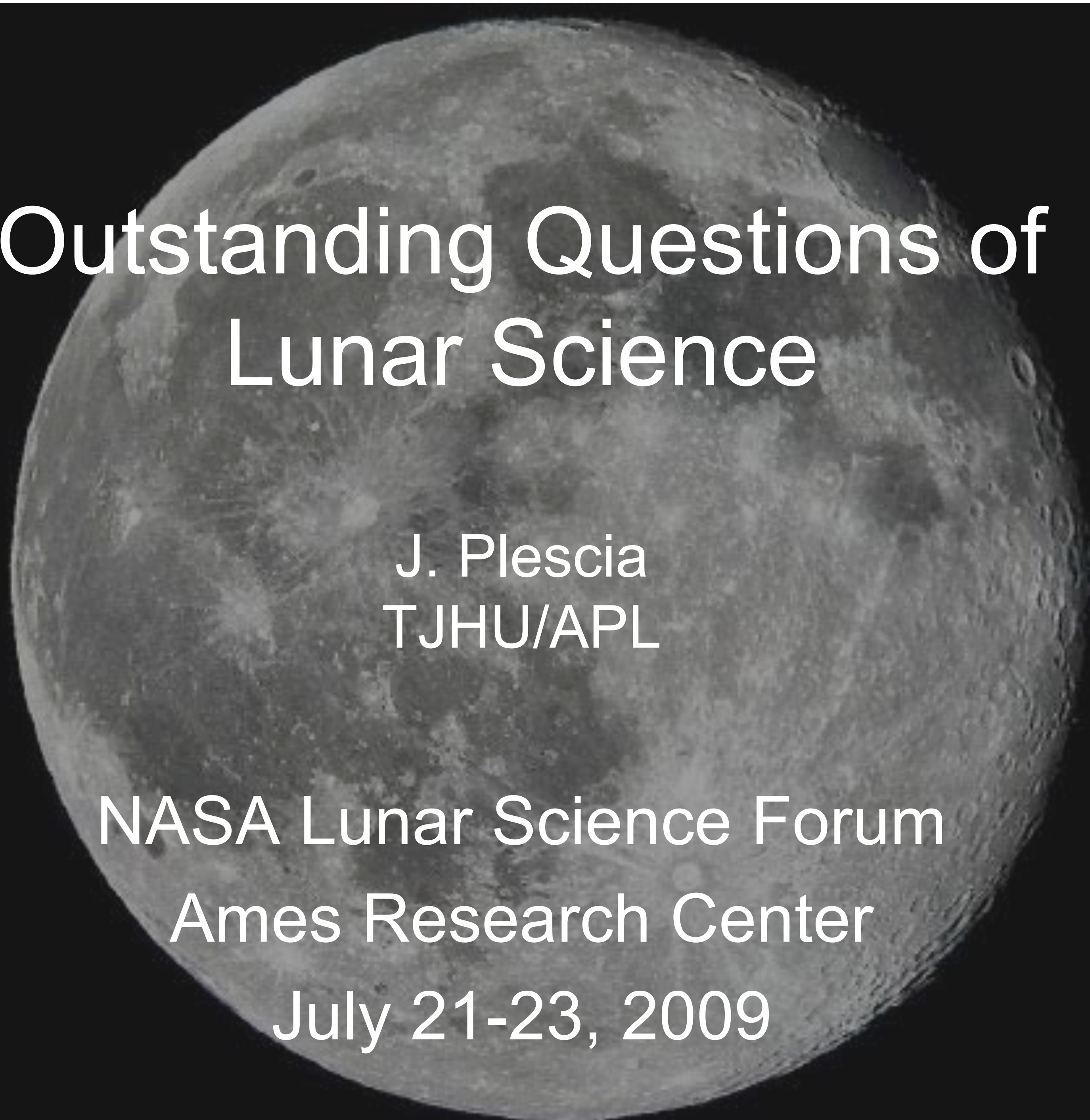


# Outstanding Questions of Lunar Science

J. Plescia
TJHU/APL

NASA Lunar Science Forum
Ames Research Center
July 21-23, 2009

# Where are we now?

Samples: Apollo, Luna, lunar meteorites

Human exploration: Apollo

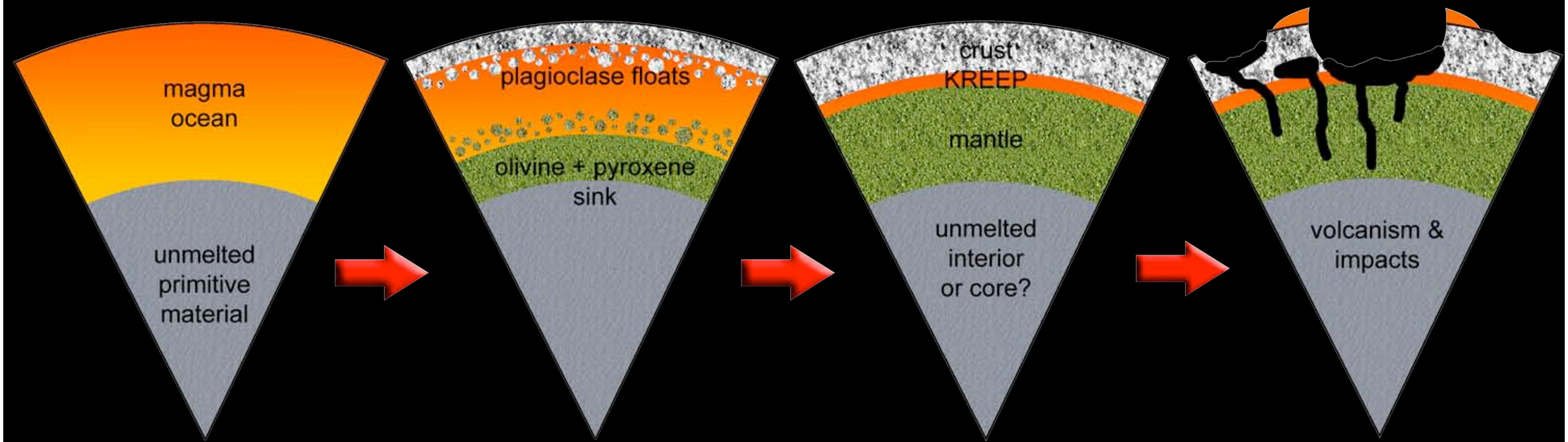
Robotic spacecraft: Lunar Reconnaissance Orbiter, Chandrayaan-1, Kaguya, Chang’e, SMART-1, Lunar Prospector, Clementine, Apollo, Luna, Lunokhod, Surveyor, Ranger, Zond

Summaries:

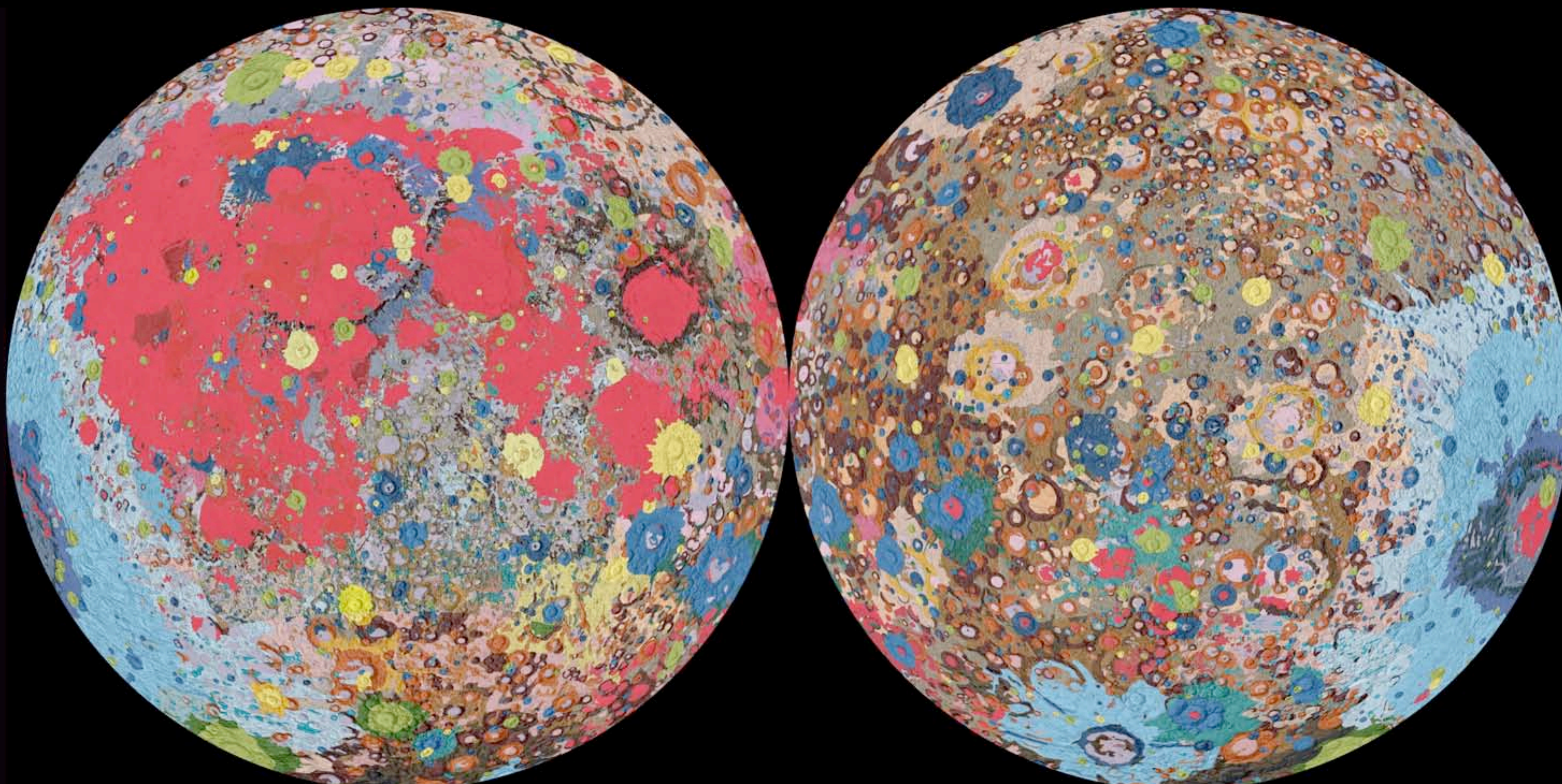
- New Views of the Moon
- The Lunar Source Book

# Giant Impact Hypothesis

# Magma Ocean Hypothesis



# Geology of the Moon



# What's left?

**New Views of the Moon**

What elemental and molecular species make up the lunar exosphere and how has it changed with time?

What was the initial thermal state of the Moon?

What was the cause of global scale-asymmetry?

What are the characteristics of the lunar core (size, composition), and did the Moon ever support a dynamo-driven magnetic field?

Was there a significant late veneer of accretion (post-core formation/early differentiation)?

Is there an undifferentiated lower mantle (limited or no involvement in magma-ocean melting); if so, what was its role in lunar magmatism?

What were the sources and magnitudes of heating to drive secondary magmatism?

What and where are the most concentrated, extensive, and readily extractable deposits of H and $^3$He?

# What’s left?

**Lunar Exploration Analysis Group (LEAG)**

- Understand the environmental impacts of lunar exploration.
- Development and implementation of sample return technologies and protocols.
- Characterize the environment and processes in lunar polar regions.
- Understand the dynamical evolution and space weathering of the regolith.
- Understand lunar differentiation.
- Understand volcanic processes.
- Understand the impact process.
- Determine the stratigraphy, structure, and geological history of the Moon.
- Understand formation of the Earth-Moon system.
- Understand the impact history of the Inner Solar System as recorded on the Moon.
- Regolith as a recorder of extra-lunar processes.

# What’s left?

**Scientific Context for Exploration of the Moon: Final Report**

- Bombardment history of the inner solar system uniquely revealed on the Moon.
- Structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated body.
- Key planetary processes are manifested in diversity of lunar crustal rocks.
- The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history.
- Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.
- The Moon is an accessible laboratory for studying the impact process on planetary scales.
- The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.
- Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state.

# Context

Interior:

core size and composition; early magnetic field; mantle structure and composition; crustal composition, dimension, heterogeneity, formation and evolution; volcanic history; origin of KREEP terrane

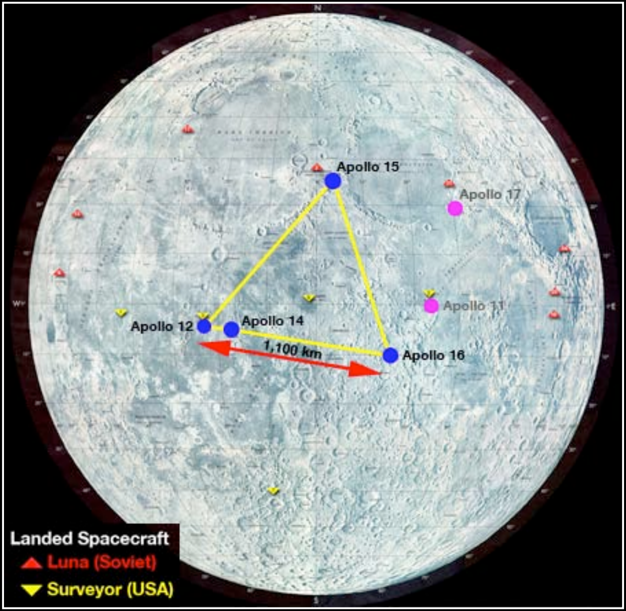
Surface:

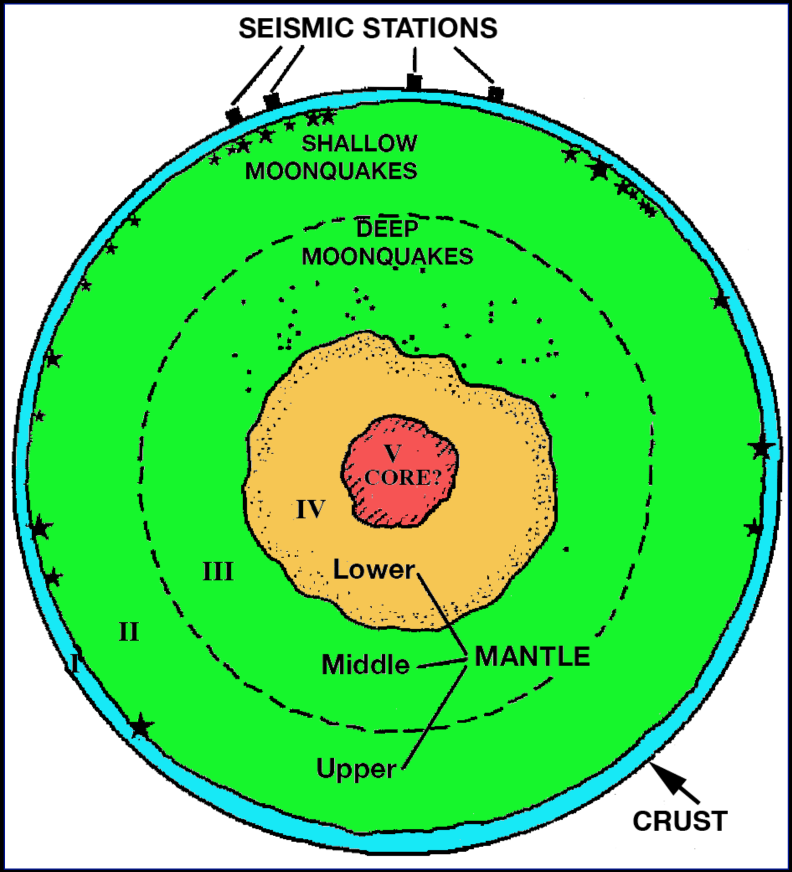
solar system bombardment history including the possibility of a terminal cataclysm; recent cratering flux; inner solar system volatile flux; cratering mechanics and melt sheet formation; the formation and evolution of planetary regoliths; exosphere origin and evolution

# Interior: Core

Estimated at <460 km radius, metallic Fe with some Ni, S, And C, but could also be molten Ti-rich silicate magma.

Determine the size, composition and state (solid/liquid) of the core of the Moon.




[Nakamura et al (1982) *PLPSC* **13th**]

# Interior: Crust-Mantle Structure

Velocity increases from surface to base of crust (45±5 km)

Constant upper mantle velocity to 560±15 km

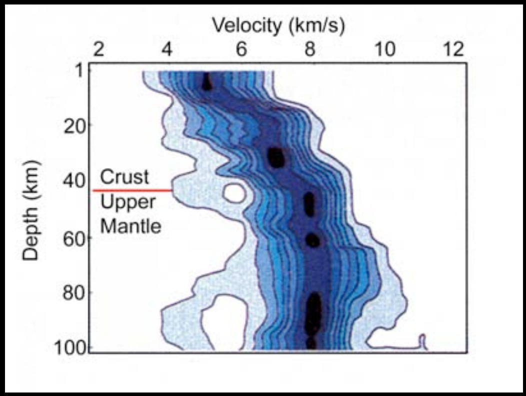
Shallow quakes at 50-220 km

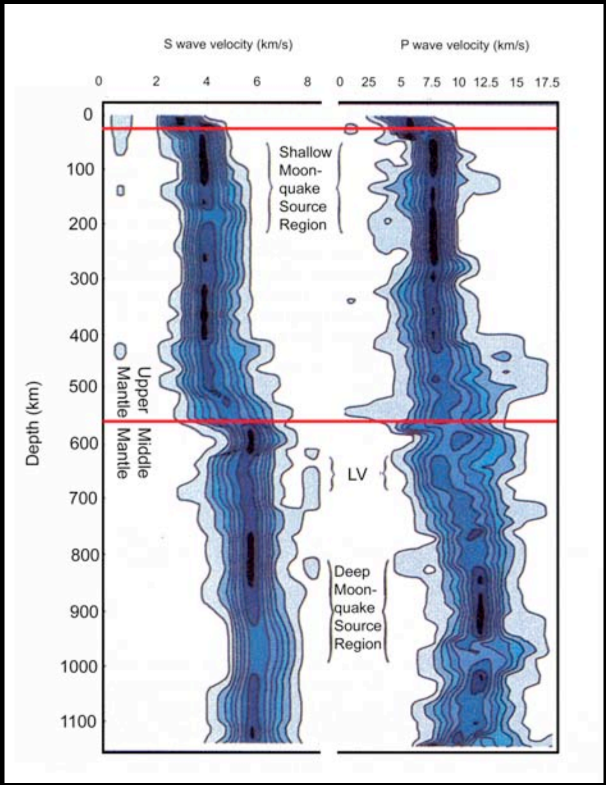
Deep quakes at 850-1000 km (sharp lower boundary)

Characterize chemical/physical stratification of mantle, particularly nature of the putative 500 km discontinuity and composition of lower mantle.

Determine composition of the lower crust and bulk Moon.

Global asymmetry.



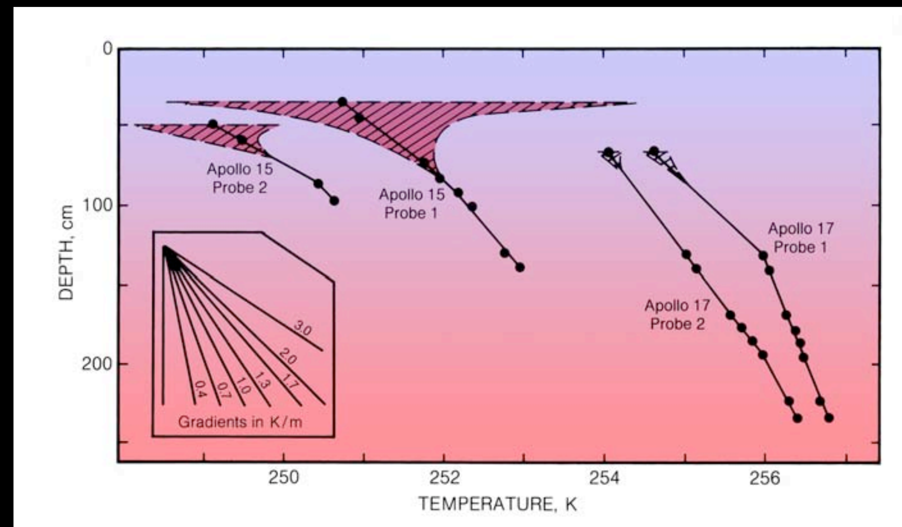



# Interior: Thermal History / Heat Flow

A15 Hadley Rille: 2.1 μW $cm^{-2}$

A17 Taurus Littrow: 1.6 μW $cm^{-2}$

Polar craters colder than anticipated




Characterize the thermal state of the interior and elucidate the workings of the planetary heat engine.

What was the initial thermal state of the Moon?

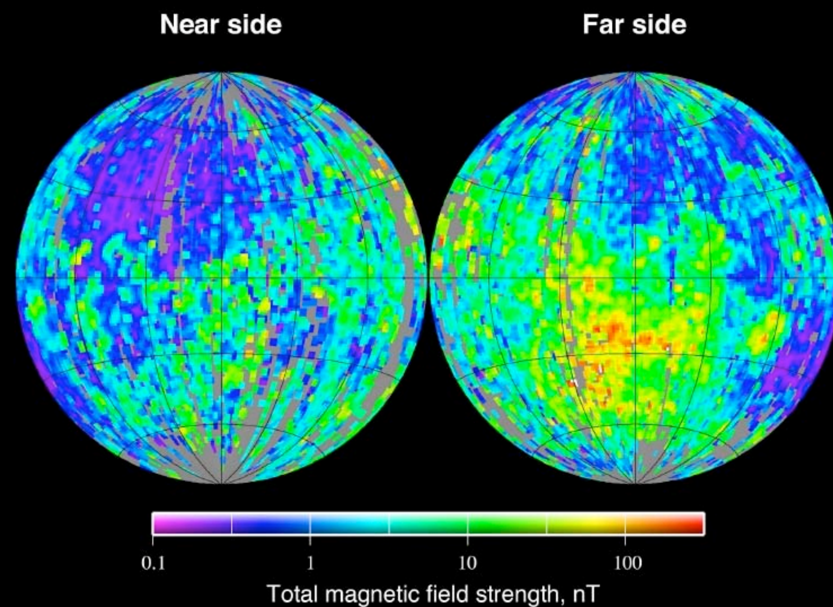
Structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated body.

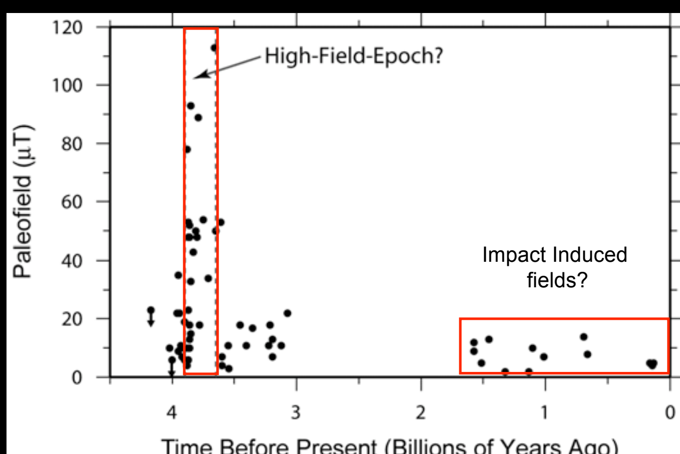
# Interior: Magnetic Field / Dynamo

Low-intensity remnant field, highest intensities within the highlands; lowest in the mare; SPA anomaly; Reiner-gamma.

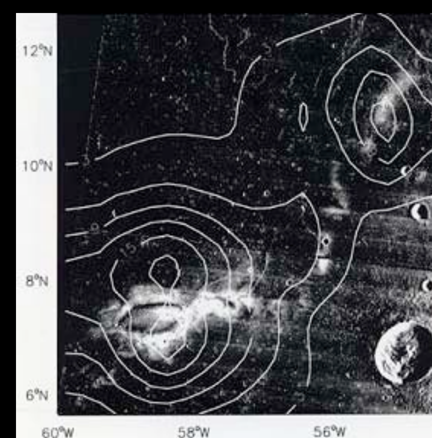
Samples have remnant magnetizations (but no orientated samples for global correlation). Correlation with age.

What are the characteristics of the lunar core; did the Moon ever support a dynamo-driven magnetic field; impact induced fields?




Wieczorek et al. (2006)



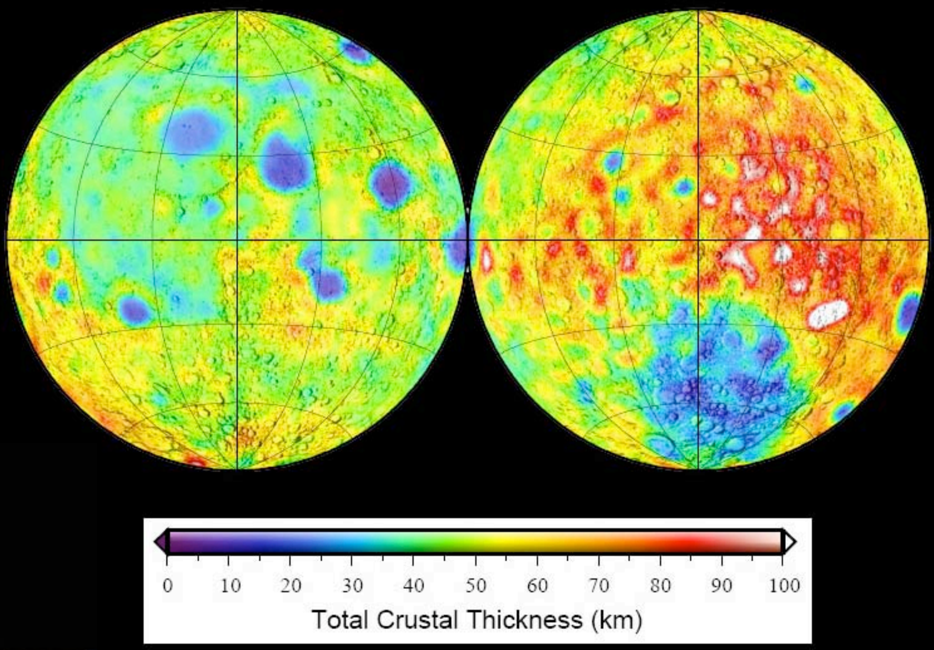
# Interior: Crustal Thickness

Average crust thickness 60-30 km (depends on the model)

Apollo seismic experiments (really only a triangle A15 – A16 – A12/14)

What is the crustal structure and its variation?

What is the cause of the global-scale asymmetry?




# Surface: Crustal Composition

Lunar samples and meteorites illustrate the range of lithologies and chemistries.

Basaltic mare, anorthositic highlands, pyroclastics

Key planetary processes are manifested in a diversity of lunar crustal rocks.

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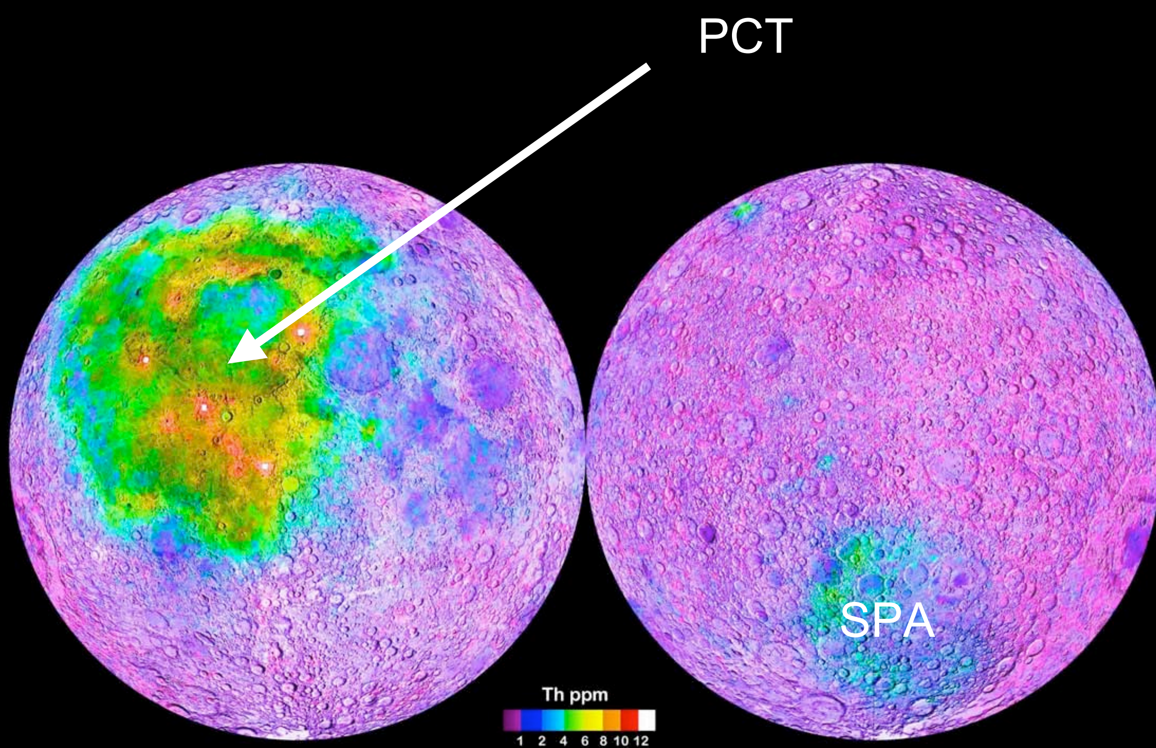


# Surface: Bombardment History

Flux considerably greater early time.

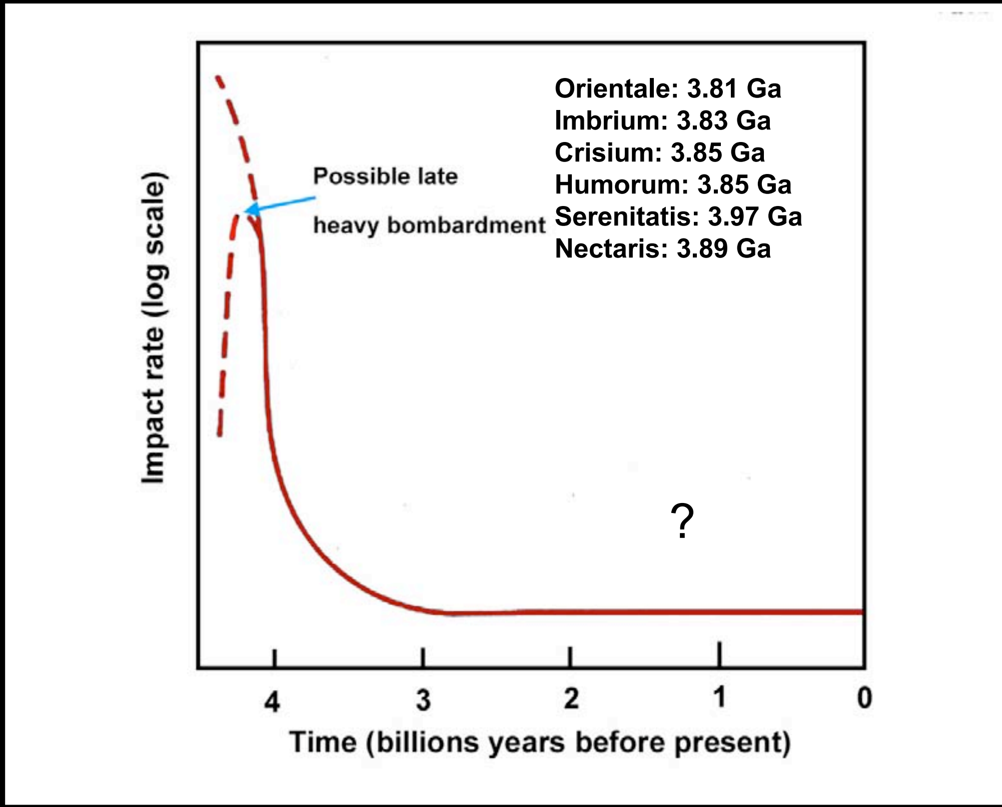
Several basins have similar ages.

Question of biased sampling – all the samples saw the same small set of events.

Bombardment history of the inner solar system.

Early cataclysm?

Episodic variations over the last 0-3 Ga?

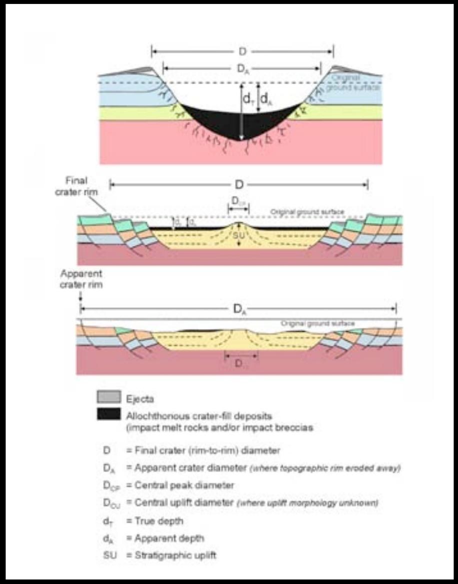


# Surface: Cratering Mechanics

Simple, complex, basins

Planetary observations – remote sensing.

Terrestrial observations – in situ, but limited.




Understand the impact history of the Inner Solar System as recorded on the Moon.

Bombardment history of the inner solar system uniquely revealed on the Moon.

# Surface: Regolith Formation / Evolution

Regolith develops due to meteoroid bombardment (macro to micro).

Regolith / megaregolith

Older the surface – thicker the regolith and the more mature.

Lateral variations, complex layered medium.

The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.

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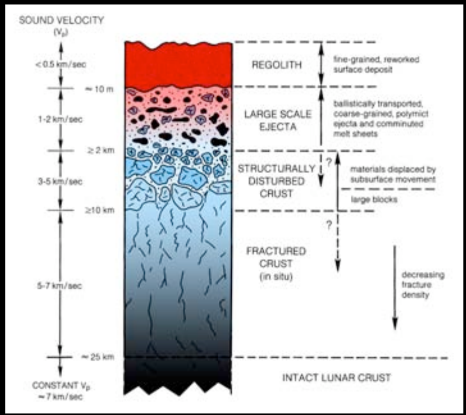
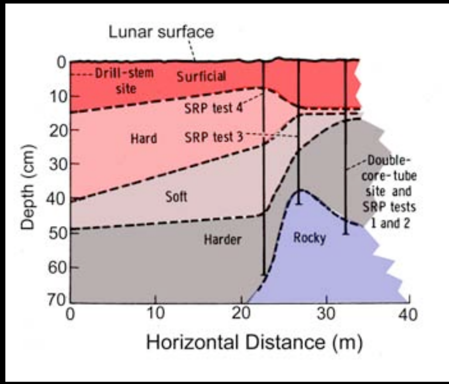


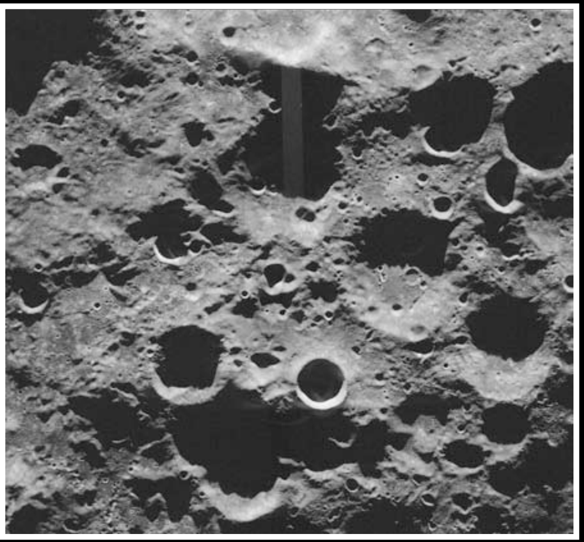



# Surface: Volatiles

Polar shadowed areas are cold-traps.

May contain various volatile species.

Solar wind, cometary, meteoritic, endogenic.



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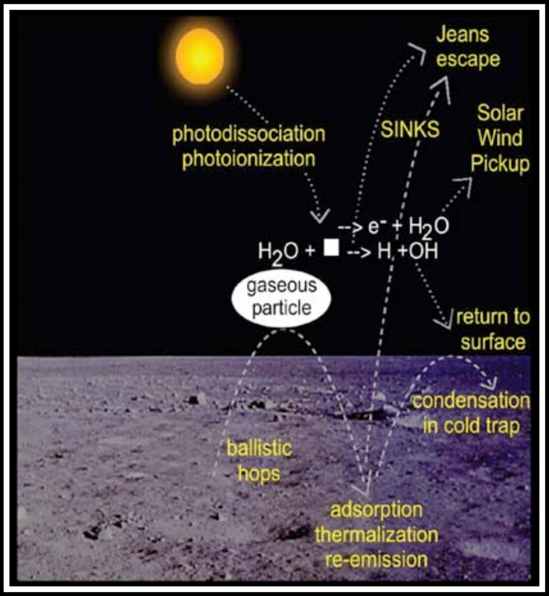


# Considerations

Almost none of the major outstanding questions can be resolved by a single mission.

Questions require
- Global access
- Detailed, planned sampling
- Numerous samples
- Multiple, extended observations

Options
- Robotic missions
  - Surface – static / mobile - drilling
  - Orbital
  - Sample return
- Human missions
  - Sortie
  - Outpost

Samples are like donuts –
One is never enough.

# Network Mission

Network of stations
- Global distribution
- Long-lived
- Continuous operation

Payload
- Seismometer
- Magnetometer
- Electrometer
- Laser retro-reflector

Seismicity – deep / shallow quakes, impacts

Crust / mantle velocity structure

Core size / physical state

Constraints on chemical / petrologic composition of mantle / core

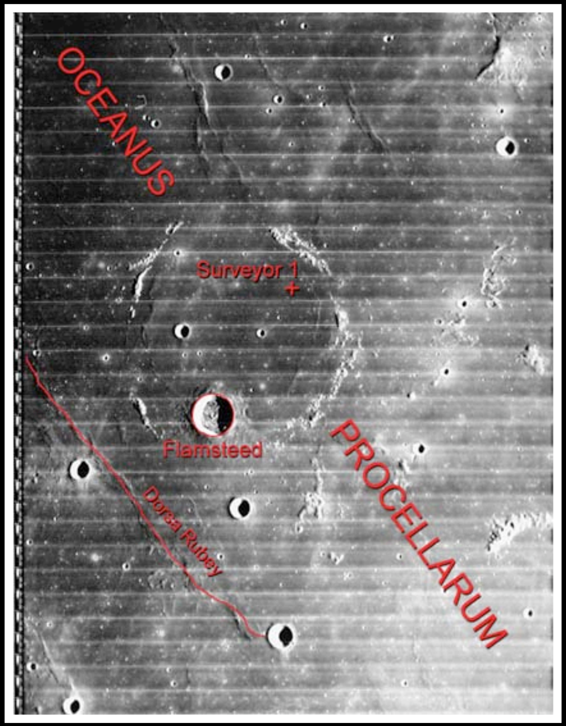
# Static Lander – Short Lifetime

Static lander

- Relatively small payload
- Short lifetime
- No mobility
- Focused experiments

Payload

- In situ radiometric dating
  - Chemistry, evolved gas, isotopic composition.

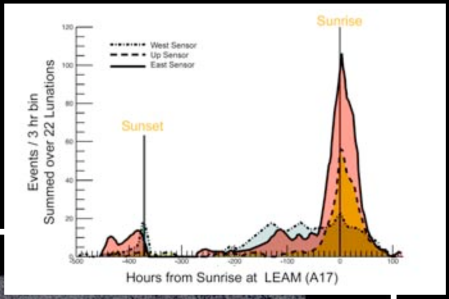



Calibration point for the cratering flux

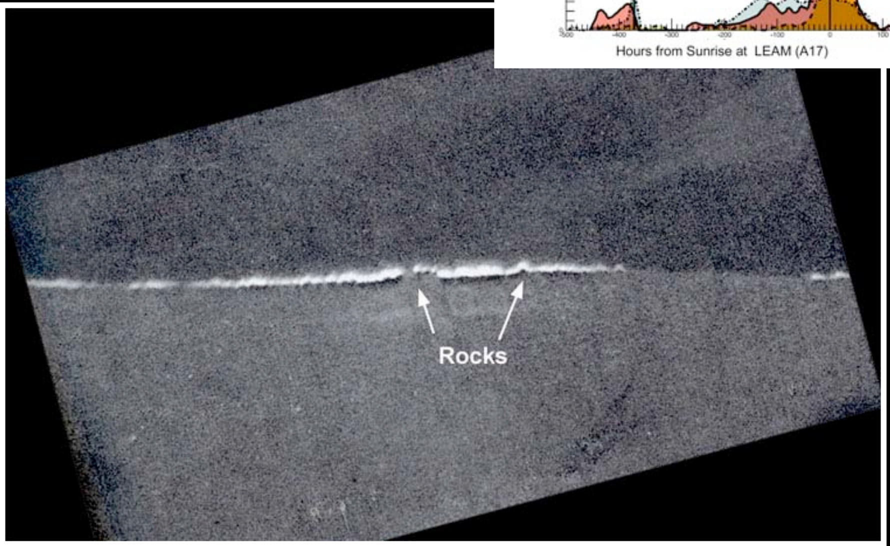
Constraints on thermal evolution and volcanic history

Regolith processes / space weathering

# Static Lander – Long Lifetime




- Static lander
  - Limited payload
  - Long lifetime (repeat terminator crossing, magnetotail)
  - Continuous awareness
  - Focused experiments
- Payload
  - Imaging
  - Dust / particle detector
  - Electric field
  - Lidar




- Dusty plasma environment
- Induced electric field / surface charging / discharging
- Dust mass flux
- Spatial distribution of dust

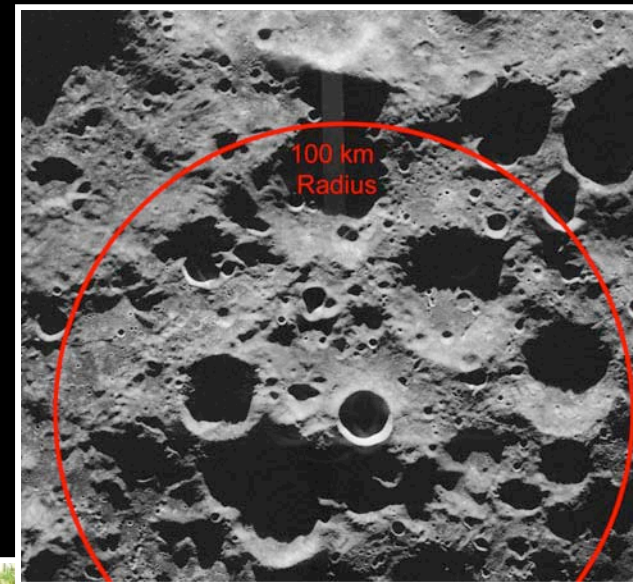
# Sortie Mission (Apollo-like)

Global access
Short stay time
Limited mobility (tens of km)

Trenching to depths of meters
Multiple trenches
Detailed sampling (environmentally controlled)

Regolith study
Vertical and horizontal variation
Buried regoliths (solar history)
Maturation processes
Space weathering

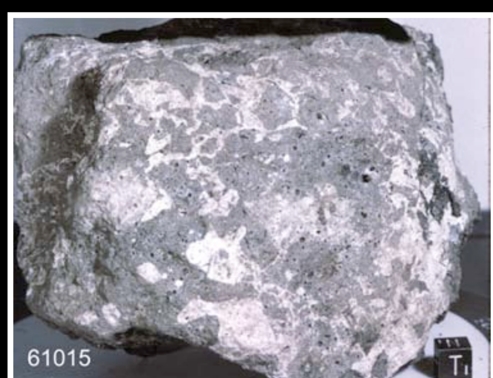
# Outpost




Permanent presence
Mobility 100s km
Extended surface operations

Impact cratering history

Sample numerous craters of different size
Melt material to allow dating of the crater
Glass lining
Extensively explore target crater


# Summary

Gobs of major scientific questions remaining.

Environment, surface and interior

Pure science – applied science

Few can be addressed with a single mission, none with a single sample or measurement.

Any mission will make some progress on some subset of the questions.

Any location can add to understanding about many questions.

Global access and samples are key.

Lunar science doesn't end. Questions are addressed, understanding matures, new problems are discovered, new techniques are developed, new samples are acquired, analysis continues.