Exploration and Science of the Moon

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NASA
Marshall Space Flight Center
Huntsville, AL

EXPLORE MARSHALL

Ames Research Center
Aerospace and Small Spacecraft
Moffett Field, Calif.

Armstrong Flight Research Center
Aeronautical Research and Testing
Edwards, Calif.

Jet Propulsion Laboratory
Deep Space Robotic Rovers and Science Missions
Pasadena, Calif.

Johnson Space Center
Human Space Flight Research and Operations
Houston, Texas

Stennis Space Center
Rocket Propulsion Testing
Bay St. Louis, Miss.

Michoud Assembly Facility
Large Vehicle Manufacturing
New Orleans, La.

Marshall Space Flight Center
Launch Vehicle Development, Chemical Propulsion, and Science Instrument Development
Huntsville, Ala.

Glenn Research Center
Electric Propulsion and Small Spacecraft Technology
Cleveland, Ohio

Goddard Space Flight Center
Science Missions and Telescopes
Greenbelt, Md.

NASA Headquarters
Washington, D.C.

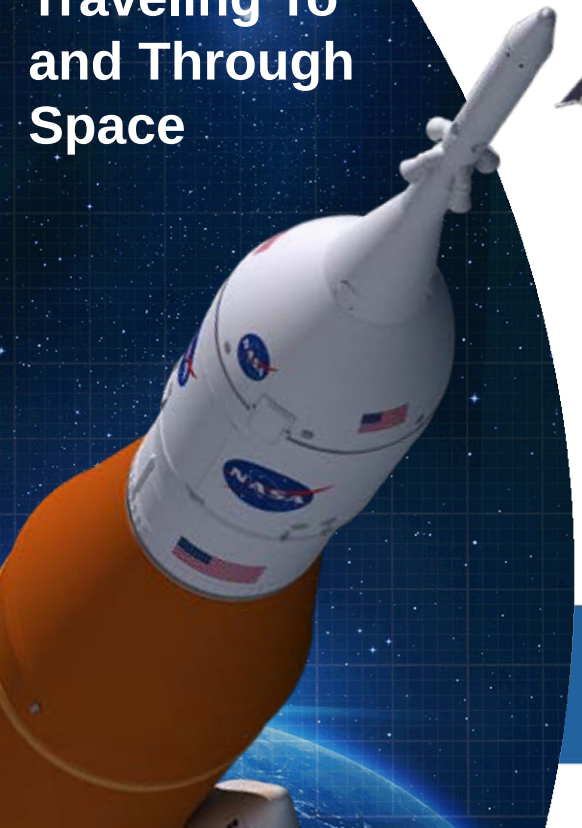
Langley Research Center
Aviation and Space Research
Hampton, Va.

Kennedy Space Center
Ground Operations and Services
Cape Canaveral, Fla.

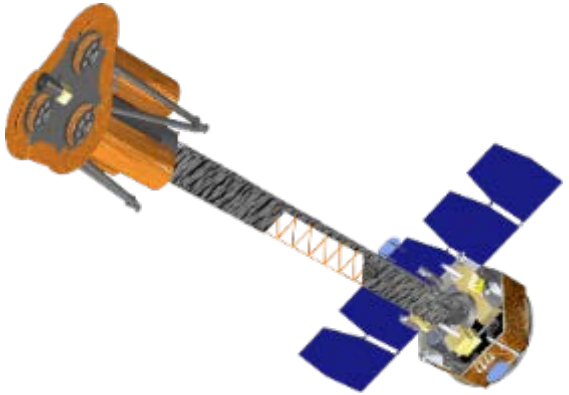
Marshall Space Flight Center

Marshall's Mission Areas

Traveling To and Through Space



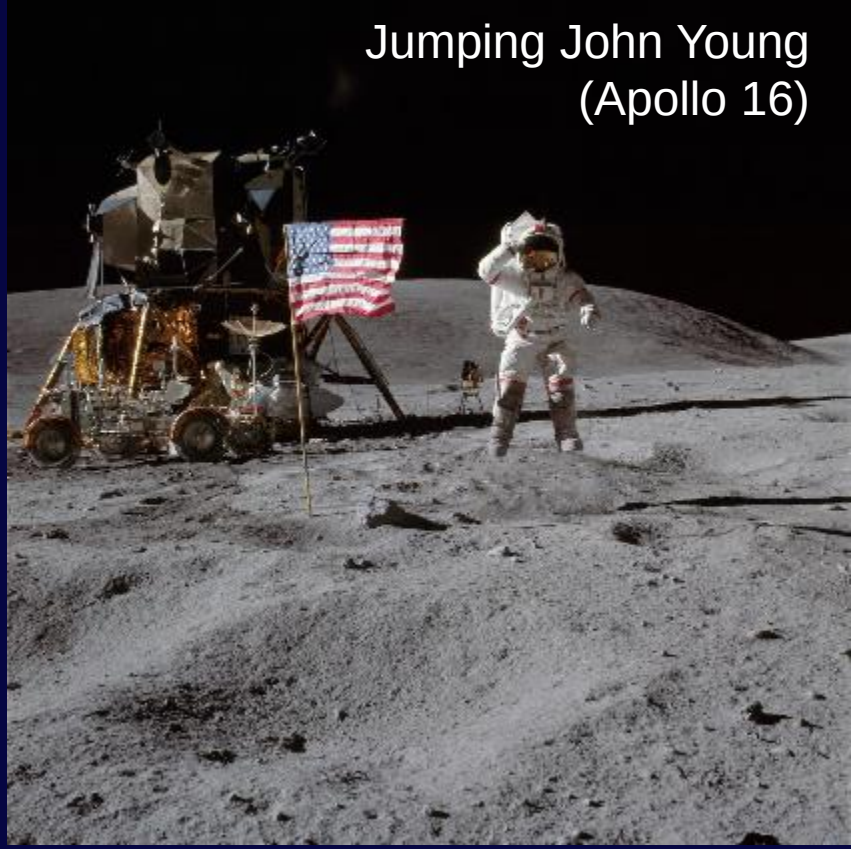
Living and Working in Space



Supporting Agency Mission Operations

Understanding Our World and Beyond

- Gravity: 1/6th of Earth.
- Essentially no atmosphere.
- Lunar day is 29.5 Earth days long (2 weeks of day, 2 weeks of night).
- Spin and orbit are coupled, so that same side always faces Earth. “Synchronous rotation”.



Jumping John Young
(Apollo 16)

The Moon: A Brief User’s Guide

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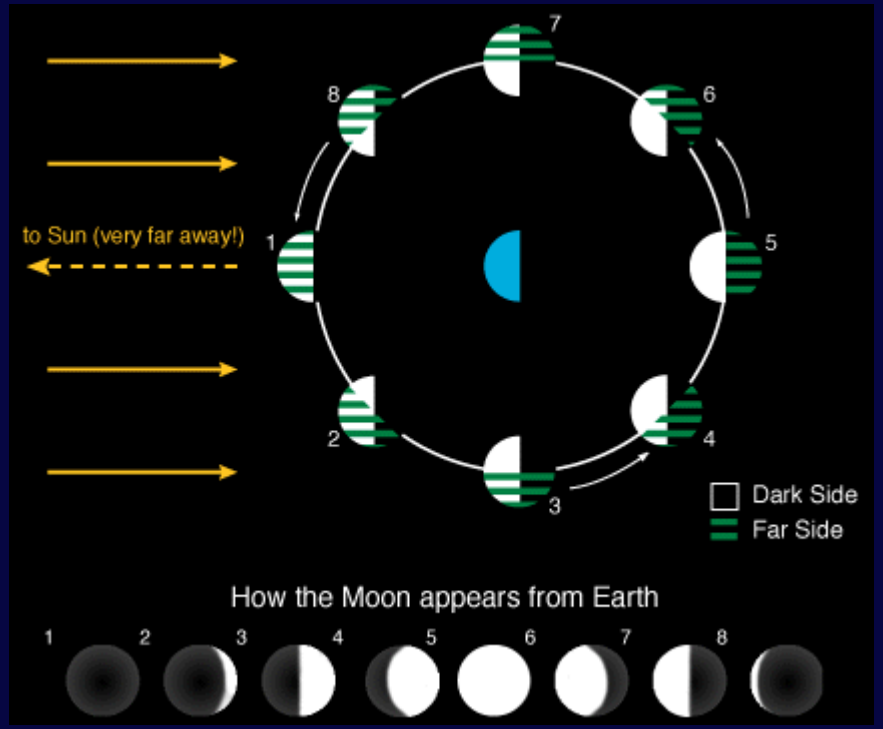


The Moon: A Brief User’s Guide

Two Major Provinces:

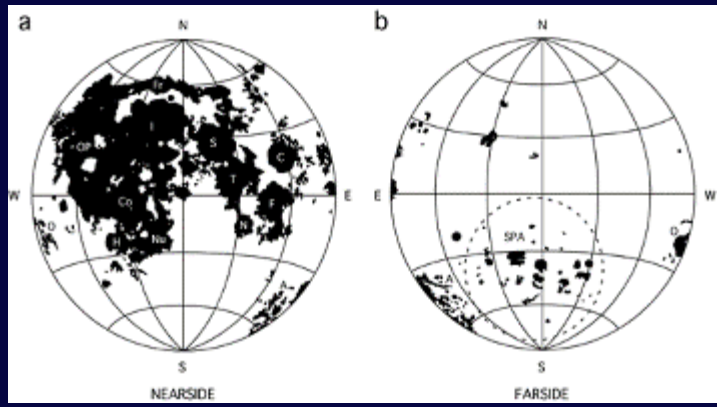
- Highlands, Maria

Maria:

- ~20% of surface (mostly on near-side)
- Basaltic (volcanic)
- ‘Young’/Lightly-cratered

Highlands (or Terra)

- ~80% of surface
- Anorthositic (Primary flotation crust)
- ‘Old’/Heavily-Cratered



The Moon: A Brief User’s Guide

Geologic History:

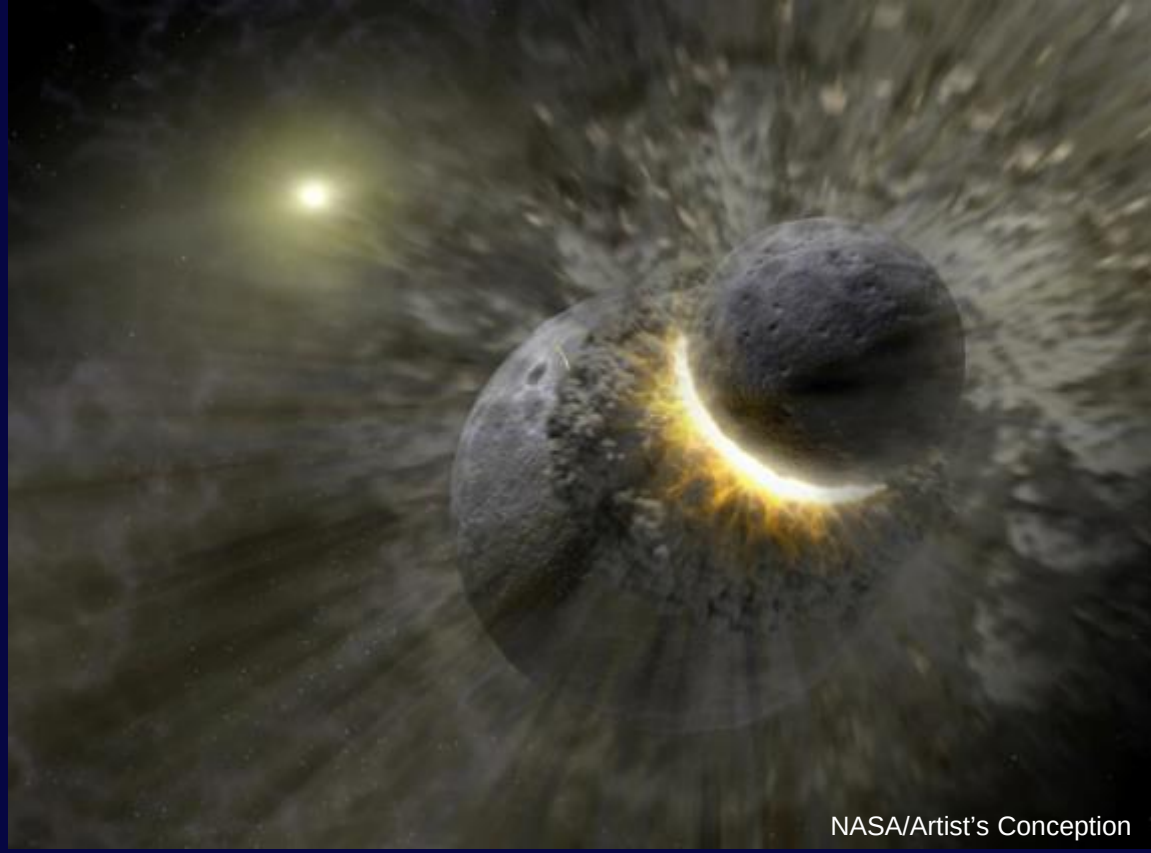
Formation (Giant Impact), Differentiation, Magma Ocean

Cooling -> Primary Crust

Heavy bombardment, large impact craters

Volcanism

Ongoing cratering



NASA/Artist's Conception

The Moon: A Brief User's Guide

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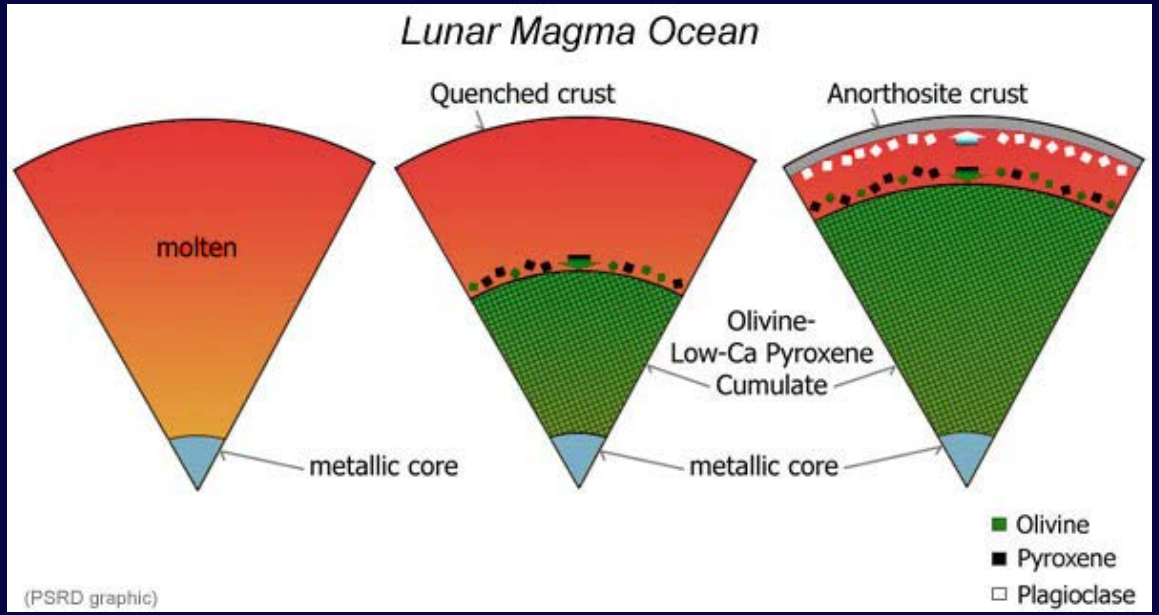

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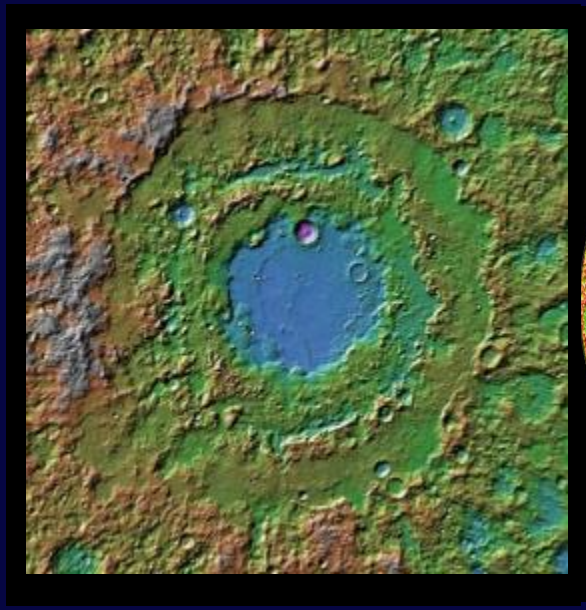
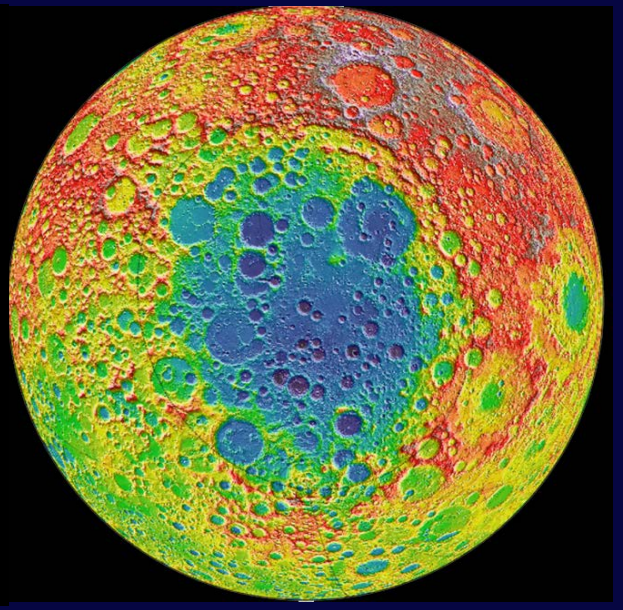


Orientale Basin
D=930 km (LOLA)



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

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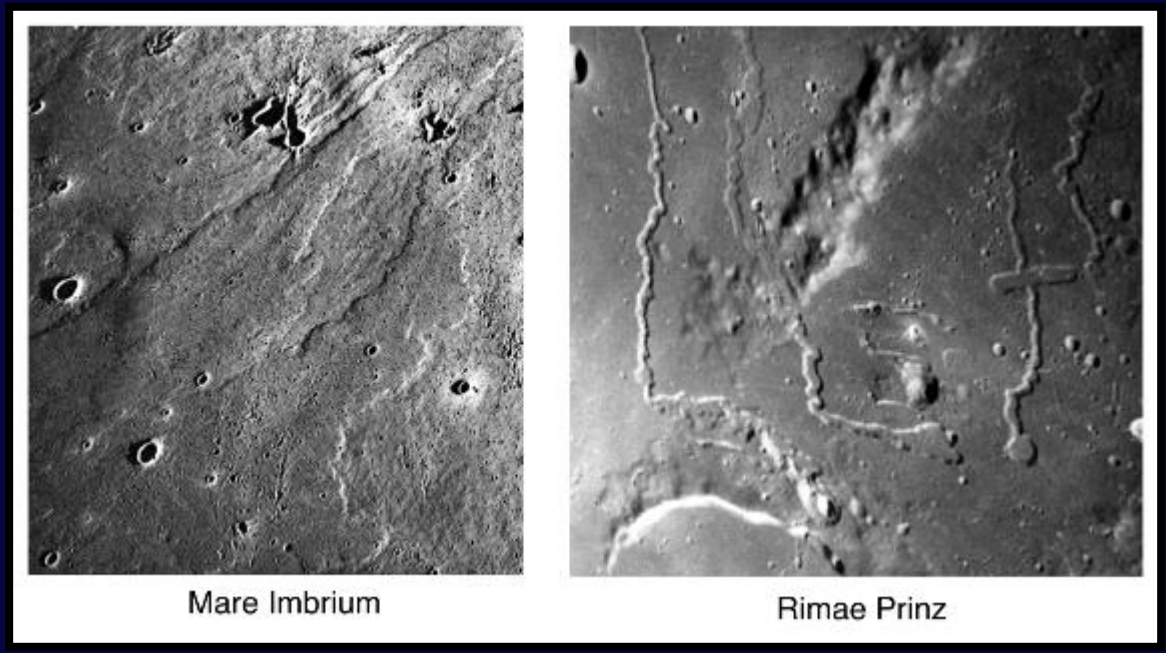

Mare Lava Flows: Similar to those on Earth

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

The Moon: A Brief User's Guide

Geologic History:

Formation (Giant Impact), Differentiation, Magma Ocean

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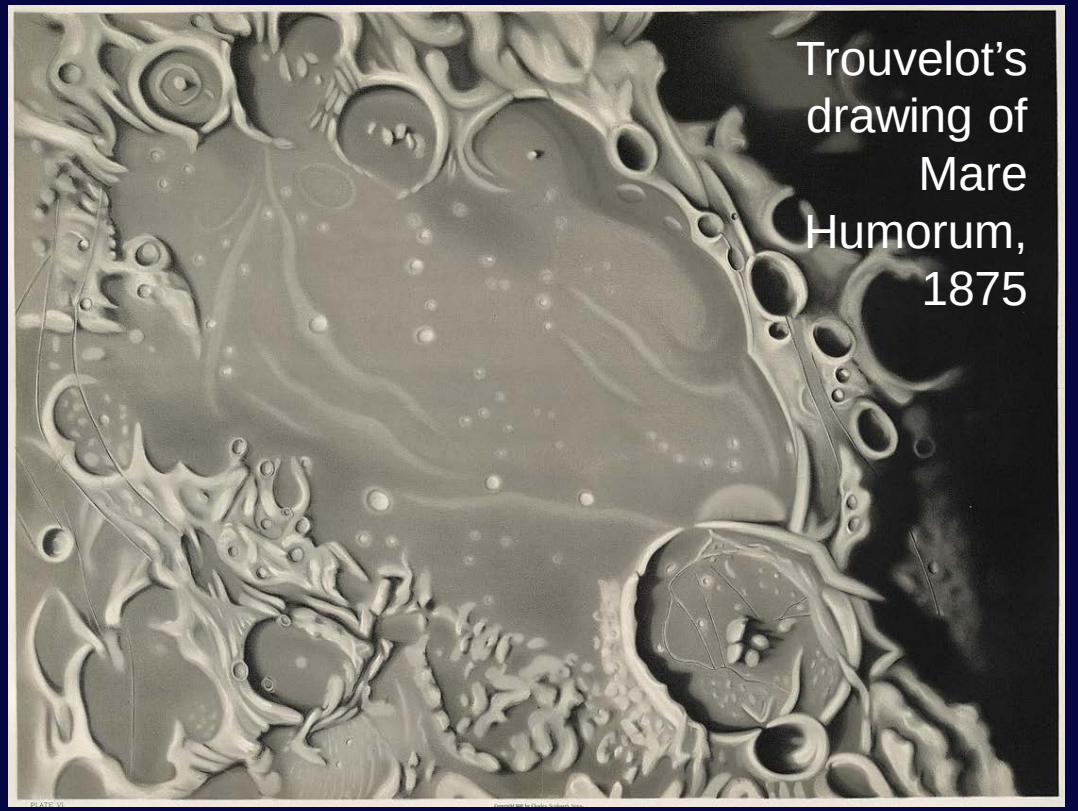
Ongoing cratering

Speyerer et al., 2016

March 17, 2013 impact crater, before and after

The Moon: A Brief User's Guide

- Antiquity: Naked eye observations
- 1600s: Telescopic observations and drawings (Galileo, Hevelius, …)
- 1800s: Photography (Daguerre, Draper, etc.)

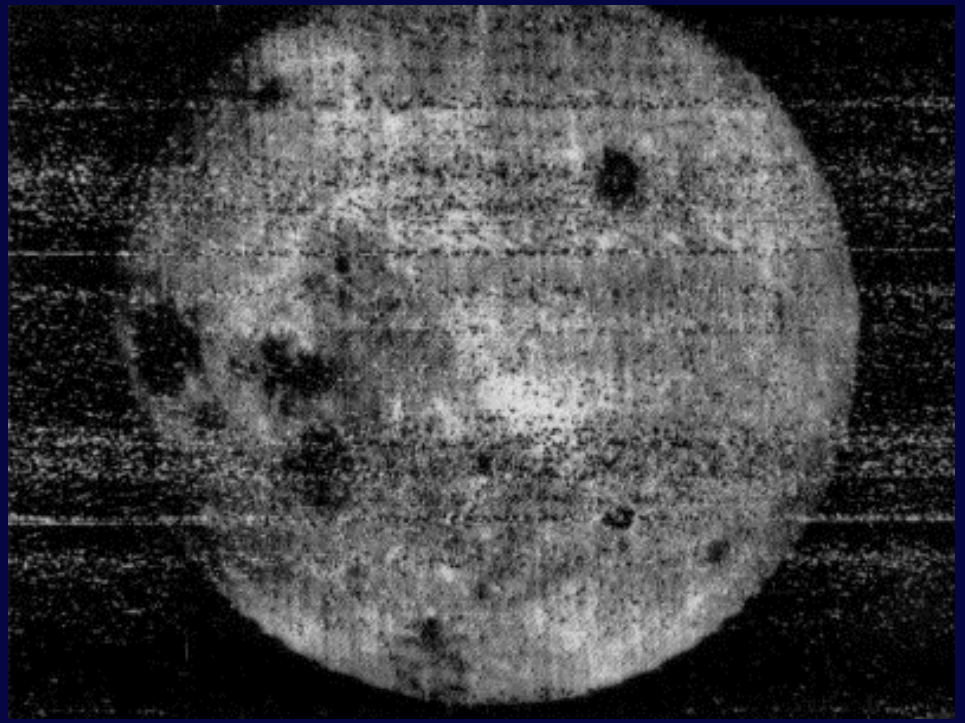


Trouvelot's drawing of Mare Humorum, 1875

Lunar Exploration: History

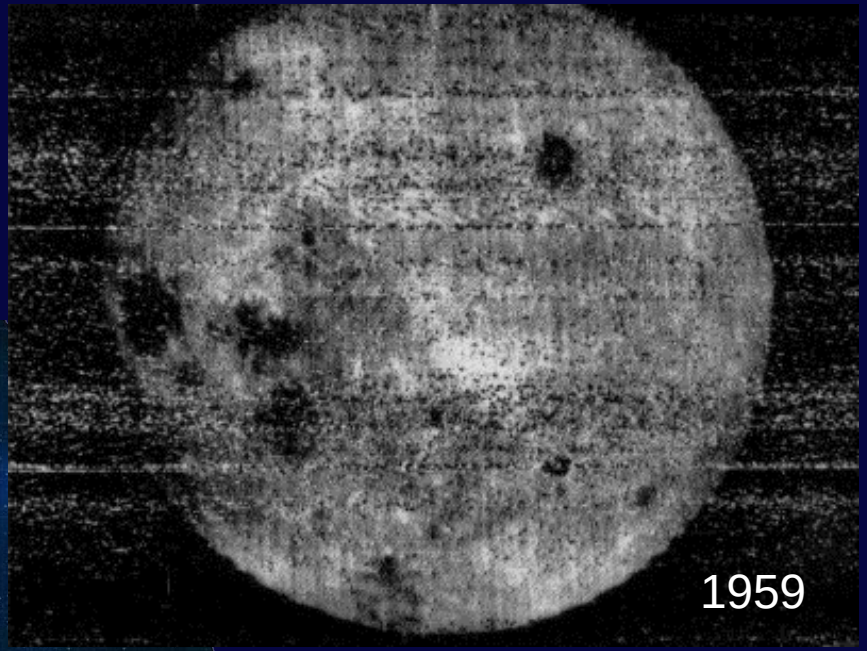
Lunar Exploration: History

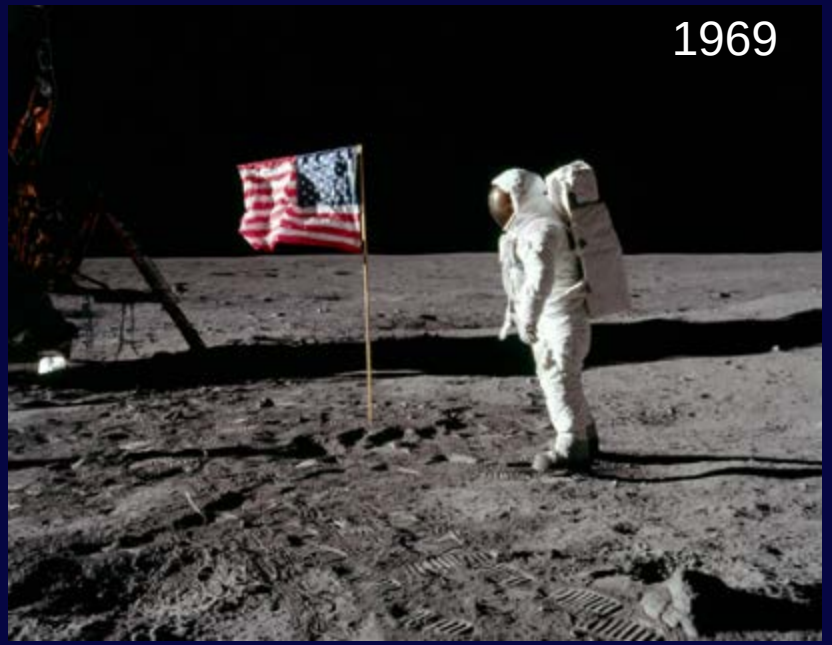
- Beginning of Spaceflight Era:
  - Sputnik, orbit of Earth, 1957
  - Luna 2, first spacecraft to crash into Moon, 1959
  - Luna 3, first images of lunar farside, 1959
  - Yuri Gagarin, first astronaut, 1961



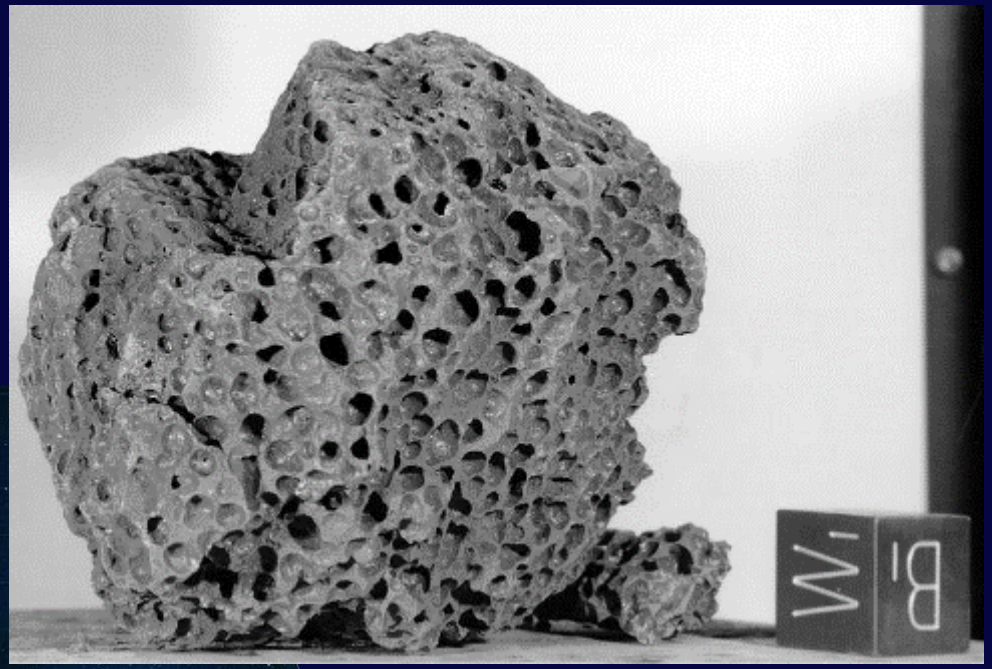
- Space Race
  - 1964/65 Ranger 7, 8, 9 (impactors)
  - 1966 Luna 9 (1st soft lander)
  - 1966 Surveyor I, III, V, VI, VII
  - 1966-67 Lunar Orbiter I-V
  - **1969-72 Apollo 11-17**
  - 1970-76 Luna 16, 20, 24
  - 1970 Lunakhod I, II

Lunar Exploration: History





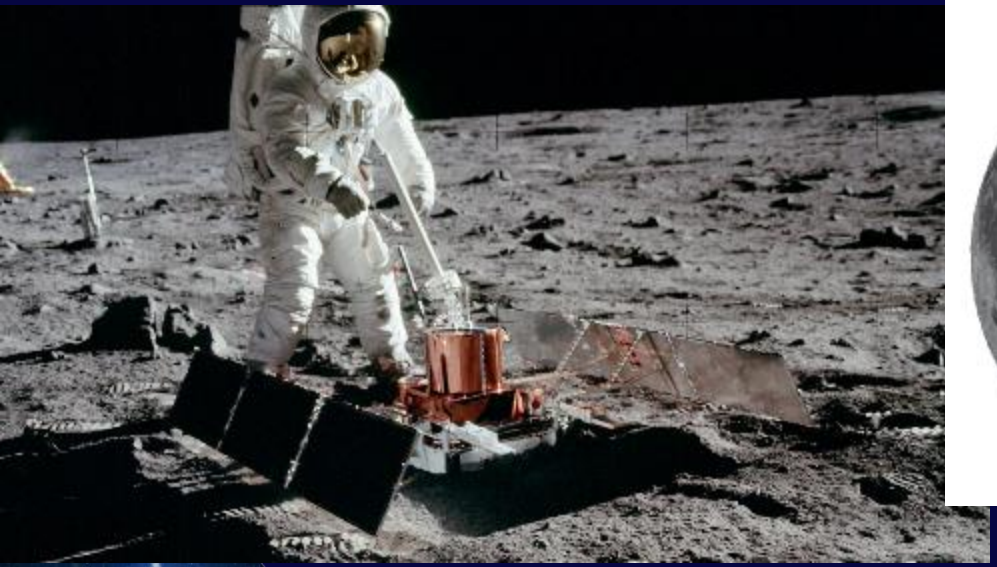
Robots to Human Exploration: <10 years



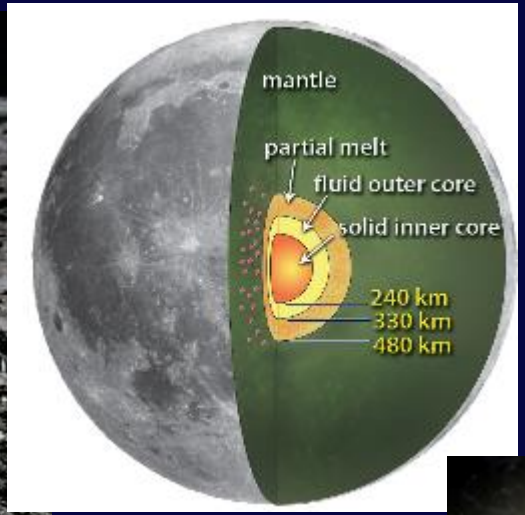
Vesicular Basalt, Apollo 15 15556
3.4 Billion years old

Anorthositic Breccia, Apollo 16, 67215
Clasts as old as 4.4 Billion years old

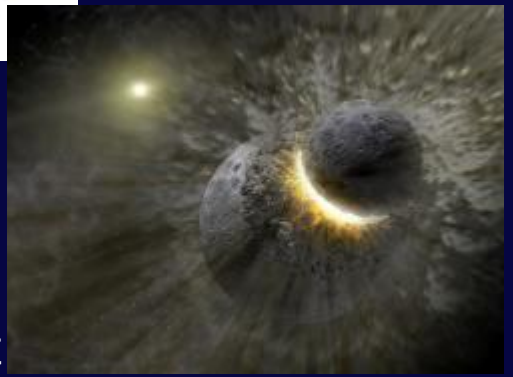
Apollo's Legacy of Scientific Exploration



Apollo 11 Passive Seismic Experiment



Weber et al., 2011



Models for lunar formation, 1975-present

Apollo's Legacy of Scientific Exploration


From 1976-1994: No lunar science missions

- 1994 Clementine
- 1998 Lunar Prospector
- 2003 Smart-1 (European Space Agency)
- 2007 SELENE / Kaguya (Japan)
- 2008 Chandrayaan-1 (India)
- 2009 Lunar Reconnaissance Orbiter
- 2009 LCROSS
- 2010 Chang’e 2 (China)
- 2011 GRAIL
- 2014 Chang’e 3/Yutu (China)
- 2019 Chang’e 4/Yutu 2 (China)
- 2019 Beresheet (Israel)

1994-2019: Global characterization

- 1994 Clementine
- 1998 Lunar Prospector
- 2003 Smart
- 2007 SELE
- 2008 Chand
- 2009 Lunar
- 2009 LCRO
- 2010 Chang
- 2011 GRAI
- 2014 Chang
- 2019 Chang
- 2019 Beresheet (Israel)

Coming Soon!?!?!?!?!:

- CLPS landers 2019
- Human lander 2024
- Sustained Presence 2028

2019-: A new Era!

NASA’s New Aim

On March 26, NASA was directed to land American astronauts on the Moon by 2024.

"We, the people of NASA, accept this challenge. We will go to the Moon in a way we have never gone before.”

"We will go with innovative new technologies and systems to explore more locations across the surface than was ever thought possible. This time, when we go to the Moon, we will stay.”

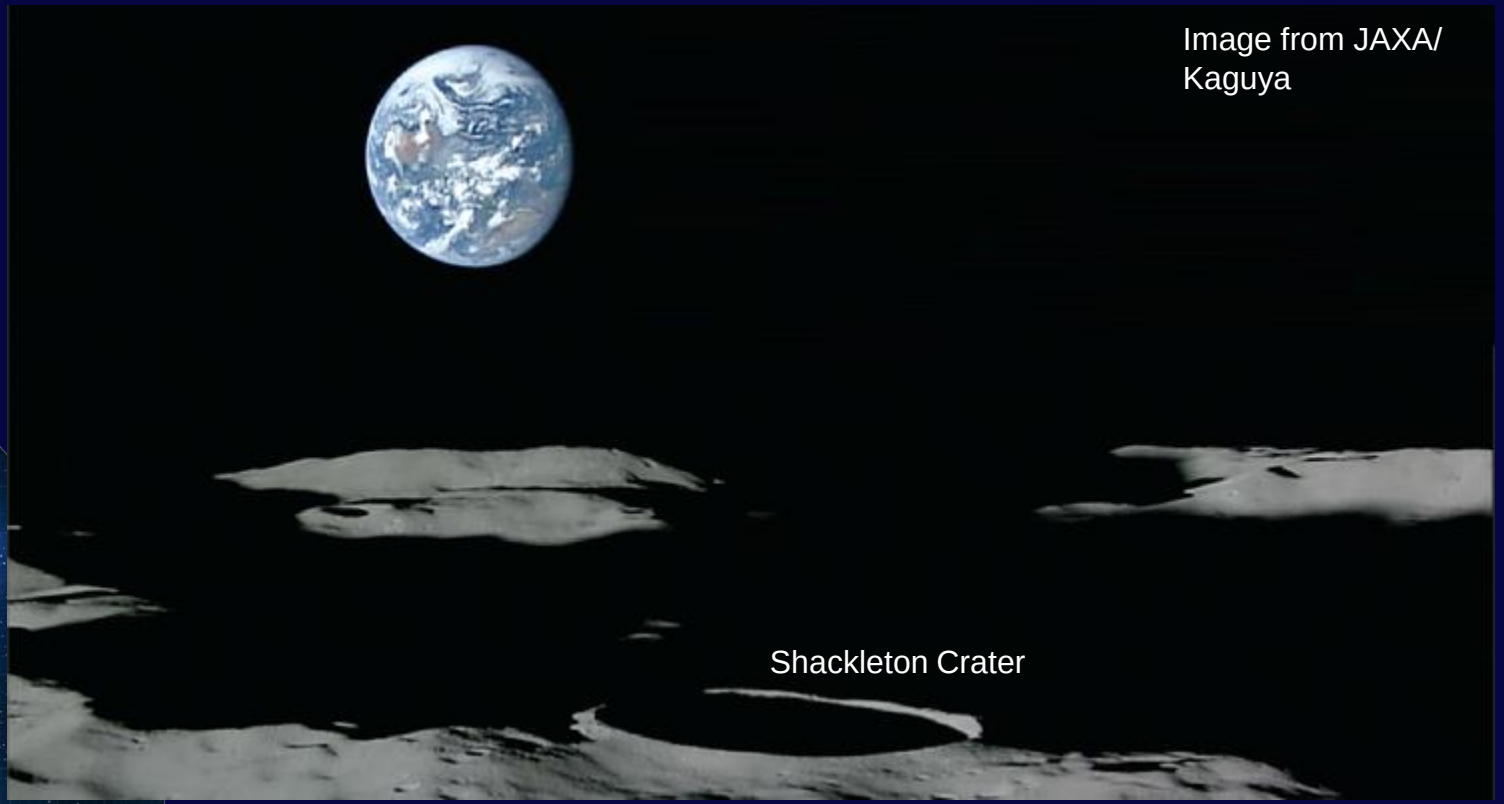
"And then we will use what we learn on the Moon to take the next giant leap - sending astronauts to Mars.”

Jim Bridenstine, NASA Administrator

Some reasons to explore…

1. Re-affirm American leadership in space;
2. Inspire the next generation (and everyone else);
3. Proves technologies and capabilities for Mars;
4. Paradigm-shifting science (see next slides).

Why do *you* think we should go?

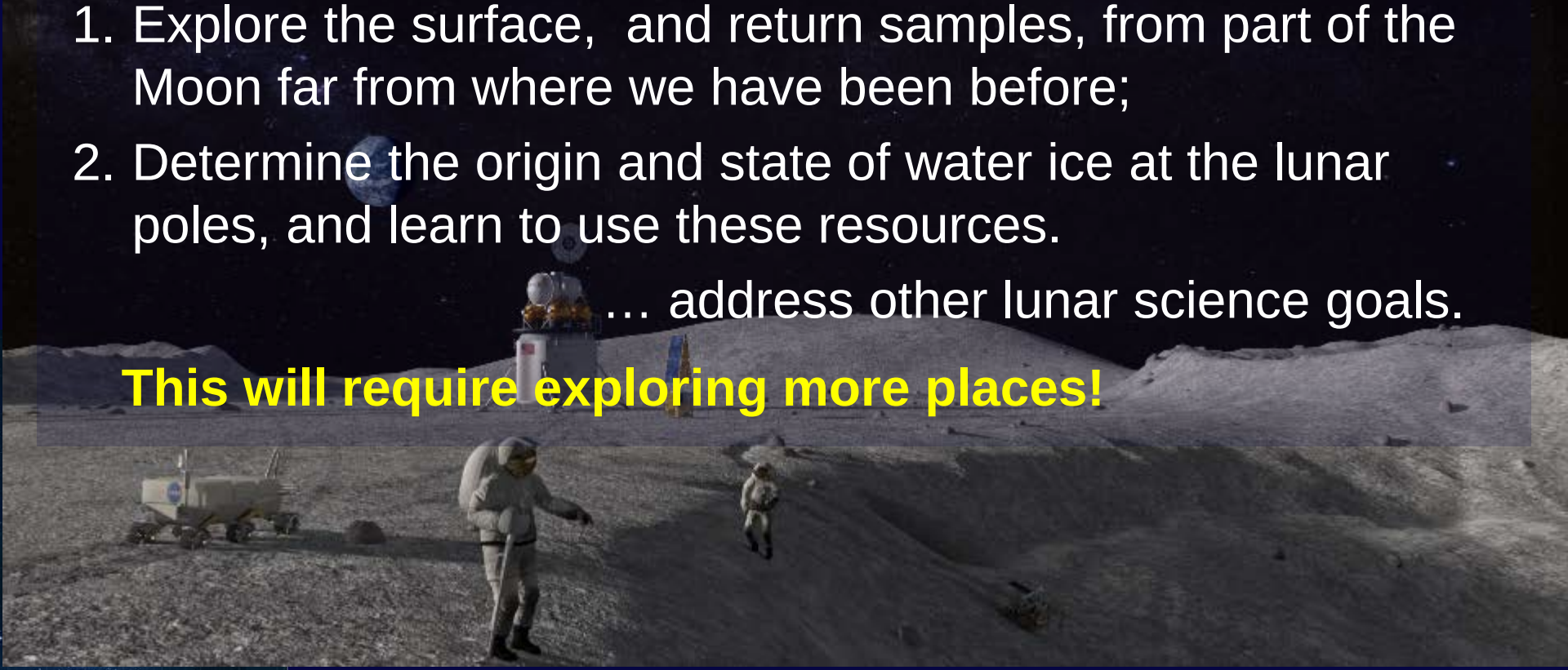


Where are we going?

1. Explore the surface, and return samples, from part of the Moon far from where we have been before;
2. Determine the origin and state of water ice at the lunar poles, and learn to use these resources.

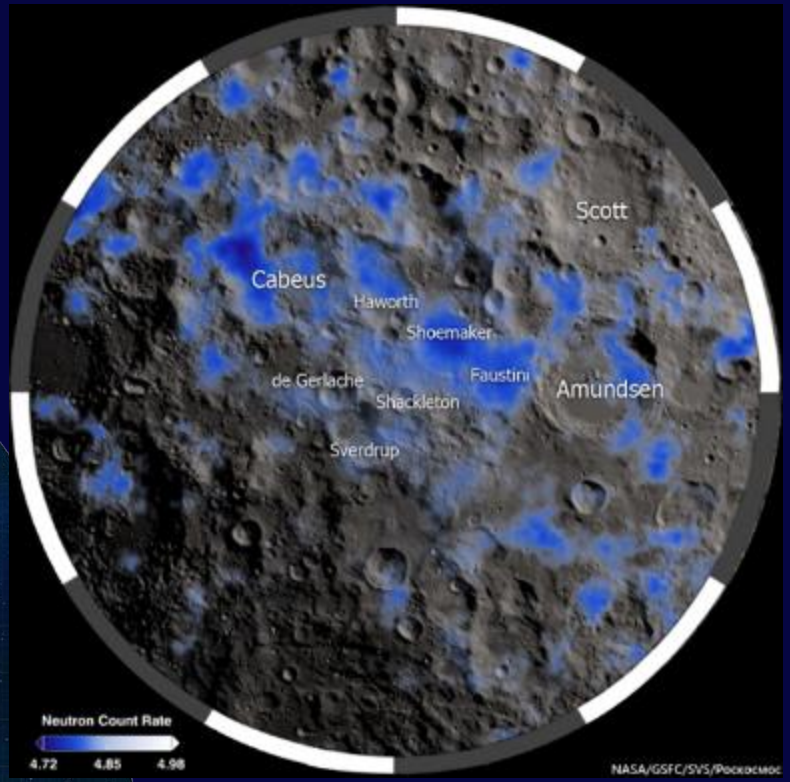
… address other lunar science goals.

This will require exploring more places!

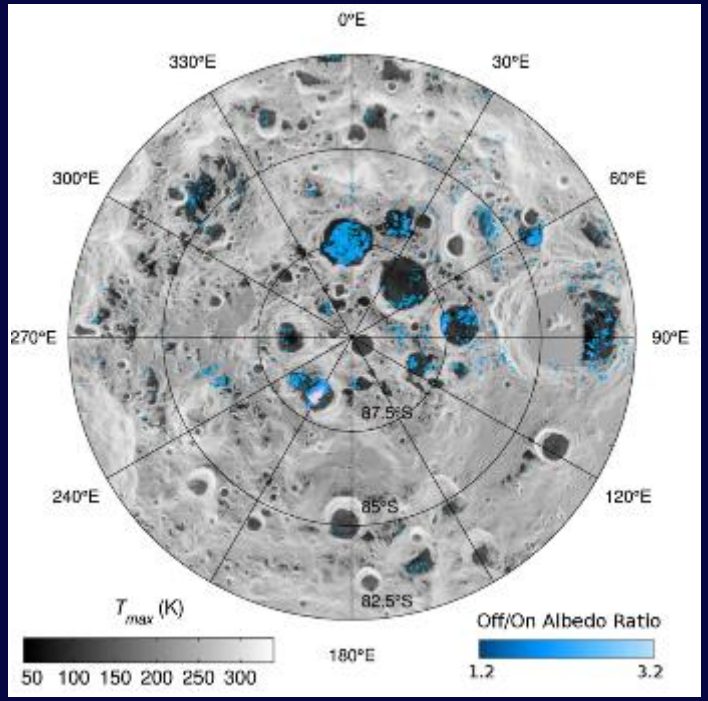


What science will we do?

LEND neutron count rate



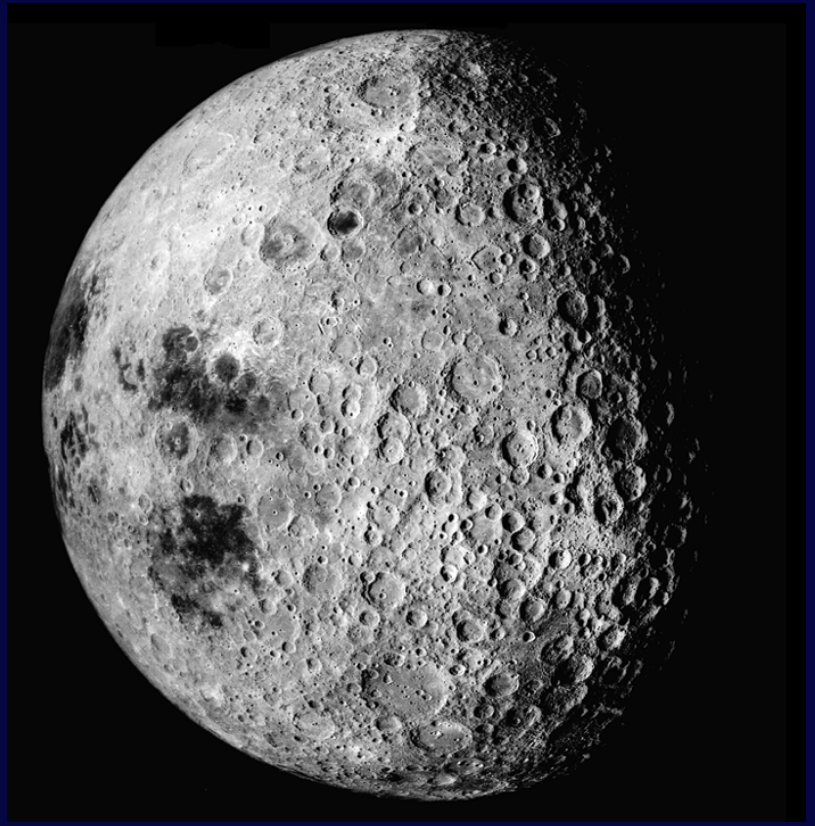
Lyman-α albedo. Consistent with water ice concentration of 0.1-2% by mass. Hayne et al. 2015



Major open science questions:
1. Distribution, source, abundance of water ice

The Moon has a long impact history that records the last 4-4.5 billion years of Solar System evolution.

Apollo established a history of impact rates, but it is solidly known only for the period 3-4 billion years ago.



Major open science questions:
2. History of Lunar Bombardment

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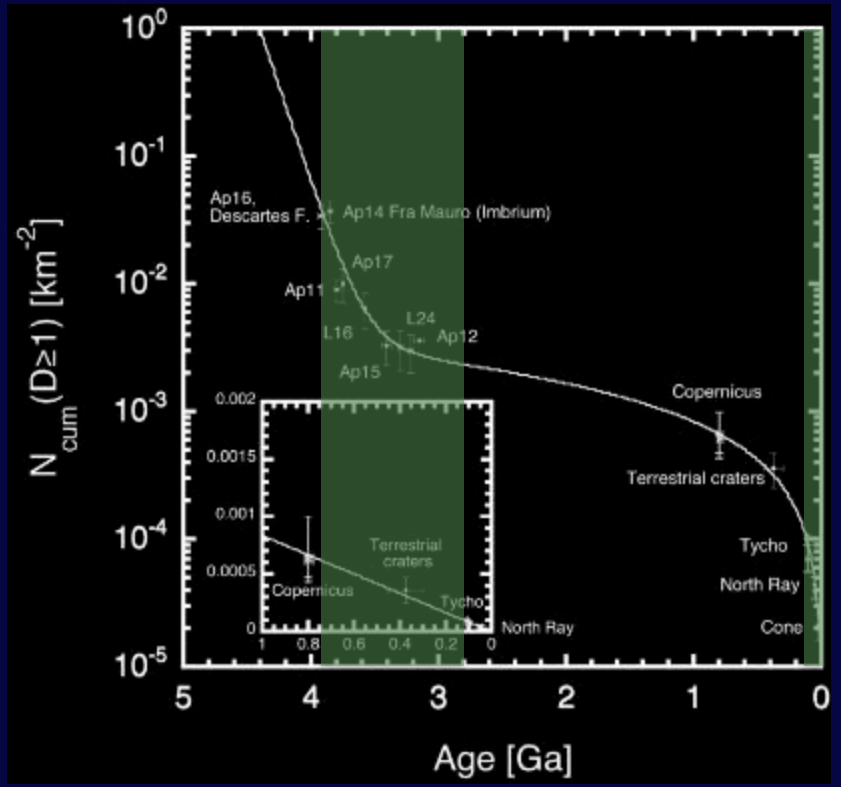


Major open science questions:
2. History of Lunar Bombardment

42 impact basins ≥300 km, all from >3.5 billion years ago.

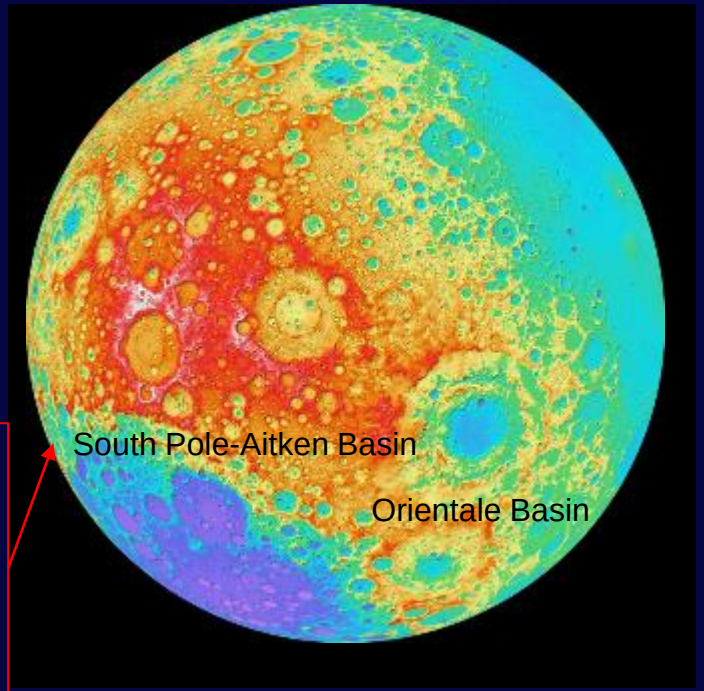
Age of each basin?

Source of Early Impactors?

Effect on Earth / origin of life?

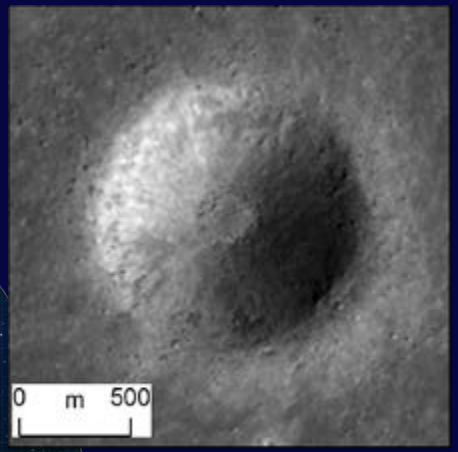
SPA @ ~4.1 Ga:
42 basins formed within 300 Myrs – much more intense Lunar Cataclysm.

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

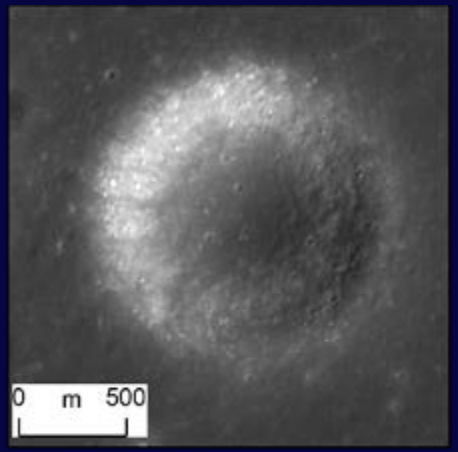


Major open science questions:
2. History of Lunar Bombardment

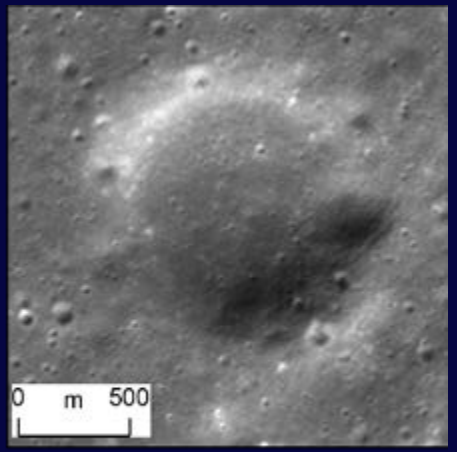
A brief aside (one slide!) about what I work on:



Fresh Crater
T~0.01 Ga



Moderately Degraded
T~3 Ga

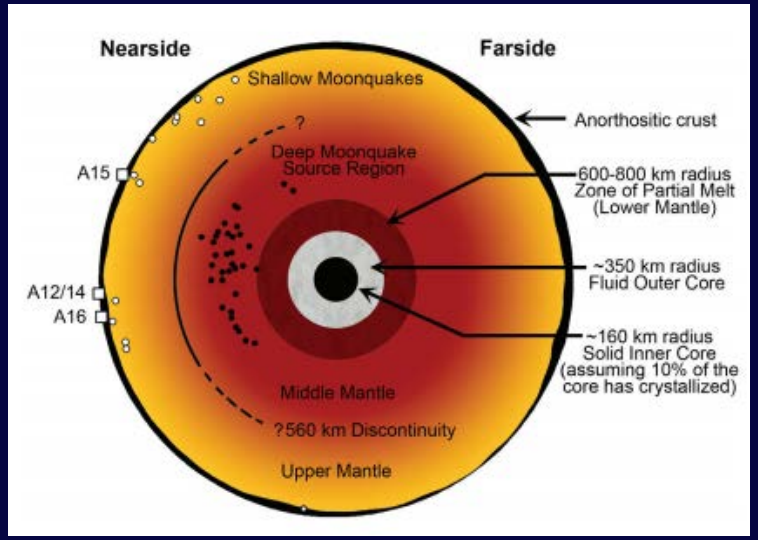


Very Degraded
T~3.7 Ga

Major open science questions:
2. History of Lunar Bombardment

- Apollo seismic experiments were ground-breaking, but left tantalizing uncertainties.

- Need a new, long-lived lunar geophysical network with multiple seismometers, preferably far-side coverage.

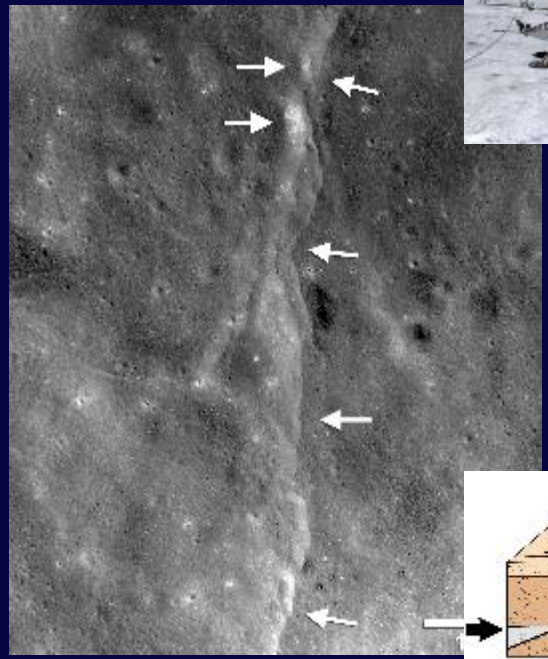


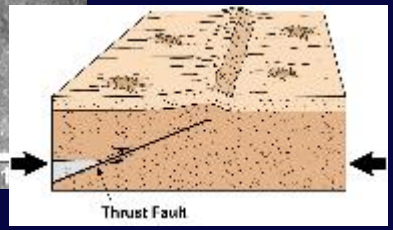
1. Can we confirm the Moon has a fluid outer core?
2. Is lunar mantle homogenous?
3. What causes deep and shallow moonquakes?

Major open science questions:
3. Lunar interior / geophysics

New paper, May 13, 2019:

- Potential link between surface faults and Apollo seismic data.
- Need a new, long-lived lunar geophysical network with multiple seismometers, preferably far-side coverage.





Major open science questions:
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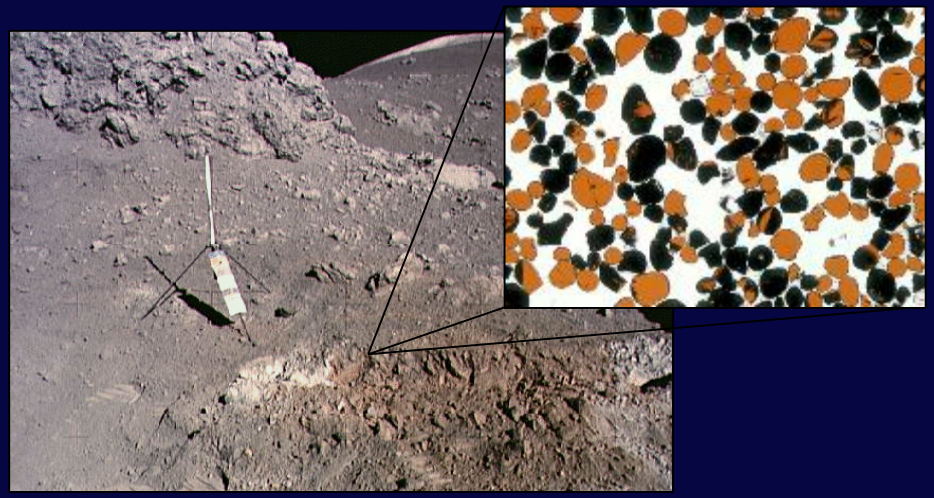
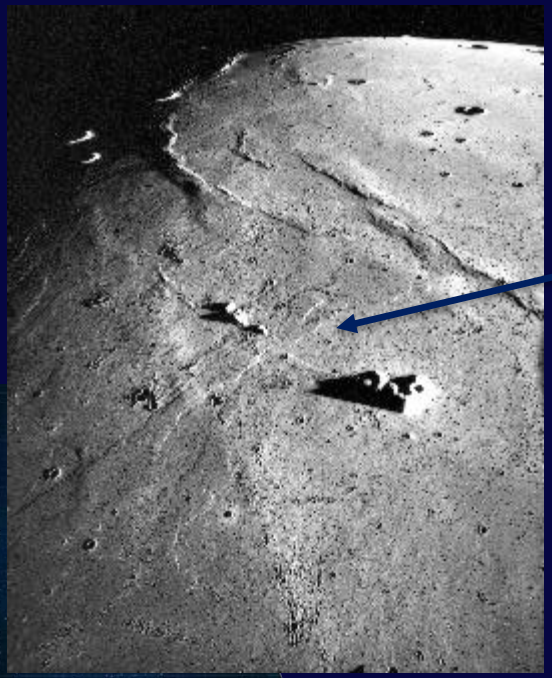
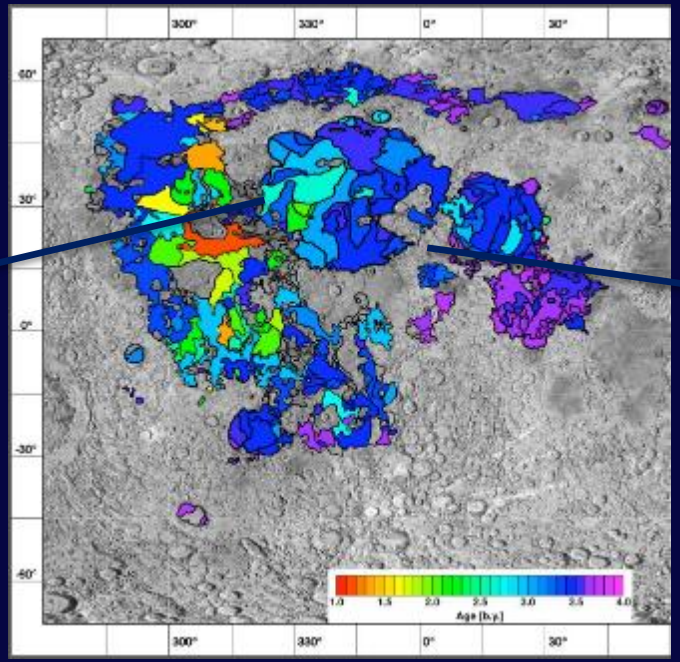


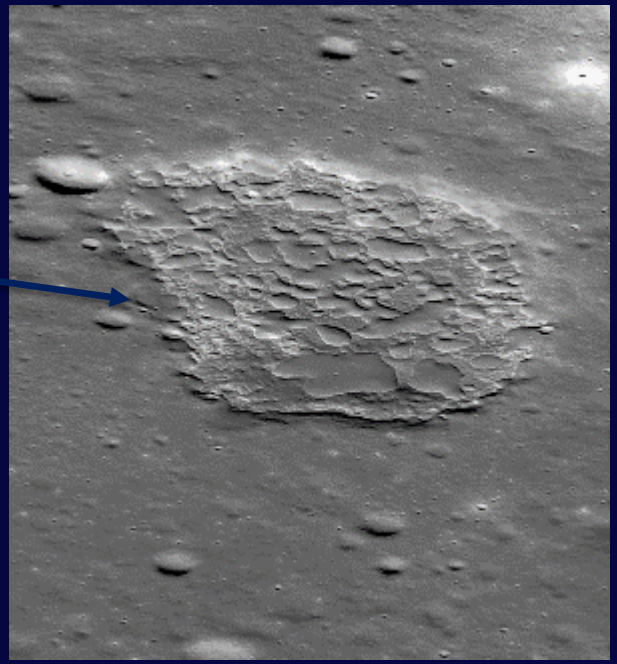
Fiery eruptions formed deposits of glassy beads collected during Apollo missions.

Compositions measured in ~2008 indicate Moon's interior contained much more interior water than previously thought. How does this fit into Moon formation? Is it a resource?

Major open science questions: 4. Lunar volcanism







Is the youngest volcanism on the Moon 2.5 billion years ago, 1 billion years ago, or a few tens of millions of years ago?

Major open science questions:
4. Lunar volcanism

Exploration of the Moon has a glorious history, but it has also just begun.

- Next 5-10 years are an exciting opportunity to build a new, sustainable program of human and robotic exploration.

Open science questions include:

- Resources for human exploration, polar water ice.
- Chronology of large impacts.
- Lunar interior, lunar seismicity.
- Volcanic processes and volcanic history.

Lets go! *The time is now*

We have the capability

We have the purpose

We have the charge

We have the responsibility

EXPLORE MARSHALL

MAKING HUMAN SPACE EXPLORATION POSSIBLE