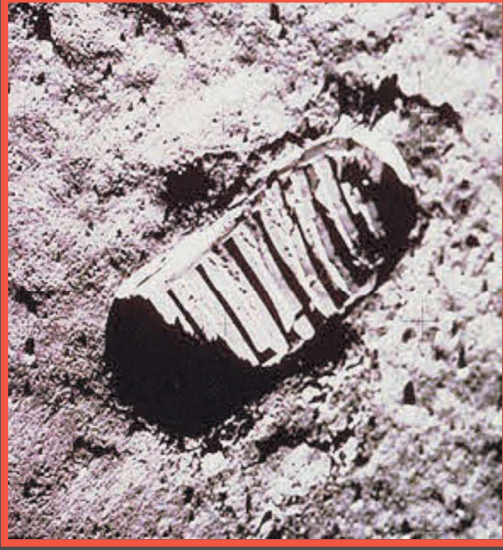


Non-Polar Lunar Human Landing Sites to Advance Knowledge of Planetary Sciences

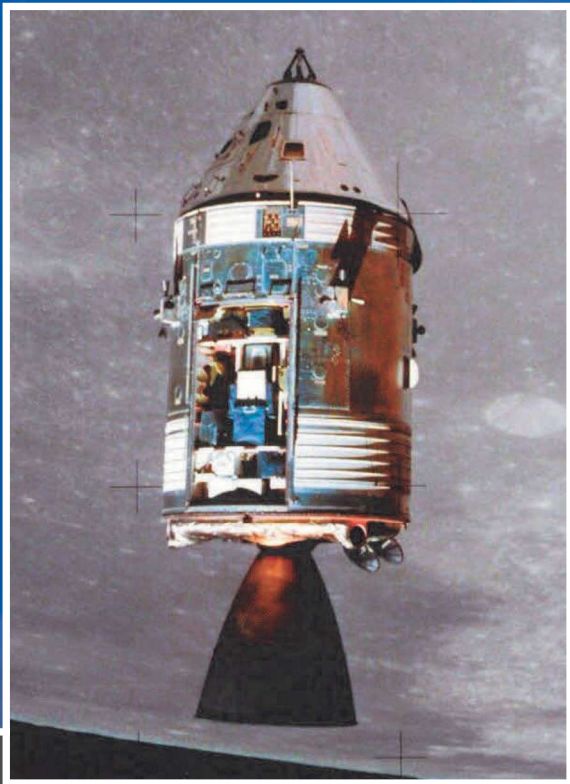
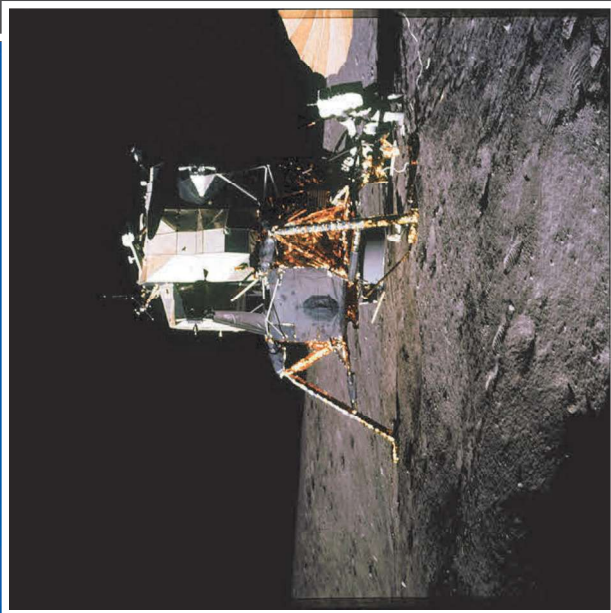


James W. Head

Department of Earth, Environmental and Planetary Sciences
Brown University, Providence, Rhode Island 02912 USA

NAS-NRC Panel - August 7, 2025

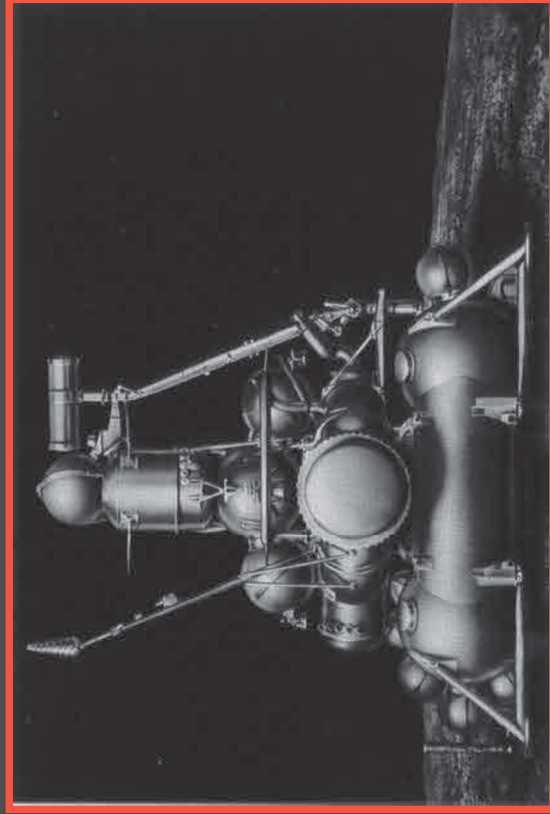
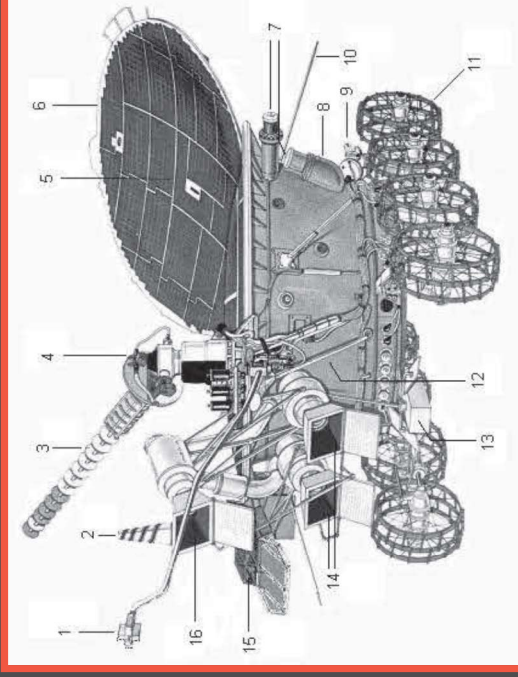
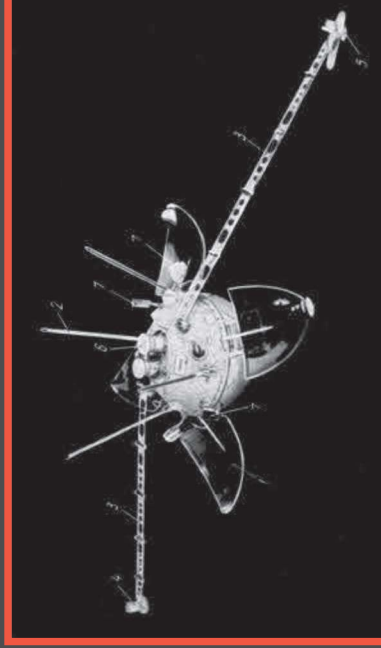
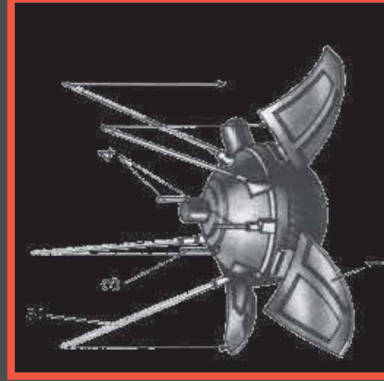
Key Non-Polar Destinations to Address Decadal-Scale Objectives with
Human Explorers (Meeting #5)

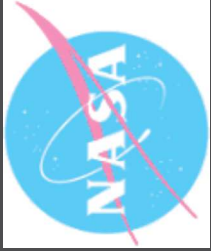


Soviet Lunar Missions:



- Luna Landers.
- Lunokhod.
- Luna Sample Return.
- Luna Orbiters
- Zond Human-rated Missions





NASA Headquarters: Systems Engineer

1968-1973



- Exploration Strategy:** What questions to address?
- Landing Site Selection:** Where do we go?
- Traverse Planning:** What to do when we get there?
- Science and Engineering Synergism:** How do we implement the science goals and objectives?
- Astronaut Training:** How do we train test pilots?
- Mission Simulations:** How do we practice?
- Mission Operations:** The actual missions!
- Post-mission Debriefing and Analysis:** Feedback.
- Re-planning of Subsequent Missions:** Feed-forward.

Precursor Lunar Robotic Missions



- **Needed to understand:**

- Nature of the surface at high resolution (Ranger).
- Bearing strength and physical properties of the surface layer (Surveyor).
- Surface morphology and small-scale topography; landing safety and interesting geological sites (Lunar Orbiter).

Robotic Lander/Orbiter Precursor Program:



- Ranger 1-9 (1961 - 1965).
- Surveyor 1-7 (1966 - 1968).
- Lunar Orbiter 1-5 (1966 - 1967).

21 Robotic Precursor Missions in 8 Years!

Robotic Precursor Missions are Totally Essential!

Apollo Scientific Goals and Objectives:



-Broadly, *to understand the nature, internal structure and history of the Moon and its environment.*

-Four-pronged approach:

- 1) **Surface science station:** Deployed surface experiments package (ALSEP).
- 2) **Surface exploration:** Lunar surface observations, photography, exploration traverses, and sampling (Field Geology Experiment); geophysical instruments (gravimeter, magnetometer, active seismic, SEP, etc.).
- 3) **Orbital exploration:** Astronaut observations and photography, SIM Bay experiments.
- 4) **Moon as a platform:** Lyman alpha telescope, gravity waves, etc.

There was a huge range of science at all levels during Apollo!!

Apollo Landing Site Selection Strategy



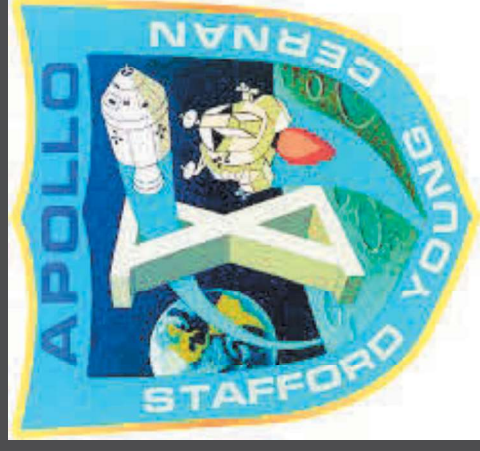
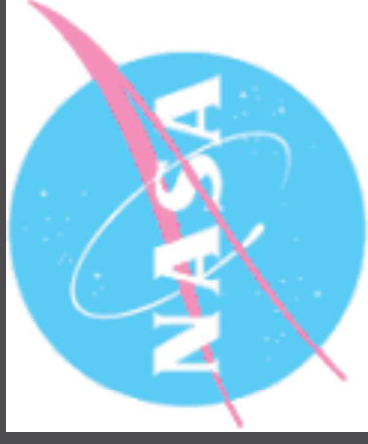
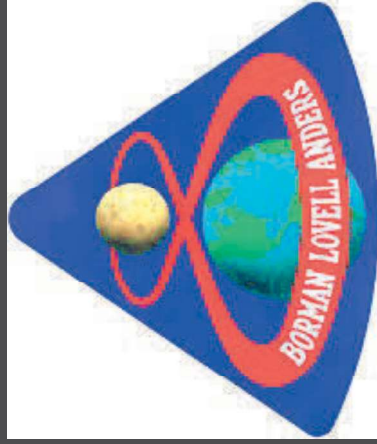
- Range of mare ages.
- Basin formation and subsurface sampling.
- Lunar history and thermal evolution.
- Seismicity and thermal structure.
- Comparative planetology.
- Increasing exploration capabilities.
- Decreasing number of mission (Apollo 18-22).

Candidate Apollo Landing Sites

- Young Dark Mantle Deposit.
- Copernicus Central Peaks.
- Censorinus Crater.
- Marius Hills.
- Gassendi Floor-Fractured Crater.
- Tycho Crater.
- Davy Crater Chain.
- Descartes and Cayley Plains.
- Fra Mauro Formation.
- Hyginus Rille.
- Hadley Apennine.
- Flamsteed P.
- Tsiolkovsky.



Head, J. W. (1970) Scientific Rationale Summaries for
Apollo Candidate Lunar Exploration Landing Sites, NASA-
Bellcomm B70 03034



Apollo Launch Dates

- Astronaut Missions -

Apollo 7	October 11, 1968
Apollo 8	December 21, 1968
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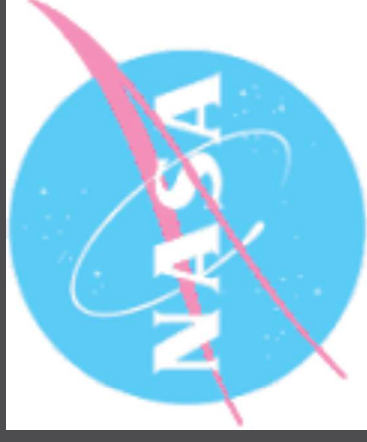
Science and Engineering Goals to Enhance Science Exploration Return

- **Land safely, deploy experiments, collect rocks & soils.**
- Increase stay-time on the lunar surface.
- Increase number of EVA periods to two.
- Demonstrate pinpoint landing to increase access.
- Provide equipment for transport of tools & samples.
- Enable orbital plane change to access high latitudes.
- Increase number of EVA periods to three.
- Provide mobility to reach distant targets.
- Send a geologist as a member of the surface crew.
- Send Lunar Roving Vehicle to next landing site (DM).



Apollo Launch Dates

- Astronaut Missions -



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Apollo 15	July 26, 1971
Apollo 16	April 16, 1972
Apollo 17	December 7, 1972

Eastern Maria



APOLLO 11



Science and Engineering Goals to Enhance Science Exploration Return

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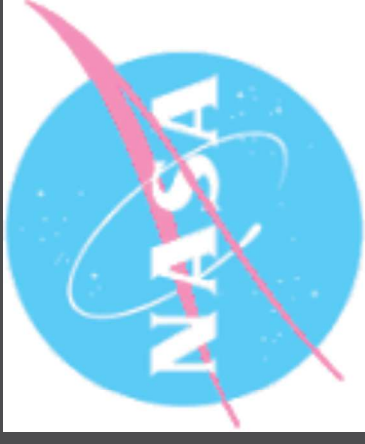


4 months later



Apollo Launch Dates

- Astronaut Missions -

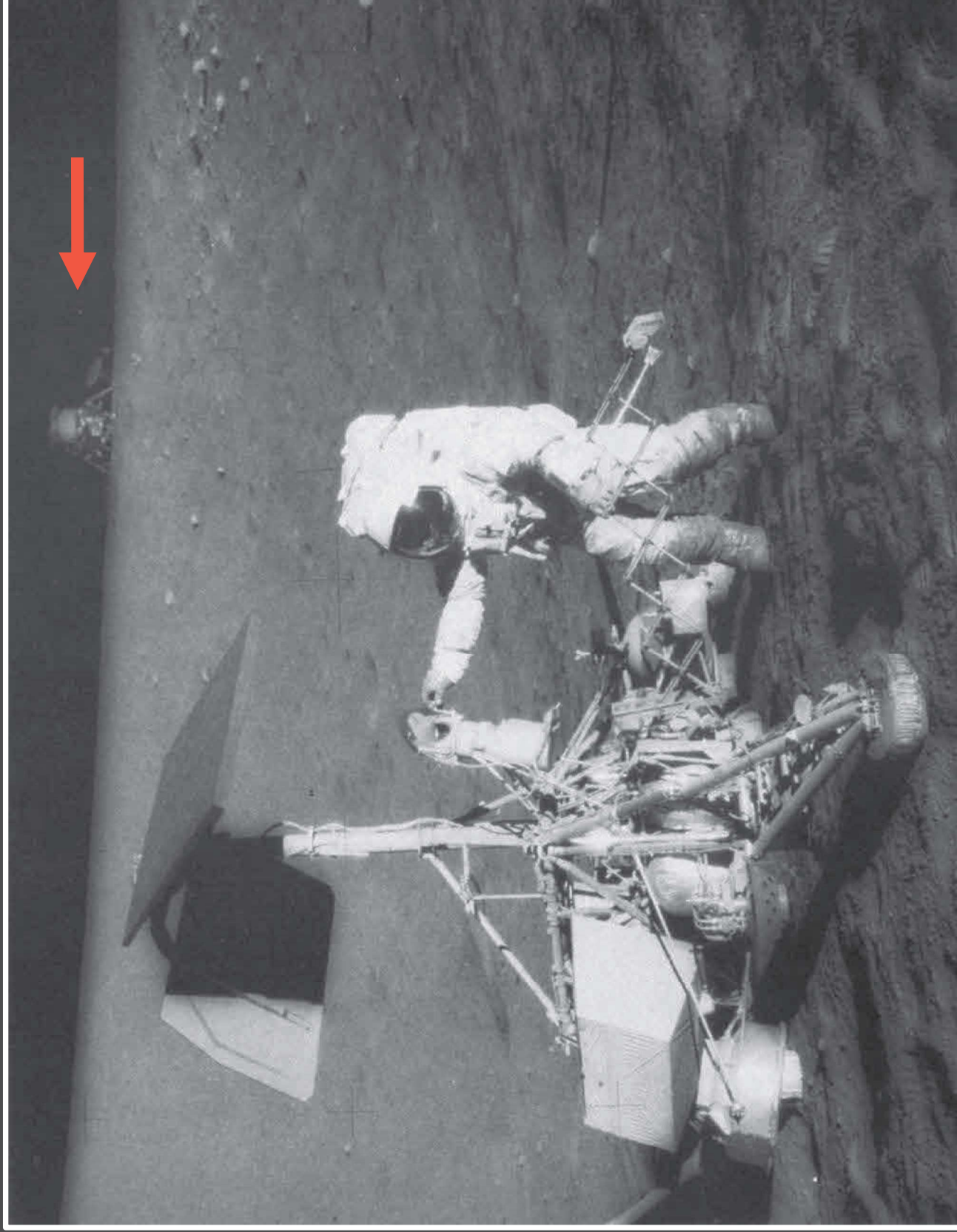


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Apollo 13	April 11, 1970
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Apollo 17	December 7, 1972

Western Maria



Apollo 12 Lands Near Surveyor



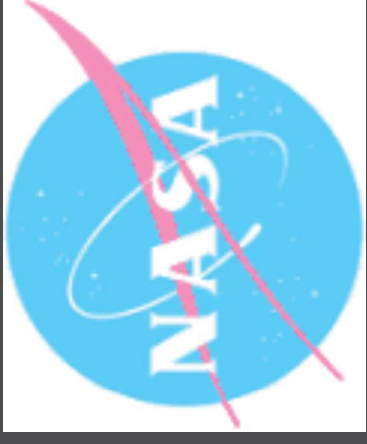
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- Send Lunar Roving Vehicle to next landing site (DM).



Apollo Launch Dates

- Astronaut Missions -



9 months later

Imbrium Basin Ejecta
Fra Mauro Formation



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APOLLO 14



Science and Engineering Goals to Enhance Science Exploration Return

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- Provide equipment for transport of tools & samples.
- **Enable orbital plane change to access high latitudes.**
- **Increase number of EVA periods to three.**
- **Provide mobility to reach distant targets.**
- Send a geologist as a member of the surface crew.
- Send Lunar Roving Vehicle to next landing site (DM).



6 months later

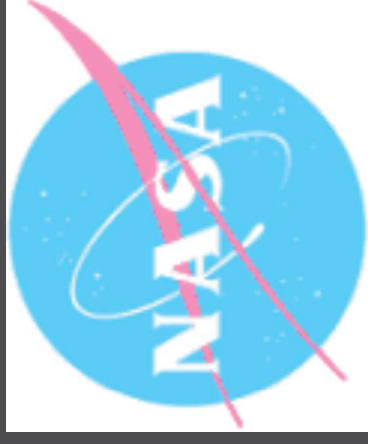


Apollo Launch Dates

- Astronaut Missions -

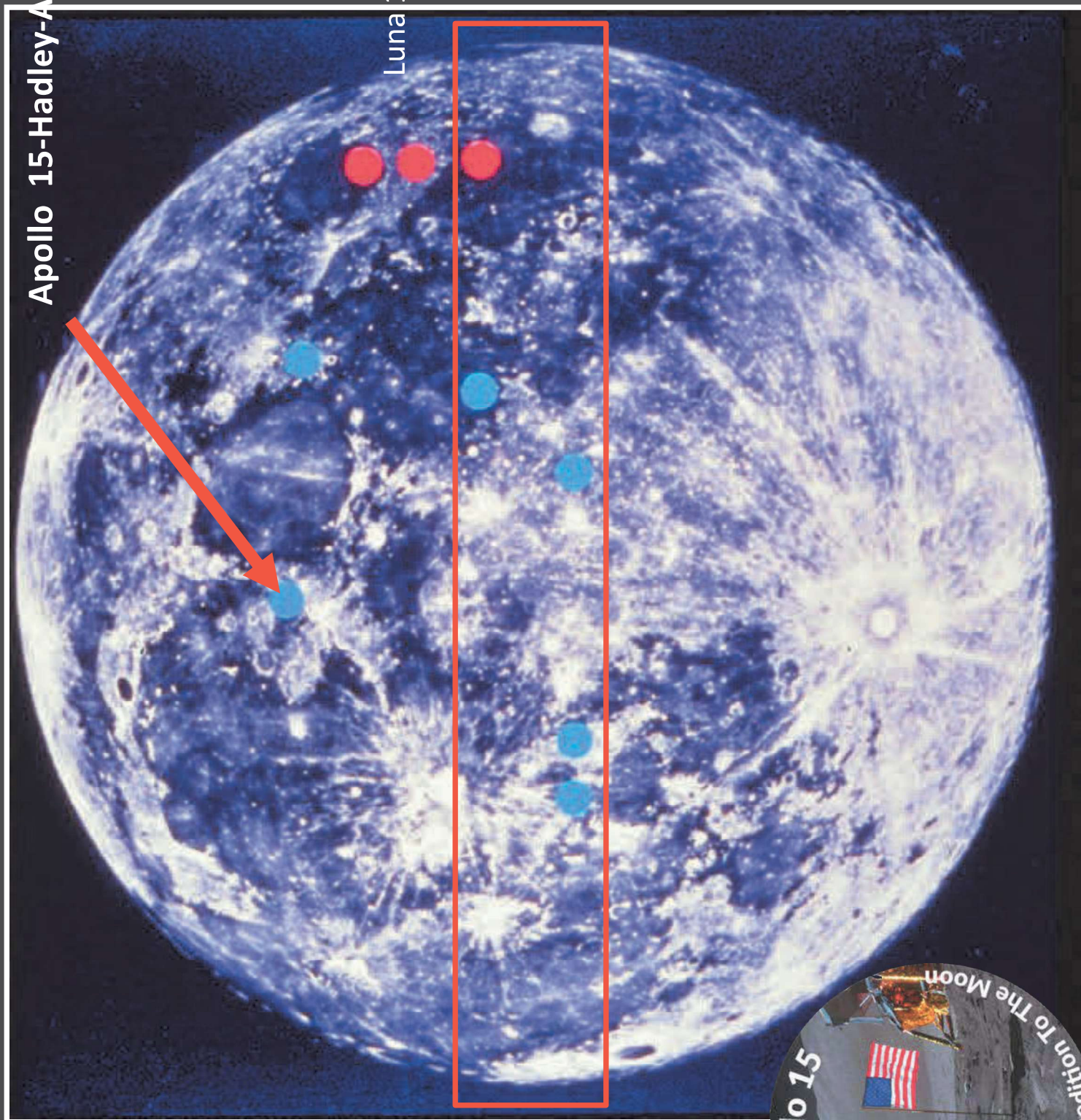
Apollo 7	October 11, 1968
Apollo 8	December 21, 1968
Apollo 9	March 3, 1969
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Apollo 17	December 7, 1972

Imbrium Basin Rim
Hadley Sinuous Rille

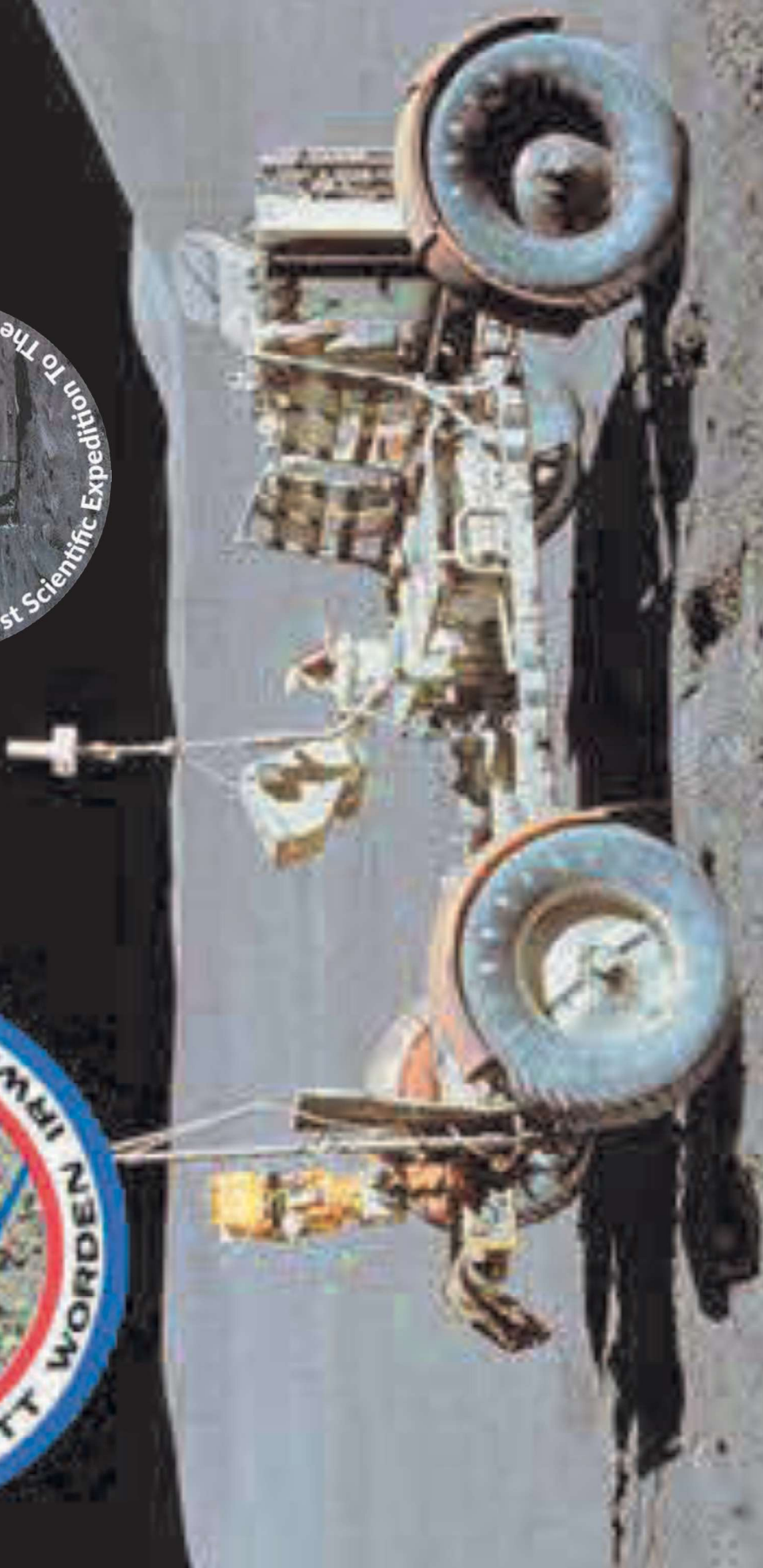


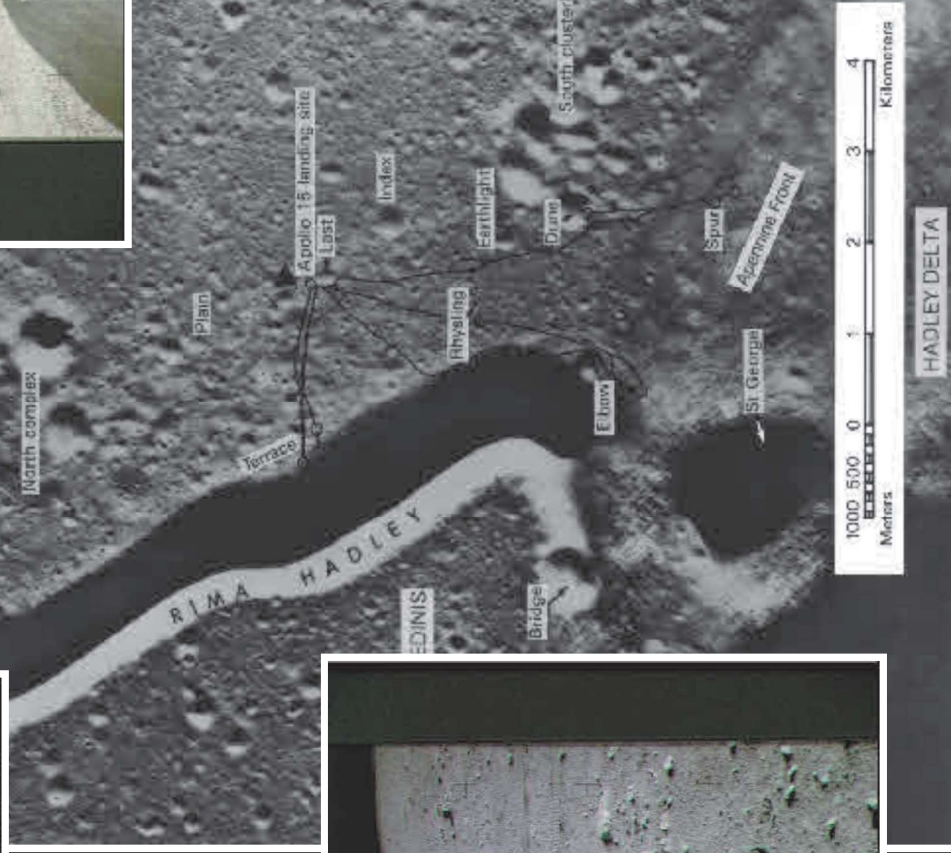
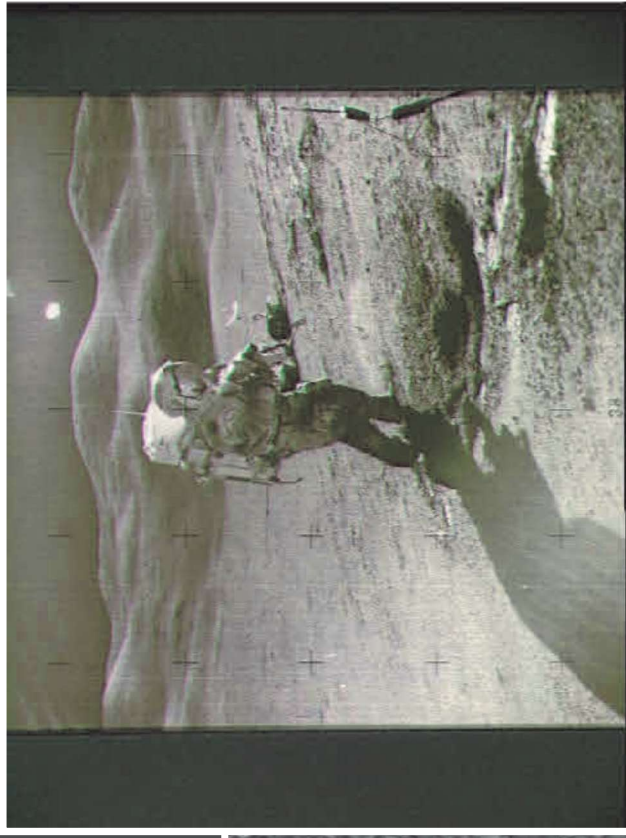
Apollo 15-Hadley-Apennines

Luna 16, 20, 24

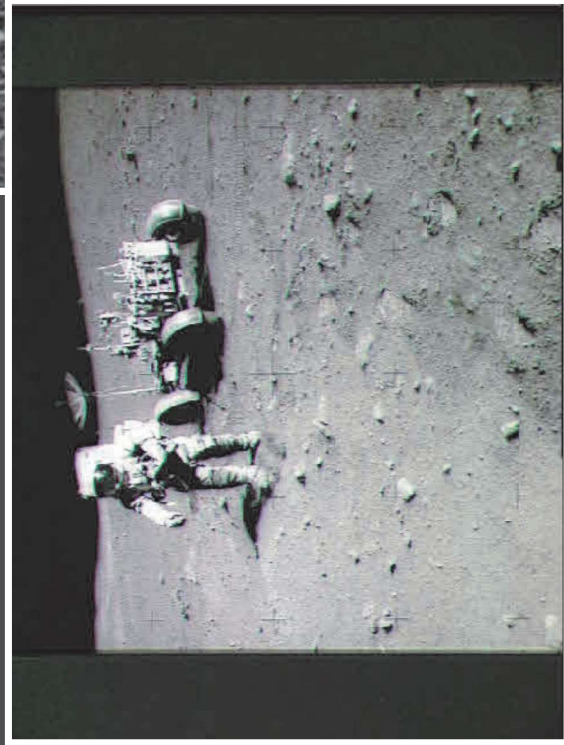


APOLLO 15





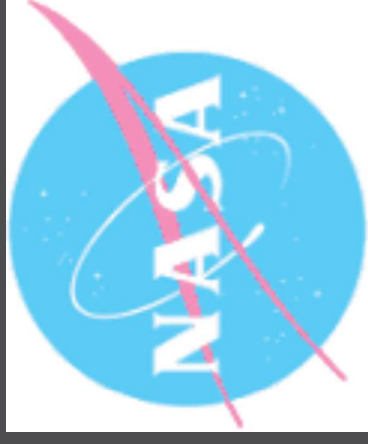
3 EVAs
7 km radius from LM
Total Traverses: ~30 km!!
77 kg of Rocks and Soils





Apollo Launch Dates

- Astronaut Missions -



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9 months later

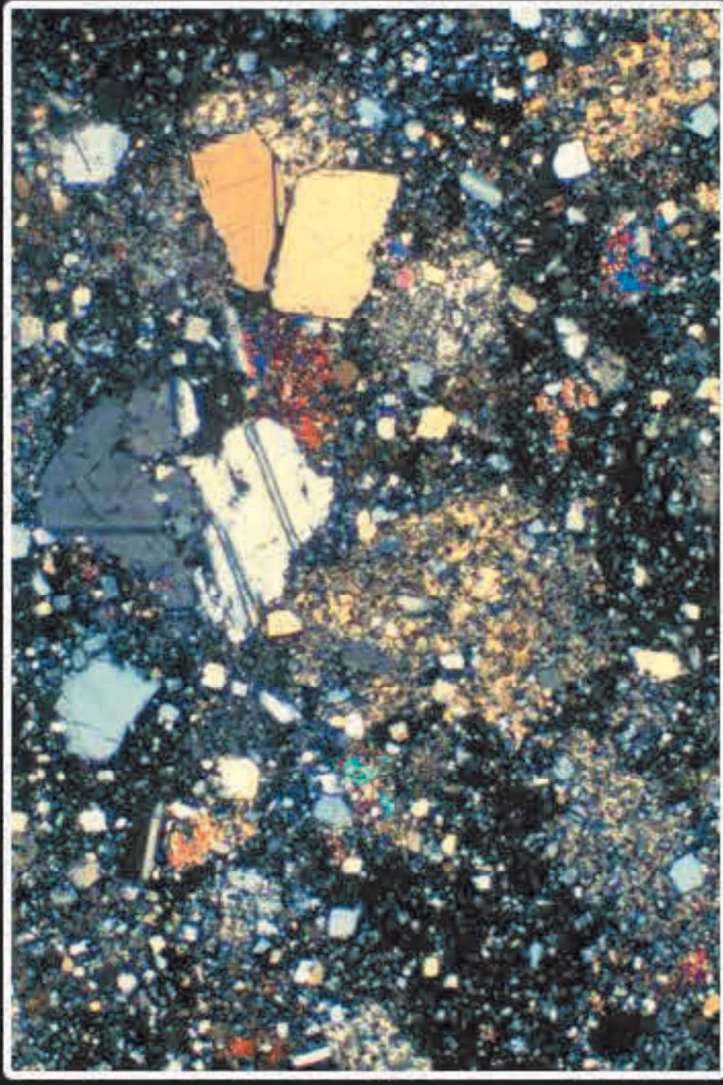
**Pre-Mare Volcanism
Cayley Formation
Descartes**



APOLLO 16



Not “Highland Volcanics”,
but
“Basin and Crater Impact Ejecta” !!



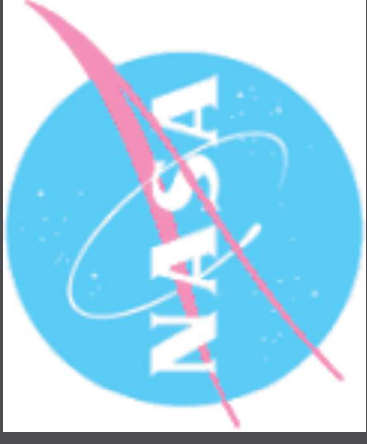
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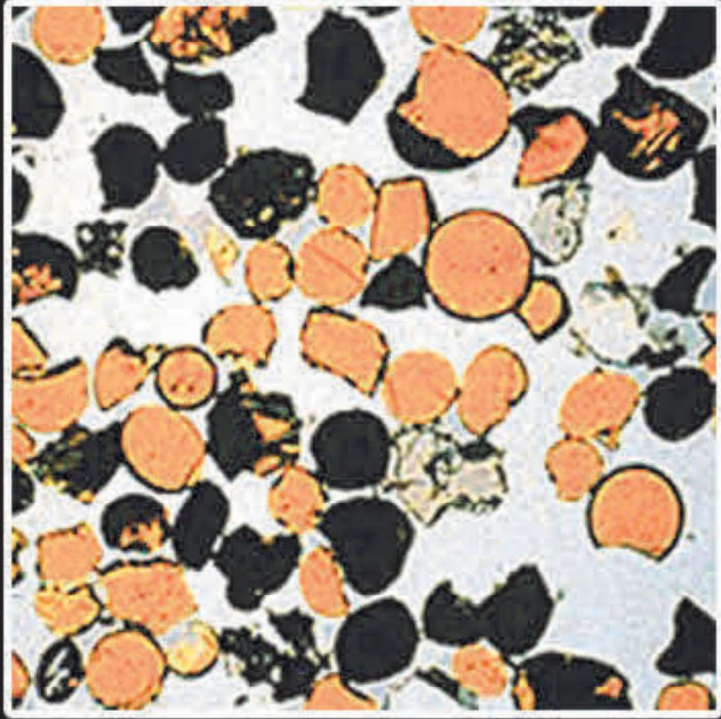
8 months later

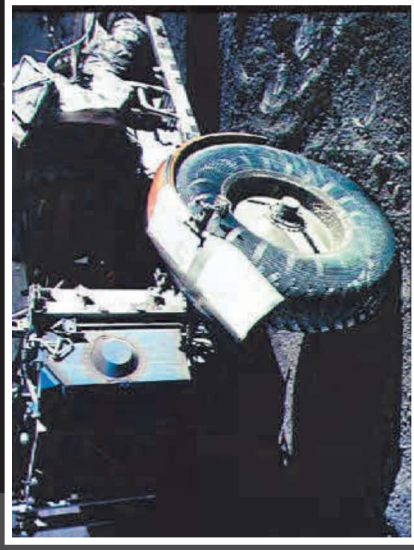


**Serenitatis Basin Rim
Dark Mantling Deposits
Young Volcanism?**



APOLLO 17



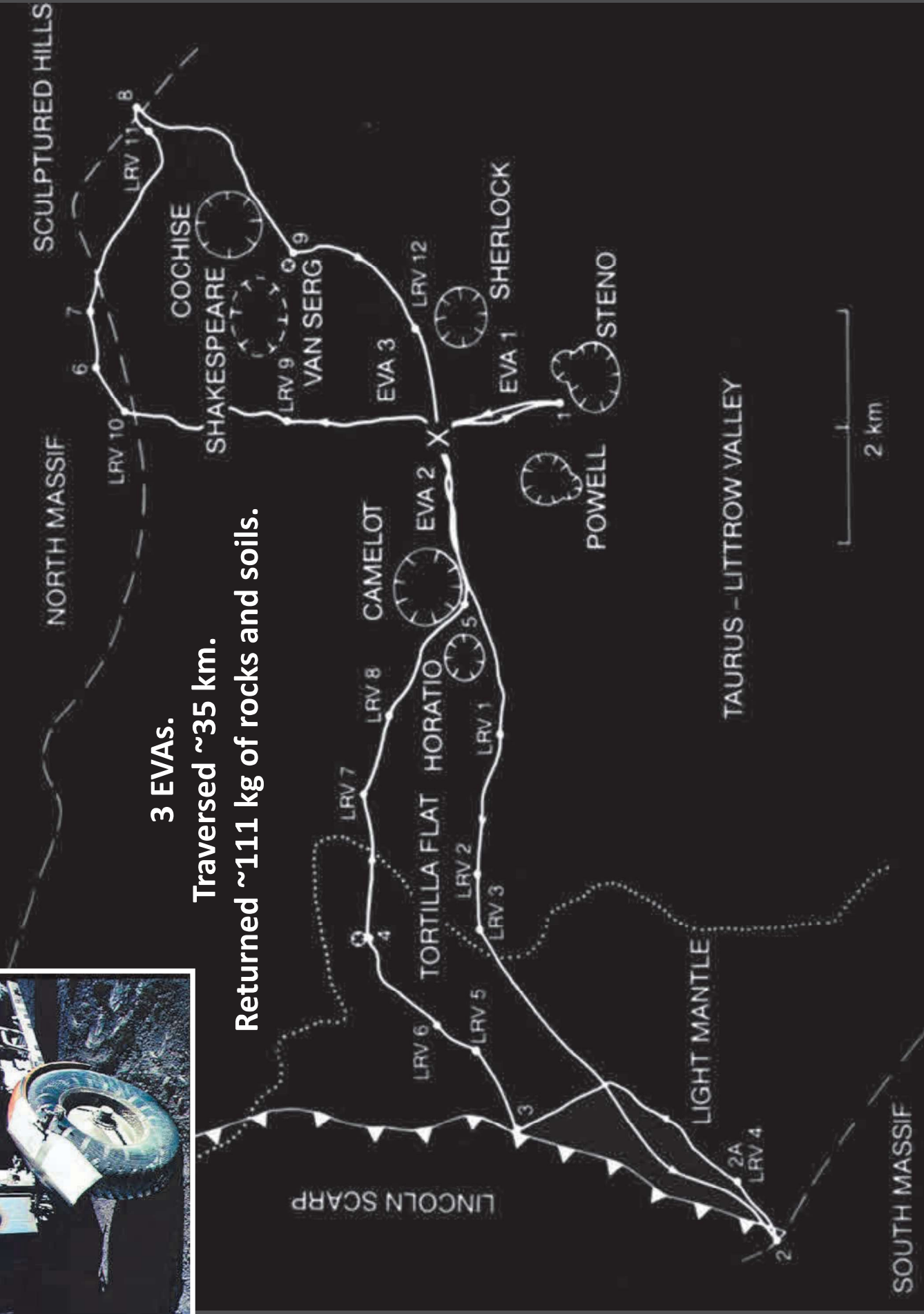


APOLLO 17

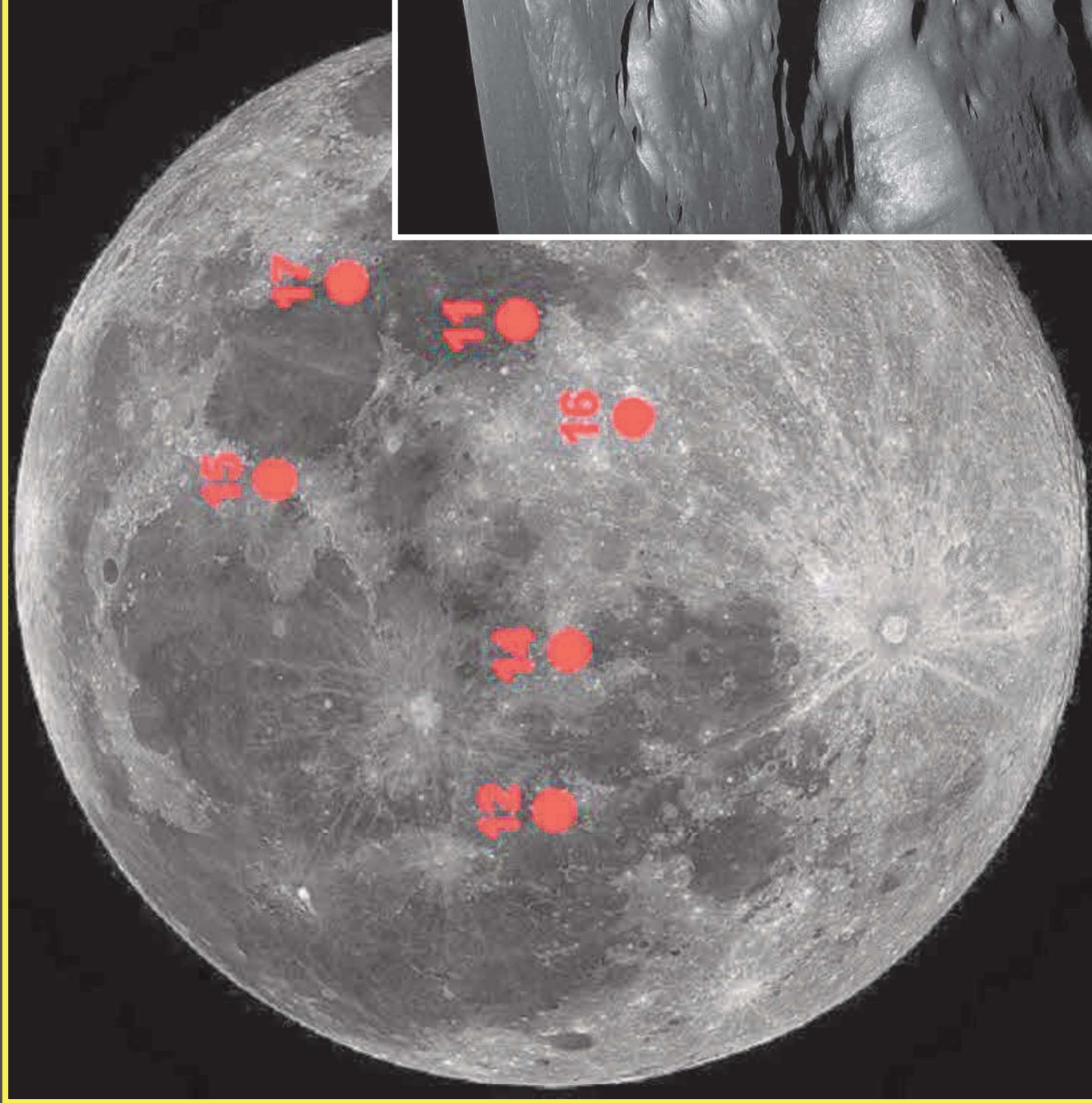
3 EVAs.

Traversed ~35 km.

Returned ~111 kg of rocks and soils.



Apollo 17: SE Edge of Serenitatis Impact Basin

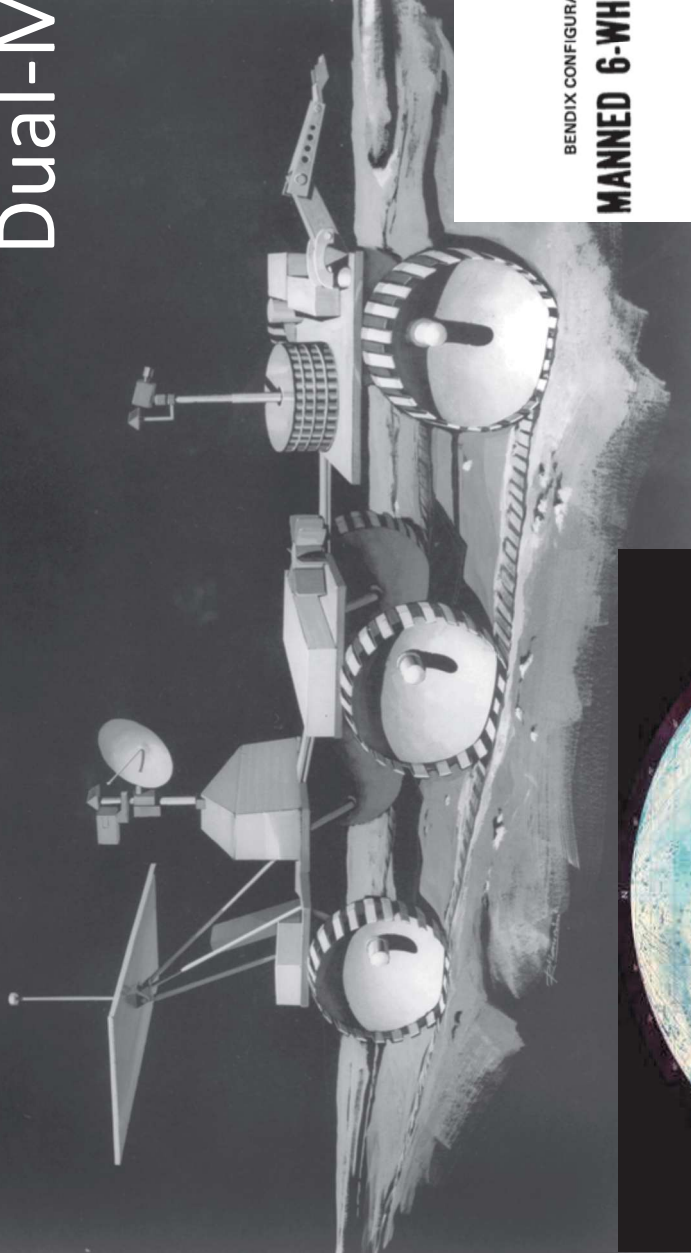


Science and Engineering Goals to Enhance Science Exploration Return

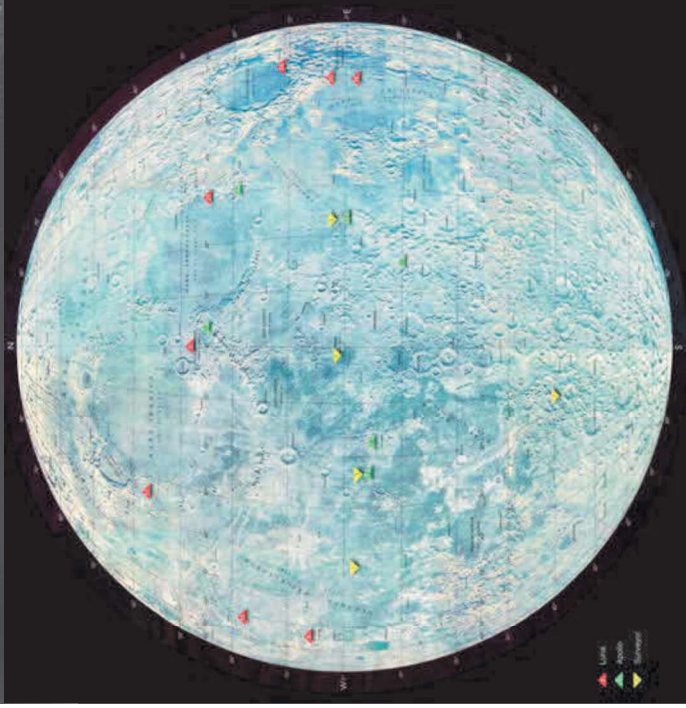
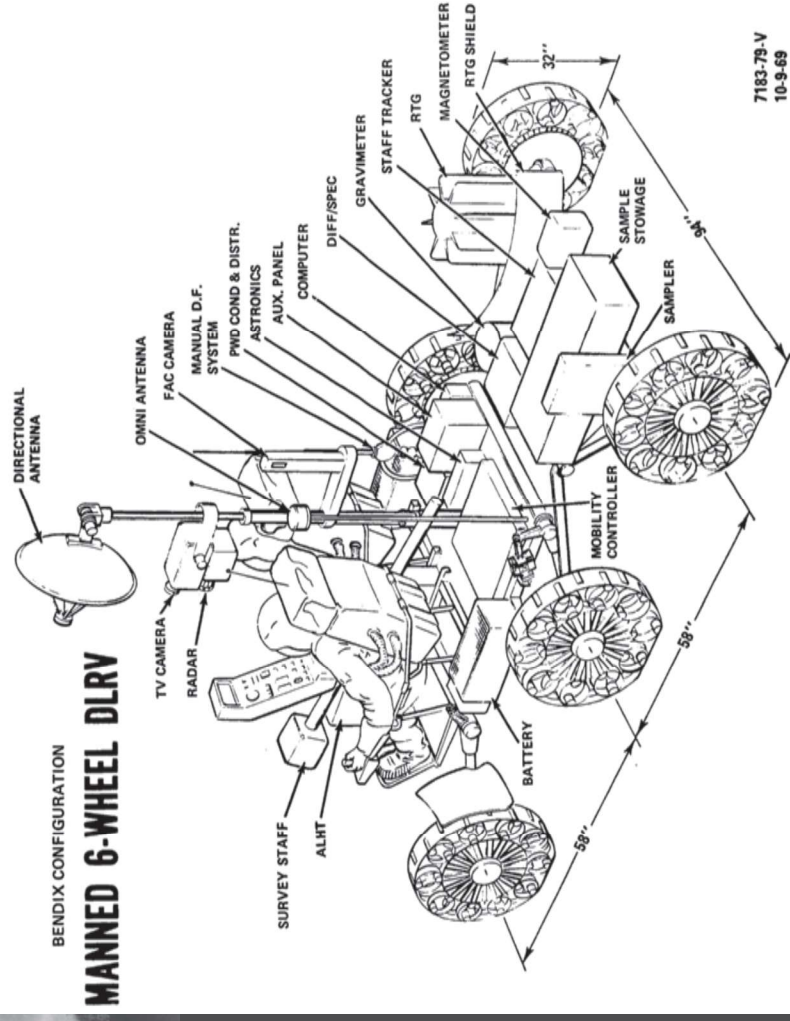
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- **Send Lunar Roving Vehicle to next landing site (DM).**

DUAL MODE ROVING VEHICLE

Grumman version - Unmanned configuration



Apollo 19-21 Dual-Mode Roving Vehicle



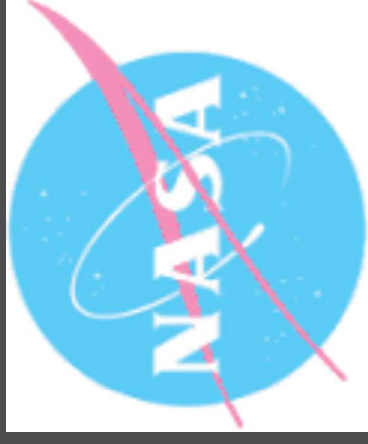
Science and Engineering Goals to Enhance Science Exploration Return

- Land safely, deploy experiments, collect rocks/soils. 11
- Increase stay-time on the lunar surface. 12
- Increase number of EVA periods to two. 12
- Demonstrate pinpoint landing to increase access. 12
- Provide equipment for transport of tools/samples. 14
- Enable orbital plane change to access high latitude. 15
- Increase number of EVA periods to three. 15
- Provide mobility to reach distant targets. 15
- Send a geologist as a member of the surface crew. 17
- Send Lunar Roving Vehicle to next landing site. 19-20.



Apollo Launch Dates

- Astronaut Missions -



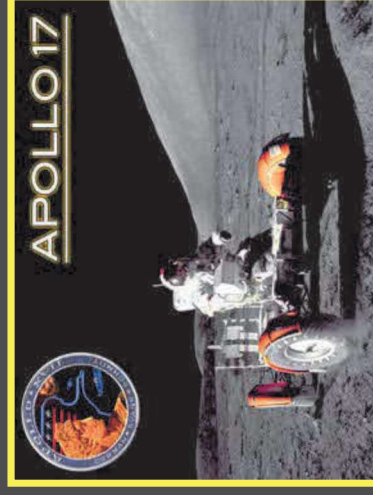
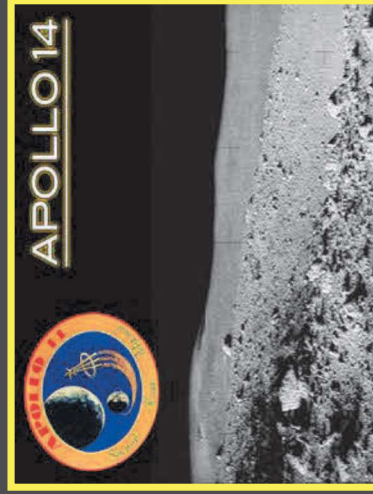
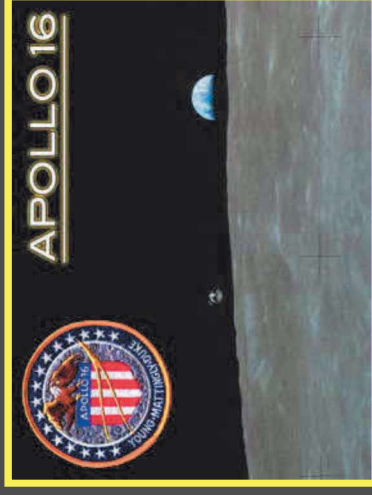
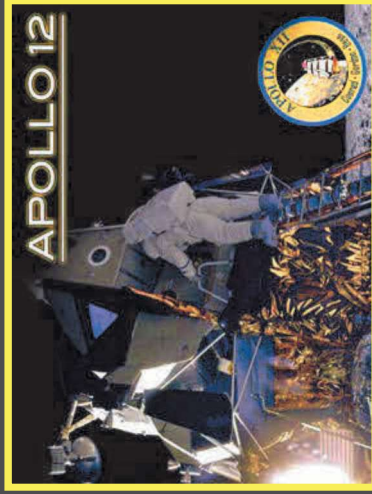
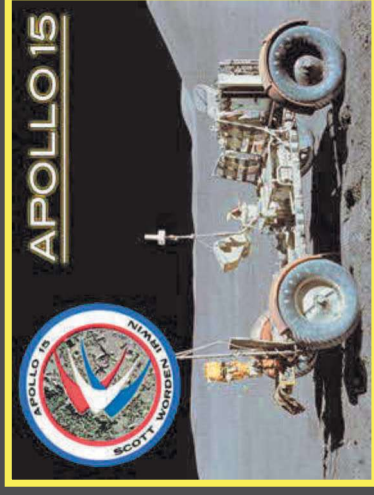
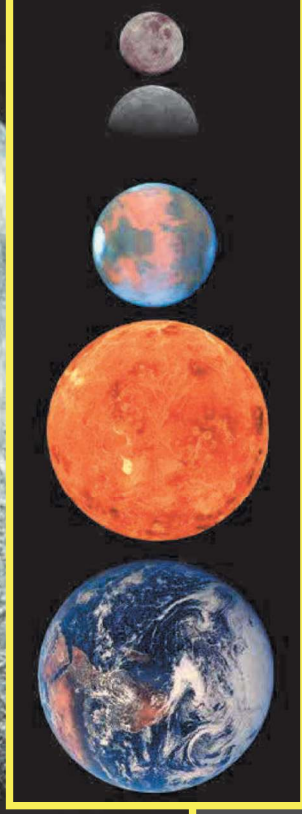
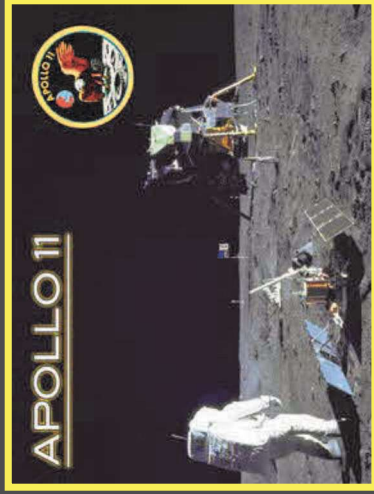
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**Six successful
human exploration
missions in
3 years, 5 months.**

**-
Three Major
Scientific
Expeditions!**



What is the Legacy of Lunar Exploration?



Cornerstone for Understanding Planets!



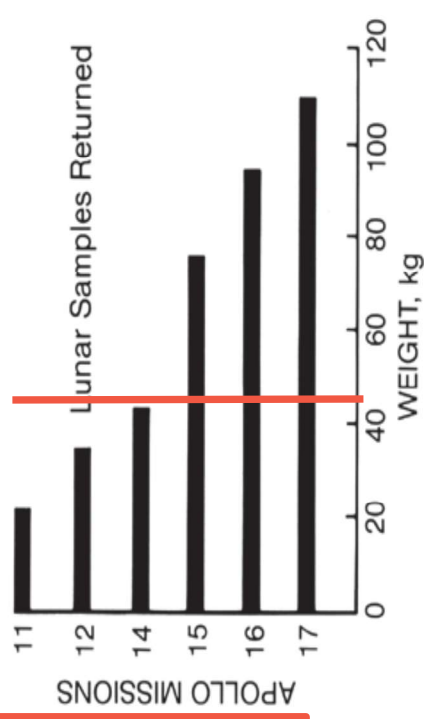
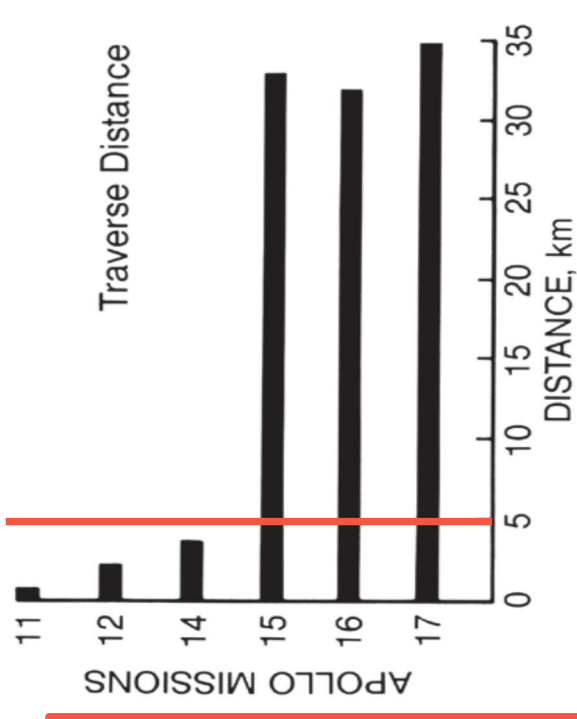
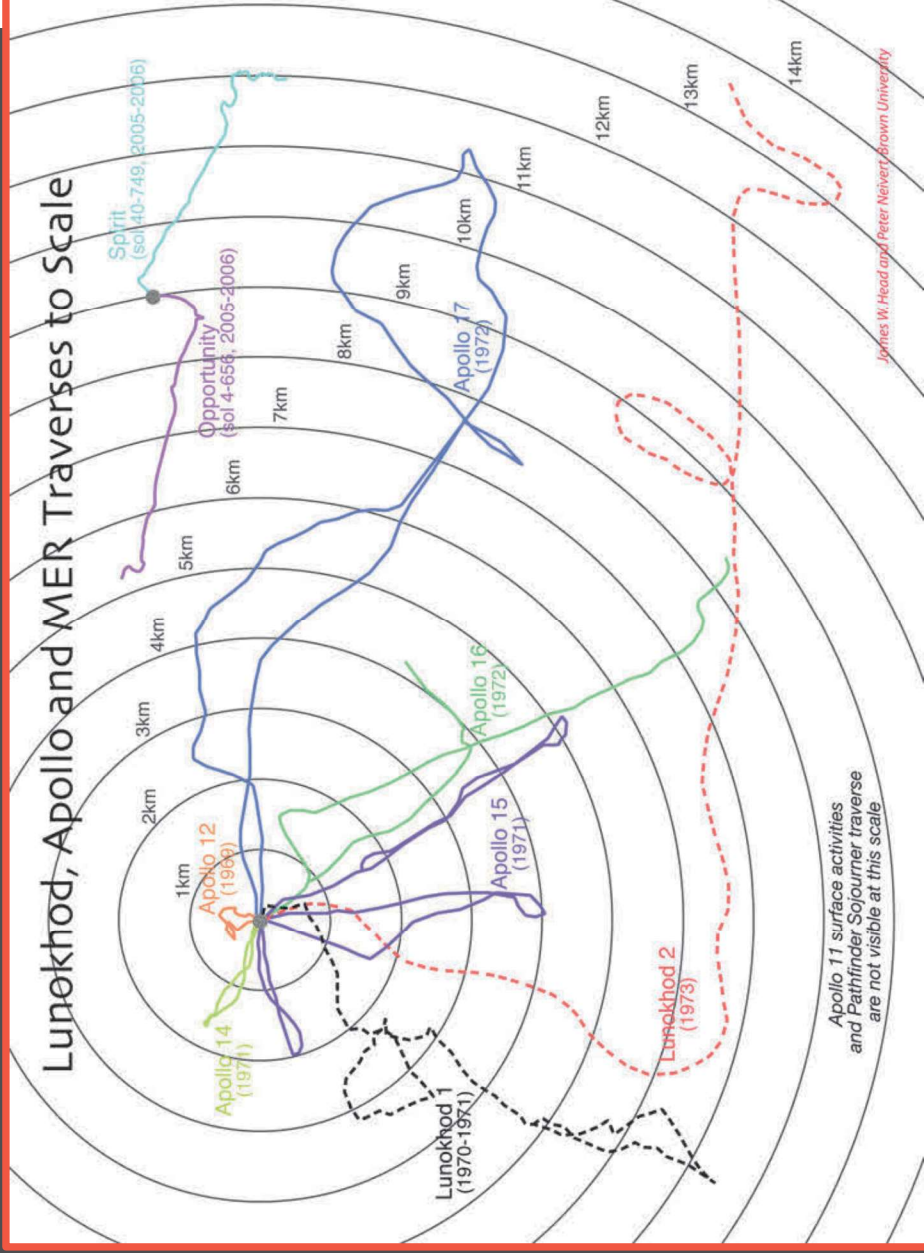
What Are the Lessons For Artemis?



- Science and Engineering Synergism.
- The Importance of Flexibility in Site Selection.
- Training of Lunar and Mars Astronauts (T³).
- The Critical Importance of Surface Mobility.
- Human and Robotic Exploration: A Partnership.
- Sorties to Bases: How to Optimize the Science.
- "History doesn't repeat itself, but it rhymes".
- The Tyranny of Traceability Matrices.



Apollo Lunar Exploration Program: Evolution of Exploration Scientific Return



**Apollo 11-17:
Traverses and Sample Return Mass**



What Are the Lessons For Artemis?



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Renaissance in Lunar Exploration – Context and Role in Planetary Exploration

- Renaissance: 2003-2025:

Rebirth of lunar science!

—  ESA: Smart-1

—  China: Chang'e 1, 2, 3

—  Japan: Kaguya

—  India: Chandrayaan-1

—  United States: Lunar

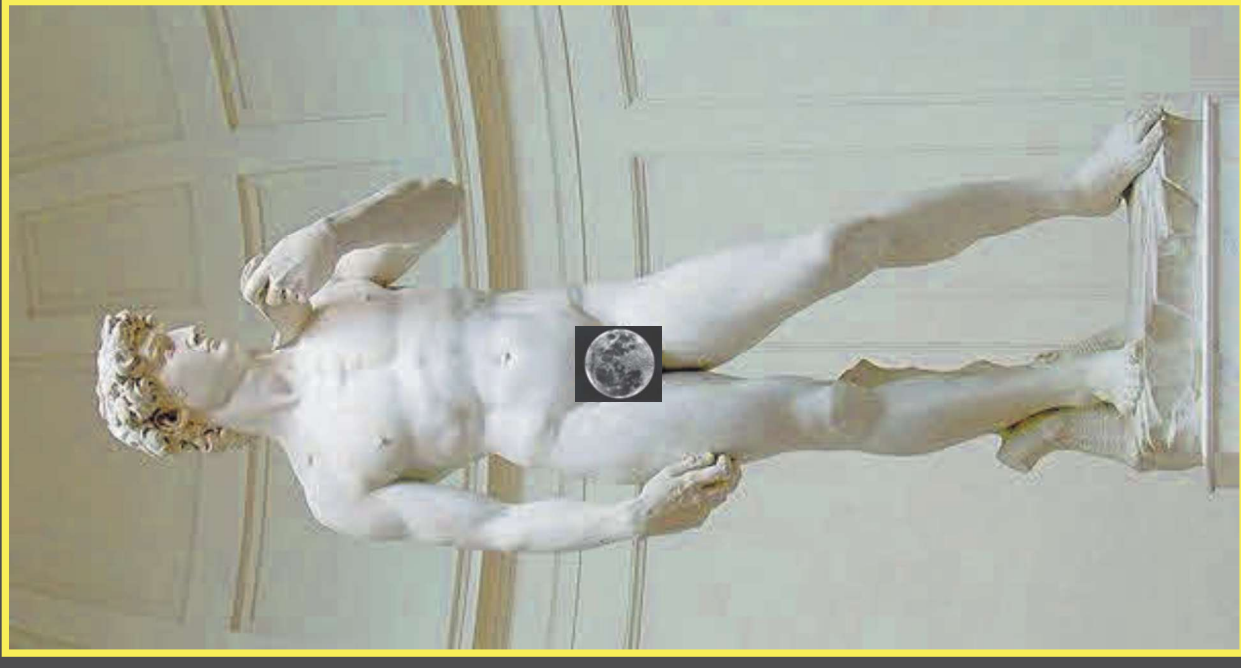
Reconnaissance Orbiter, L-Cross, GRAIL, LADEE.

—  Russia: Lunar Glob, Resource

—  X-Prize

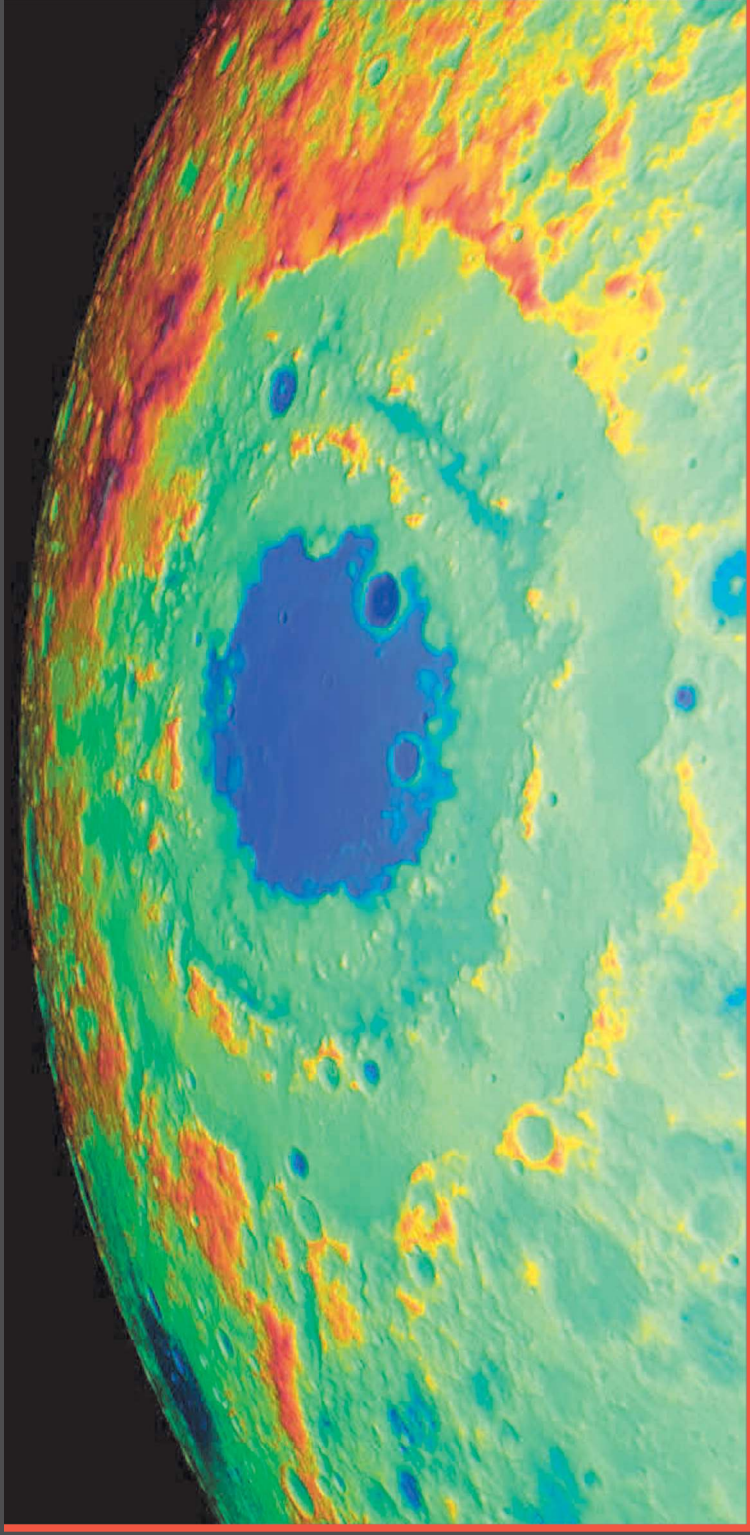
- “Everything has changed
but our way of thinking.”

A. Einstein.



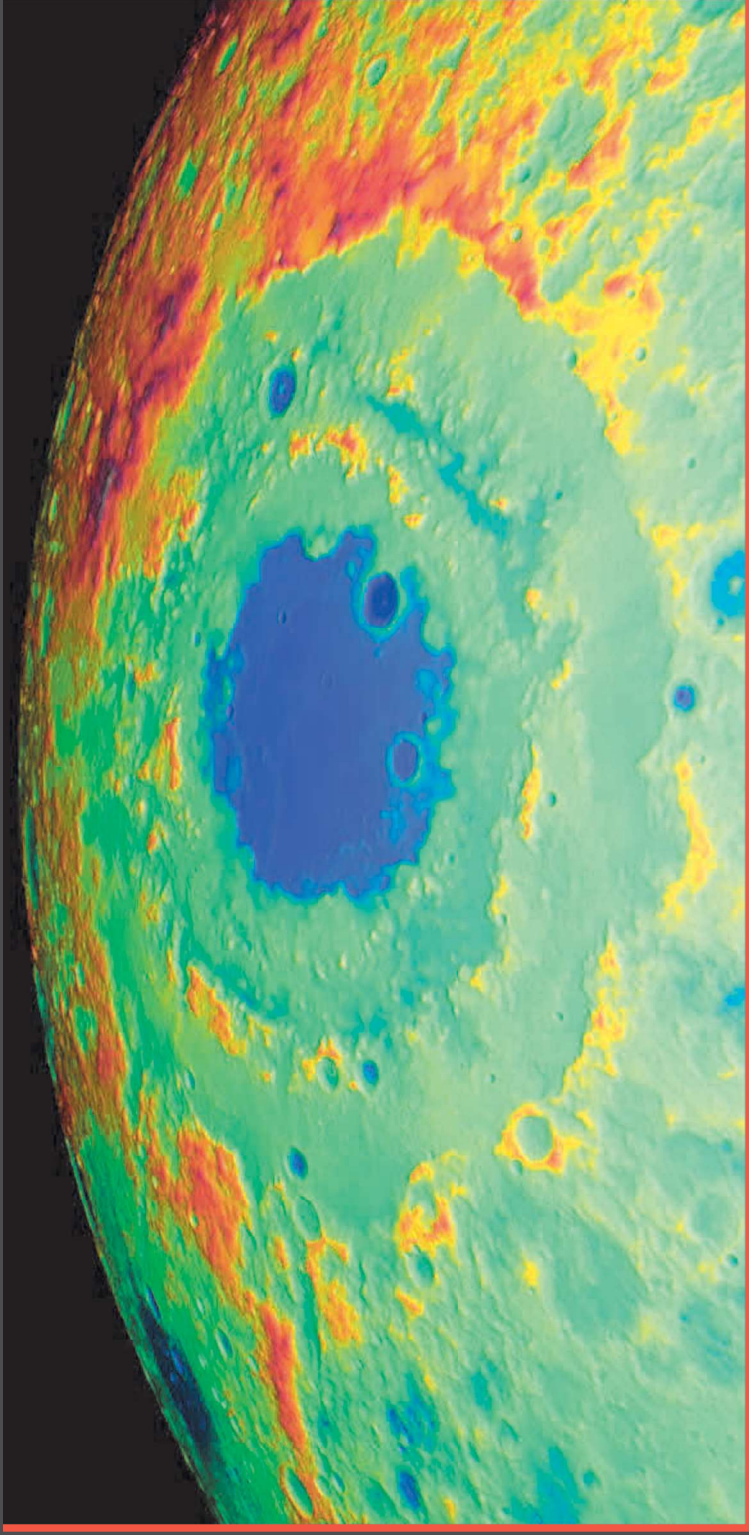
(Modified without permission from Michelangelo, 1504)

Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin



1. The importance of coordinated human/robotic exploration.
2. Why the Orientale multi-ring basin?
3. Human/Robotic Scientific Destinations at Orientale.
4. The Human/Robotic Architecture: A Basis for Design Reference Missions.

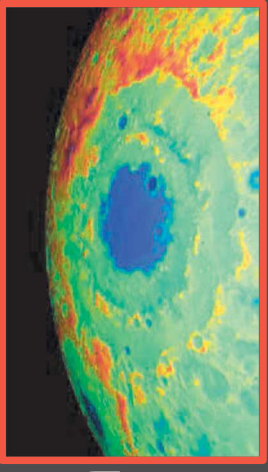
Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin



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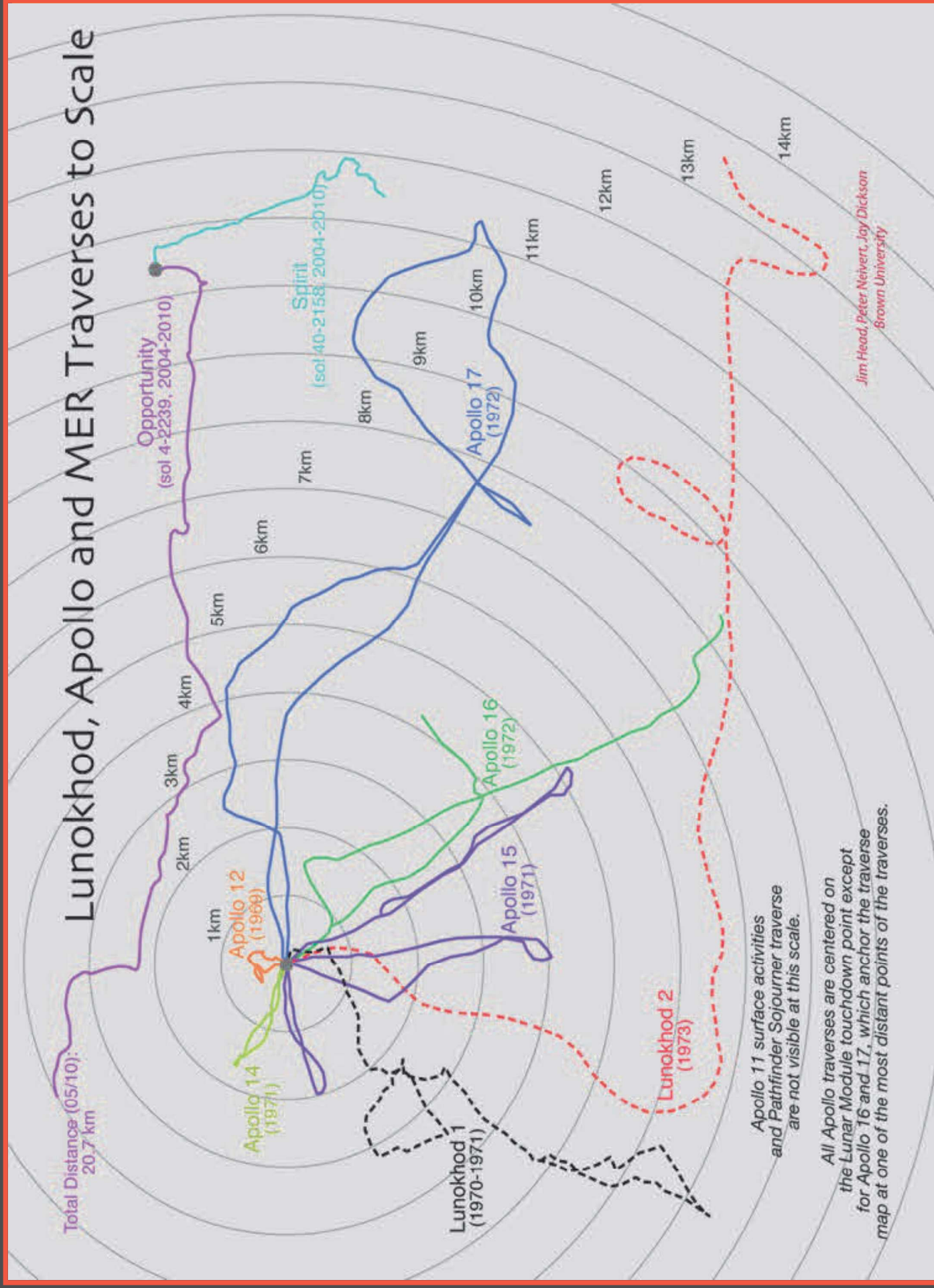
Human/Robotic Exploration Optimization

Centers on Six Themes



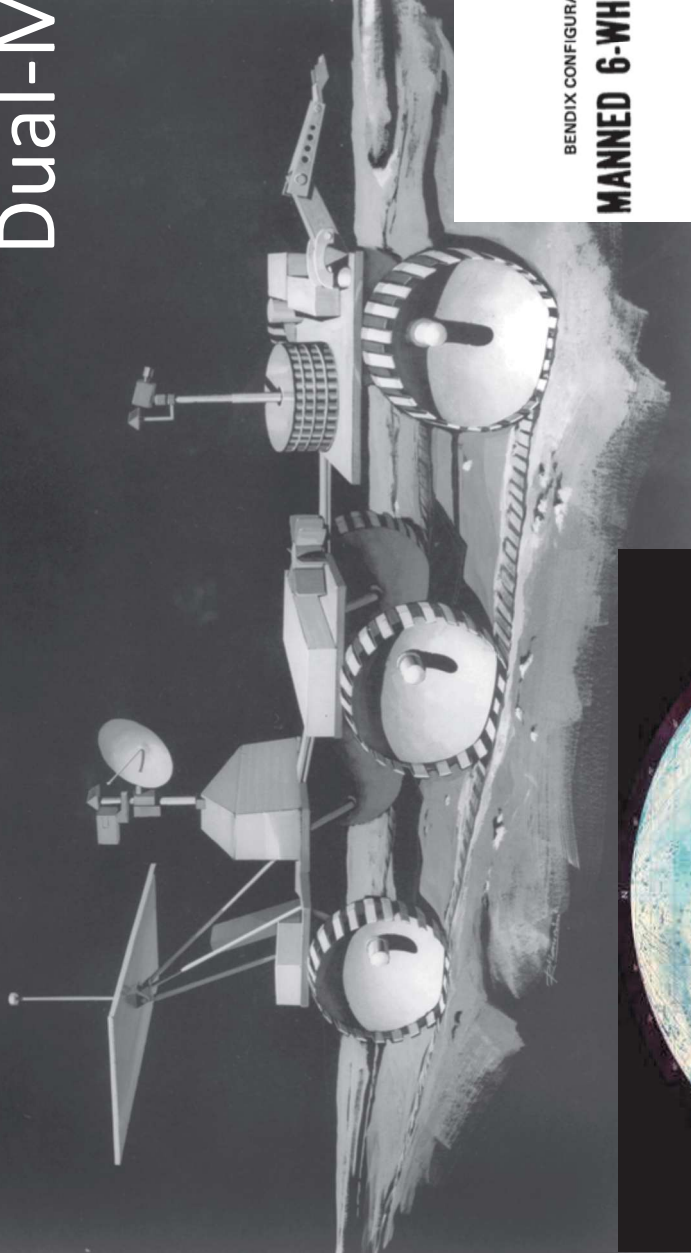
- I) Precursor (What do we need to know before we send humans?).
- II) Context (What are the robotic mission requirements for final landing site selection and regional context for landing site results?).
- III) Infrastructure/Operations (What specific robotic capabilities are required to optimize human scientific exploration performance?).
- IV) Interpolation (How do we use robotic missions to interpolate between human traverses?).
- V) Extrapolation (How do we use robotic missions to extrapolate beyond the human exploration radius?).
- VI) Progeny (What targeted robotic successor missions might be sent to the region to follow up on discoveries during exploration and from post-campaign analysis?).

What is the Relationship of Human and Robotic Exploration?

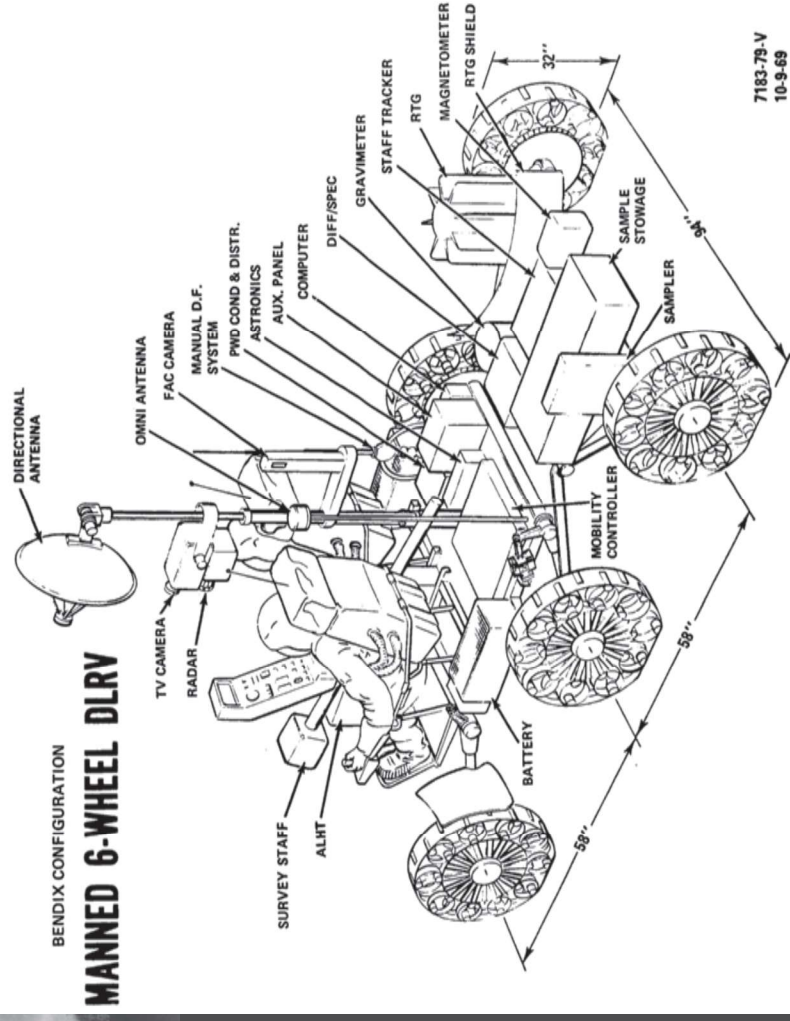


DUAL MODE ROVING VEHICLE

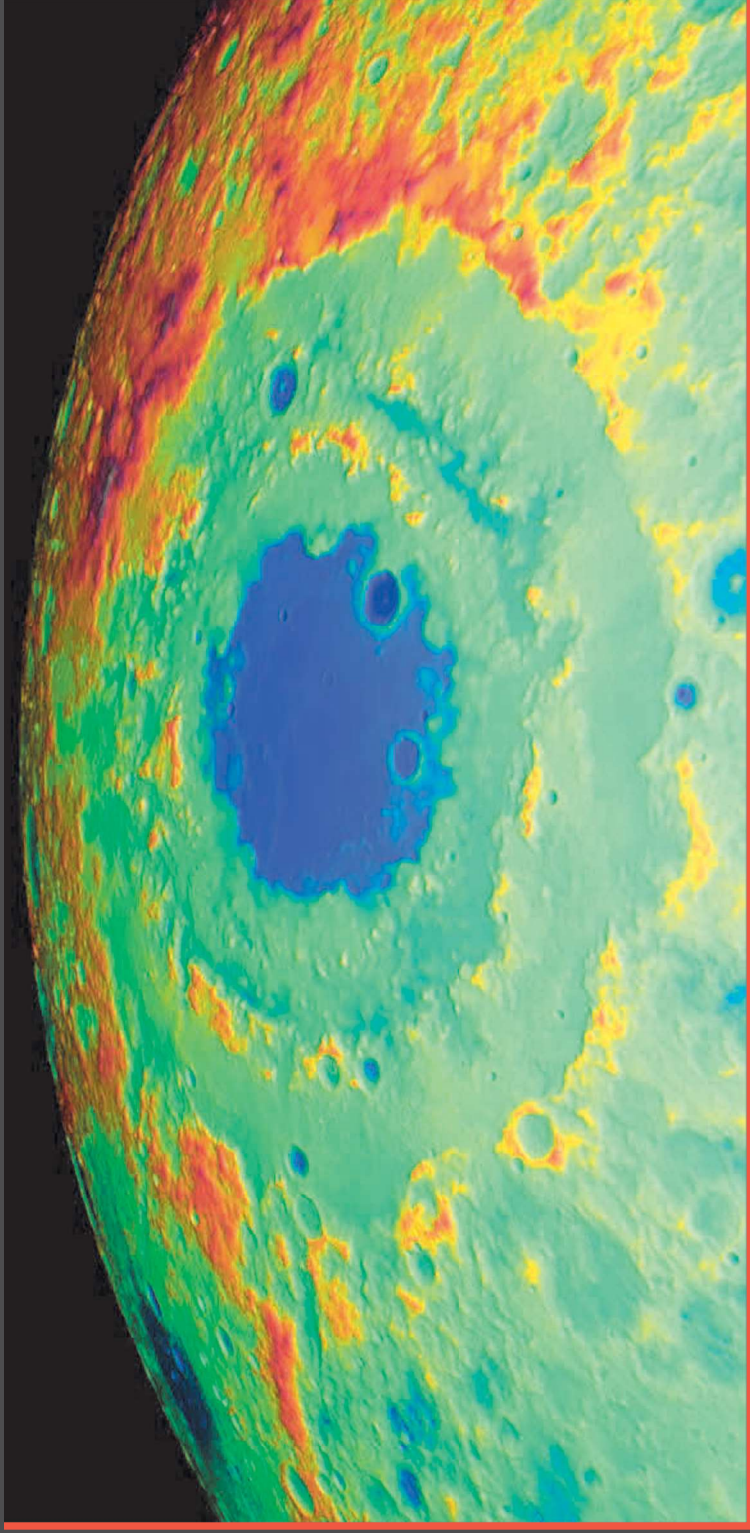
Grumman version - Unmanned configuration



Apollo 19-21 Dual-Mode Roving Vehicle

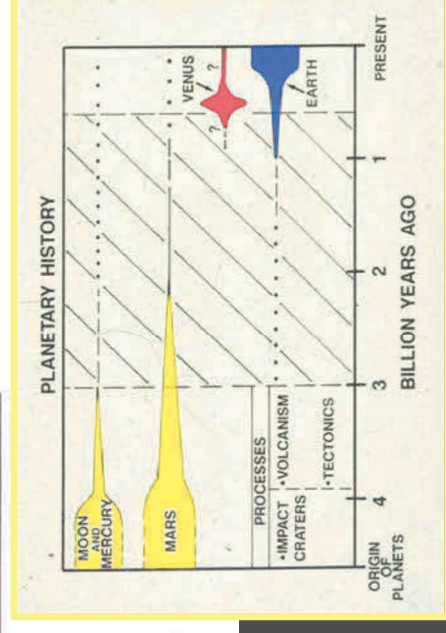
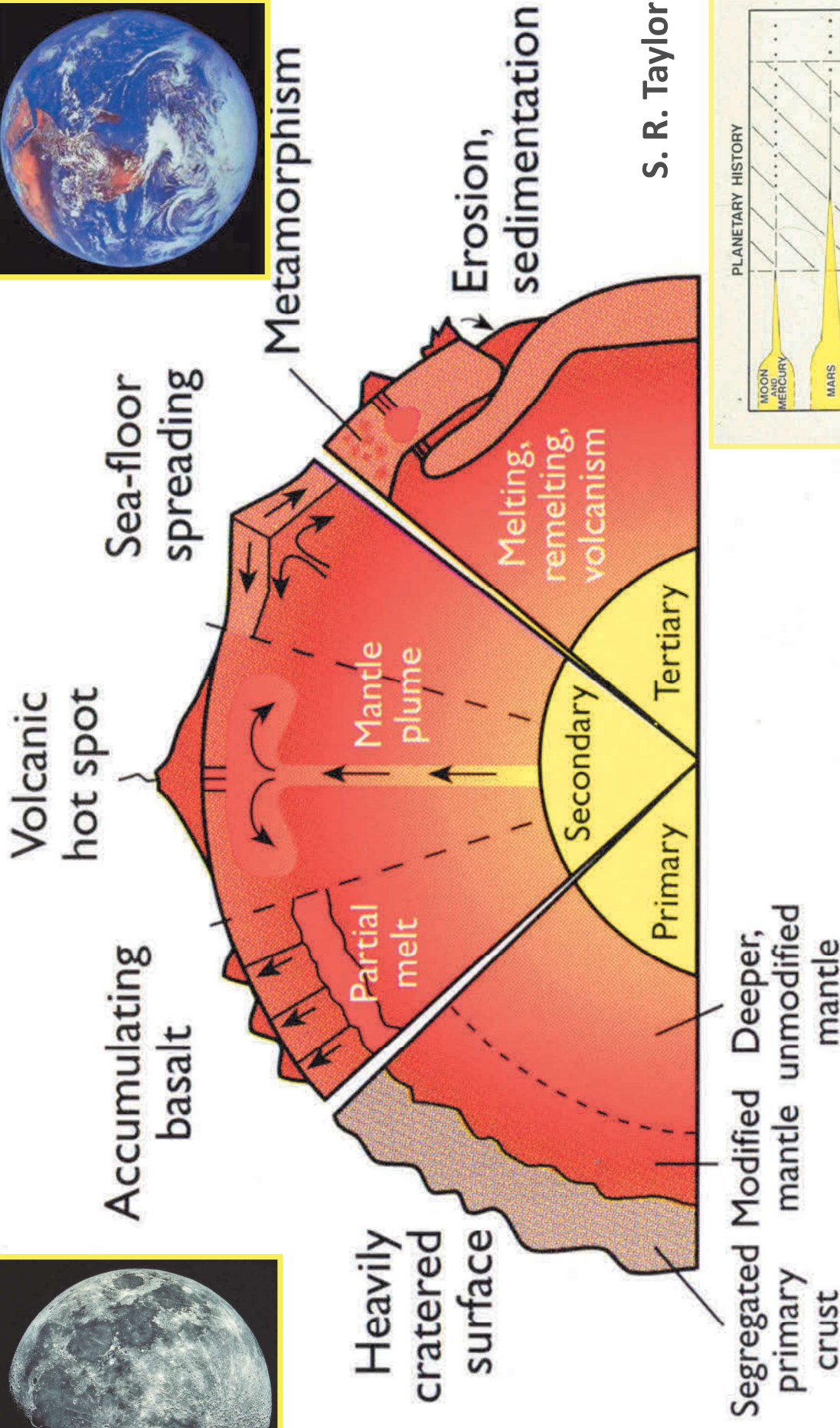


Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin

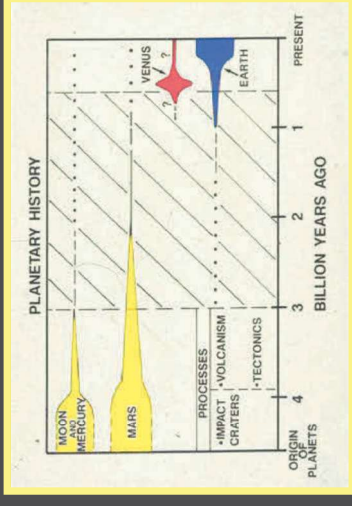
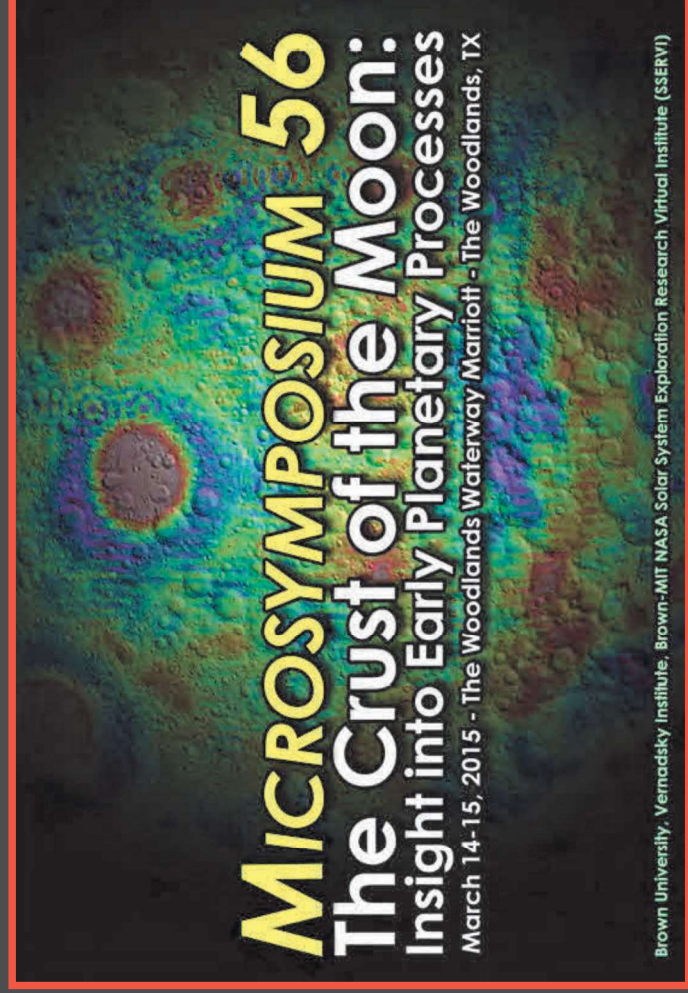


1. The importance of coordinated human/robotic exploration.
2. Why the Orientale multi-ring basin?
3. Human/Robotic Scientific Destinations at Orientale.
4. The Human/Robotic Architecture: A Basis for Design Reference Missions.

Formation and Evolution of Planetary Crusts

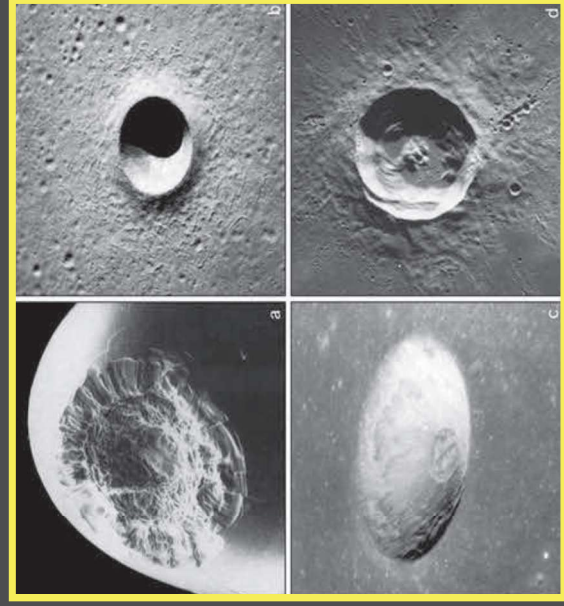


The Moon is a Laboratory for the Study of Primary and Secondary Crusts in Early Planetary History.

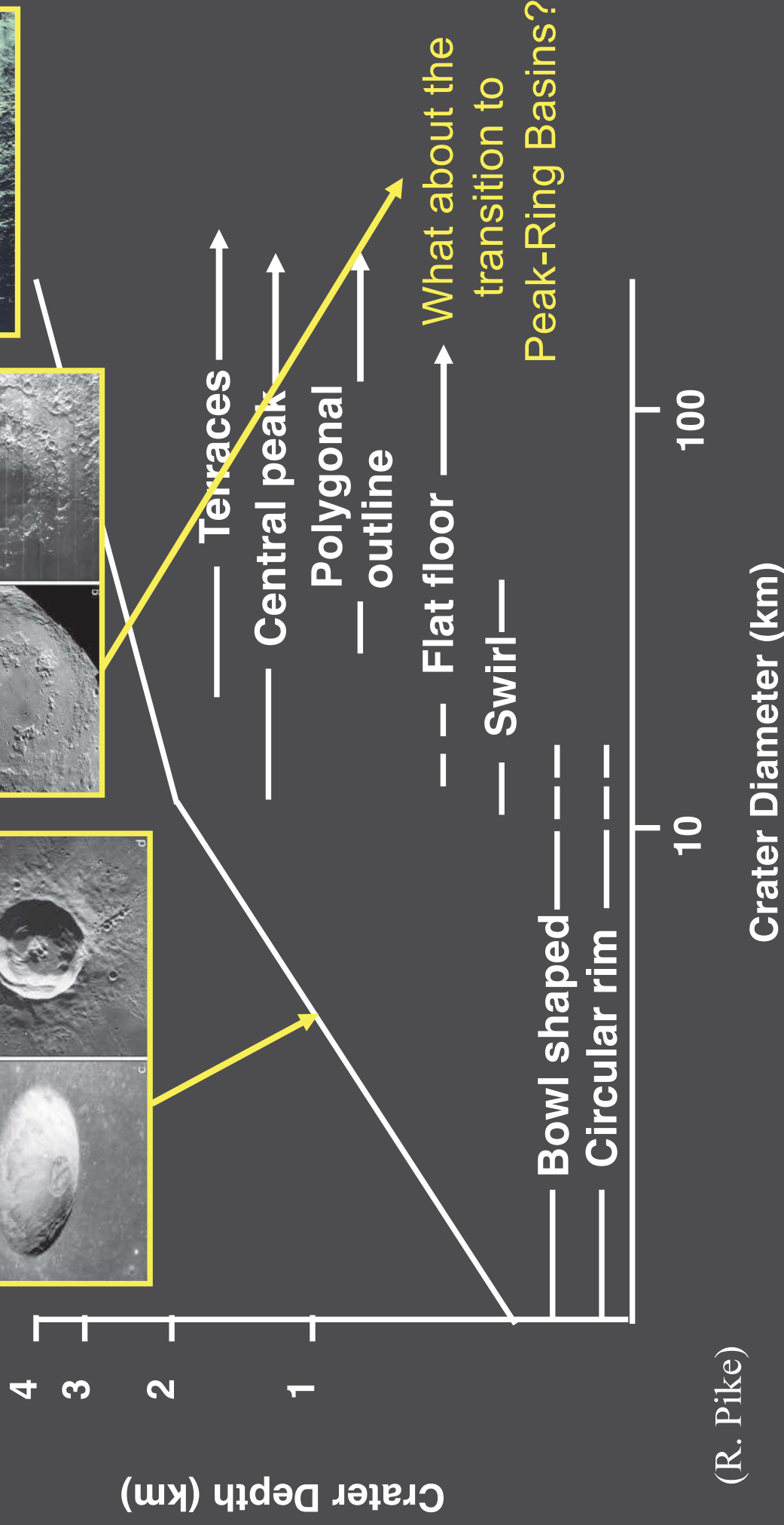
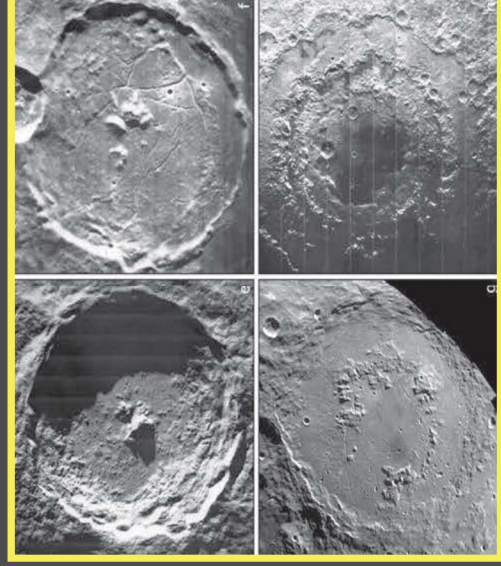


- 1. Crustal geometry/physical structure
- 2. Crustal chemistry/mineralogy/petrology;
- 3. Exogenic crustal modification by impacts;
- 4. Chronology: Crustal formation/evolution.

1. Major Lunar Features: Multi-ring basins:



Fresh Crater
Characteristics

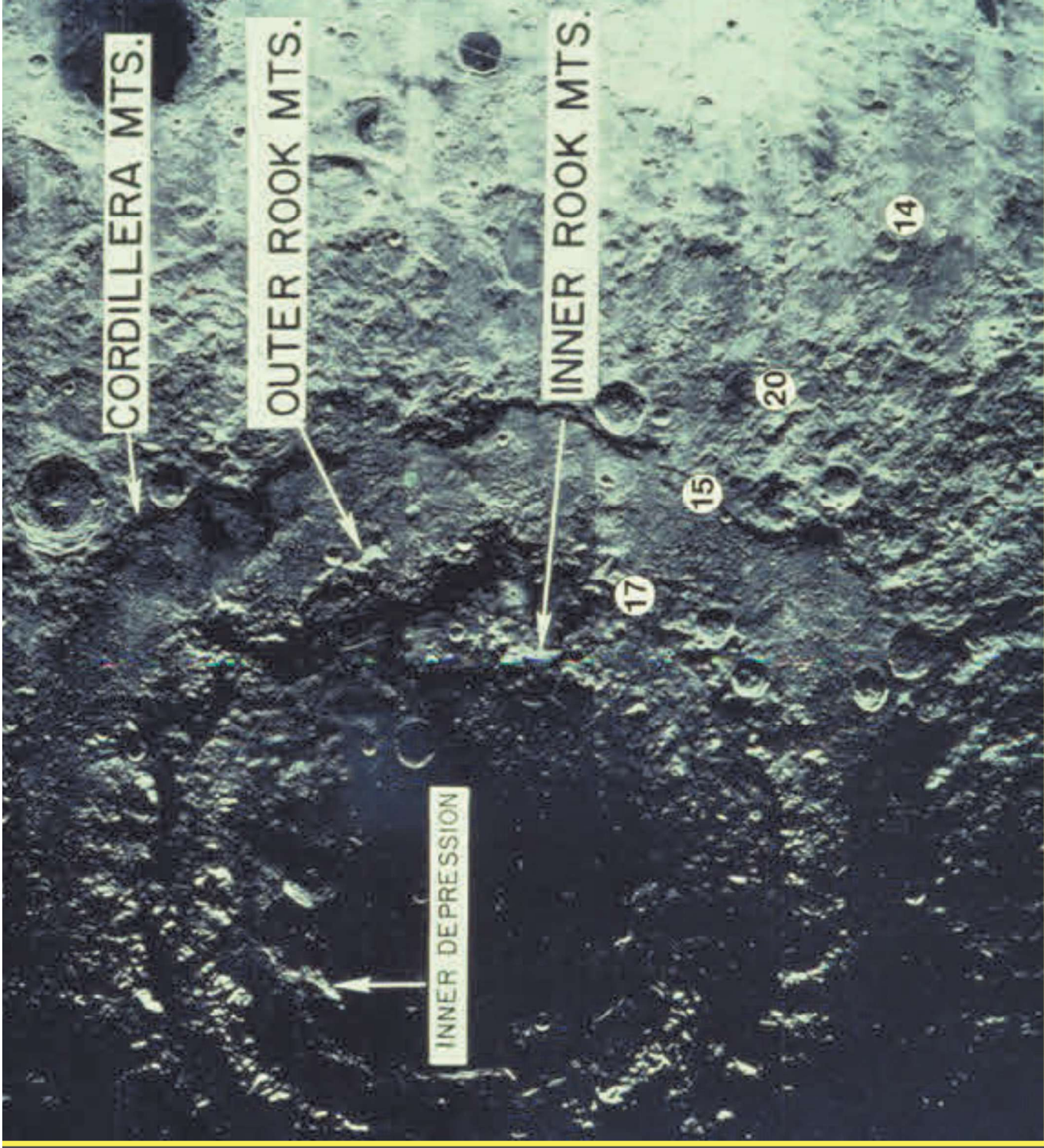


Lunar Orientale Impact Basin:

2. The Type Area for Lunar Basin Formation and Evolution.



Link to Existing Mission Sample Context



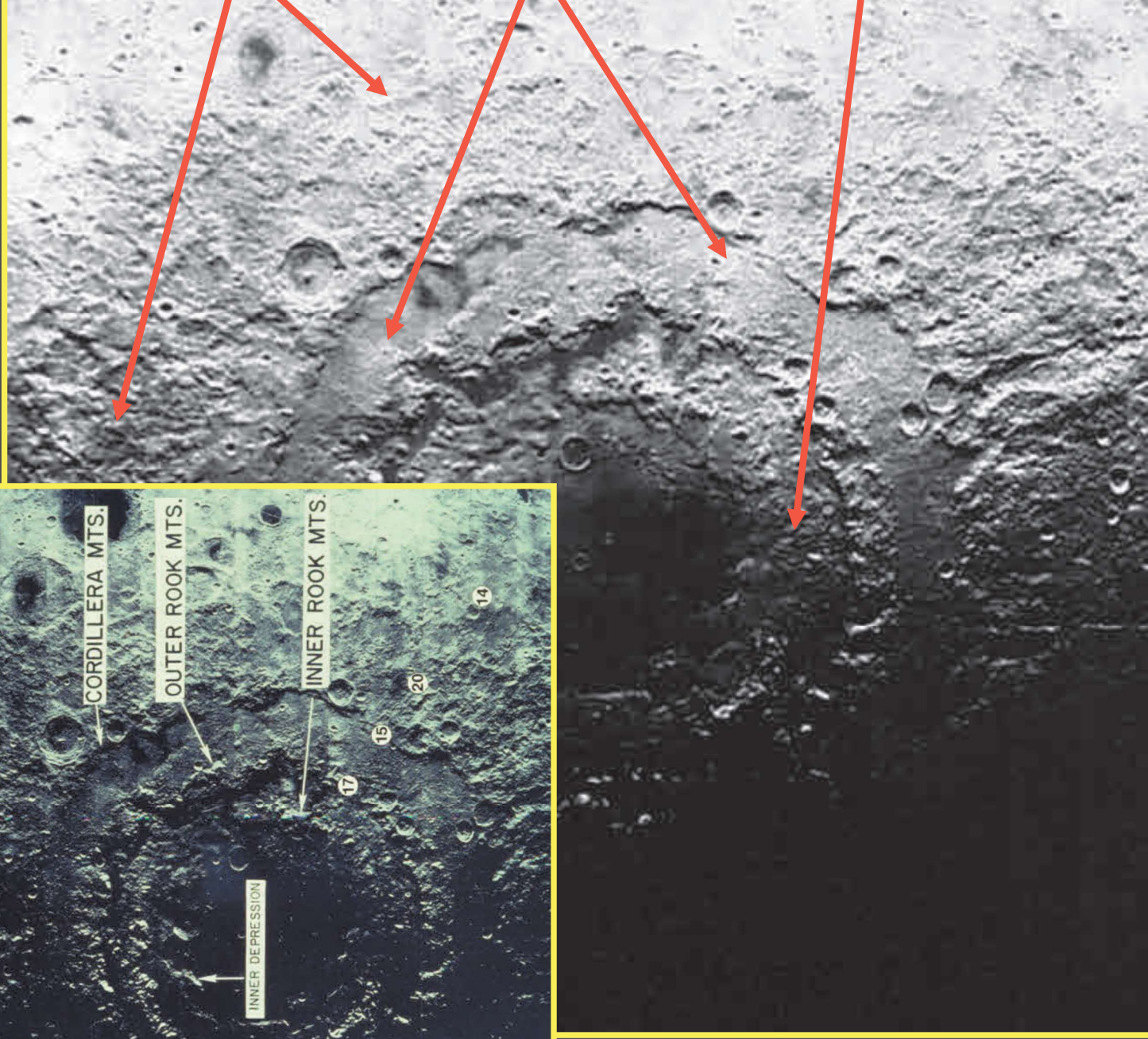
Oriente Basin: Rings & Geologic Units

**Hevelius Formation
(Basin Ejecta Deposit)**

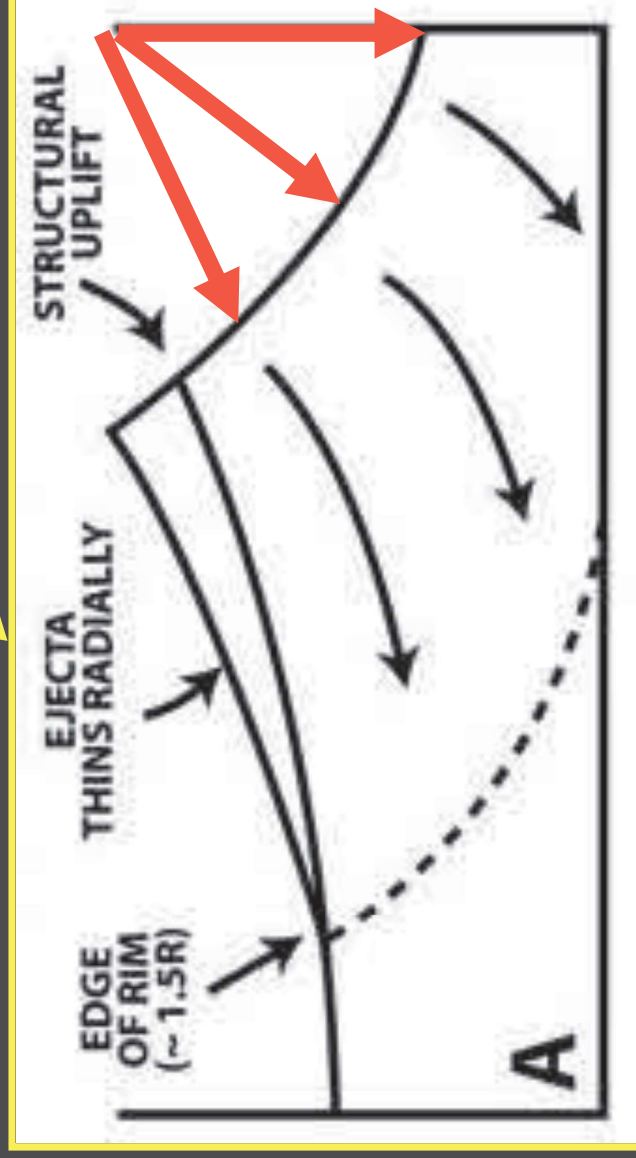
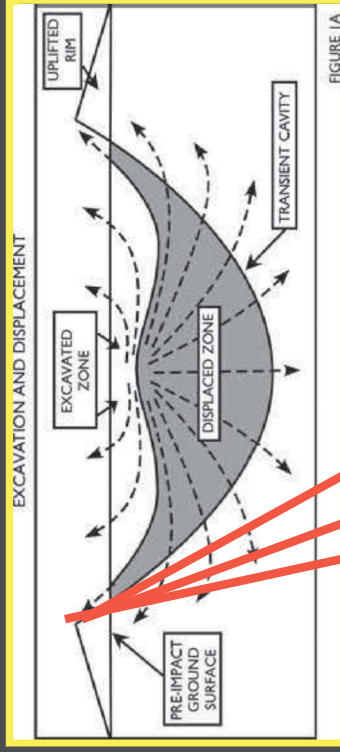
**Montes Rook Fm.
(Knobby, Domatic Deposit)**

**Maunder Formation
(Basin Impact Melt Deposit)**

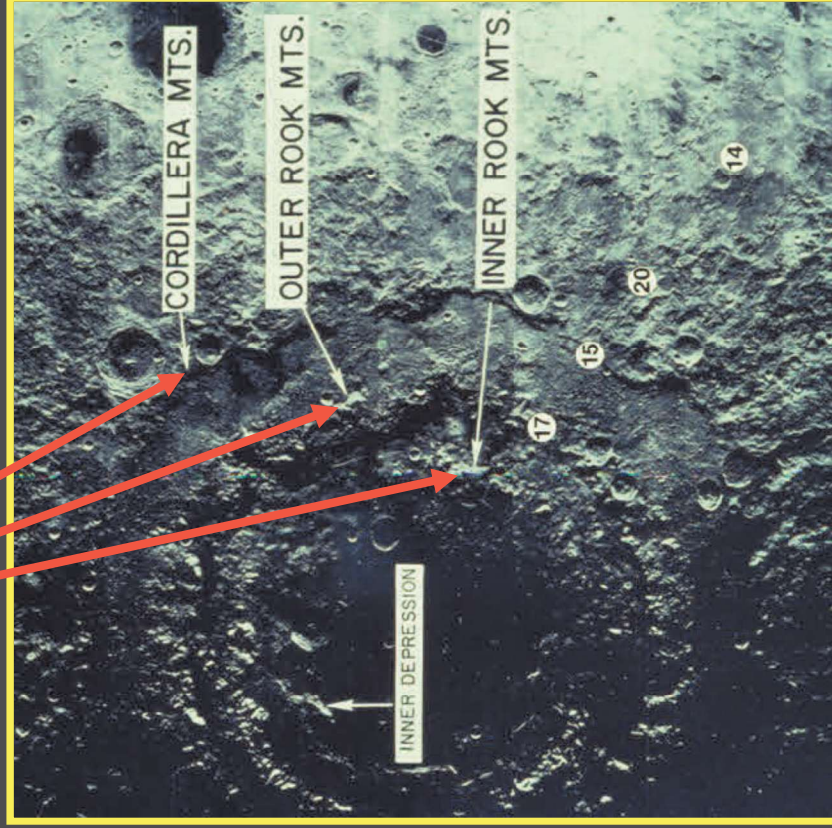
(J. McCauley, D. Wilhelms,
D. Scott, K. Howard, C. Hodges)



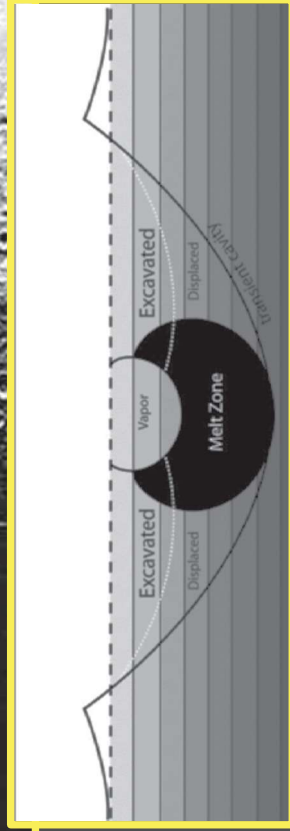
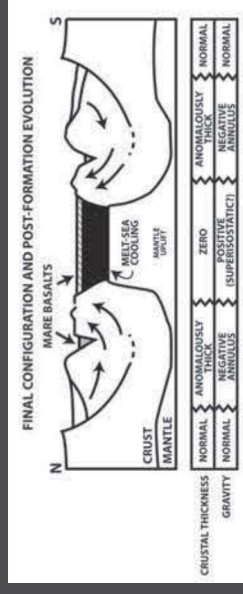
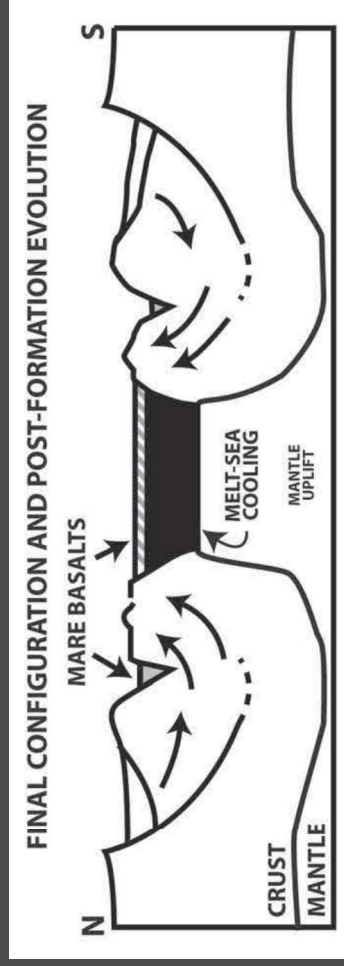
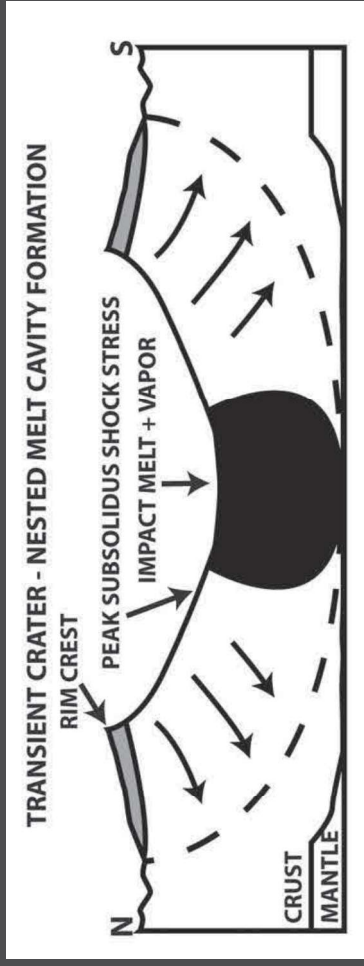
3. Initial Crater/Basin Formational Stage : Where is Transient Cavity Rim Crest?



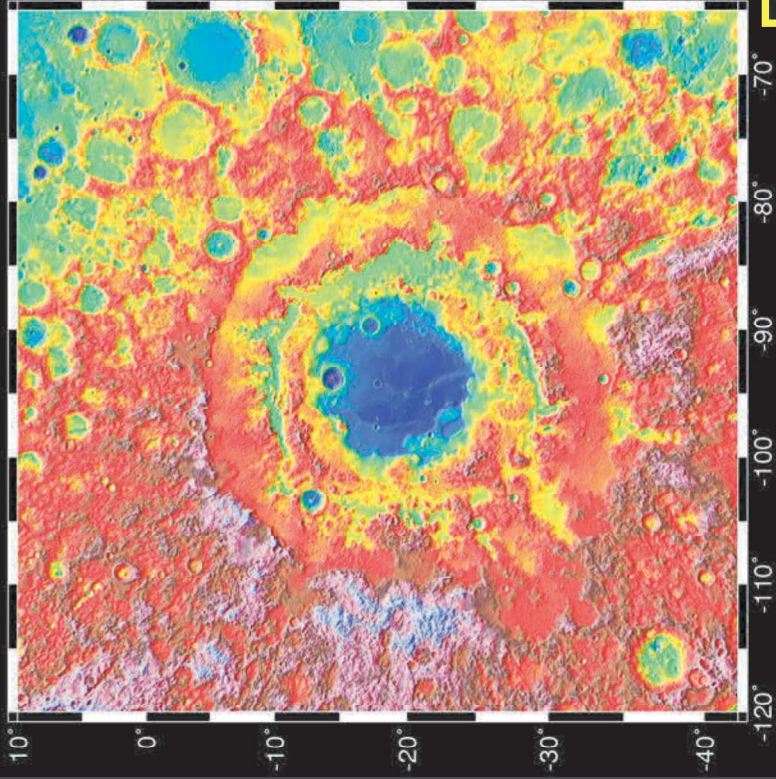
- Displaced and compressed material causes structural uplift of the crater/basin rim.
- Power law decay of ejecta thickness radially away from crater/basin rim crest.
- Combined topography decays to $<10\%$ of rim crest height within ~ 1.5 crater radius.



3. Orientale Basin Formation: Origin of Rings and Scale of Basin Structure

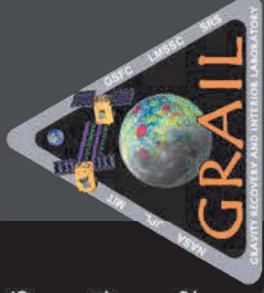


Topography

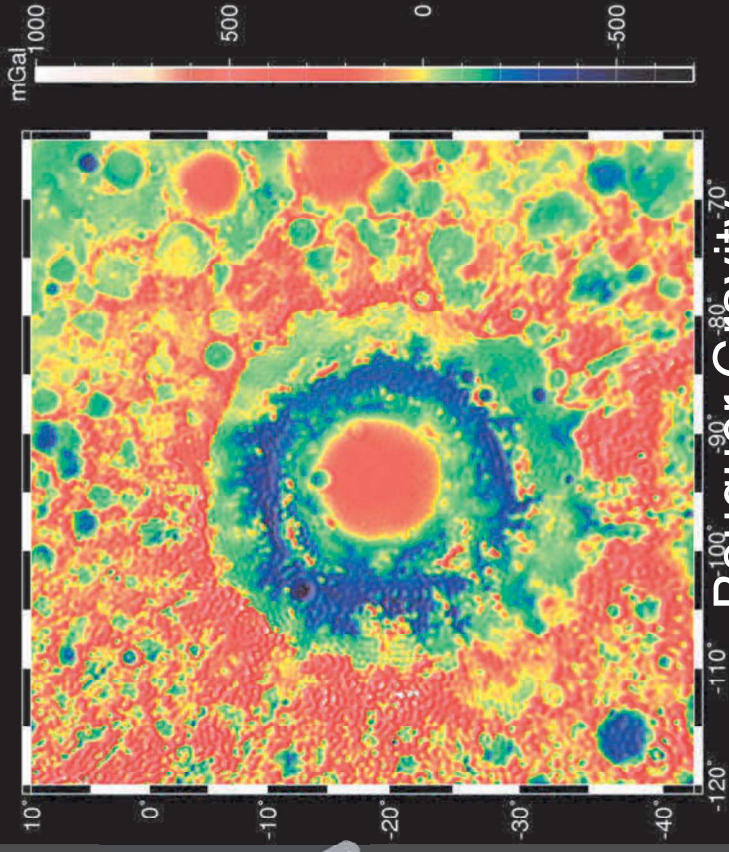


Orientale Basin

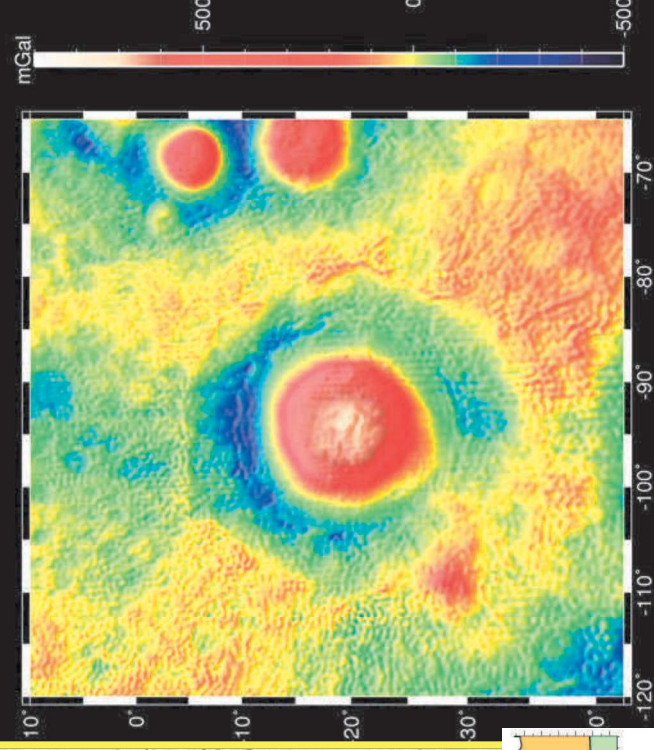
Basin



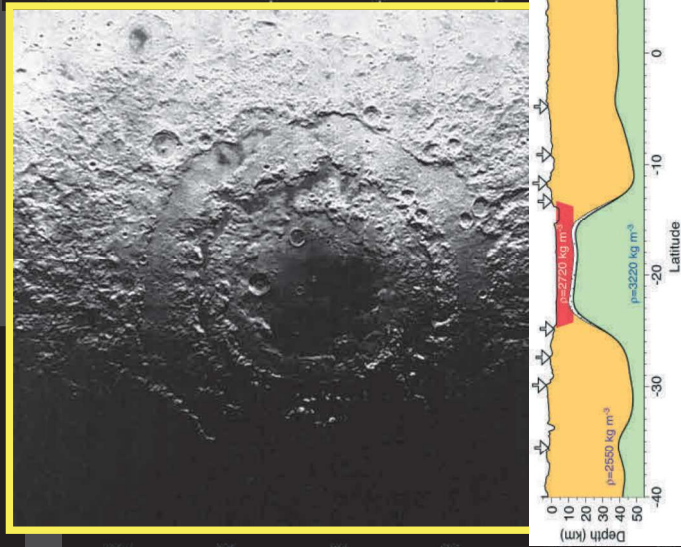
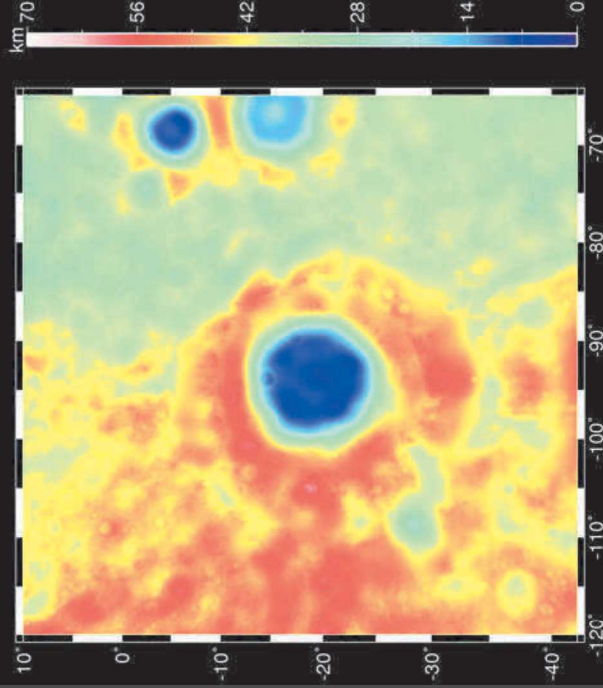
Free-air Gravity



Bouguer Gravity



Crustal Thickness



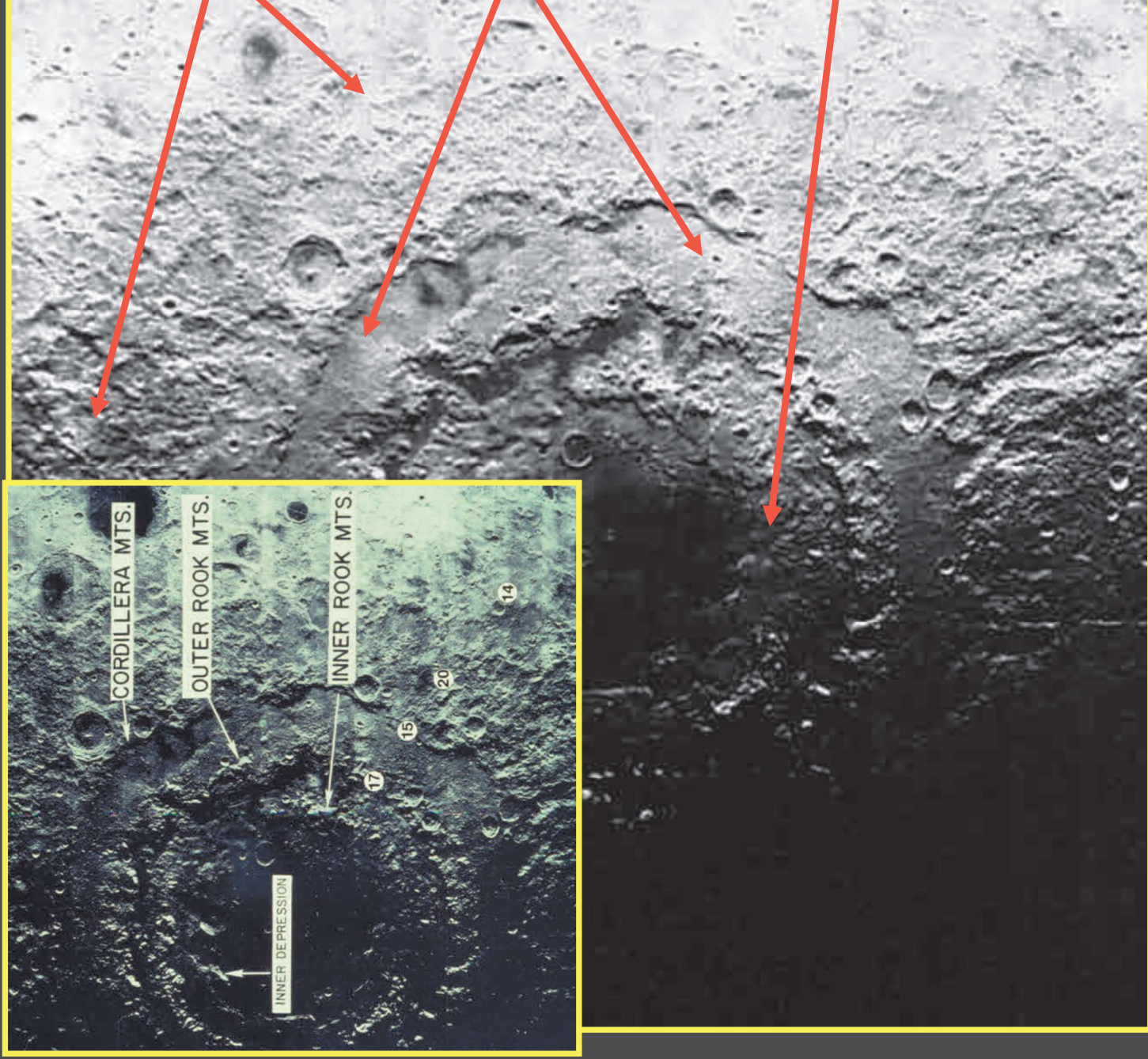
4. Orientale Basin Formation: Characteristics and Origin of Geological Units

**Orientale Basin:
Rings & Geologic Units**

**Hevelius Formation
(Basin Ejecta Deposit)**

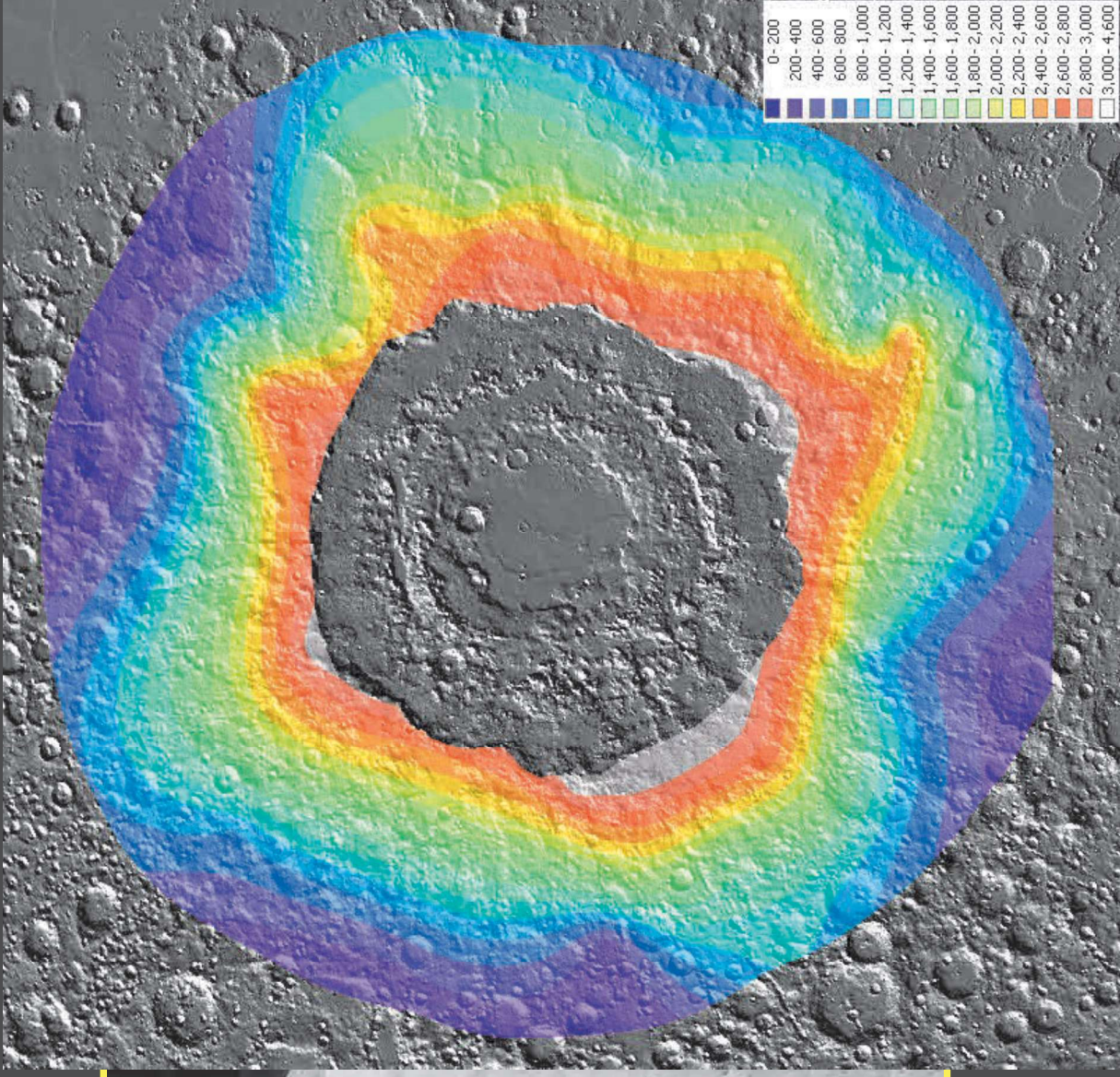
**Montes Rook Fm.
(Knobby, Domical Deposit)**

**Maunder Formation
(Basin Impact Melt Deposit)**



(J. McCauley, D. Wilhelms,
D. Scott, K. Howard, C. Hodges)

5. Composition of the Ejecta from the Orientale Basin: Crust and Mantle



(Fassett and Head, 2011, GRL)

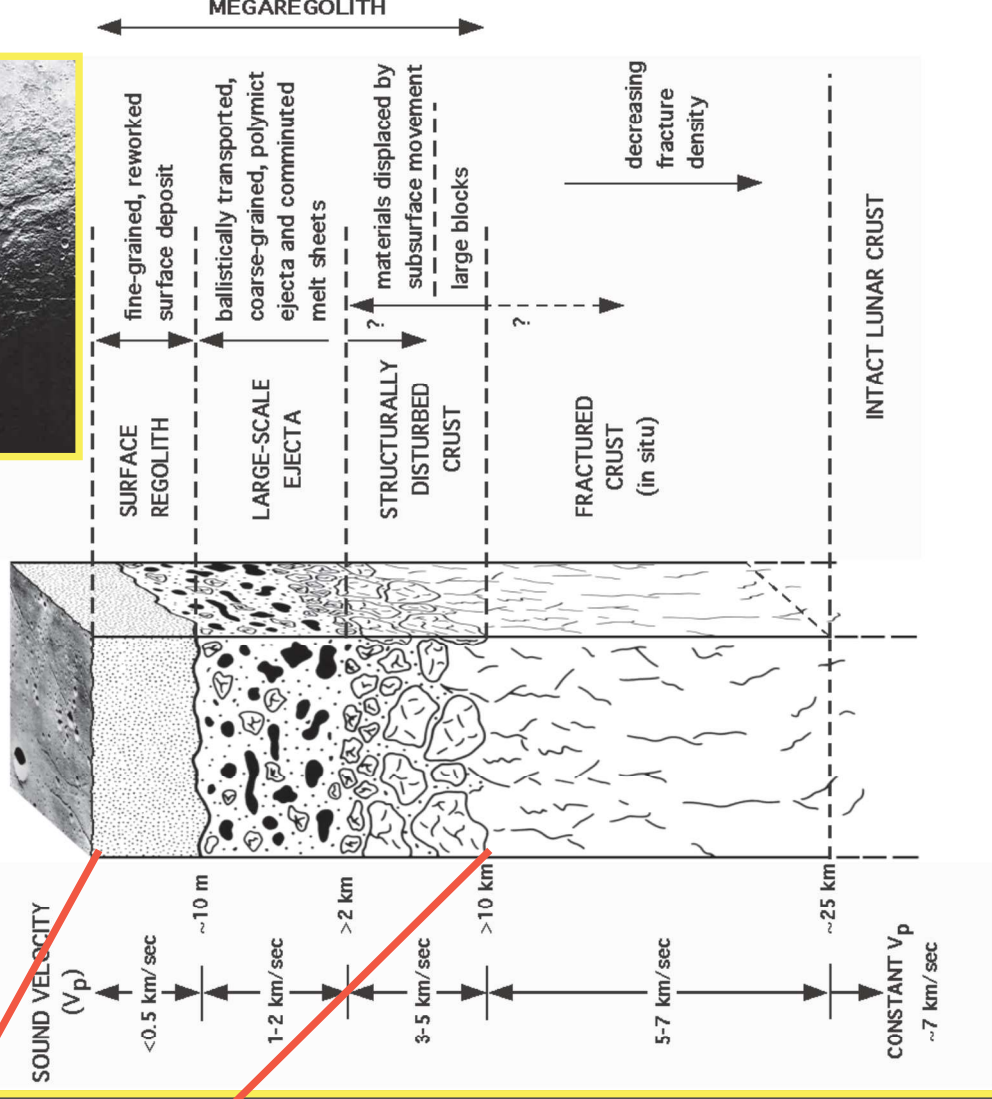
Ejecta Thickness (Isopach) Map of the Hevelius Formation

6. Structure and Composition of the Lunar Crust: The Magma Ocean Model

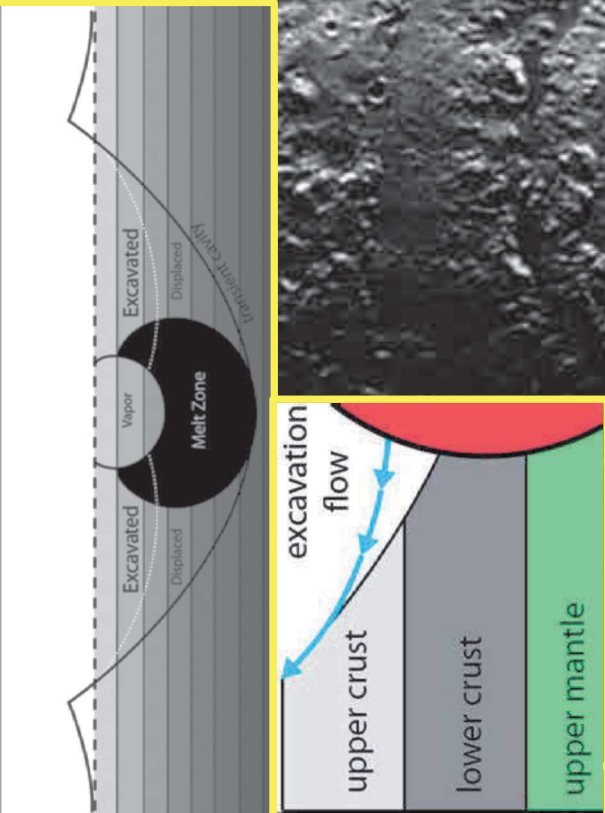
Megaregolith
(~10 km thick)

Upper Anorthositic Crust
(~15 km thick)

Lower Noritic Crust
(~25 km thick)



- Crust averages $\sim 50 \pm 16$ km thick.
- Upper and lower crust about equal.
- Upper crust heavily modified in the upper ~ 10 km by impact processes.



Oriental Basin: Rings & Geologic Units

**Hevelius Formation
(Basin Ejecta Deposit)**
Feldspathic breccias; homogeneous, well-mixed.

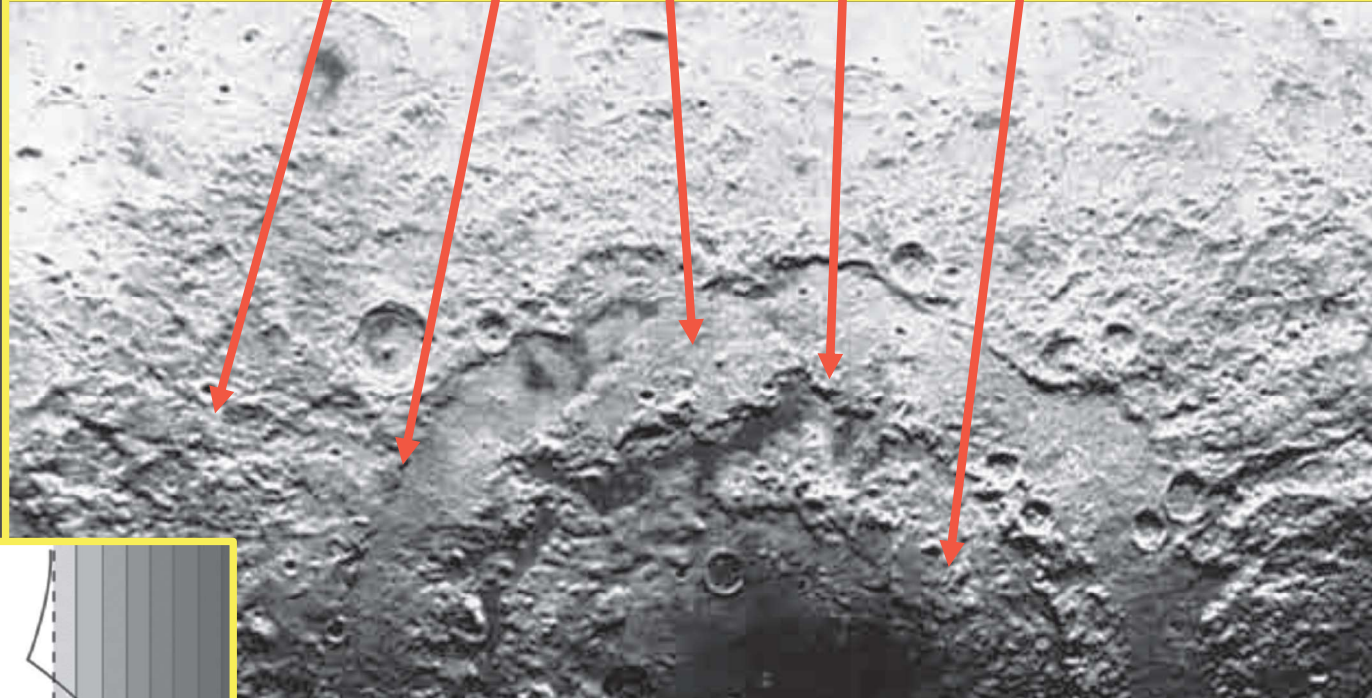
Cordillera Mountains:
Feldspathic breccias;
unweathered.

**Montes Rook Fm.
(Knobby, Domical Deposit)**
Feldspathic breccias; some anorthosite blocks.

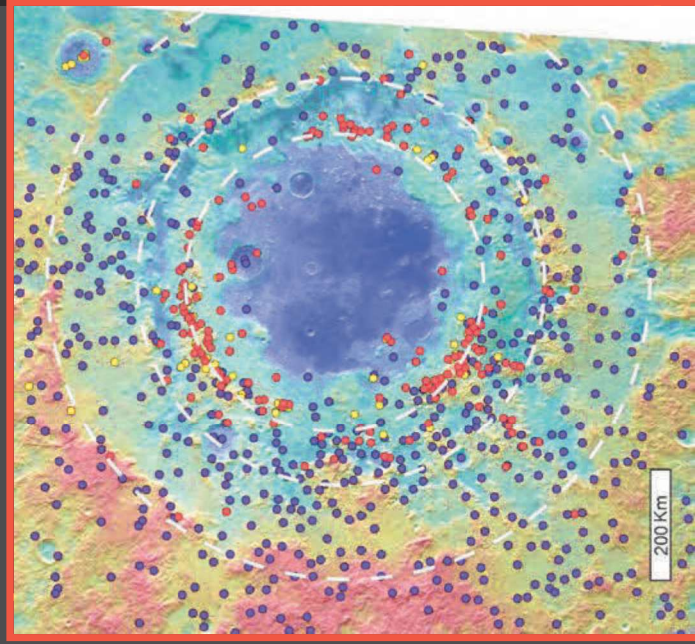
Outer Rook Mountains:
Norites, noritic anorthosite
and anorthosite; more crystalline
blocks.

Inner Rook Mountains:
Massifs are crystalline anorthosite;
discrete peaks and clusters of peaks.

**Maunder Formation
(Basin Impact Melt Deposit)**



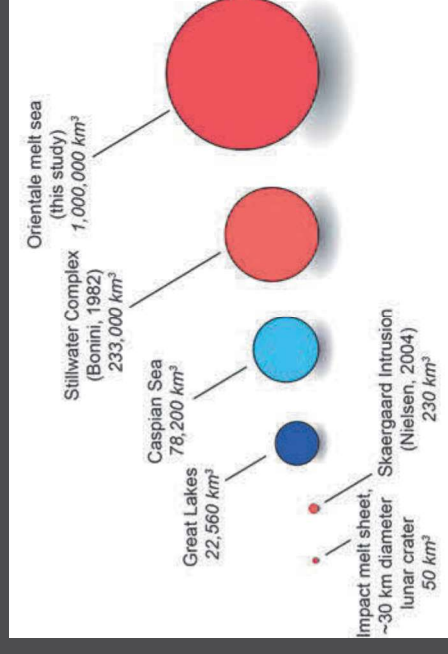
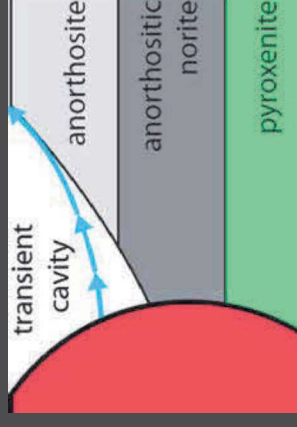
Moon Mineralogy Mapper (M3)



Red Dots (Inner Rook Mountains):
Materials >~98% plagioclase (Cheek et al., 2012)

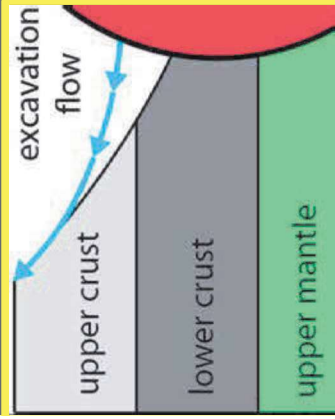
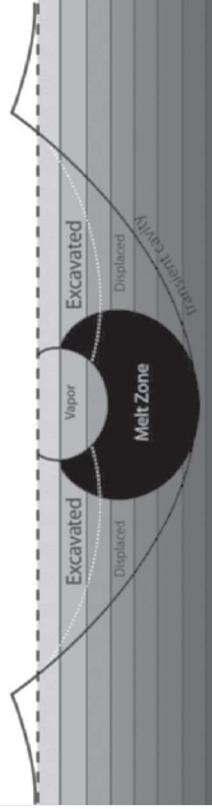
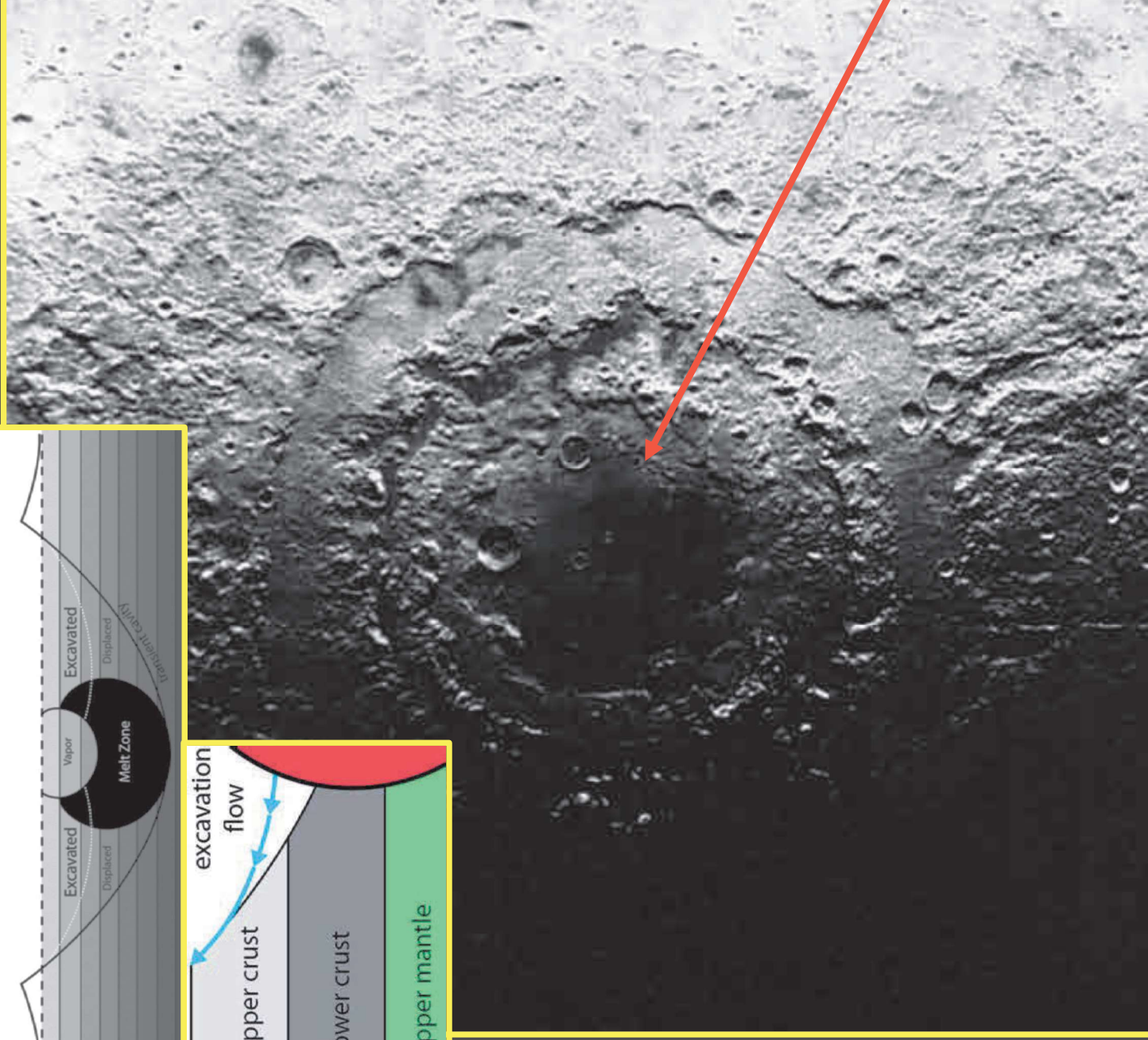
(Pieters et al., 2009, 2011;
Head et al., 2010, 2012; Cheek et al., 2012)

7. Orientale Impact Melt Sea

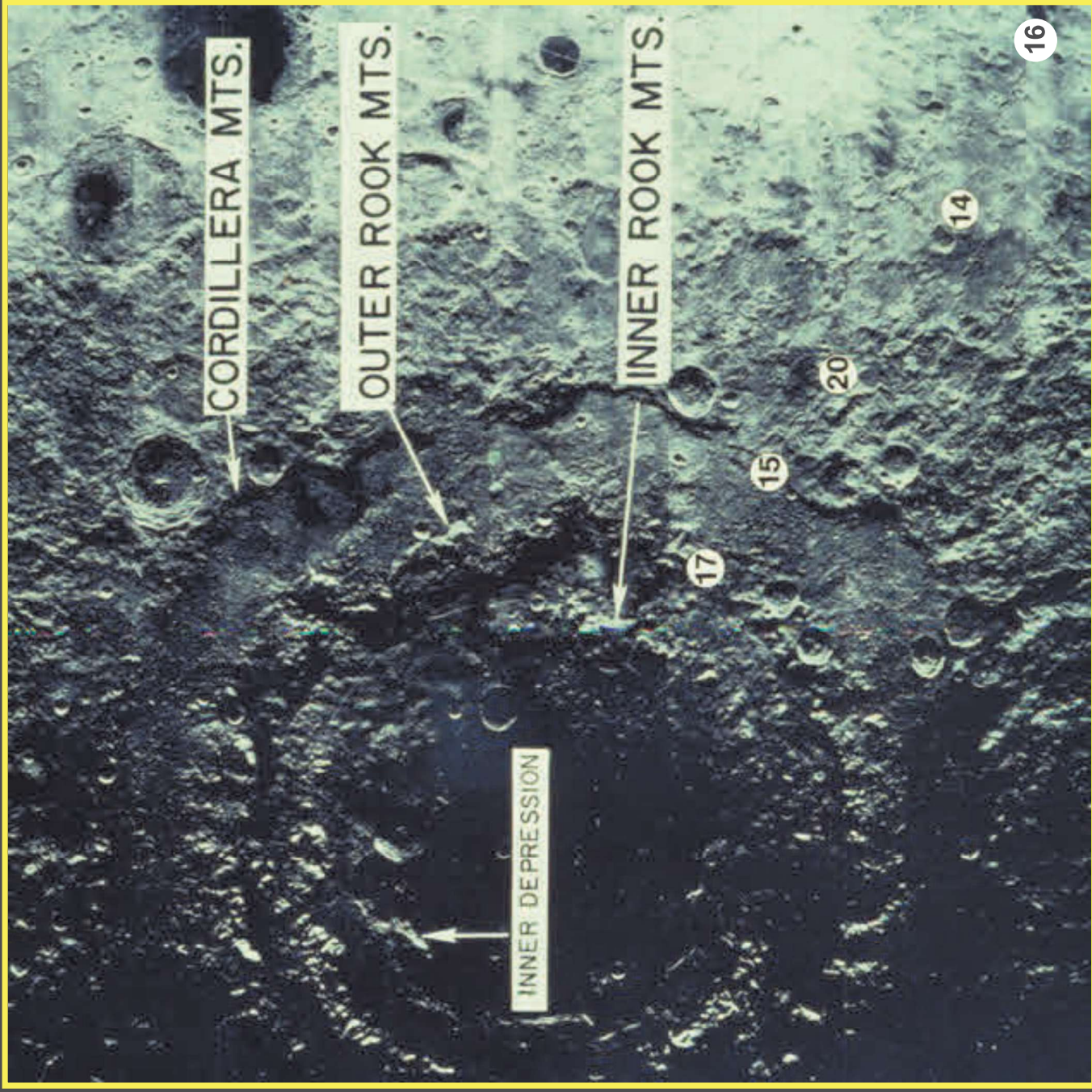


**Maunder Formation
(Basin Impact Melt Deposit)**

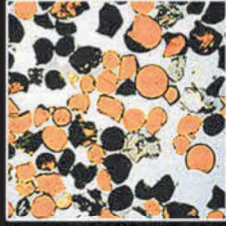
(Wilson and Head, 2010;
Vaughan et al, 2011, 2012)



8. Lunar Orientale Basin: Link to Apollo Missions Environments/Results



APOLLO 17



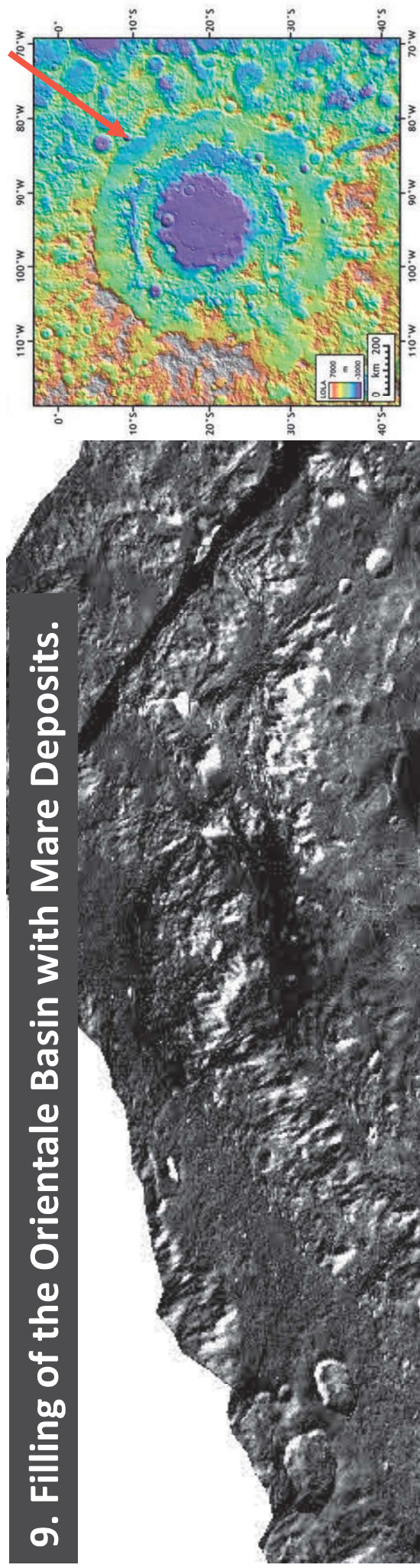
APOLLO 15



APOLLO 16



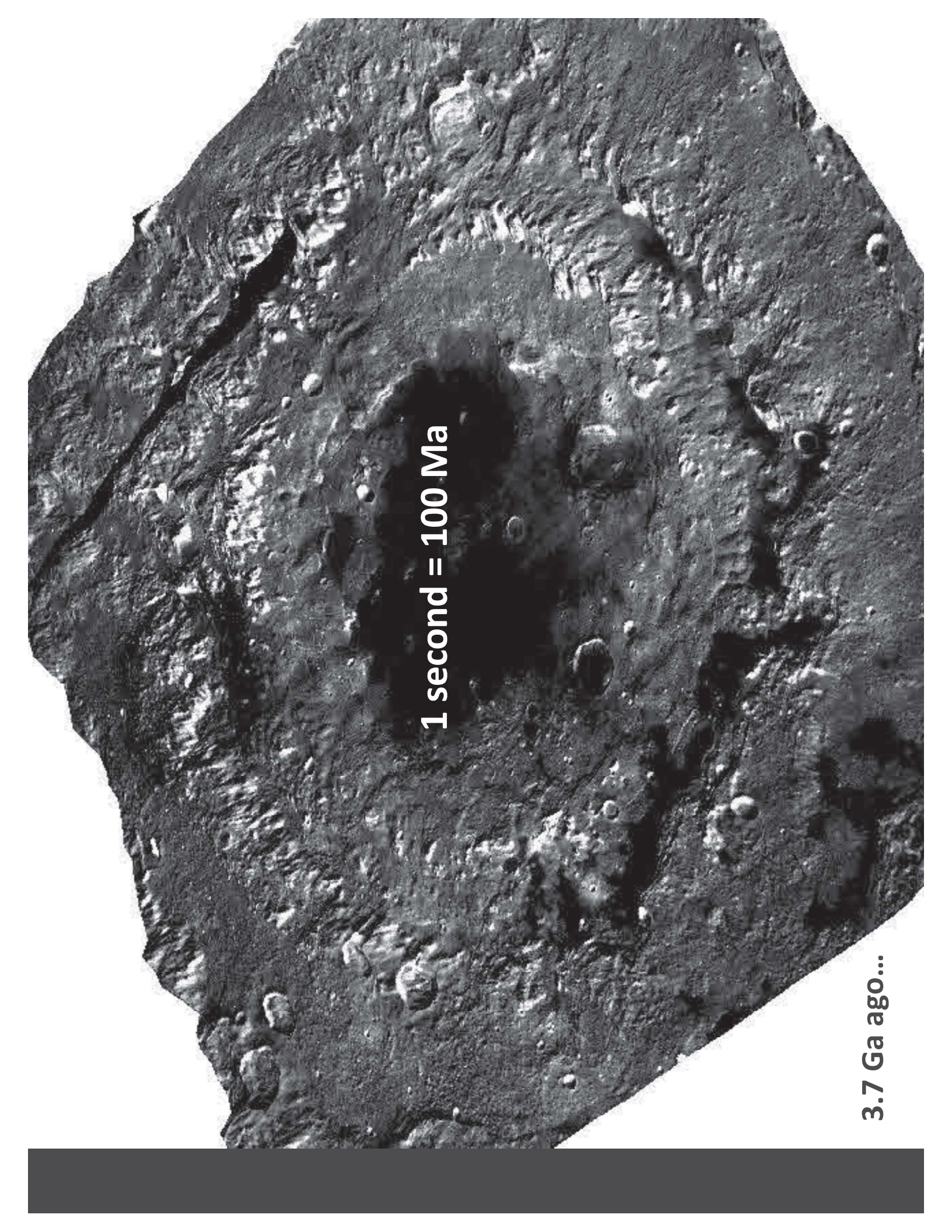
9. Filling of the Orientale Basin with Mare Deposits.



1 second = 100 Ma

3.7 Ga ago...

(Whitten et al., 2010)



1 second = 100 Ma

3.7 Ga ago...

1.66 Ga

2.43 Ga

2.88 Ga

Maunder

3.20 Ga

3.22 Ga

3.36 Ga

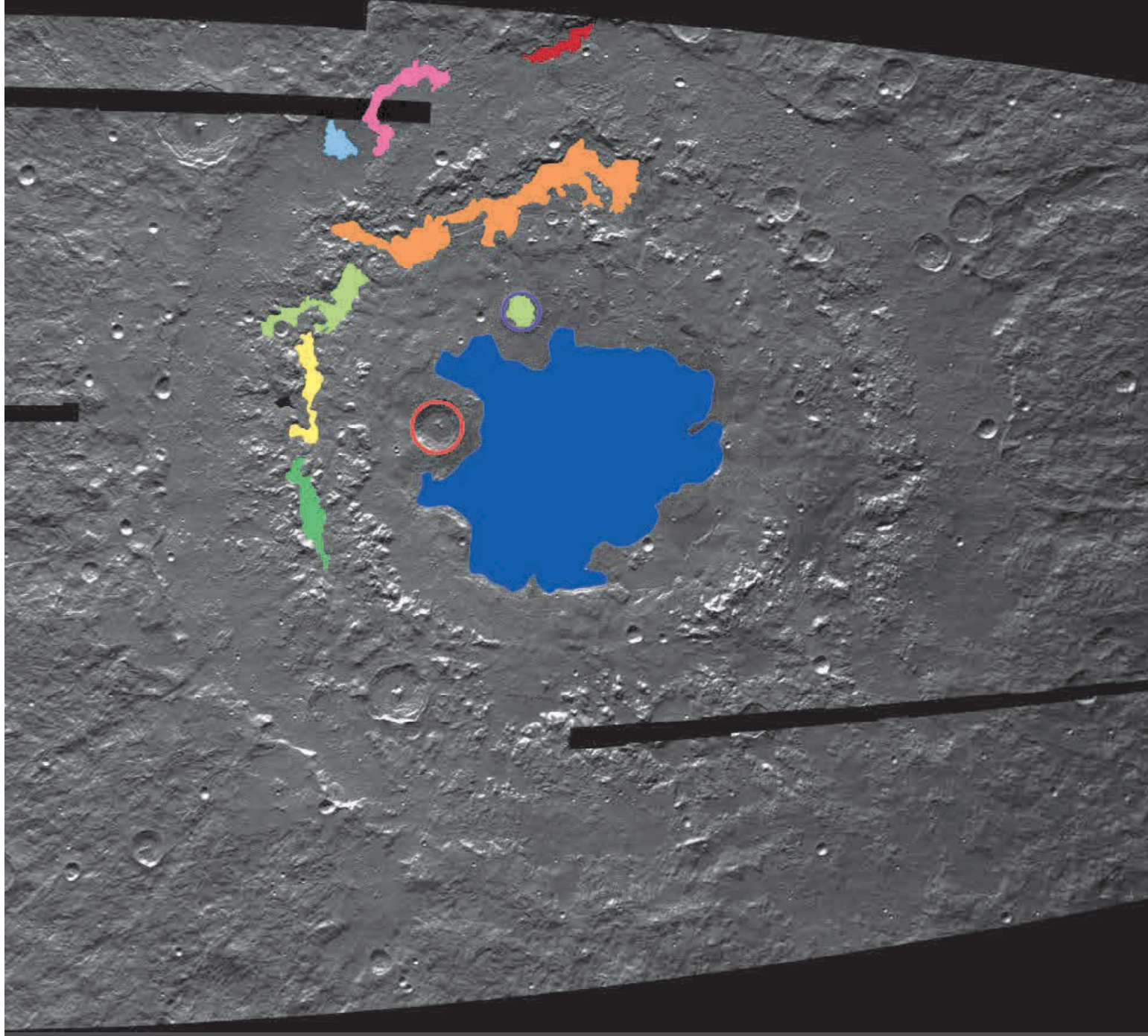
3.45 Ga

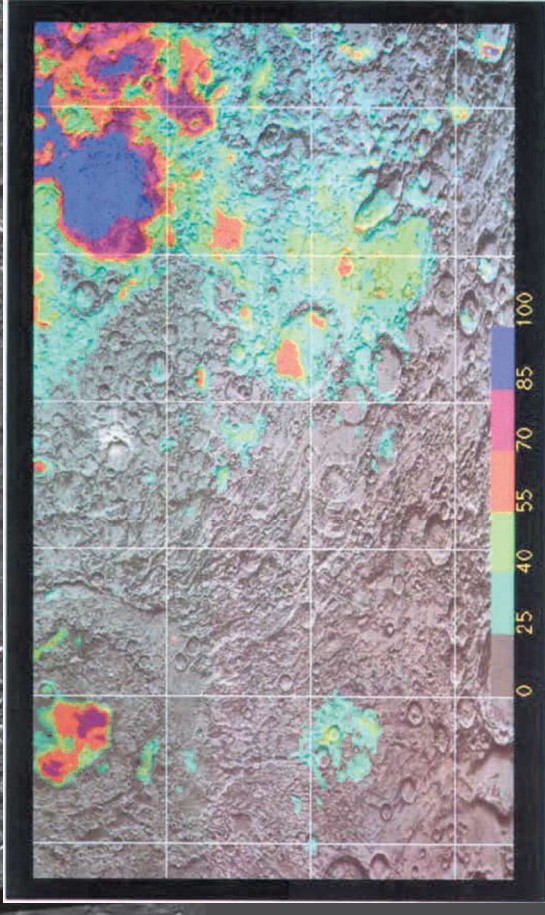
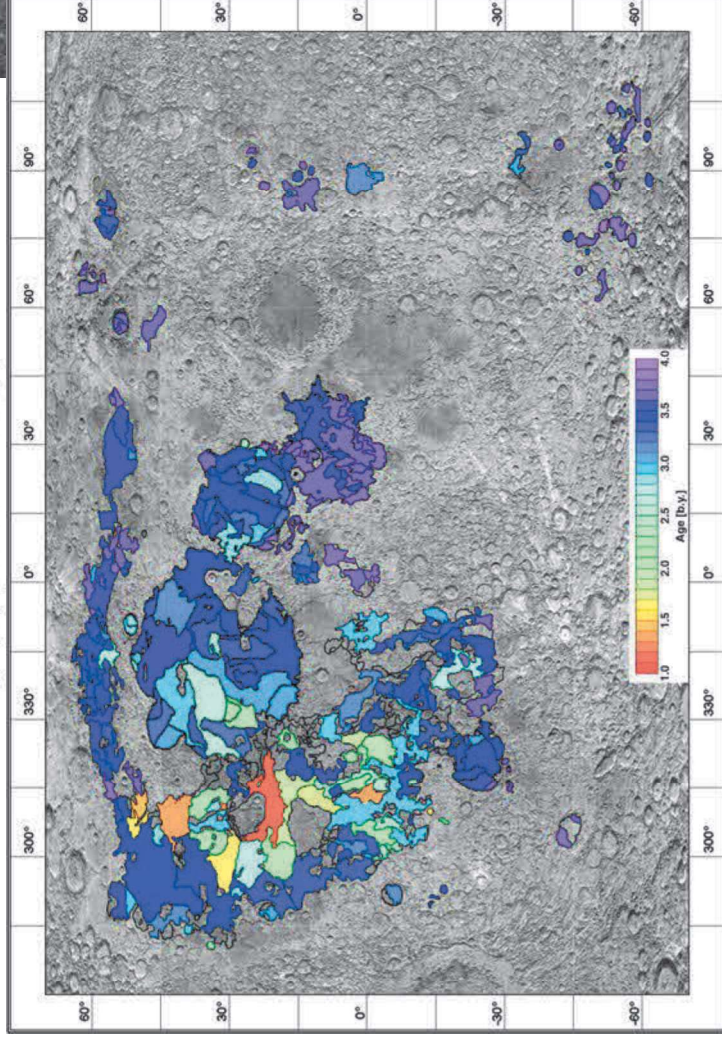
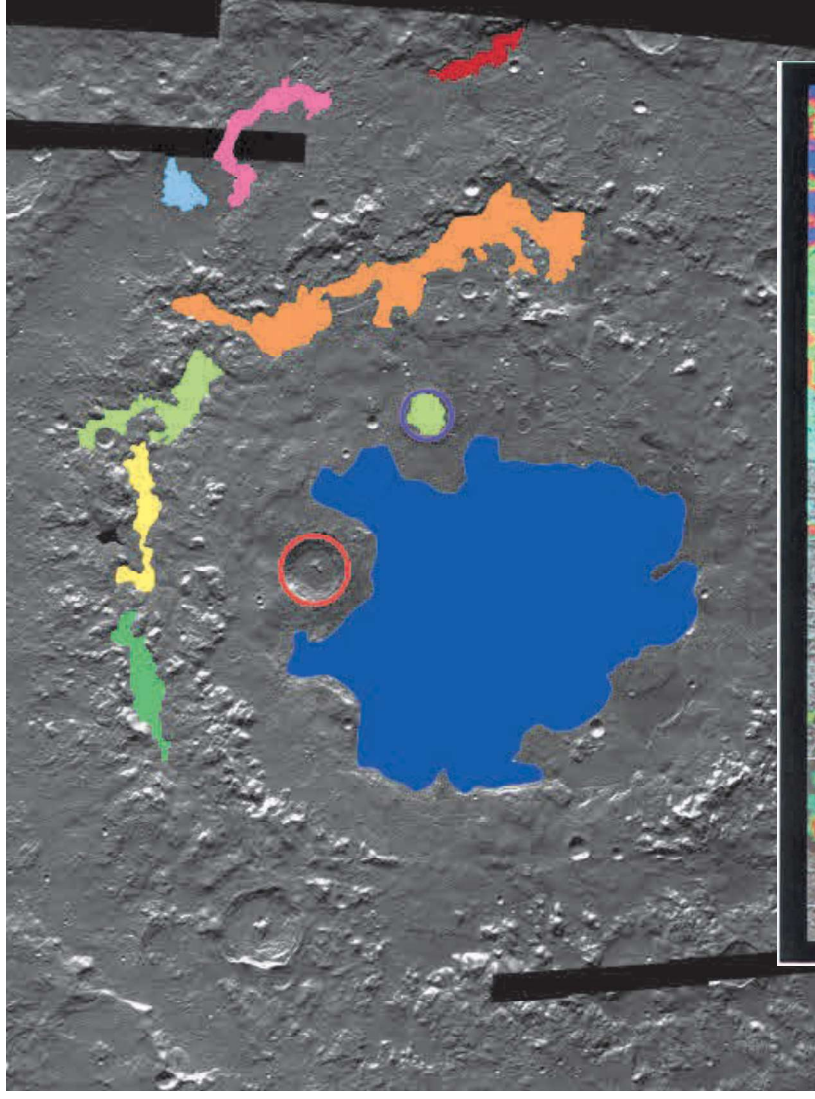
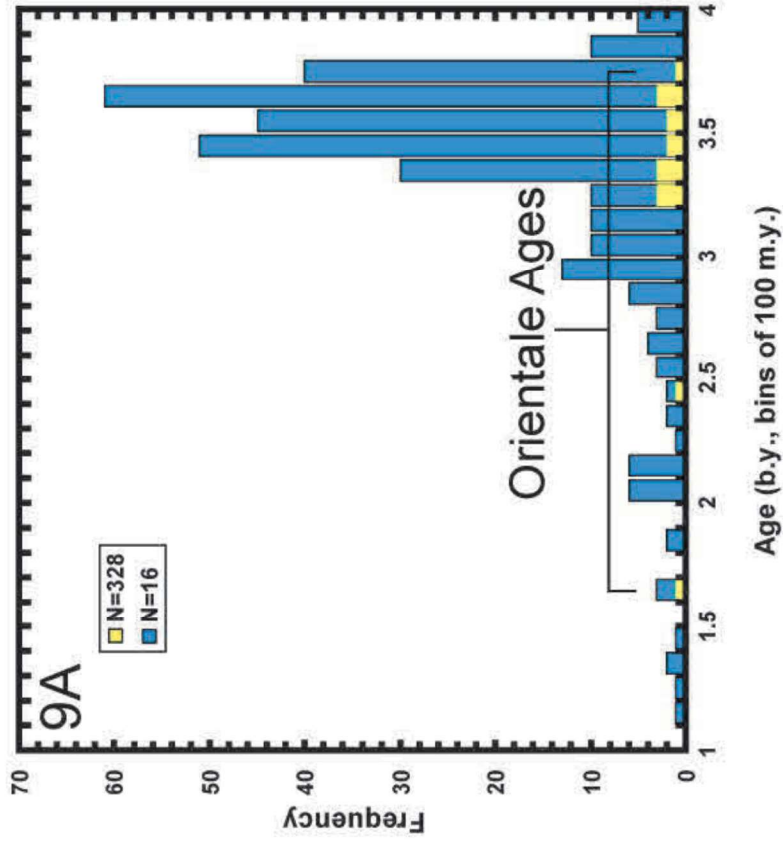
3.47 Ga

3.59 Ga

3.63 Ga

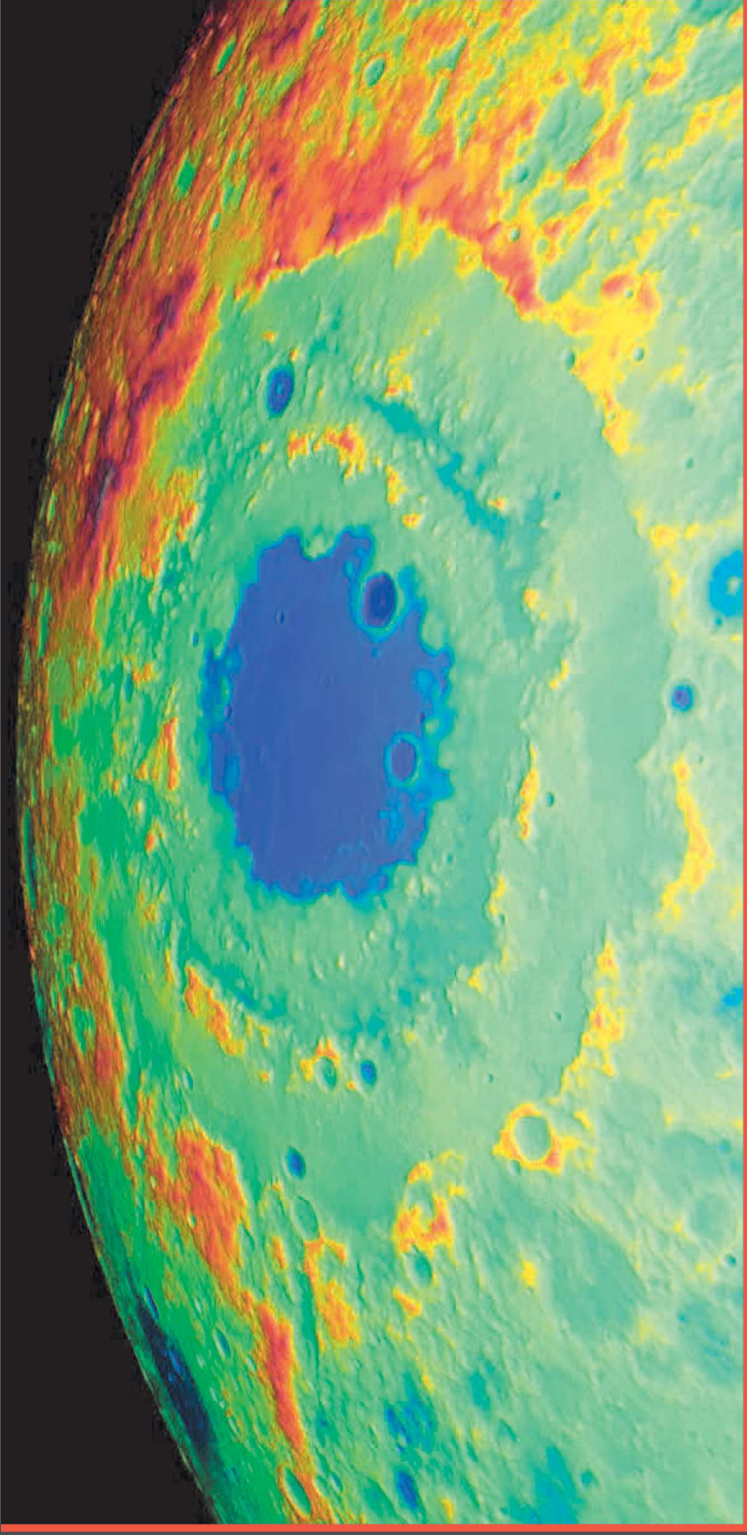
Kopff



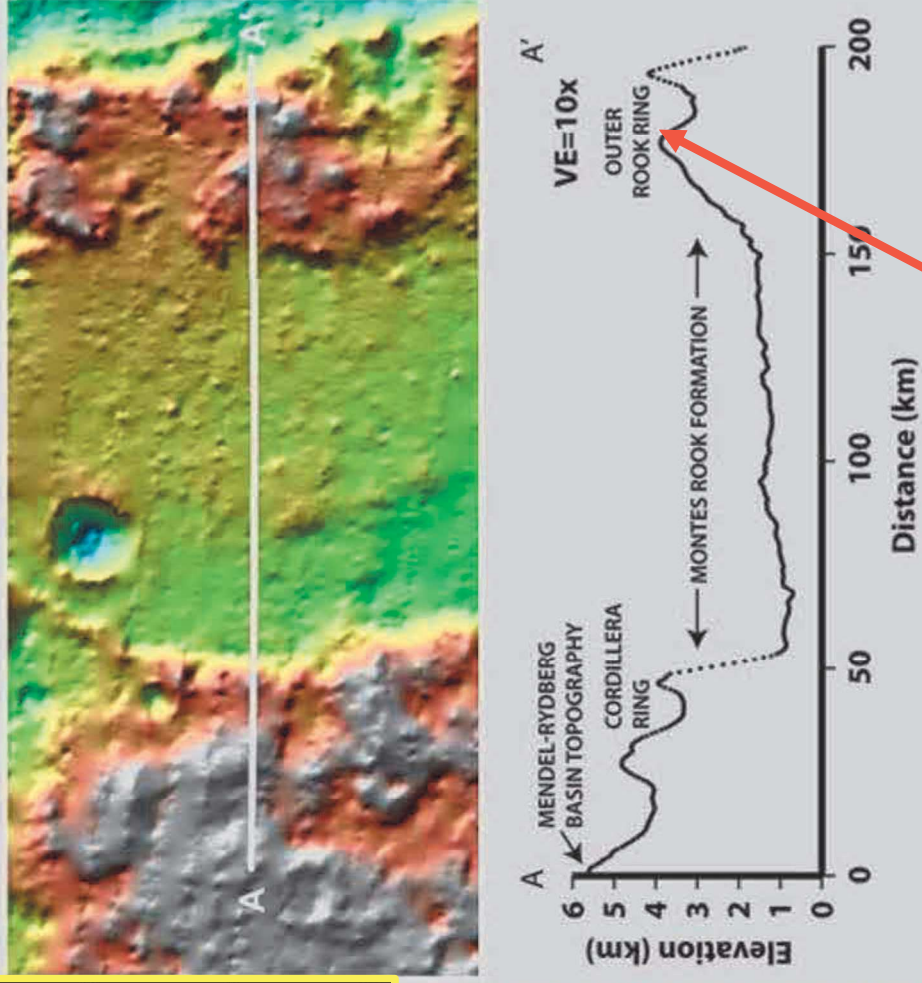
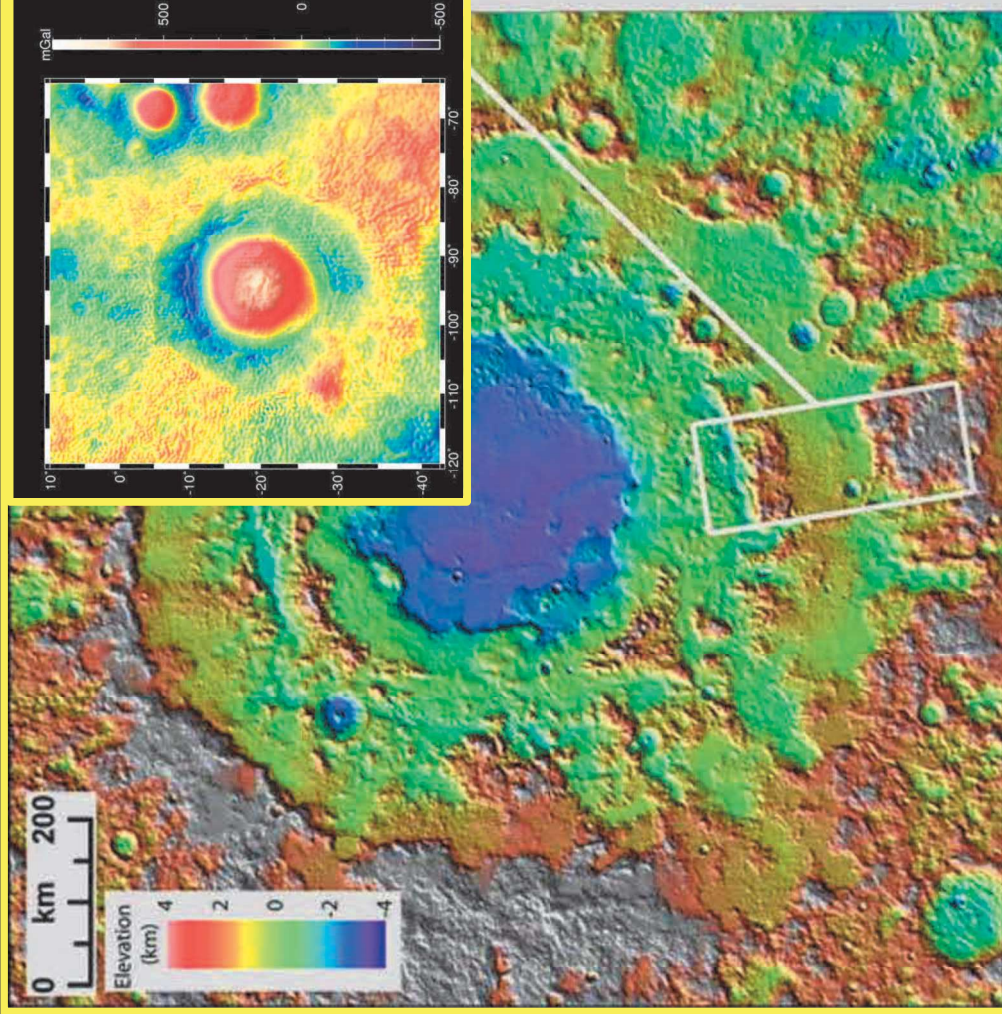


Summary of Orientale Maria Lessons for South Pole-Aitken Basin (Whitten et al., 2010)

Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin

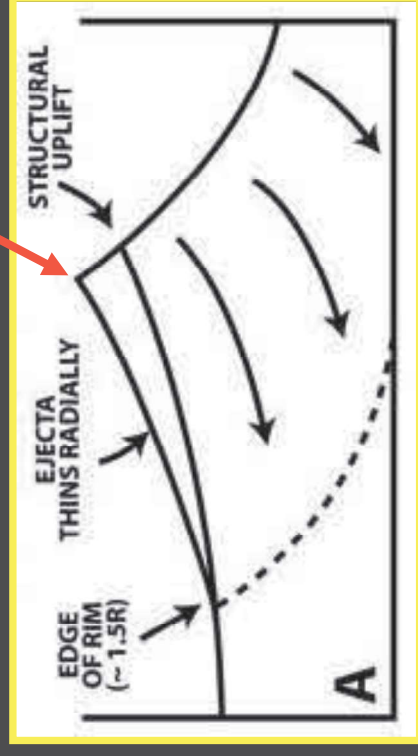


1. The importance of coordinated human/robotic exploration.
2. Why the Orientale multi-ring basin?
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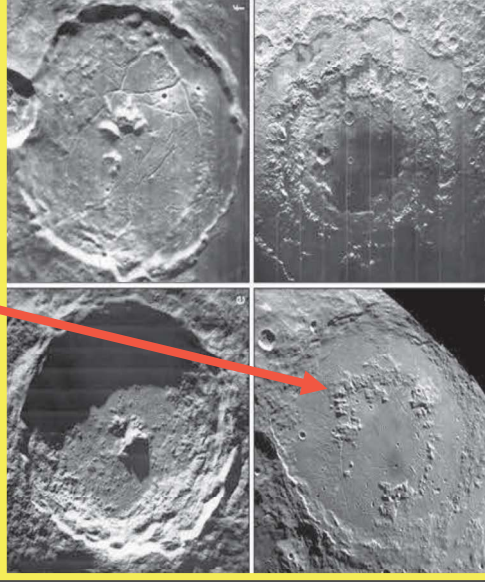
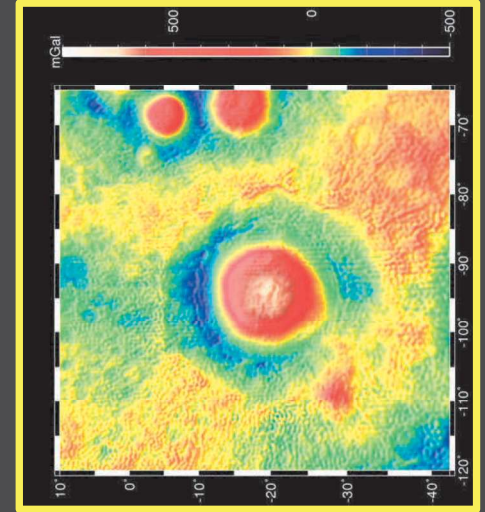
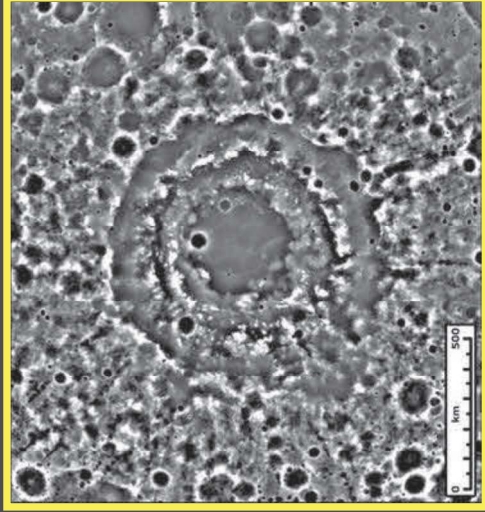
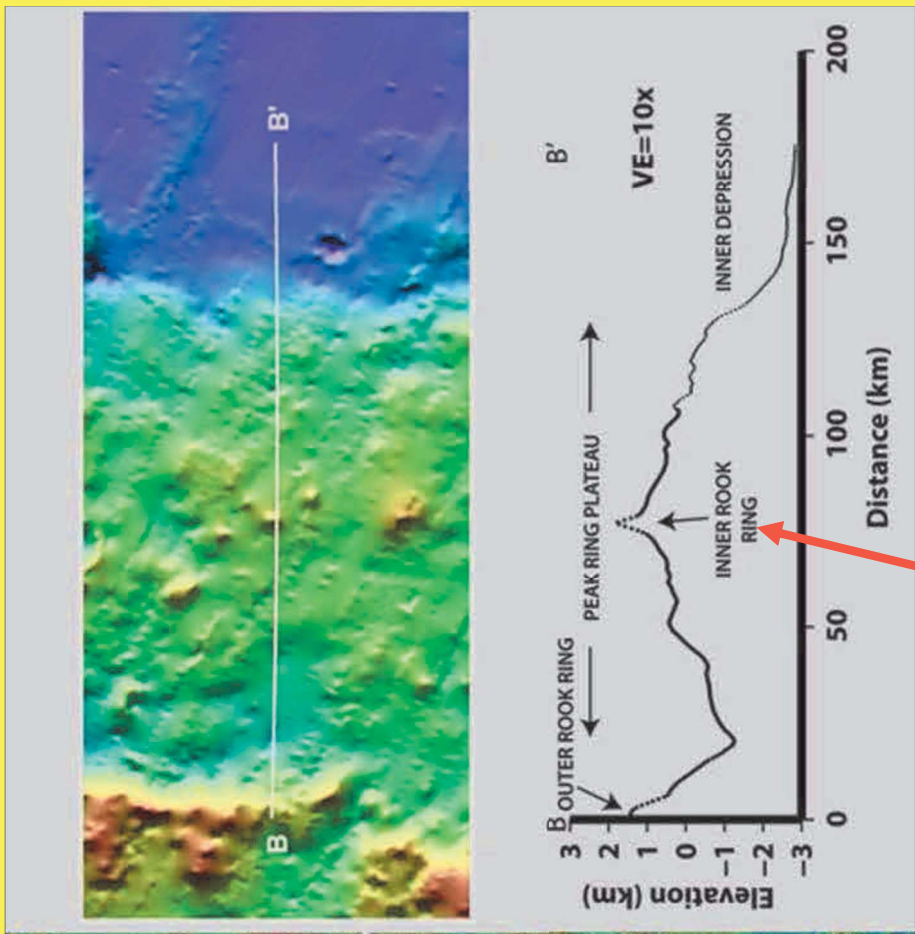
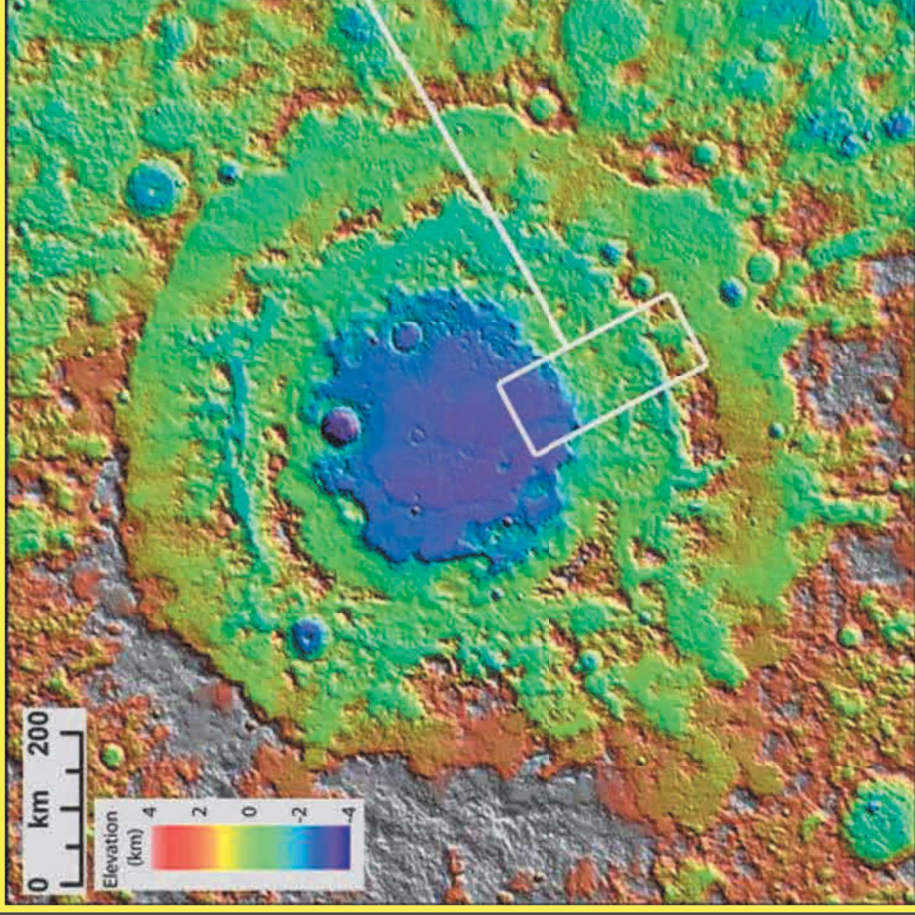


Region of Interest (ROI) 1: Origin of Basin Rings/Crustal Structure

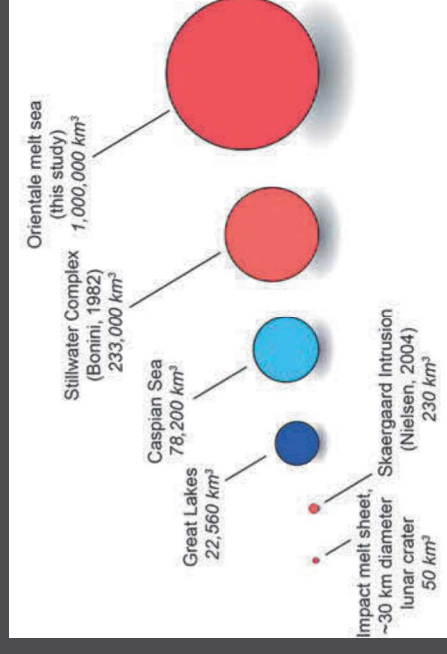
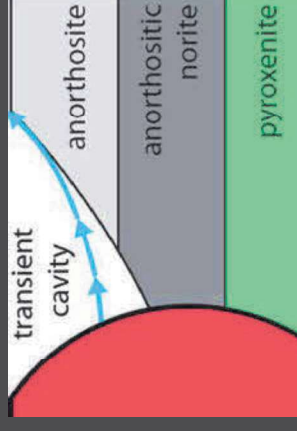
-If the Outer Rook ring represents the transient cavity rim crest, what is the origin of the Cordillera mountain ring and the Montes Rook Formation?



ROI 2: What is the Origin of the Inner Rook Mountains?

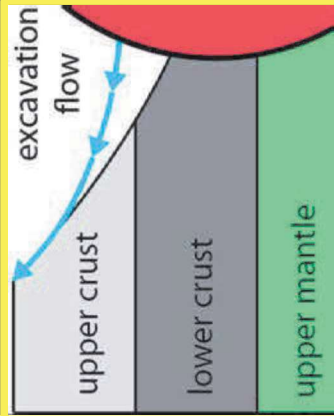
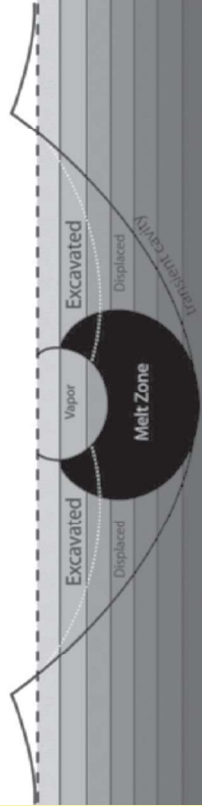
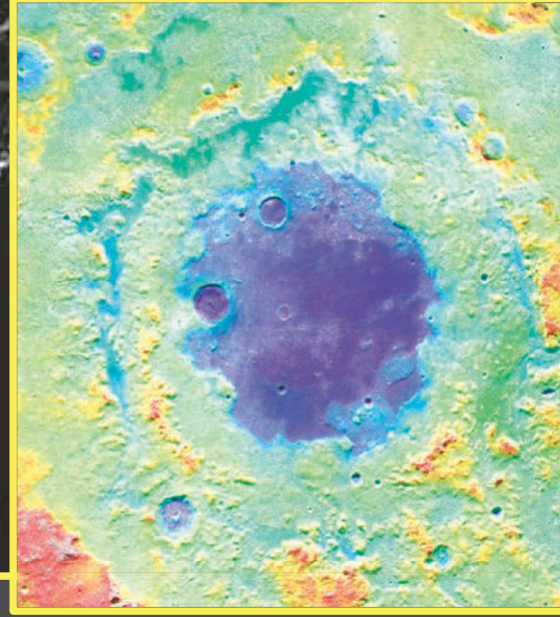
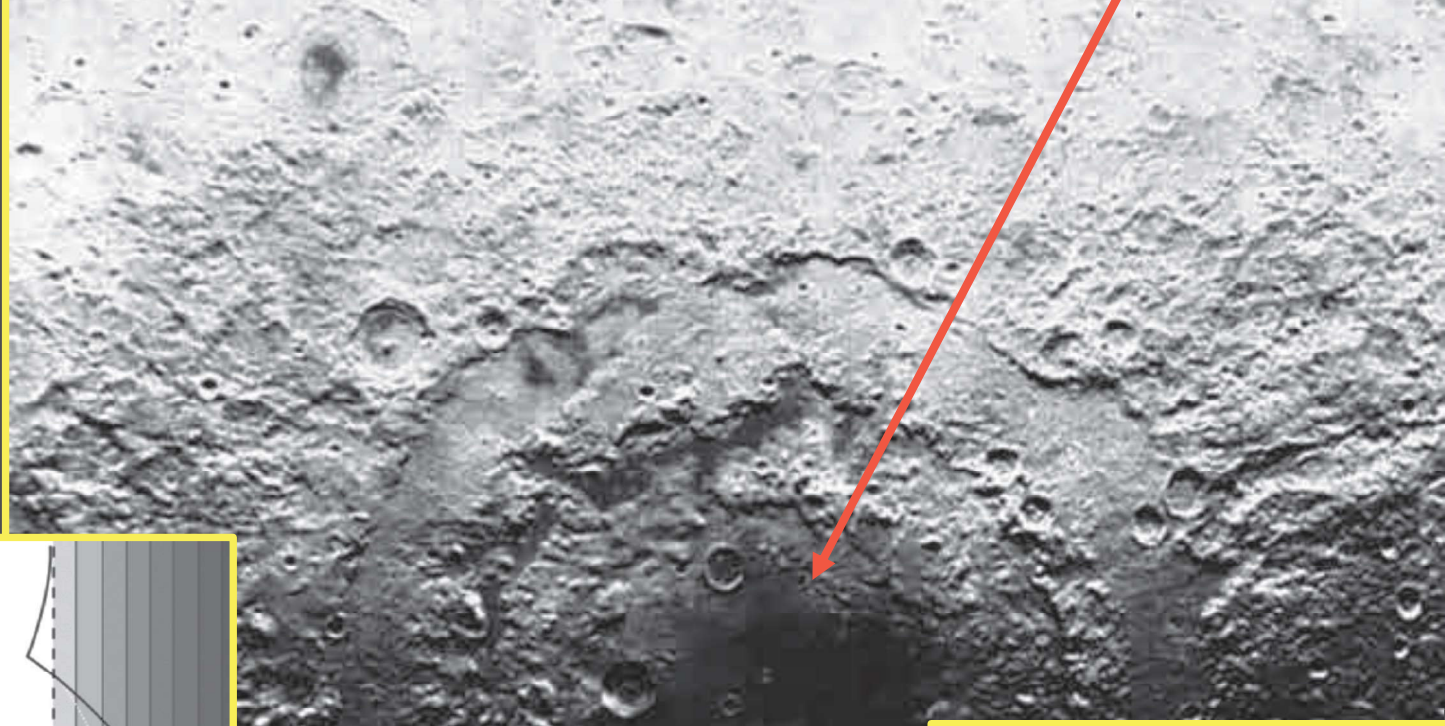


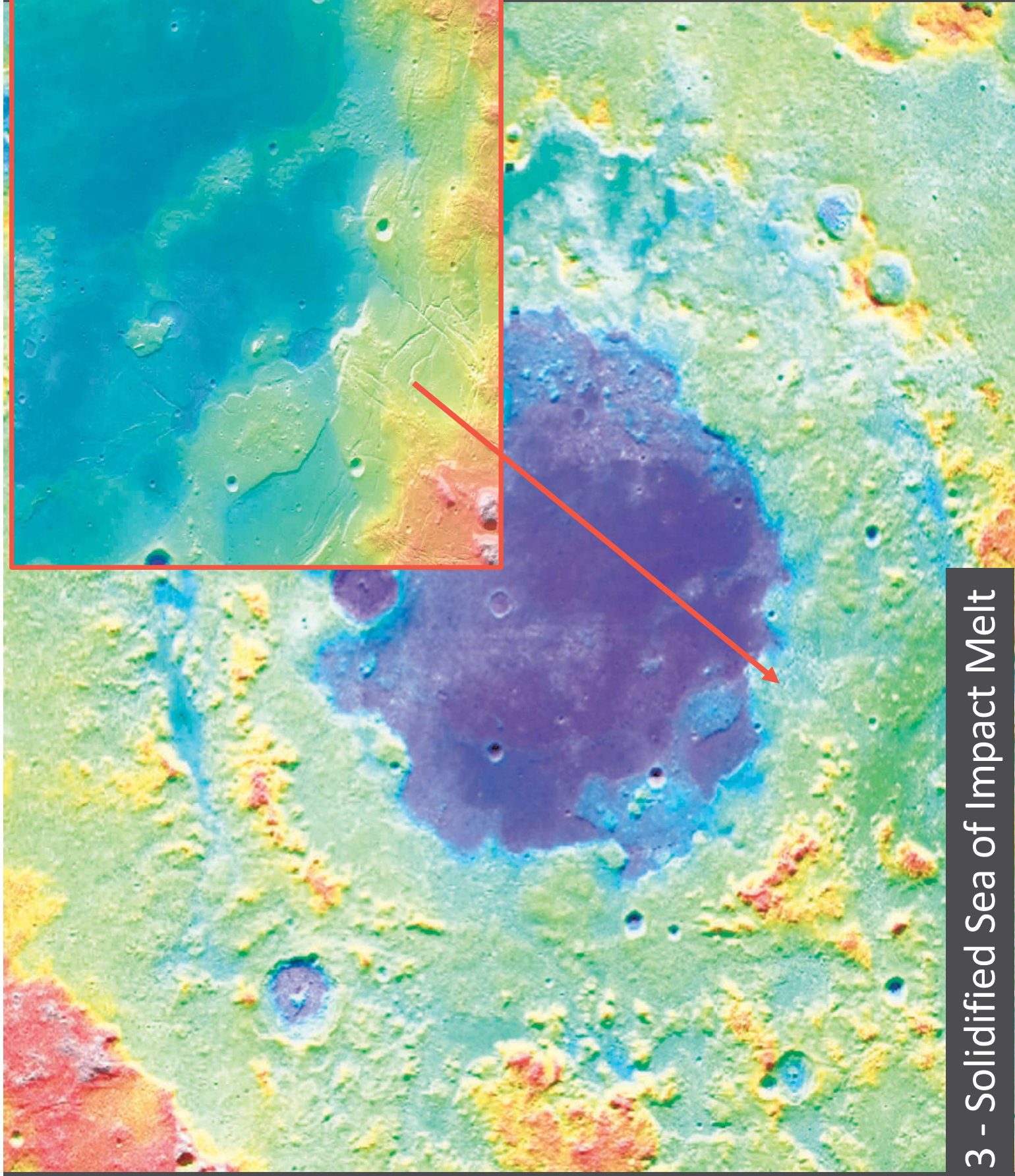
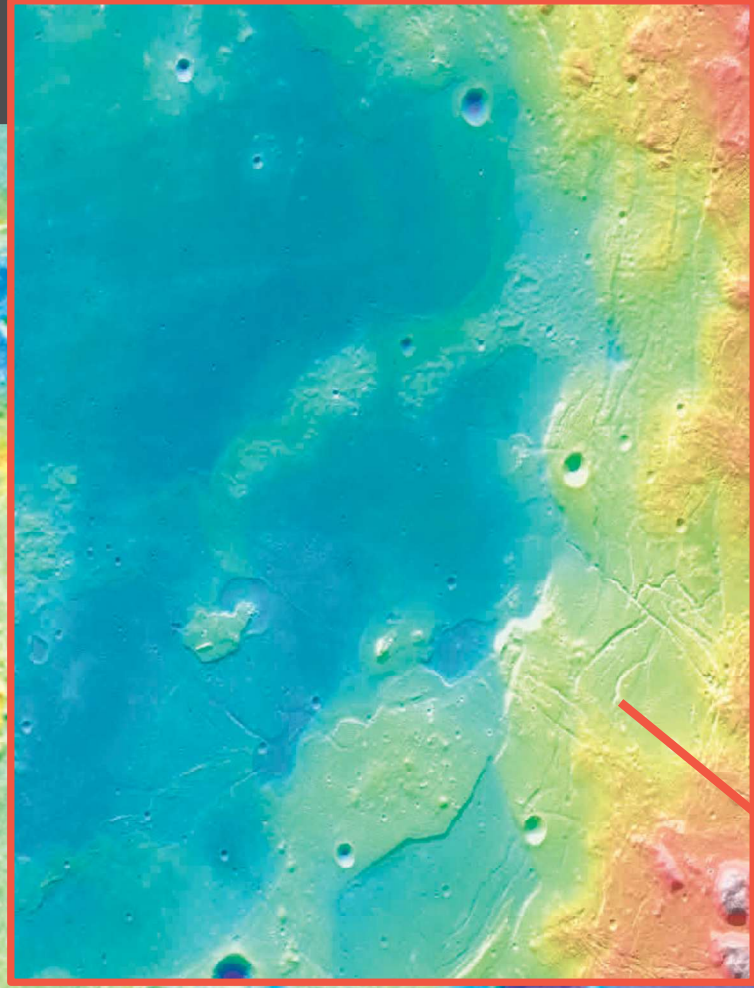
ROI 3-Orientale Impact Melt Sea



Maunder Formation
(Basin Impact Melt Deposit)

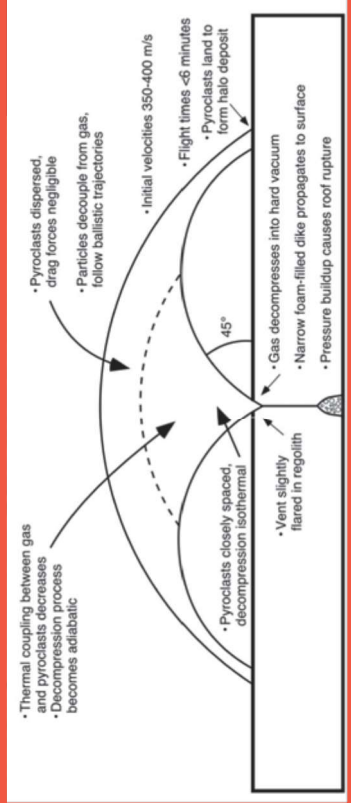
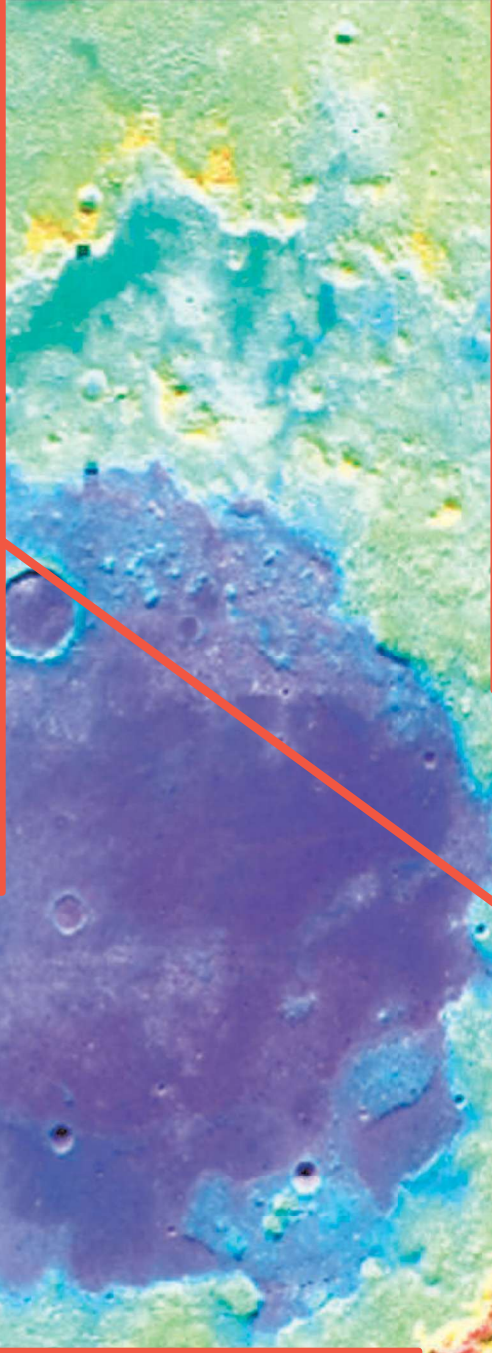
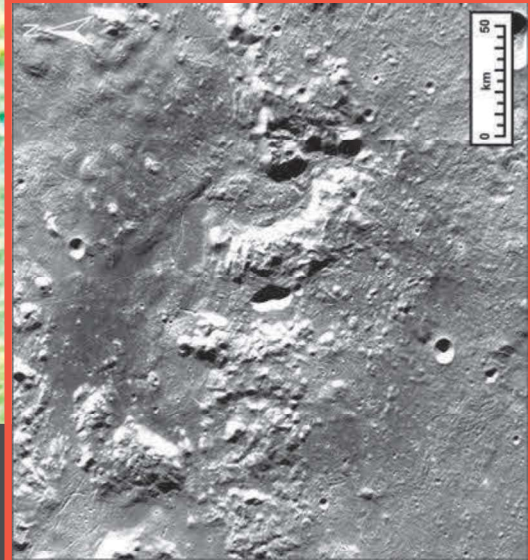
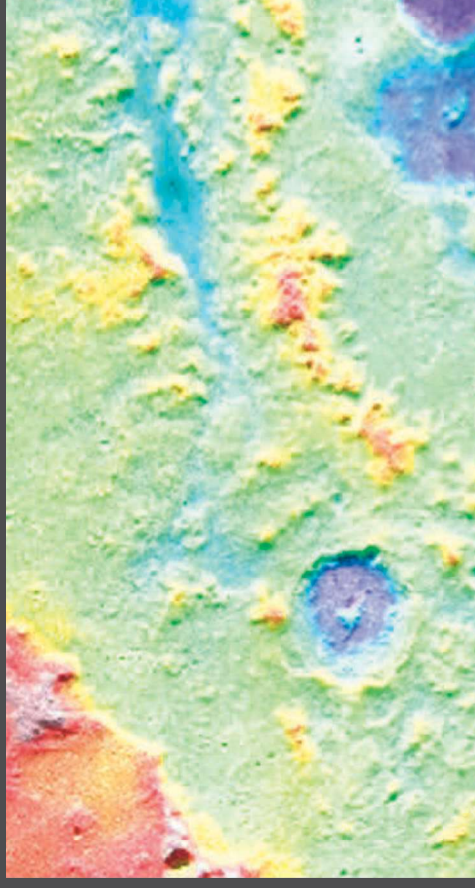
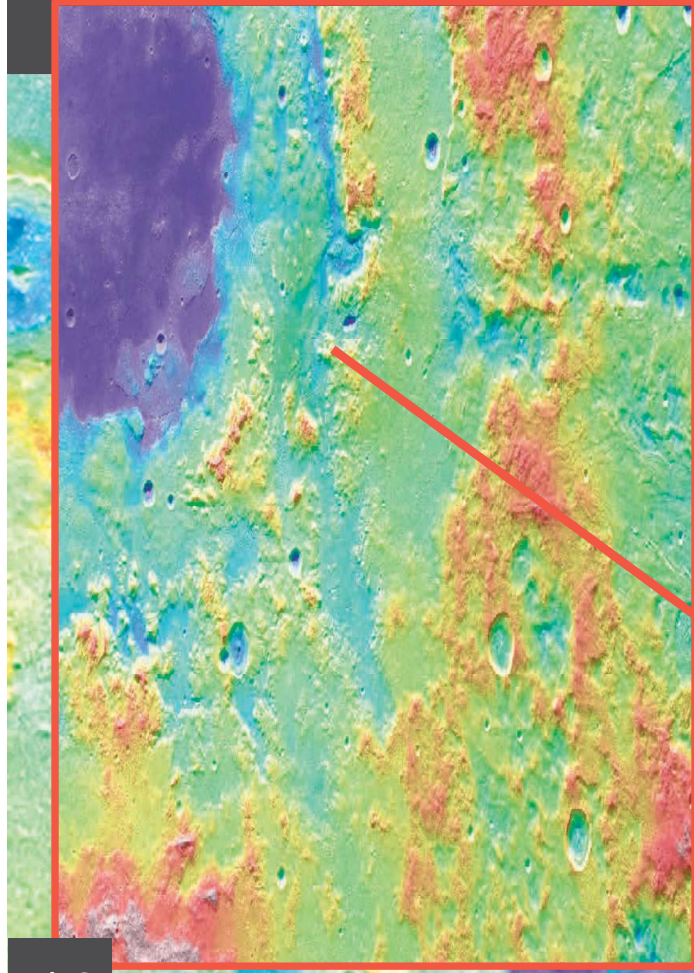
(Wilson and Head, 2010;
Vaughan et al, 2011, 2012)



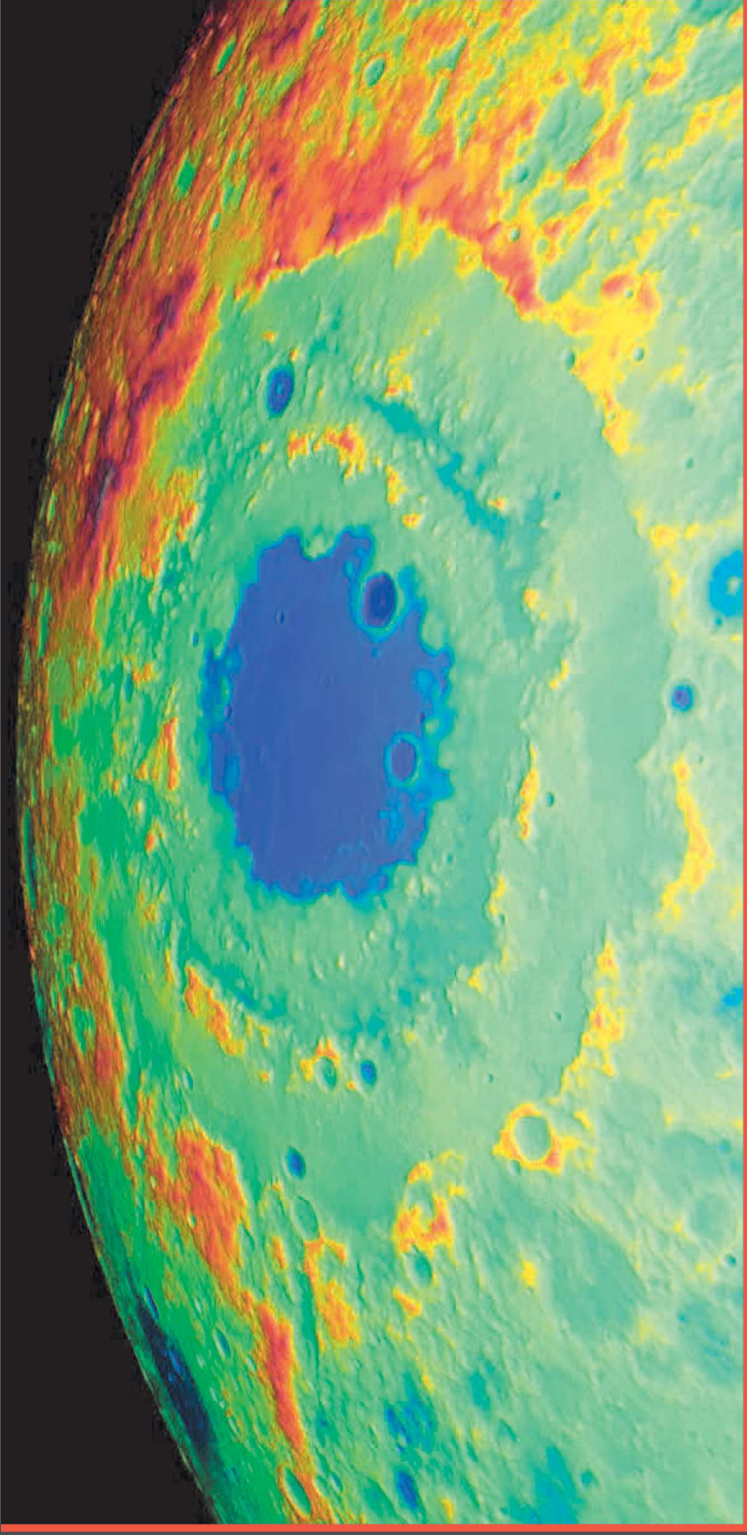


ROI 3 - Solidified Sea of Impact Melt

ROI 4-Explosive Volcanic Ionian Ring



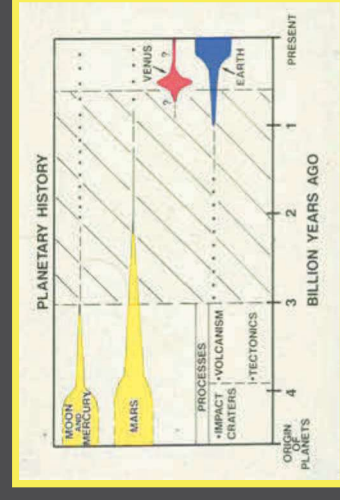
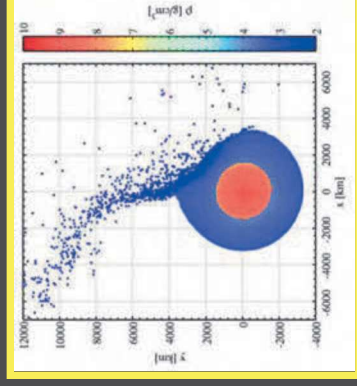
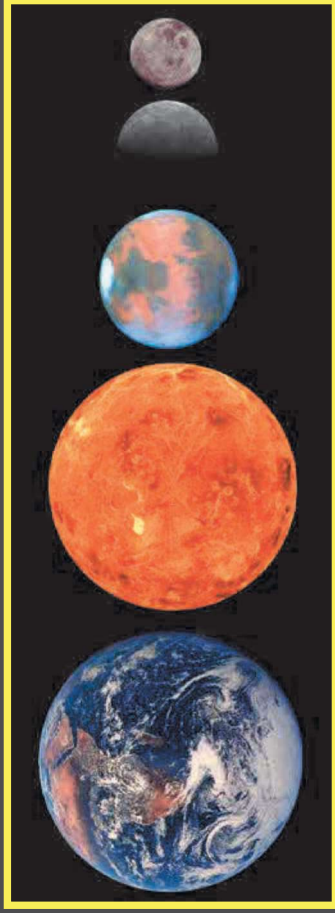
Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin



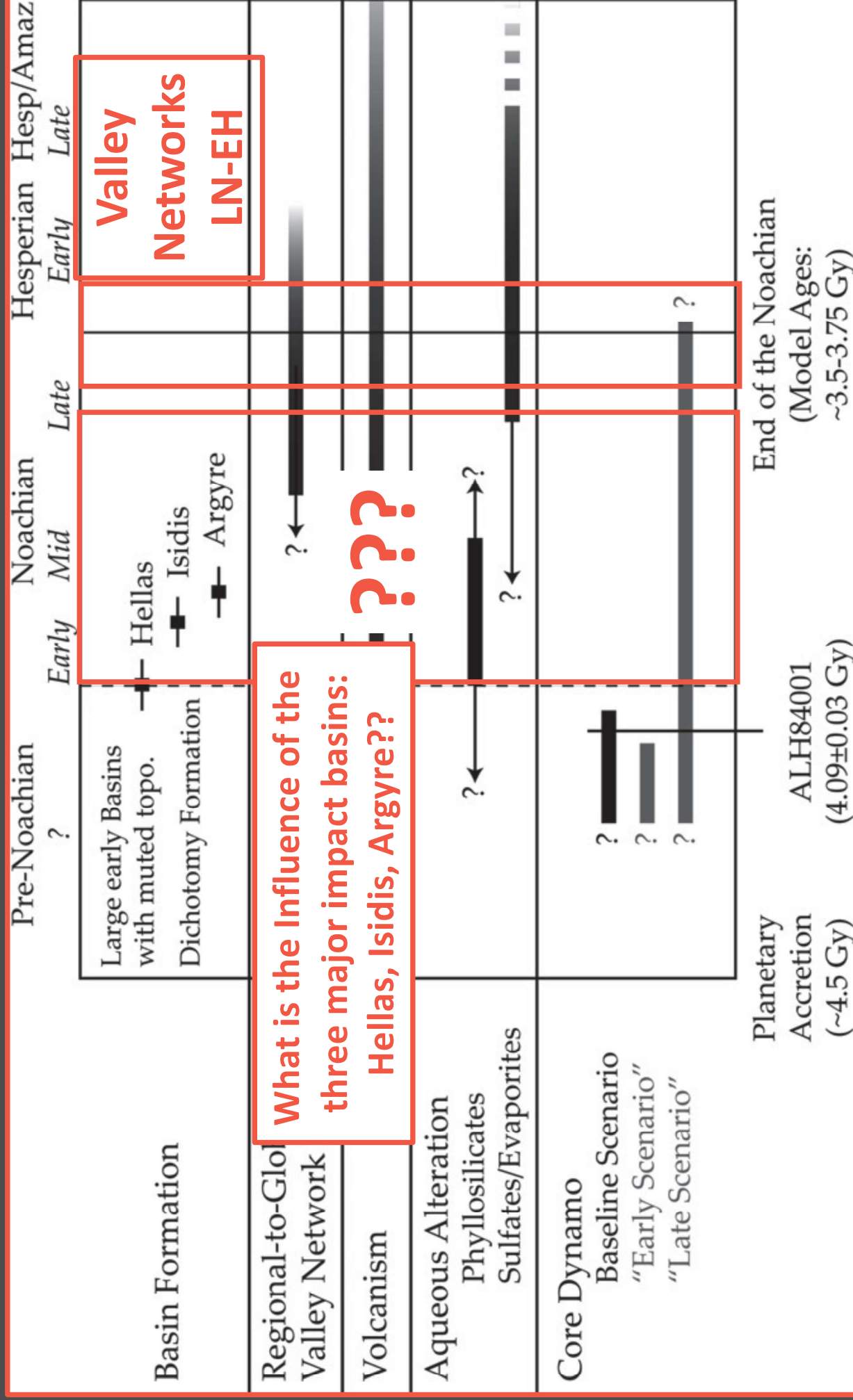
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Orientalle Basin Site Summary

- Addresses Major Fundamental Science Questions.
- Firmly Establishes Lunar Basin Chronology Data Point.
- Flexible Extension Away From Lunar Base.
- Applicable to Robotic Support and Human Sorties.
- Application to Moon-Mars Architecture.
- The Role of Impact Basins in Early Mars Evolution.
- Fundamental Role In Comparative Planetology.



Sequence and Timing of Conditions on Early Mars

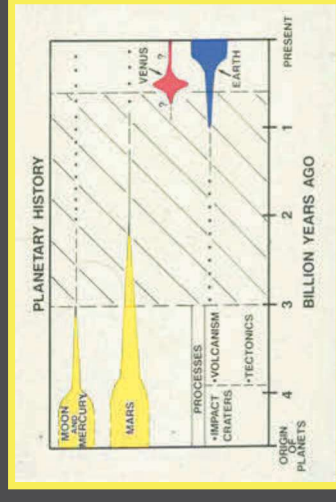
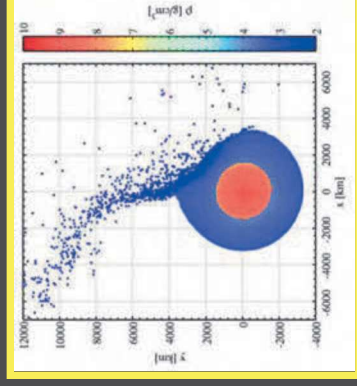
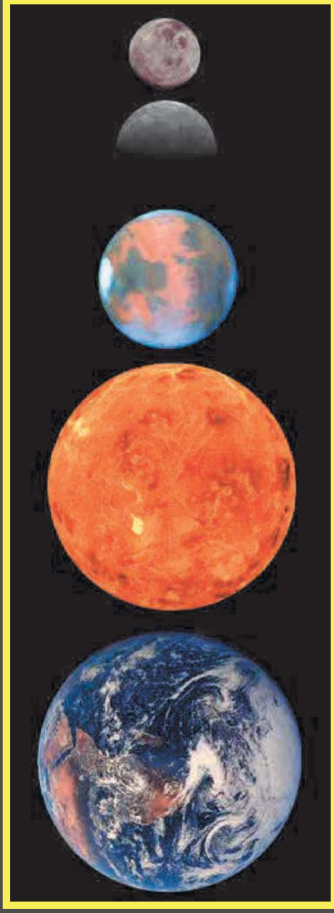


A Stratigraphic Approach

(Fassett and Head, 2011, *Icarus* 211, 1204)

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Chinese Manned Lunar Landing Program

-Candidate Landing Sites Under Study-

