)



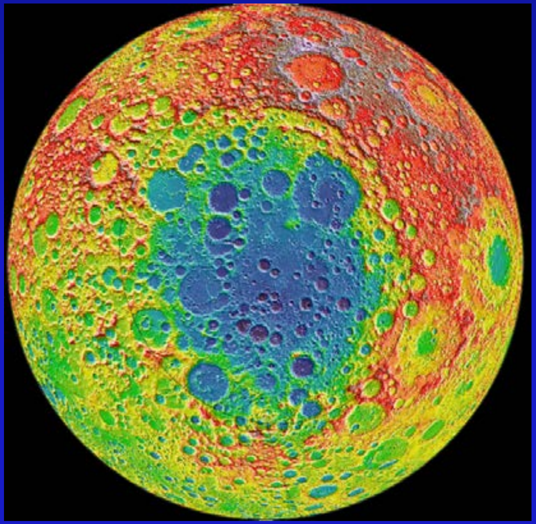
Tycho Crater D=90 km
(Kaguya Terrain Camera)



Schrodinger Basin
D=310 km (Clementine)

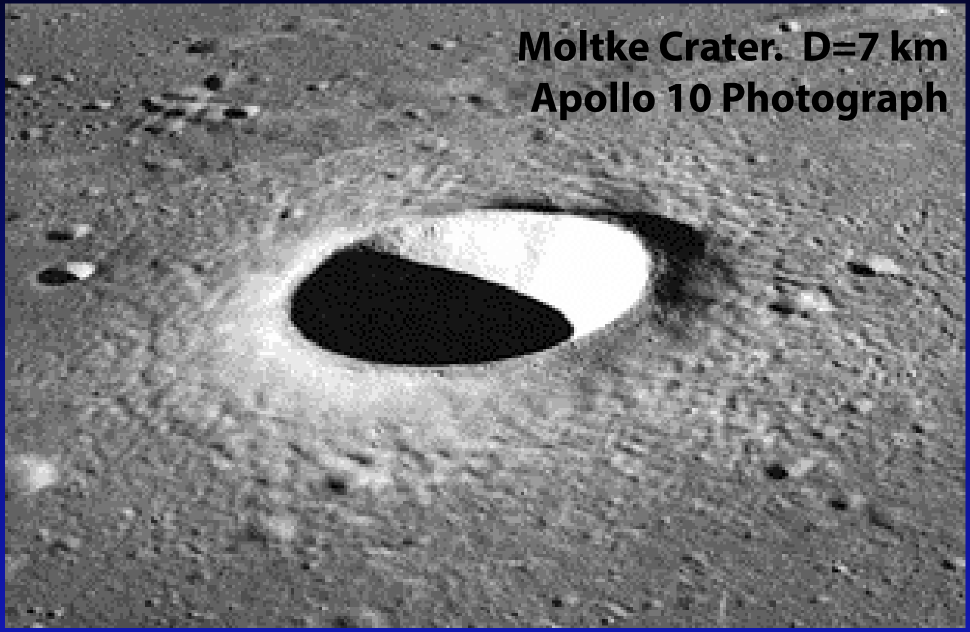


Orientale Basin
D=930 km (LOLA)



South Pole/Aitken Basin
D~2400 x 2000 km (LOLA)

Simple (Bowl-shaped) Craters



Meteor Crater. D=1.1 km

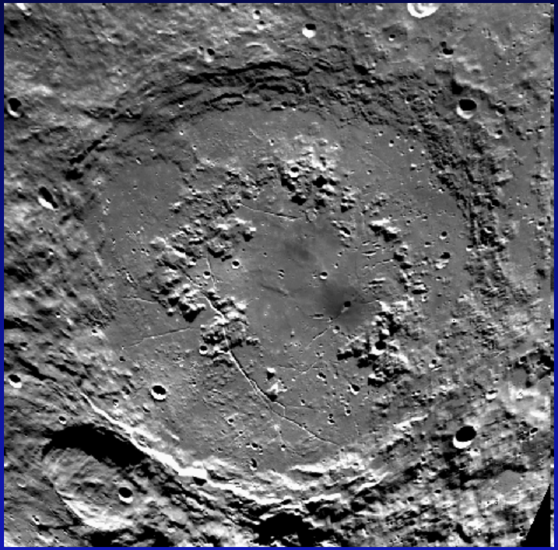
Key Characteristics:

- Generally circular outline (even for oblique impacts);
- Uplifted rim
- Hummocky Ejecta (within 1 crater diameter)

Complex Craters

Tycho Crater on the Moon. D=90 km
Kaguya Terrain Camera

Schrodinger Crater on the Moon .
D=310 km, Clementine

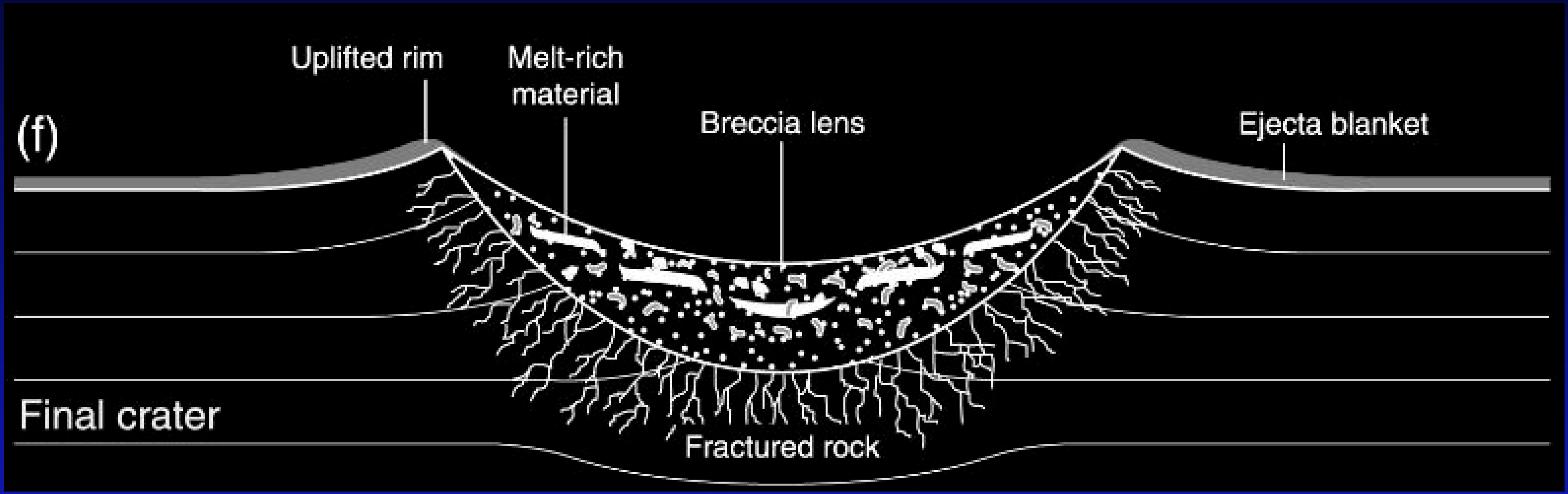


Key Characteristics:

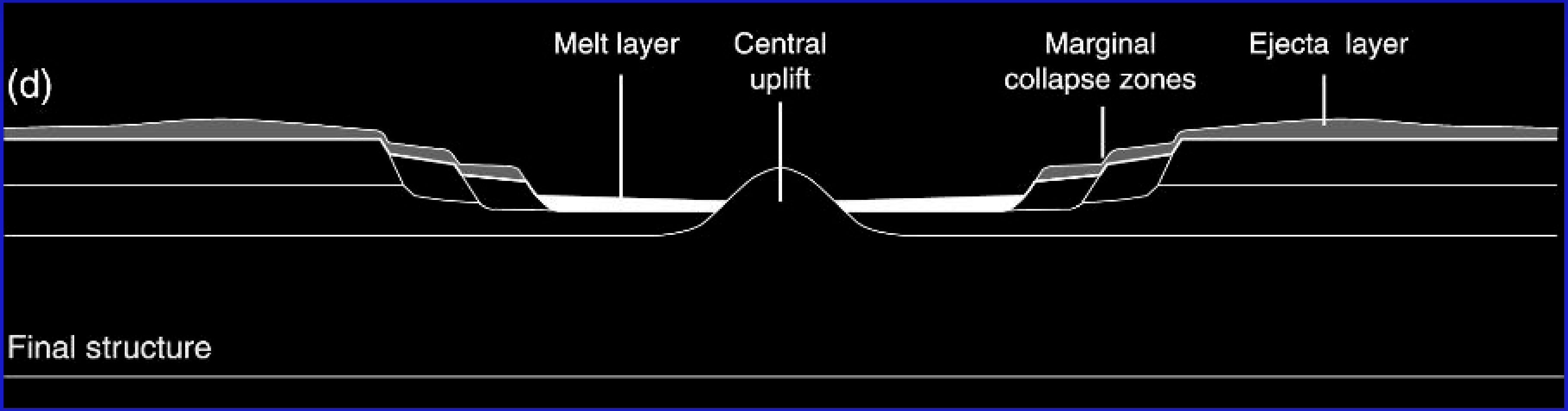
- Central Peak / Central Uplift / Central Ring
- Flat Floor
- Terraced Rim

Idealized Cross-sections

Simple Crater. D < ~20 km



Complex Crater. D > ~20 km



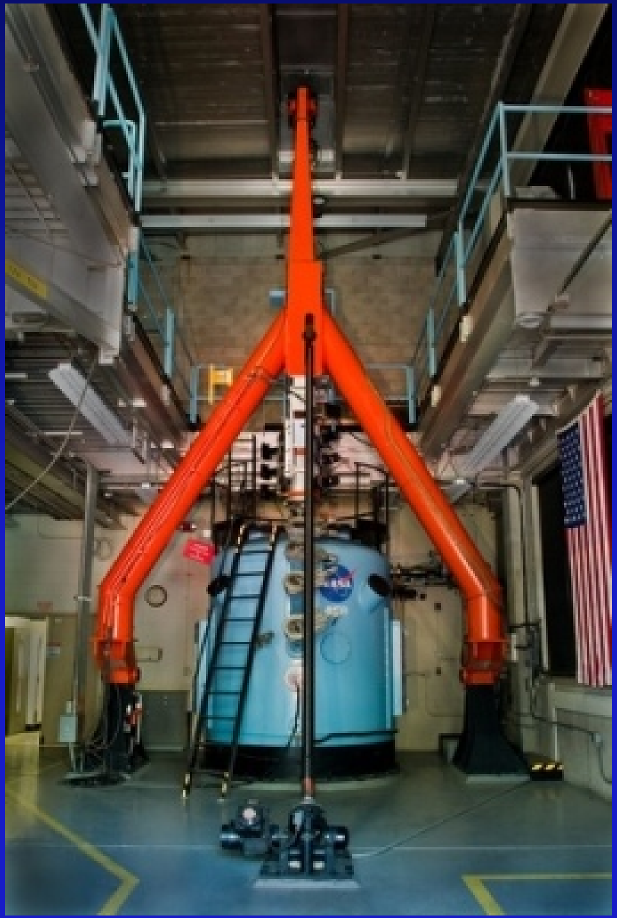
The Impact / Explosion Analogy

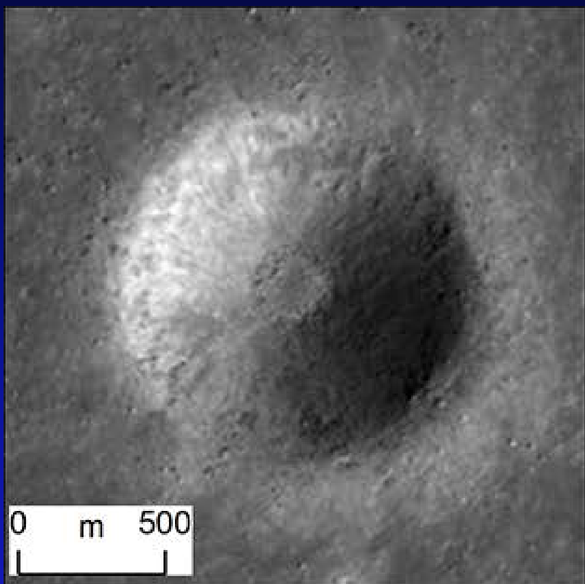
Sedan explosion crater, D~400 m
Nevada Test Site. 7/5/1962

How do we study impact craters?

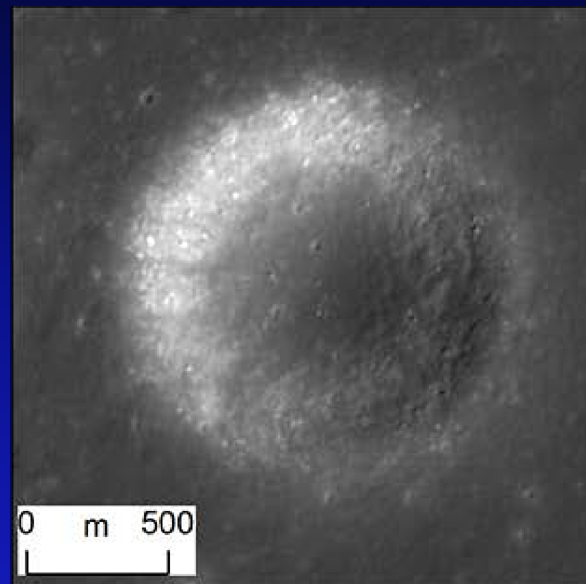
- Controlled Laboratory Experiments:
  NASA Ames Vertical Gun Range



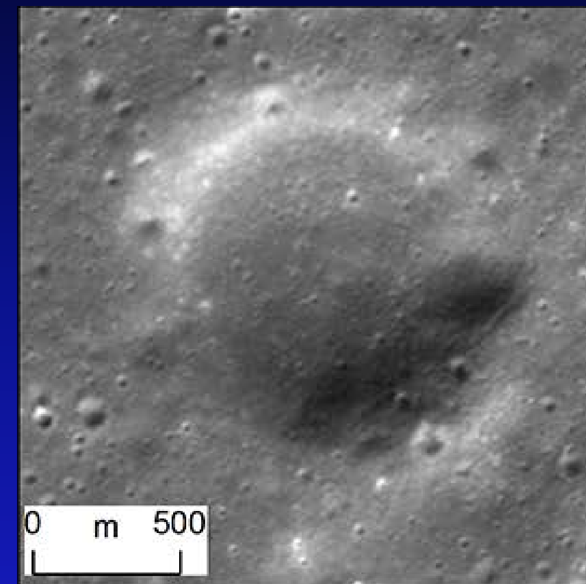
My Lunar Science: *Erosion* on the Moon



Fresh Crater
T~0.01 Ga



Moderately Degraded
T~3 Ga



Very Degraded
T~3.7 Ga

Calibrate the age of craters from their freshness, to reduce sole reliance on crater counts.

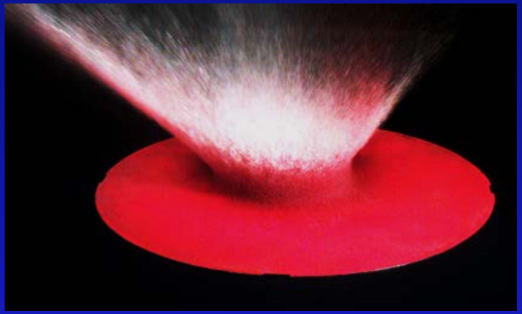
My Lunar Science: *Erosion* on the Moon

"… [impact cratering] is analogous, but generally at a larger scale, to the effect of a raindrop … ."

Alan Howard, 2007

(Geomorphology)

North Massif, Apollo 17



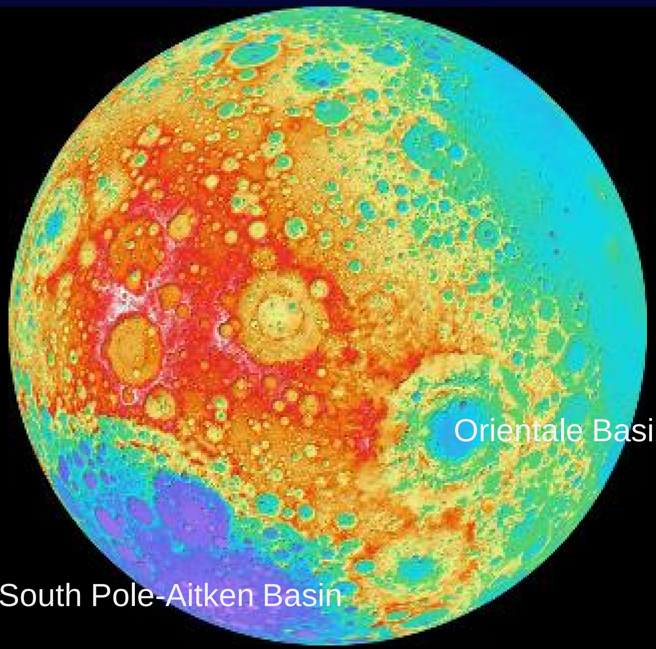
Raindrops on Earth = Impacts on the Moon

Typical rate of topographic change is ~200 × less than measured in the western US.

Other Big Science Questions About the Moon

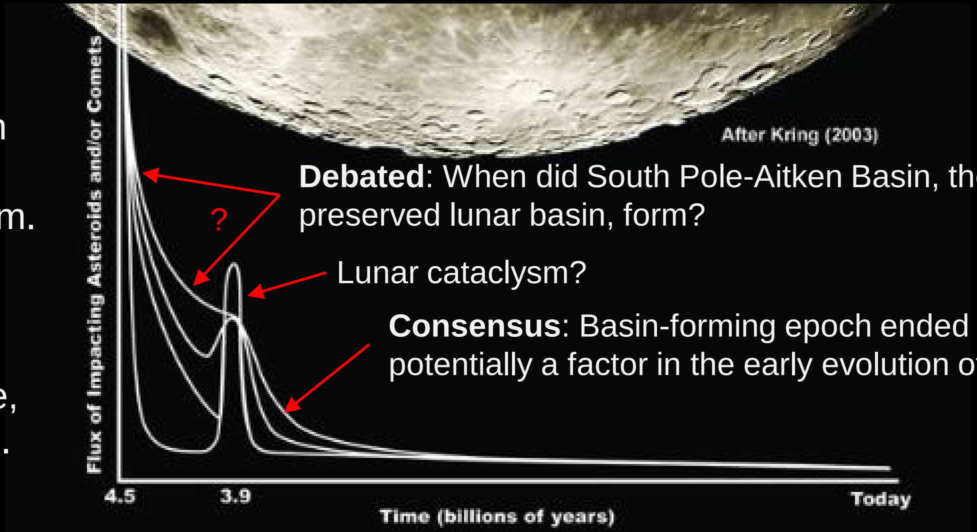
Impact History of the Inner Solar System

From the Moon, we learn about Earth, Mars, etc.



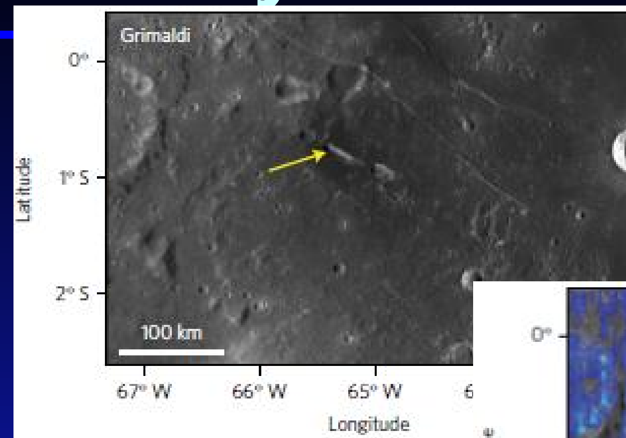
SPA @ ~4.1 Ga:
42 basins formed within 300 Myrs – much more intense Lunar Cataclysm.

SPA @ ~4.5 Ga:
42 basins formed over 700 Myrs – less intense, or no, Lunar Cataclysm.

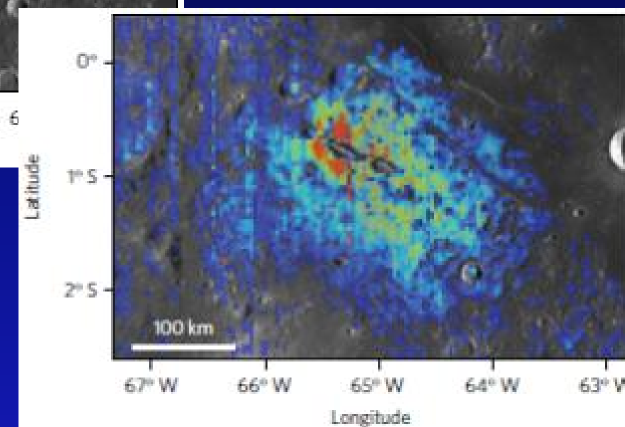


Volcanic and Volatile History of the Moon

2014 Holuhraun eruption, Iceland



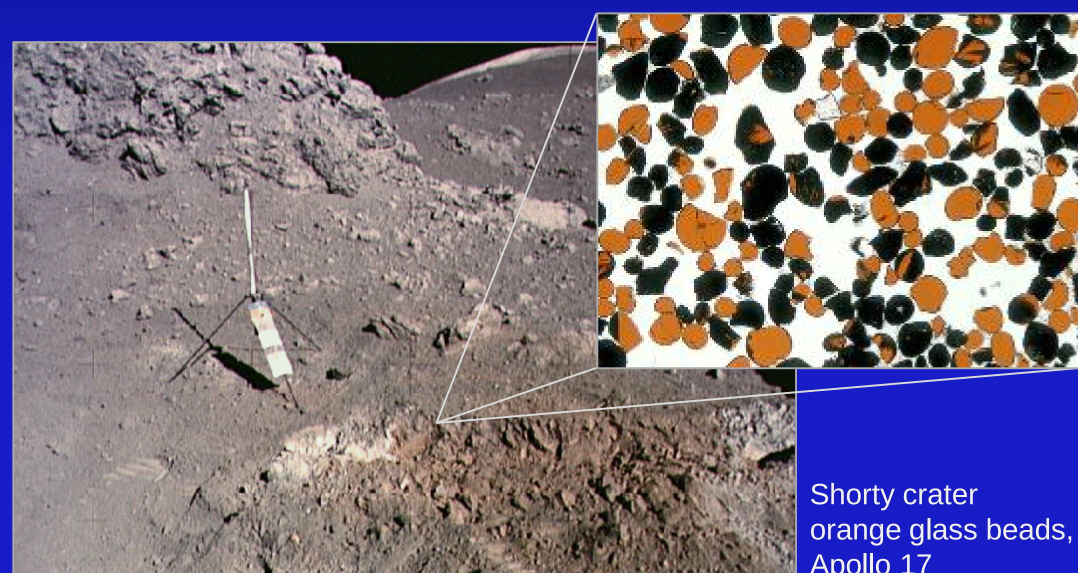
Pyroclastic deposit at Grimaldi as identified from Lunar Reconnaissance Orbiter Camera and Moon Mineralogy Mapper.



Water content observed on the lunar surface, ranging from <0.005% (blue) to >0.03% (red).

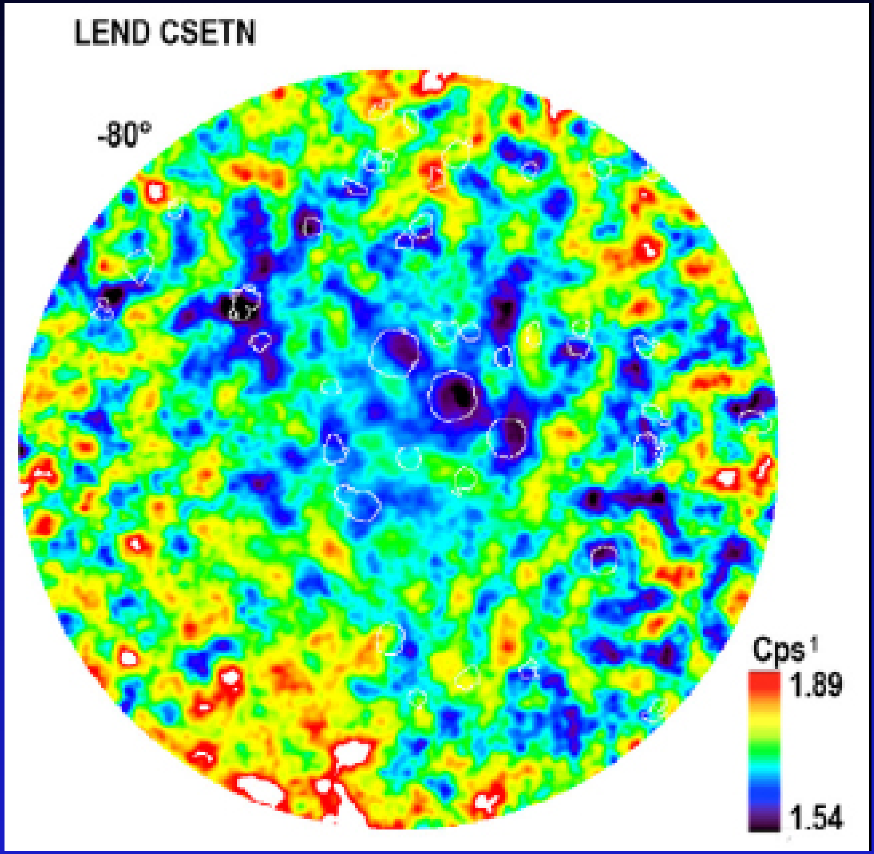
Fiery eruptions formed deposits of glassy beads collected during Apollo missions.

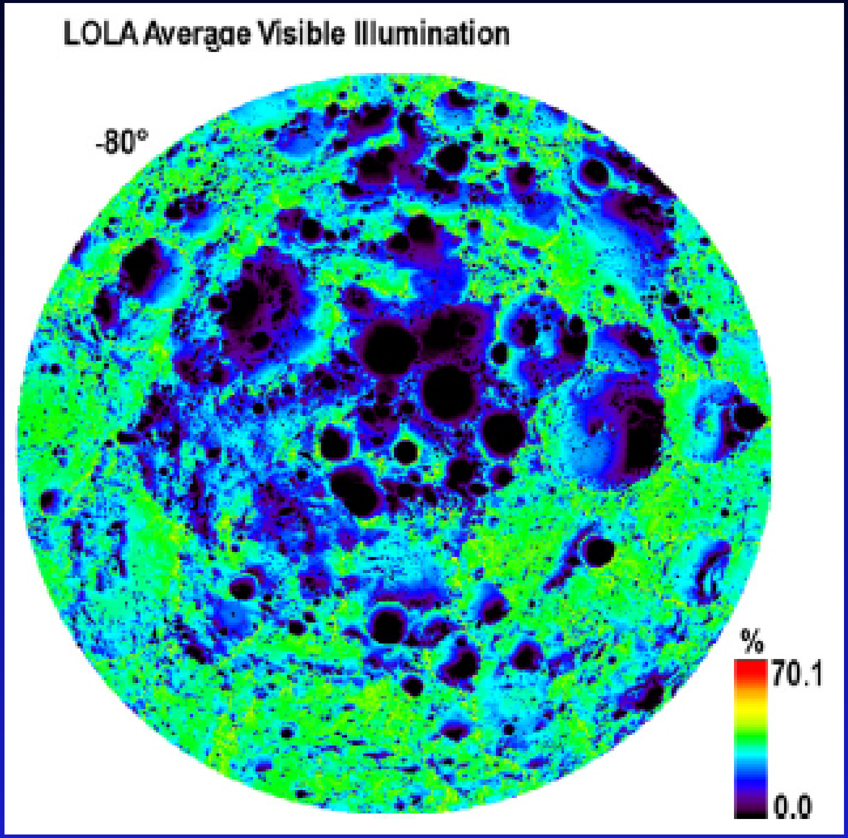
Compositions indicate Moon contained more volatile materials than previously thought.



Shorty crater orange glass beads, Apollo 17

Polar Volatile Resource Distribution on the Moon





LP and LRO see enriched hydrogen (left) in permanently shadowed regions near the Moon's poles. These may represent ice deposits that could be used as resources for human exploration of the Moon.

Where did these deposits come from, how much water is there, and how is it distributed?

Summary

- Exploration of the Moon has a glorious history, but it has also just begun.
  - Next ten years are an exciting opportunity to build a new, sustainable program of human and robotic exploration.

- Big open questions remain about:
  - Lunar formation, differentiation.
  - Volcanic processes and volcanic history.
  - Chronology of large impacts.
  - Resources for human exploration.