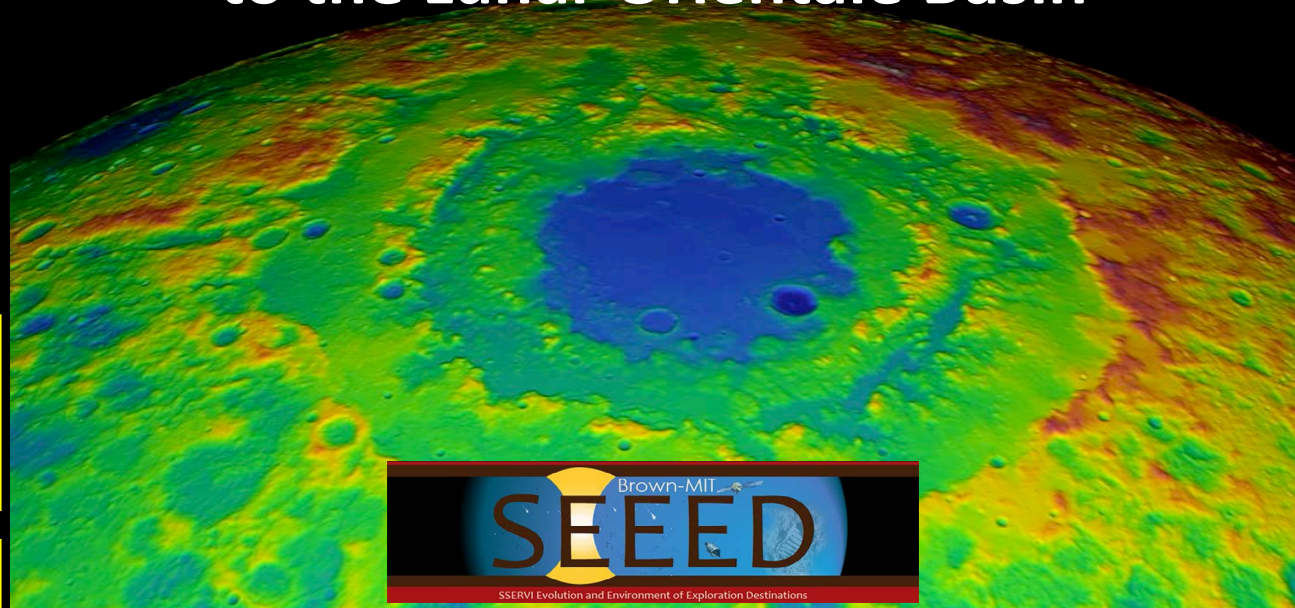


# Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin



James Head, Carle Pieters, David Scott, Brandon Johnson, Ross Potter:  
Brown Univ., Providence, RI USA

Jeffrey Hoffman: MIT, Cambridge, MA USA

Bernard Foing: ESA ESTEC, Noordwijk, The Netherlands

Lev Zelenyi, Igor Mitrofanov: Institute for Space Research, RAS, Moscow, Russia

Mikhail Marov, Alexander Basilevsky, Mikhail Ivanov: Vernadsky Institute, RAS,  
Moscow, Russia

Ralf Jaumann, DLR Institute of Planetary Research, Berlin, Germany

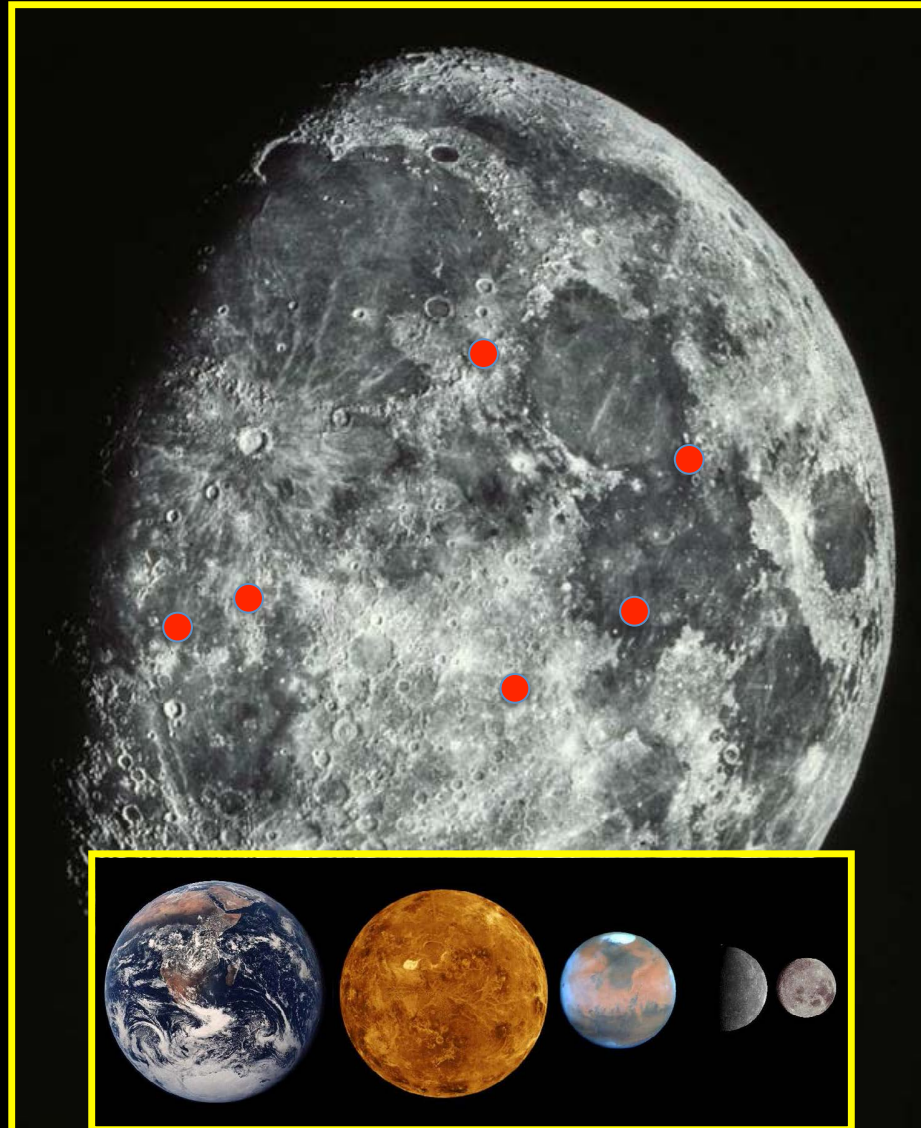
Long Xiao: China University of Geosciences, Wuhan, Hubei, China

Junichi Haruyama, Makiko Ohtake: ISAS, JAXA, Sagami-hara, Japan

P. Senthil Kumar: CSIR-NGRI, Hyderabad, India

Oded Aharonson: Weizmann Institute, Rehovot, Israel

# Apollo Lunar Exploration Program: Six Scientific Expeditions to the Moon

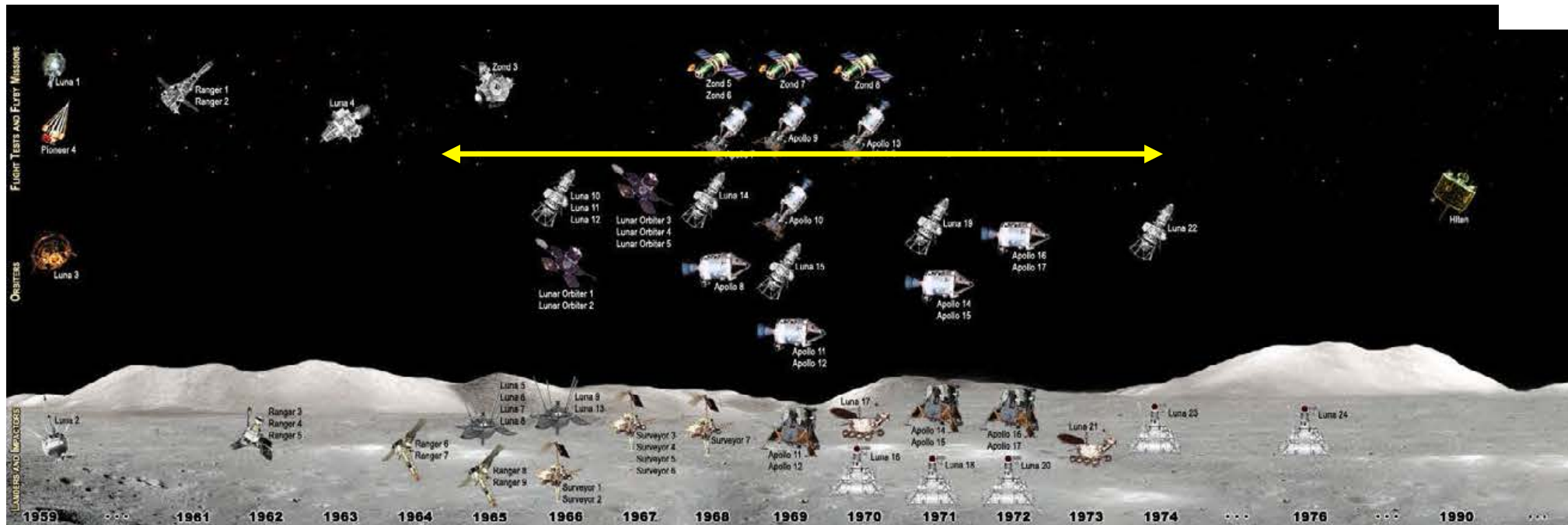


**Established the Moon as a Cornerstone for  
Solar System Science**

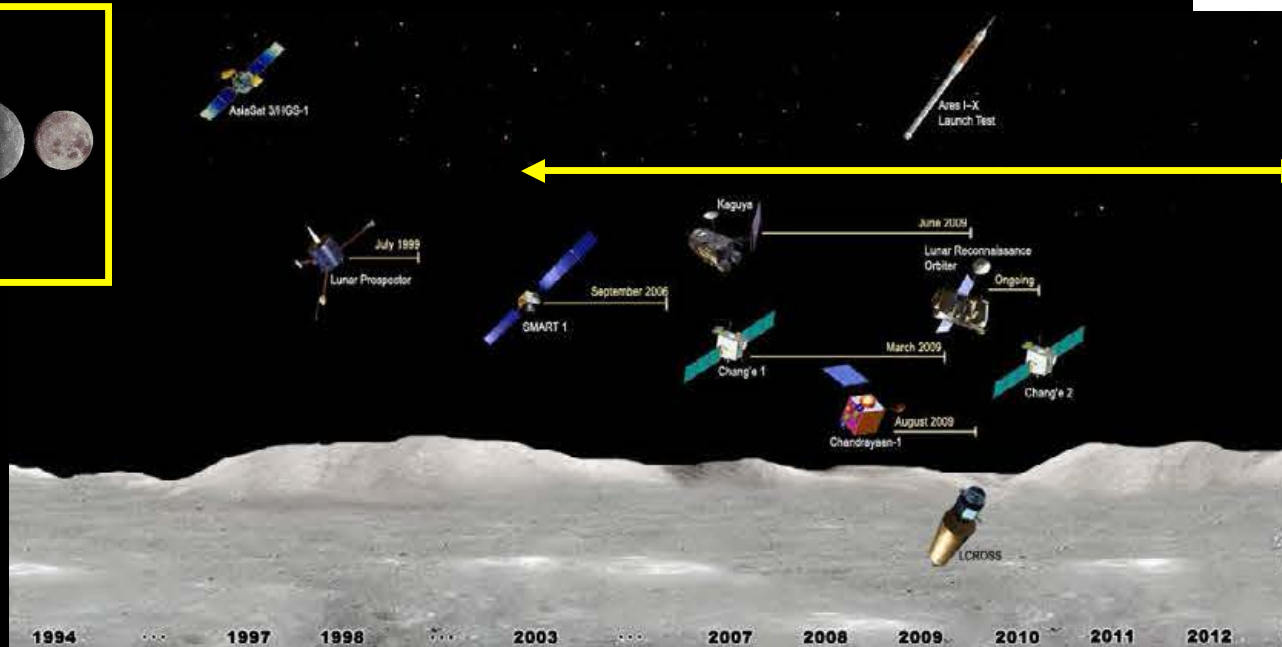
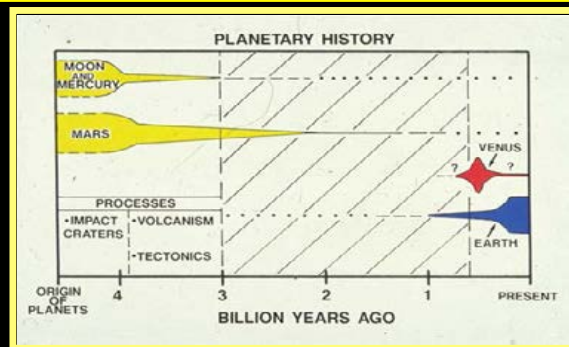
# The Moon as a Cornerstone for Solar System Science



- One or more spacecraft currently/recently orbiting each of the terrestrial planets.
- We have fundamental questions about the formation and evolution of each of these planetary bodies, and together the terrestrial planetary bodies as a whole.
- Many of these questions can only be answered in the context of lunar exploration



-Moon: Dozens of missions, orbiters, landers, rovers, Astronauts!



# Renaissance in Lunar Exploration – Context and Role in Planetary Exploration

- Renaissance: 2003-2023:  
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

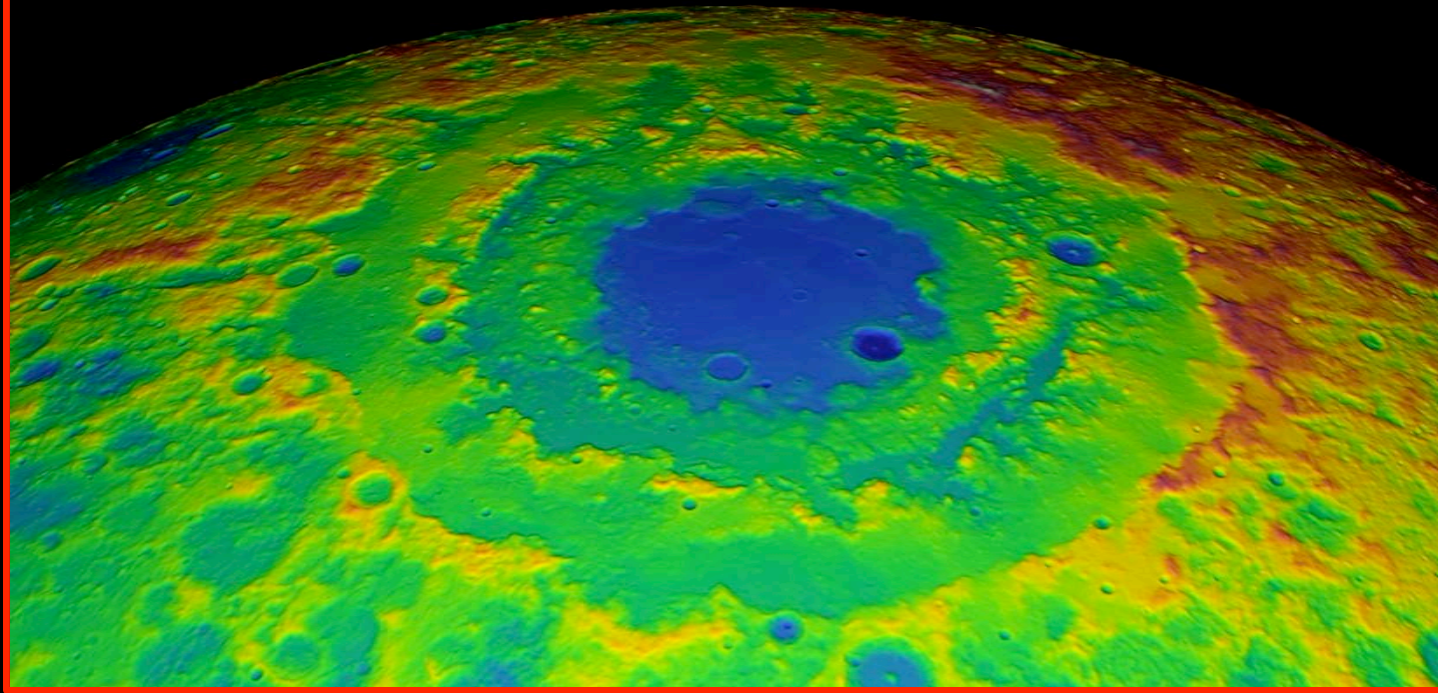
- “Everything has changed  
but our way of thinking.”

A. Einstein.



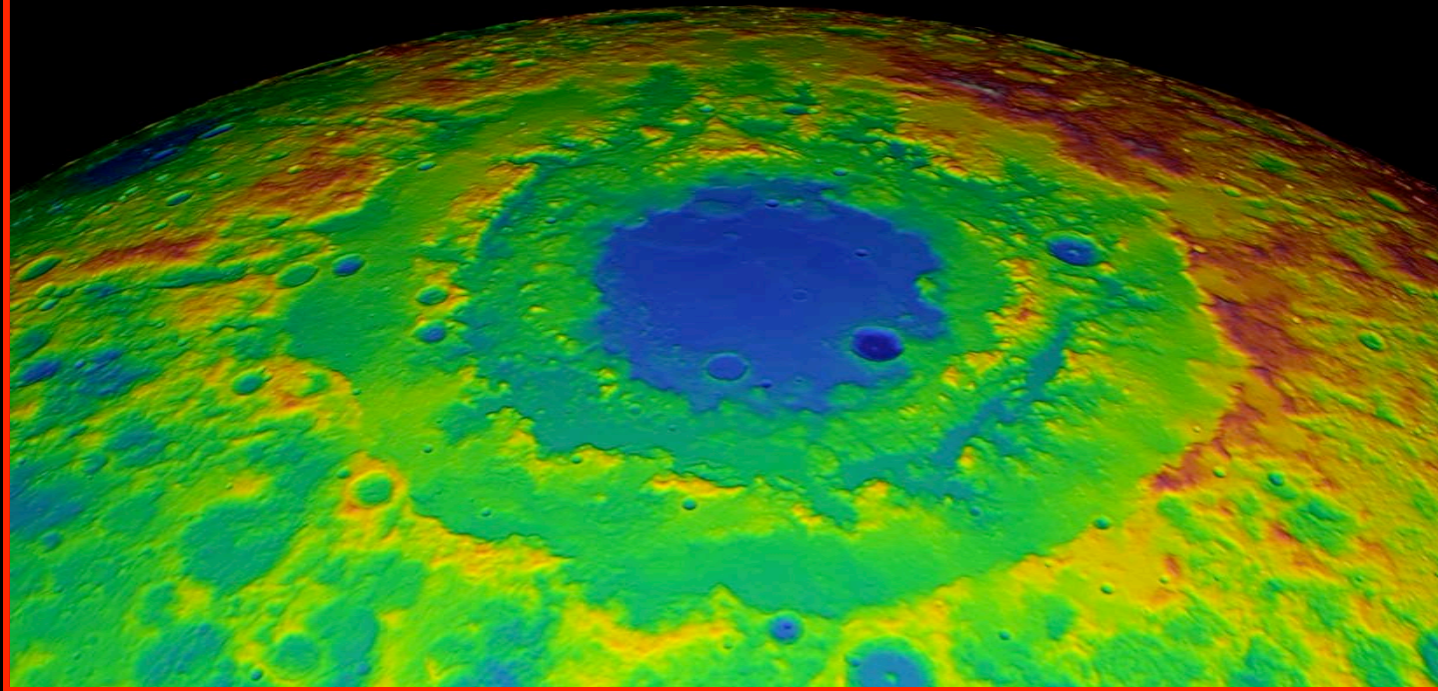
(Modified without permission from *Michelangelo*, 1504)

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



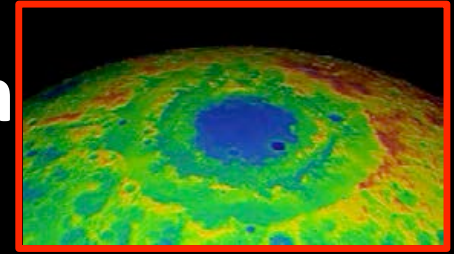
- 1. The importance of coordinated human/robotic exploration.**
- 2. Why the Orientale multi-ring basin?**
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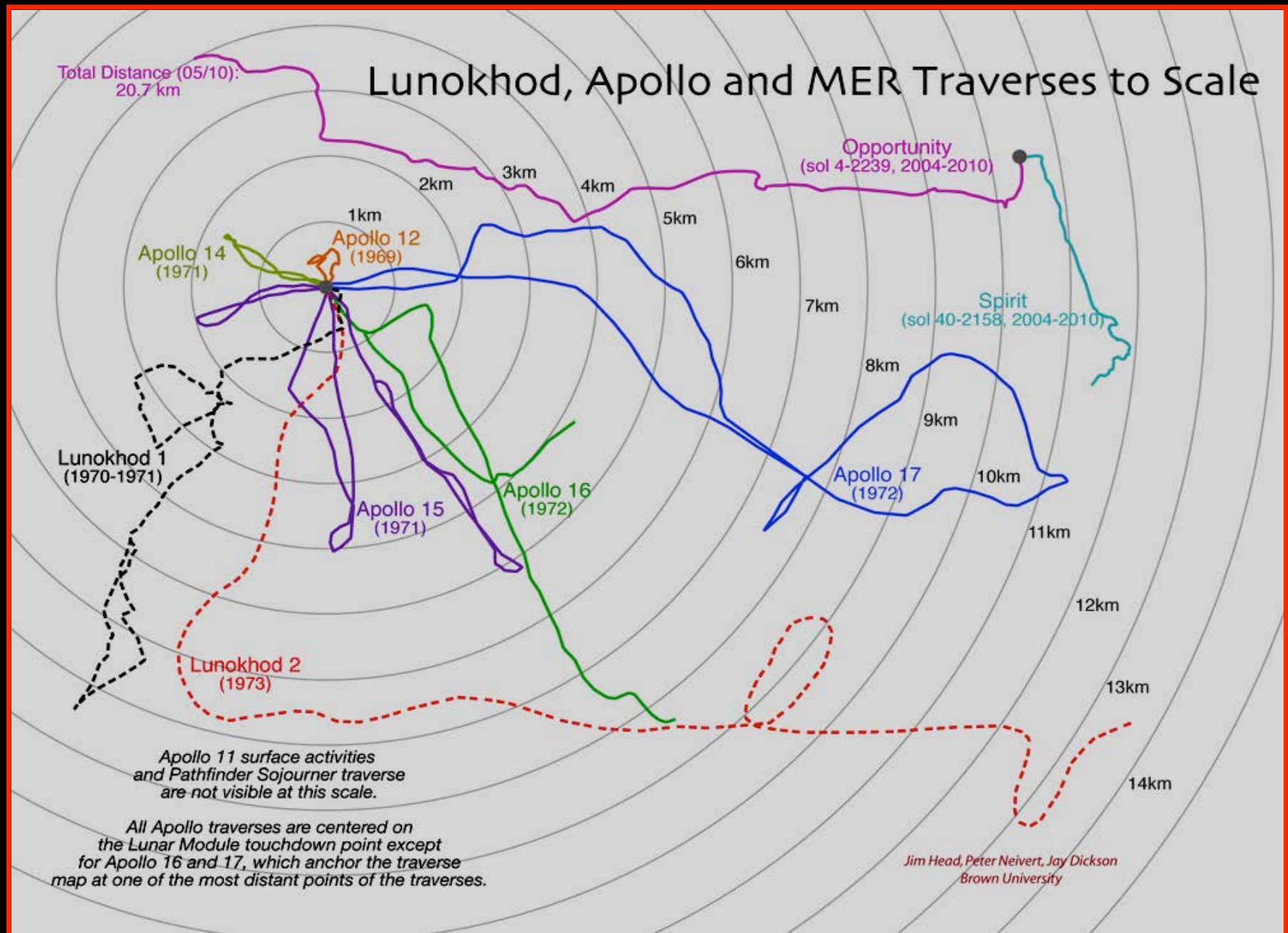
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# Human/Robotic Exploration Optimization Centers on Six Themes



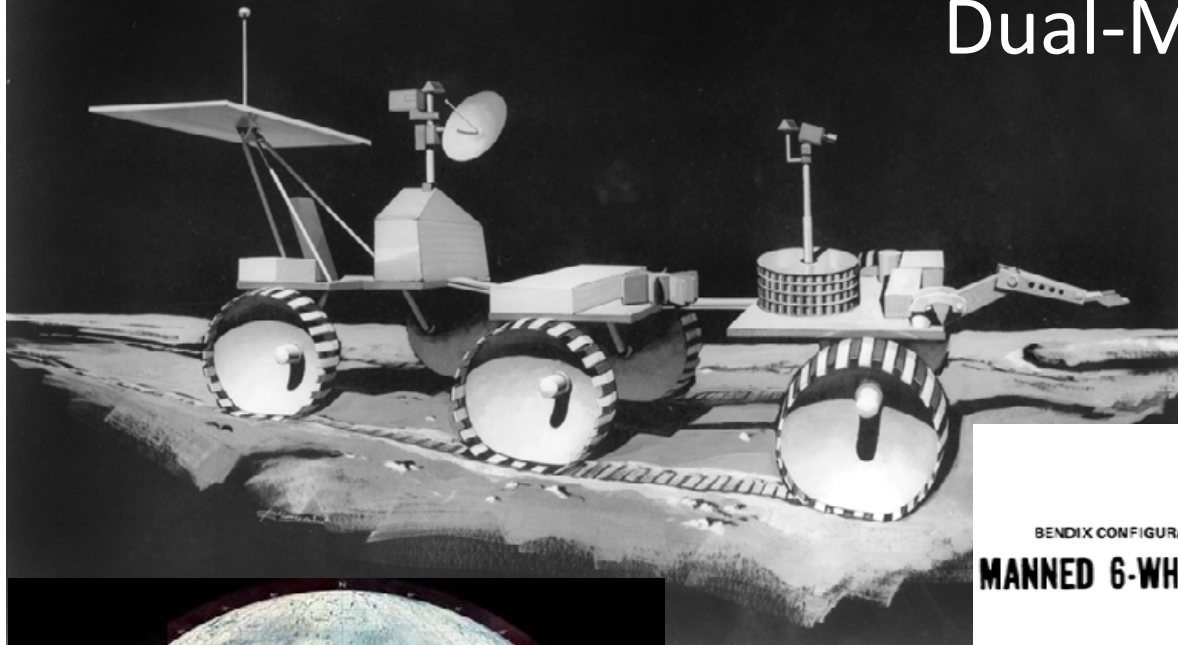
- I) Precursor (What do we need to know before we send humans?).
- II) Context (What are the robotic mission requirements for final landing site selection and regional context for landing site results?).
- III) Infrastructure/Operations (What specific robotic capabilities are required to optimize human 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?

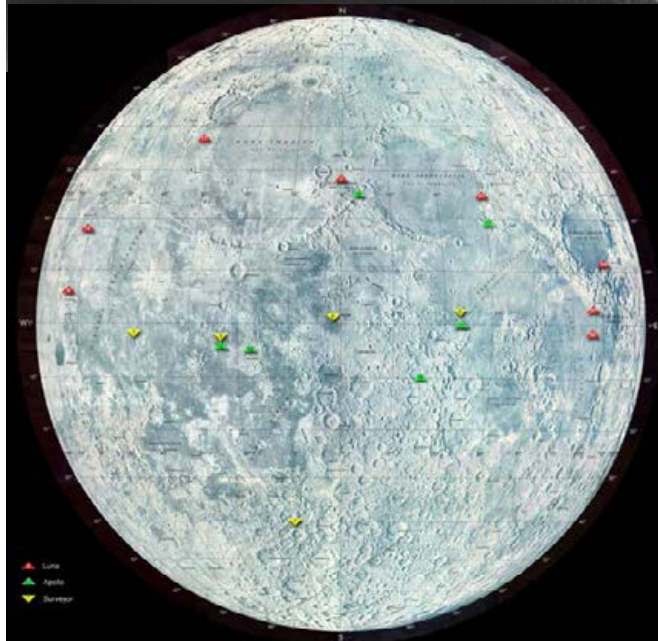


## DUAL MODE ROVING VEHICLE

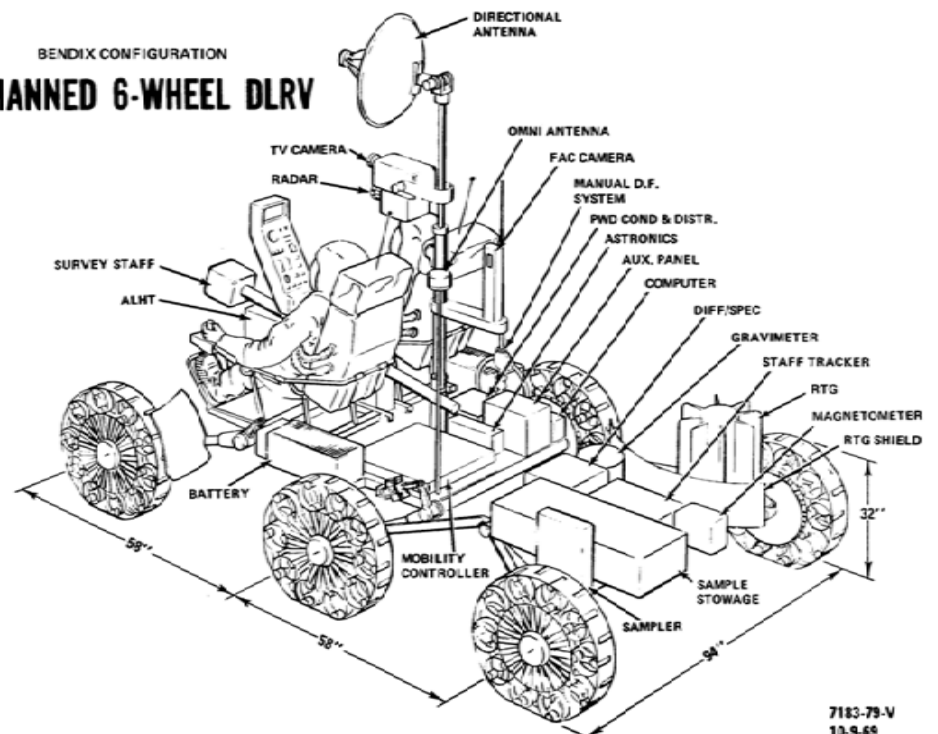
Grumman version - Unmanned configuration



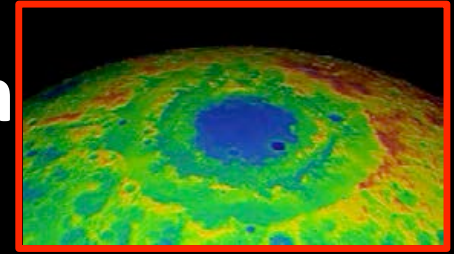
## Apollo 19-21 Dual-Mode Roving Vehicle



### BENDIX CONFIGURATION MANNED 6-WHEEL DLRV

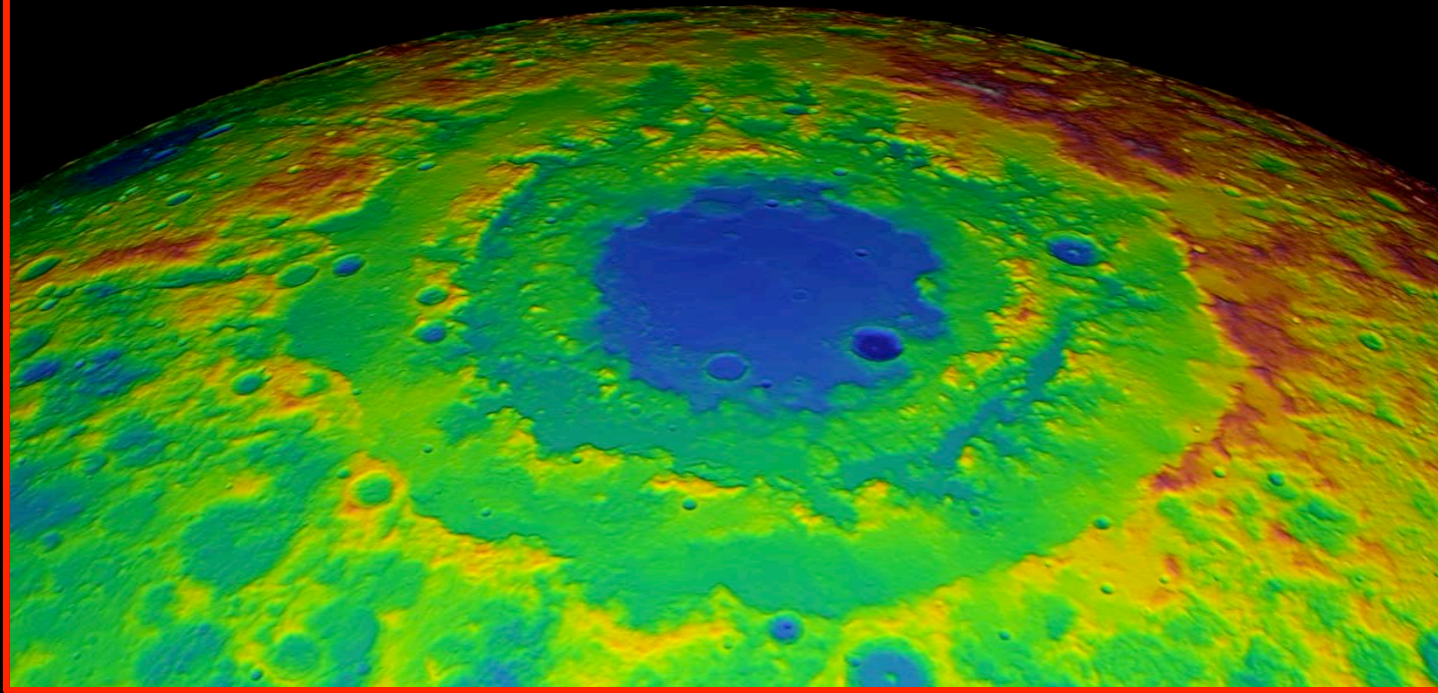


# Human/Robotic Exploration Optimization Centers on Six Themes



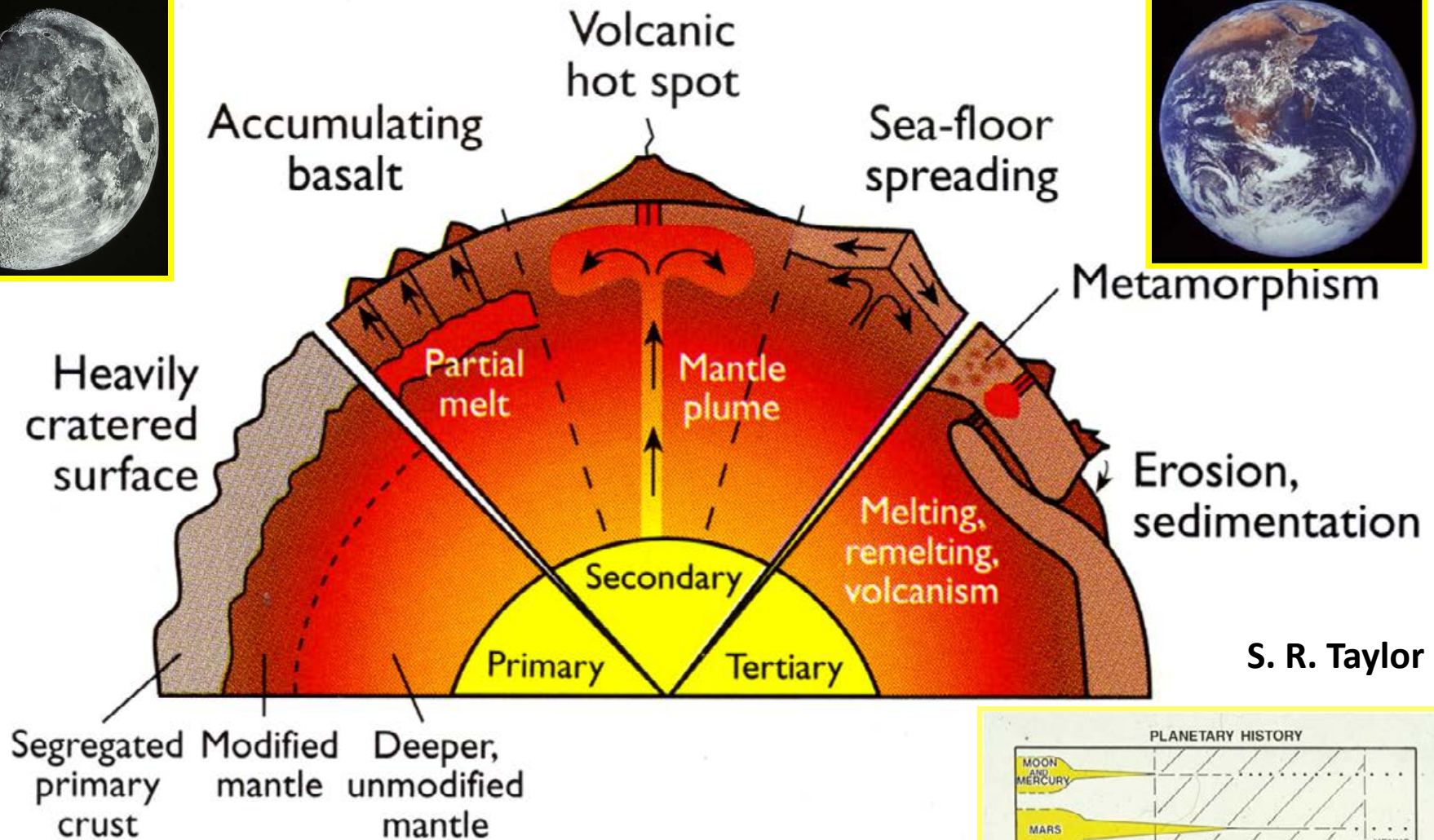
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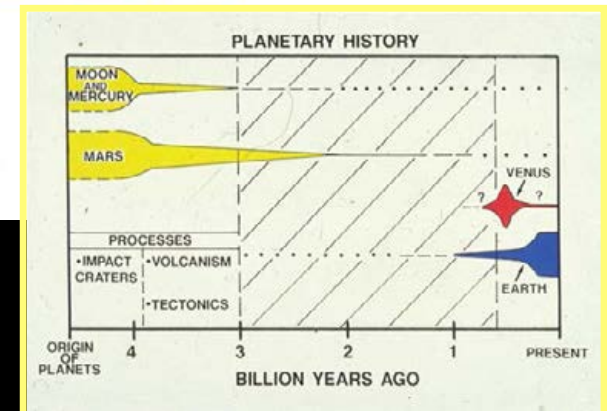
1. The importance of coordinated human/robotic exploration.
2. **Why the Orientale multi-ring basin?**
3. Human/Robotic Scientific Destinations at Orientale.
4. The Human/Robotic Architecture: A Basis for Design Reference Missions.

# Formation and Evolution of Planetary Crusts



S. R. Taylor

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





SSSERVI Evolution and Environment of Exploration Destinations

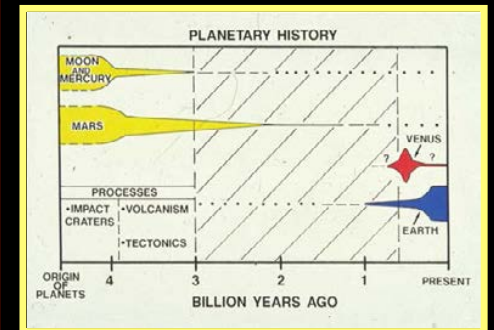


# **MICROSYMPOSIUM 56**

## **The Crust of the Moon: Insight into Early Planetary Processes**

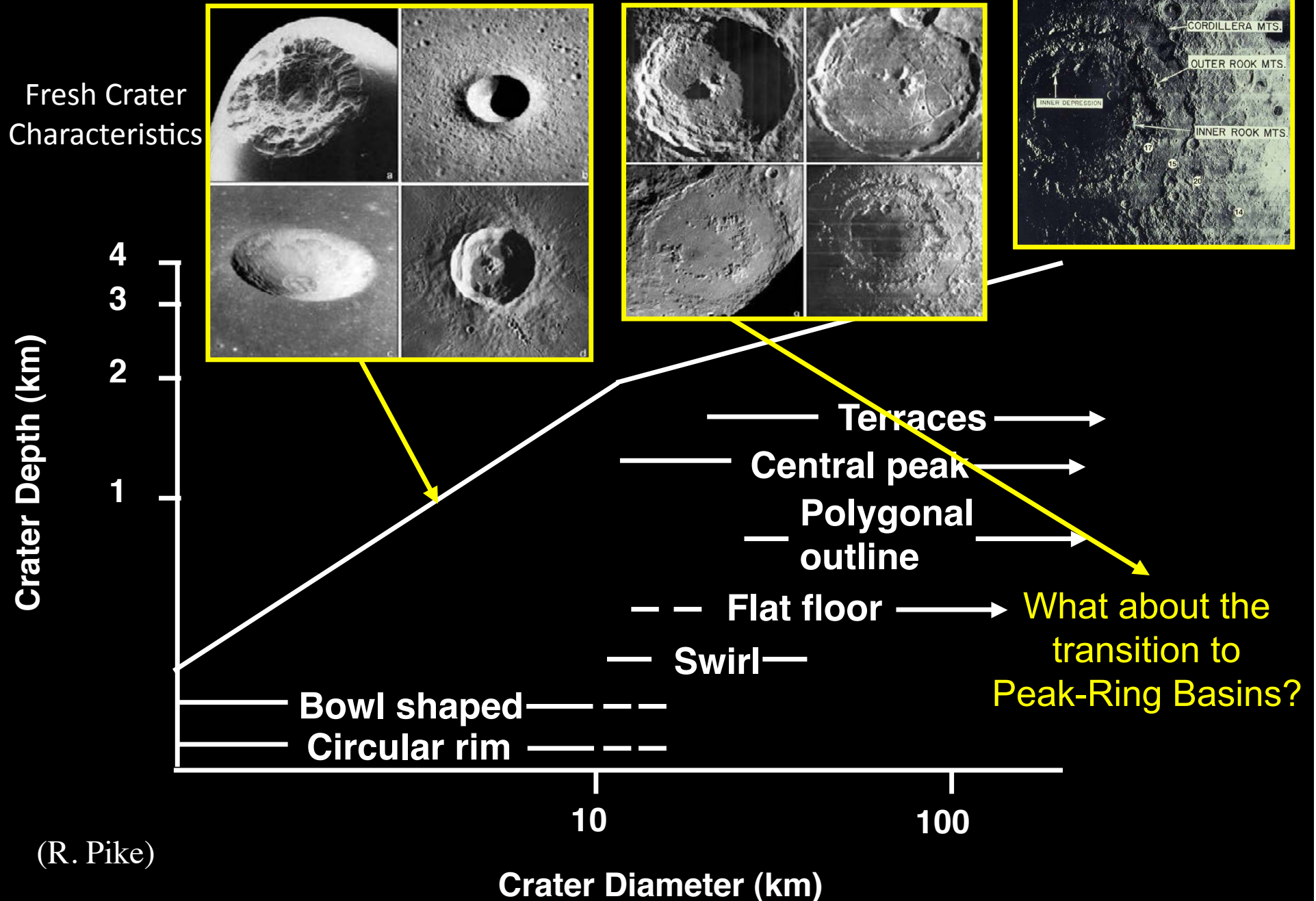
March 14-15, 2015 - The Woodlands Waterway Marriott - The Woodlands, TX

Brown University, Vernadsky Institute, Brown-MIT NASA Solar System Exploration Research Virtual Institute (SSSERVI)

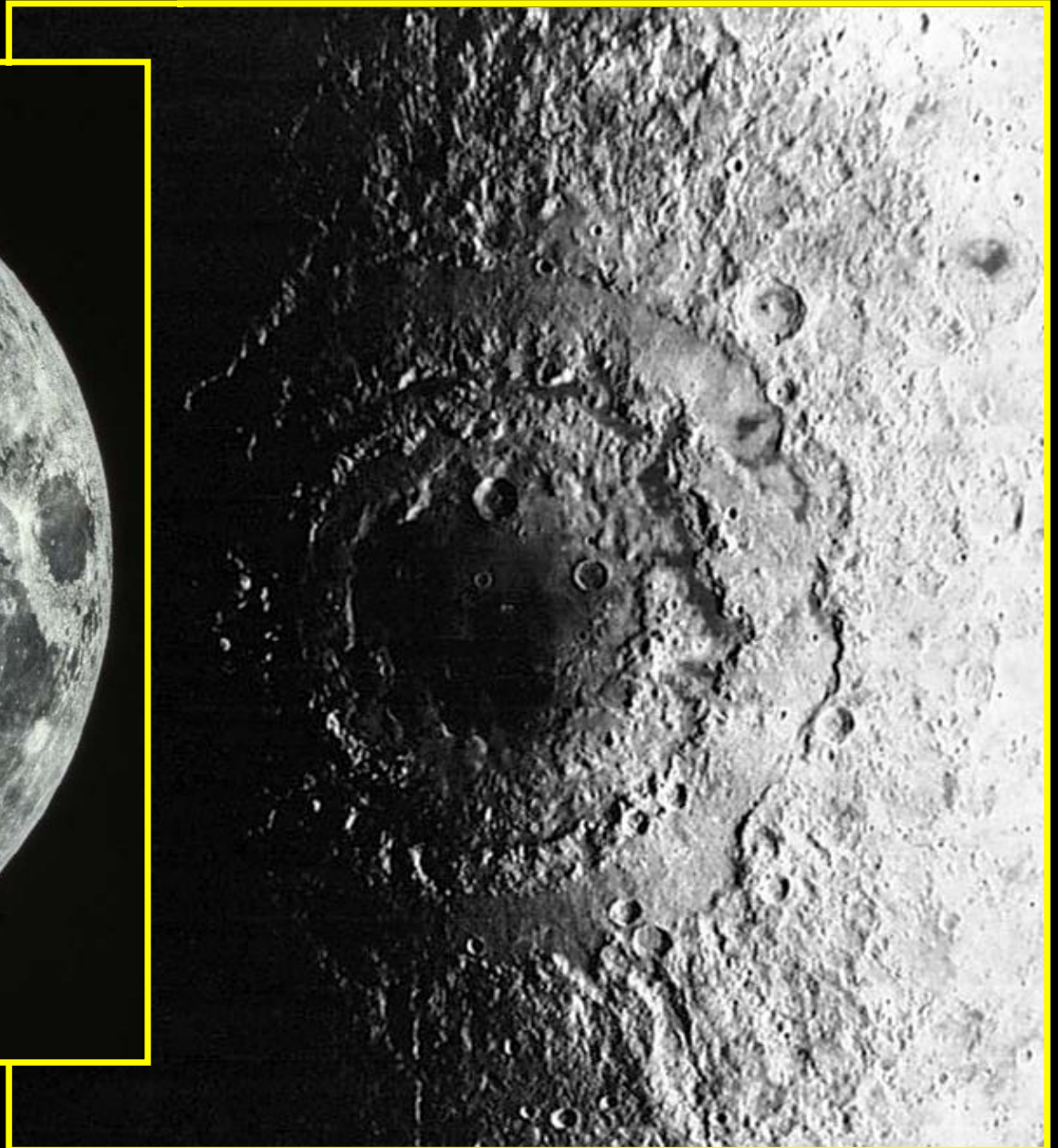


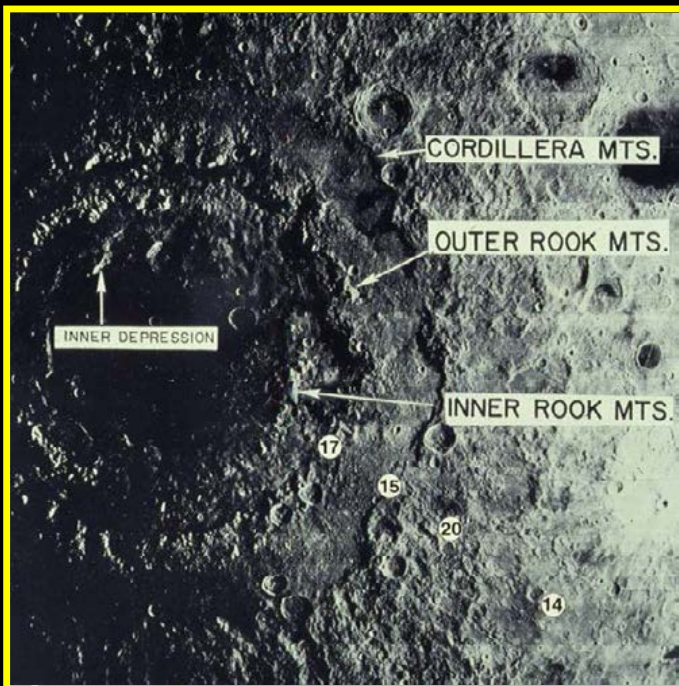
- 1. Crustal geometry/physical structure
- 2. Crustal chemistry/mineralogy/petrology;
- 3. Exogenic crustal modification by impacts;
- 4. Chronology of crustal formation/evolution.

# 1. Major Lunar Features: Multi-ring basins:



## **Lunar Orientale Impact Basin: 2. The Type Area for Lunar Basin Formation and Evolution.**





## **Oriente Basin: Rings & Geologic Units**

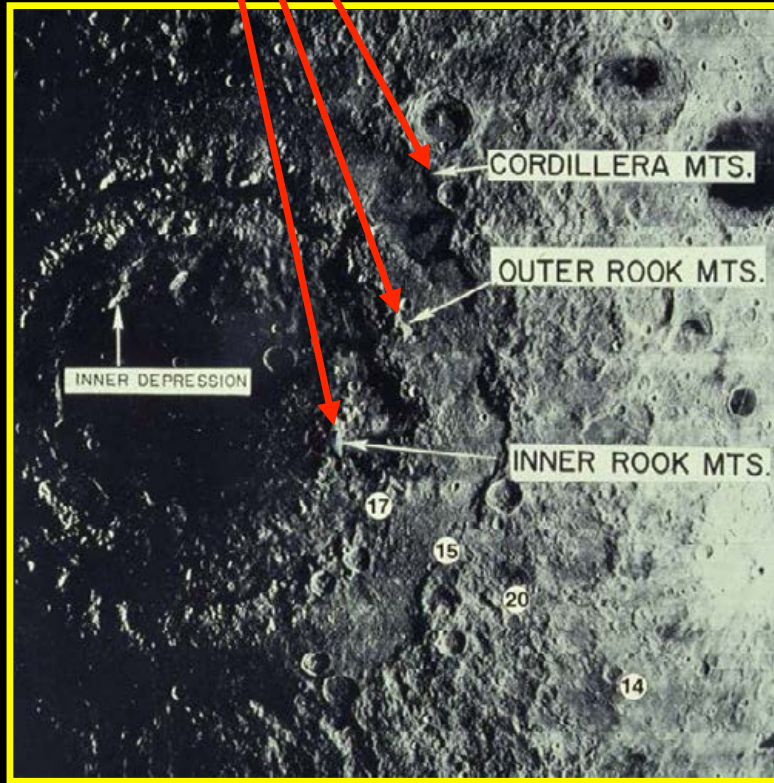
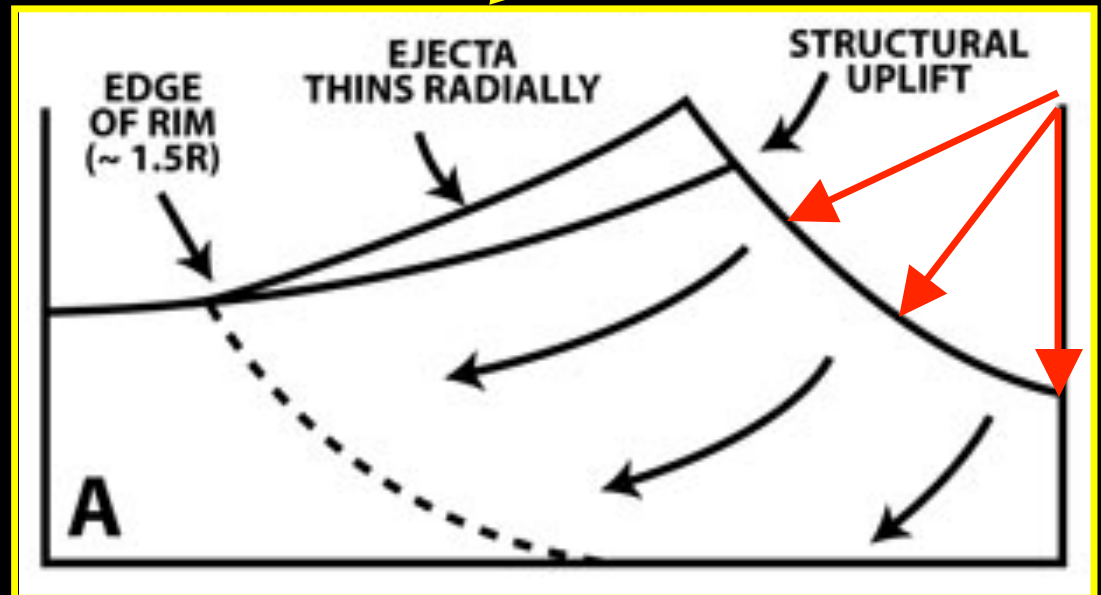
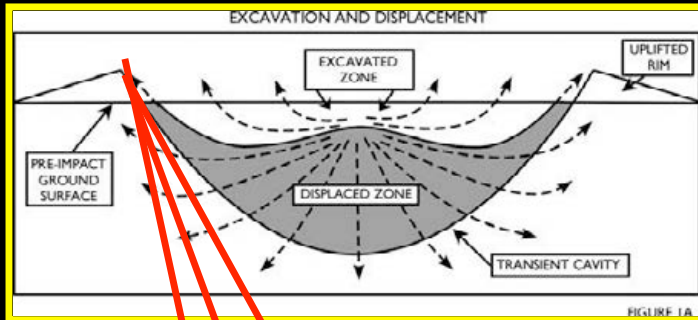
**Hevelius Formation  
(Basin Ejecta Deposit)**

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

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

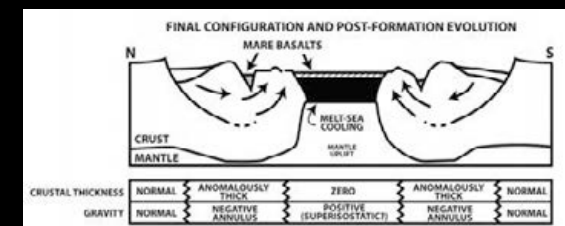
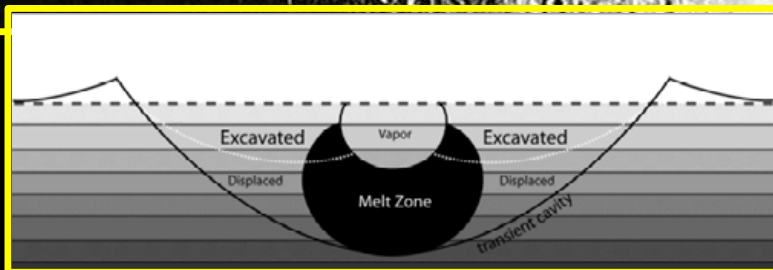
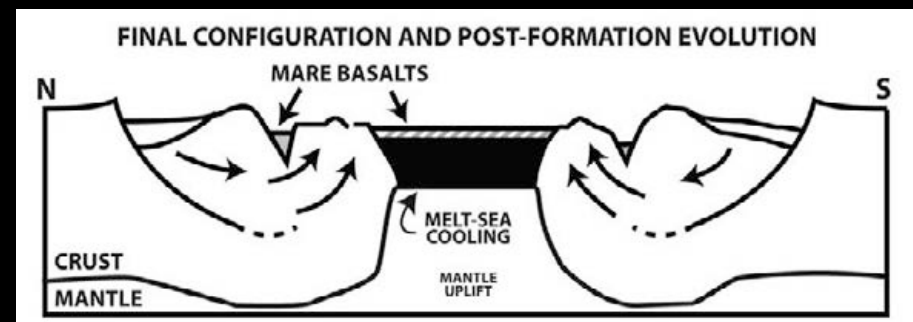
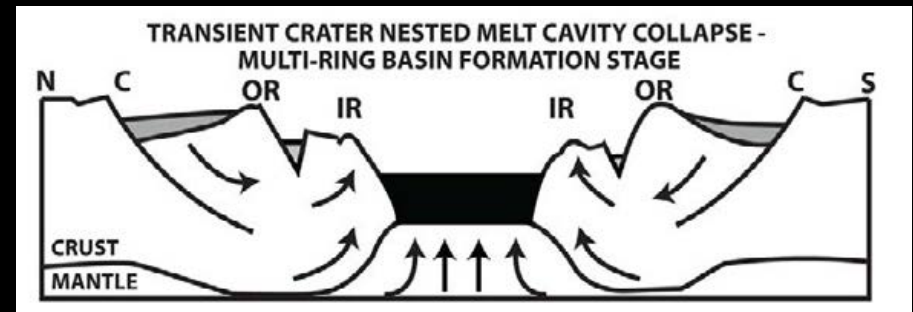
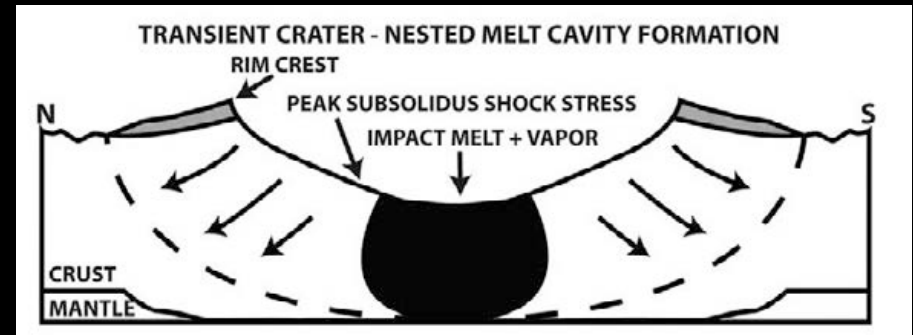
(J. McCauley, D. Wilhelms,  
D. Scott, K. Howard, C. Hodges)

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

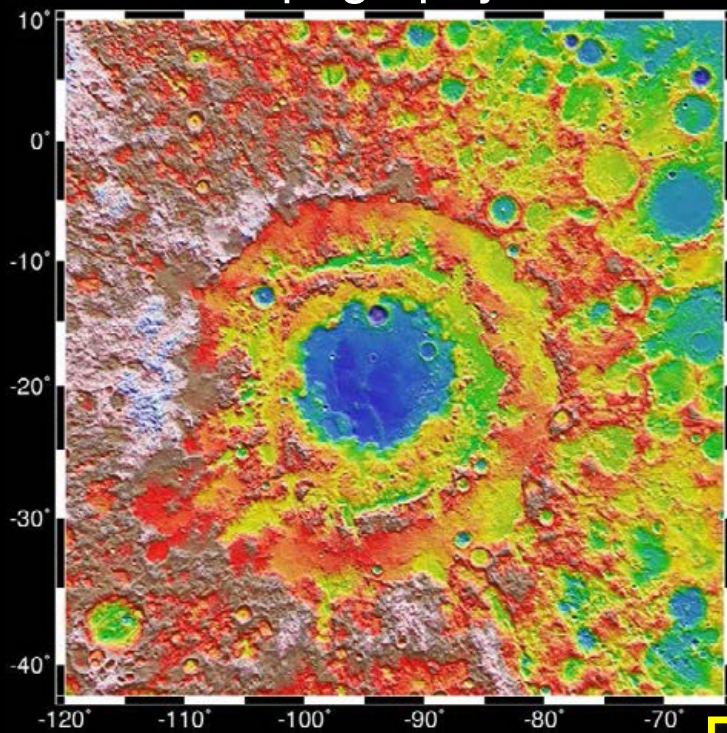


- Displaced and compressed material causes structural uplift of the crater/basin rim.
- Power law decay of ejecta thickness radially away from crater/basin rim crest.
- Combined topography decays to  $<10\%$  of rim crest height within  $\sim 1.5$  crater radius.

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



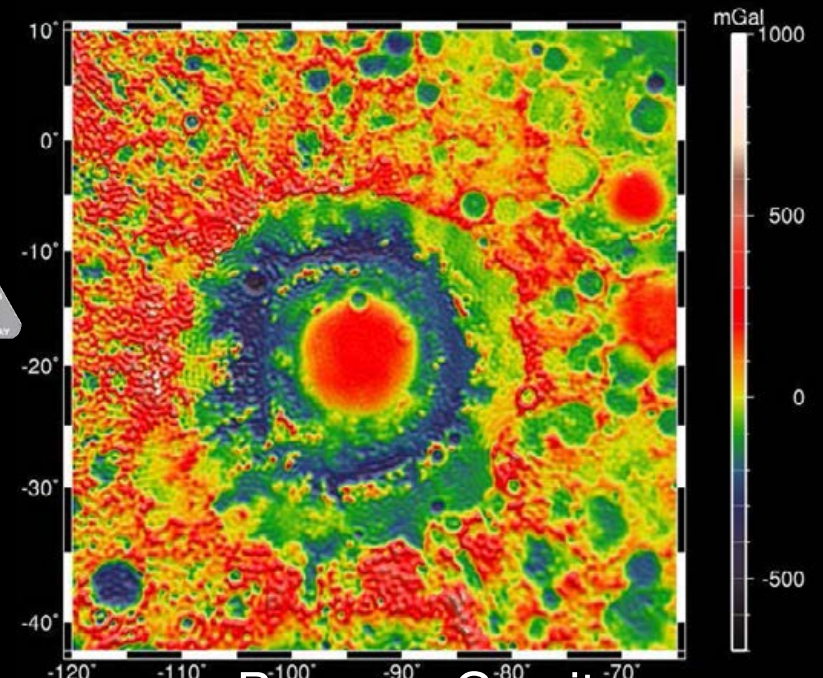
# Topography



# Orientale Basin

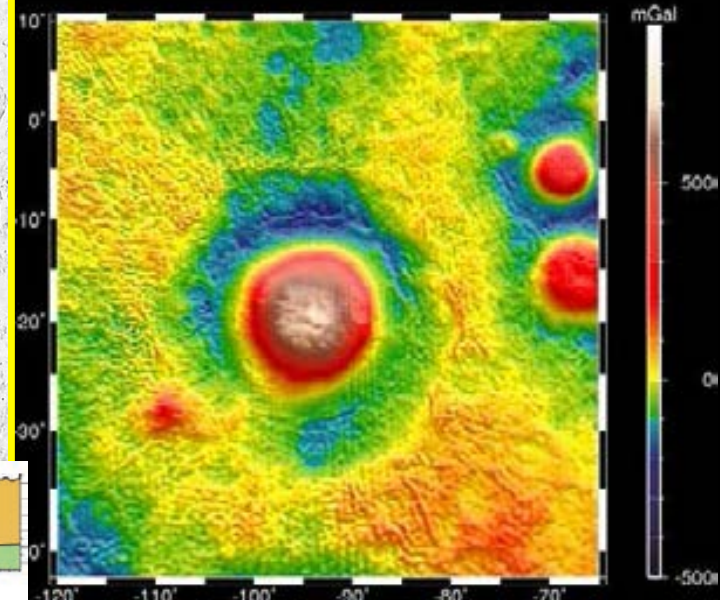
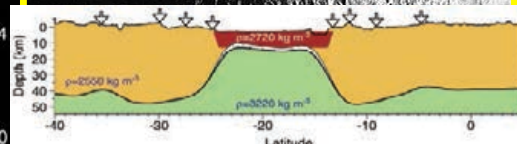
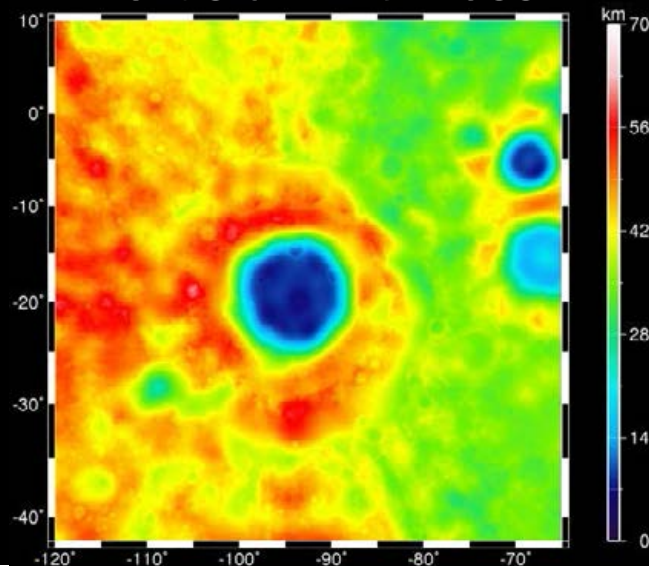


# Free-air Gravity

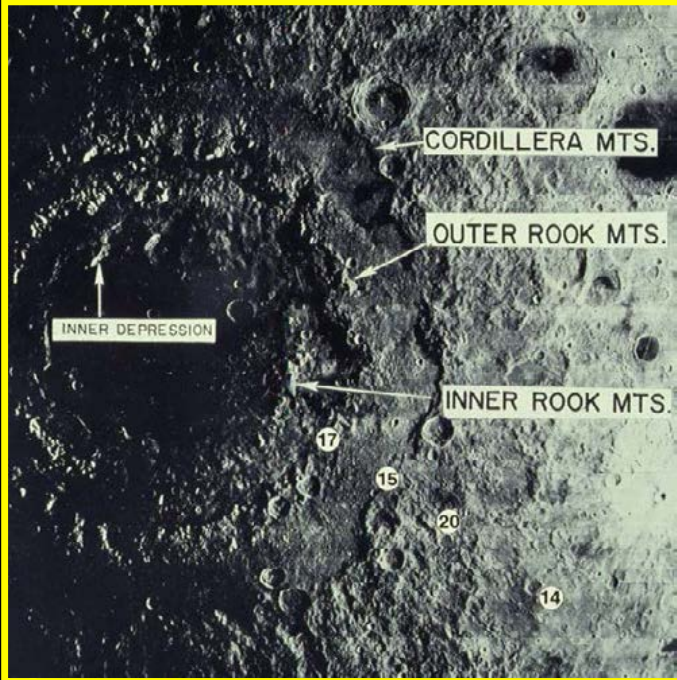


# Bouguer Gravity

# Crustal Thickness



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



**Orientale Basin:  
Rings & Geologic Units**

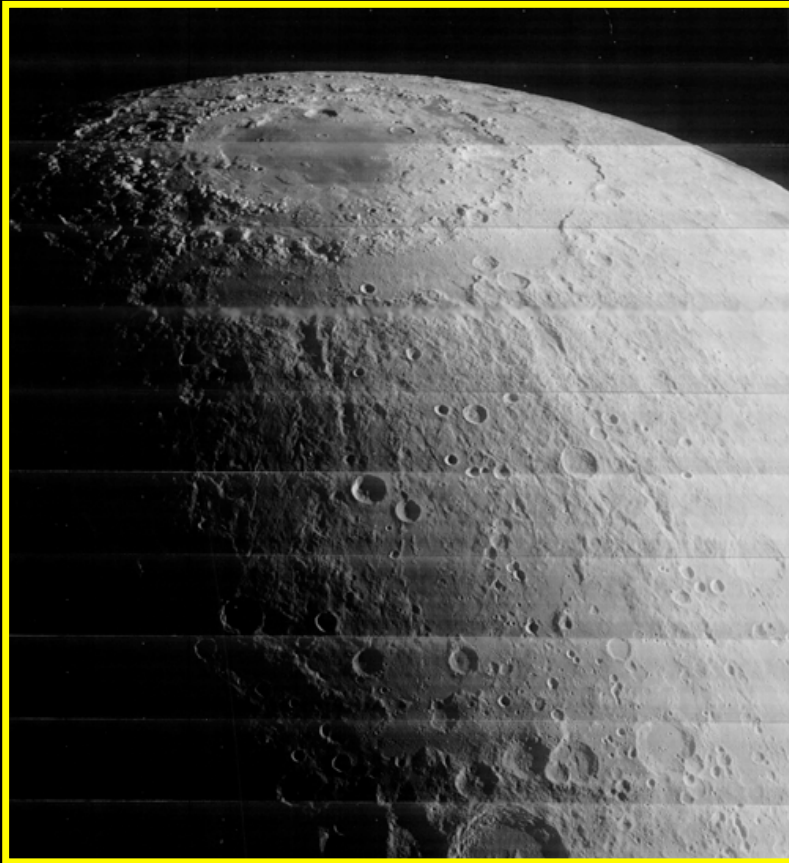
**Hevelius Formation  
(Basin Ejecta Deposit)**

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

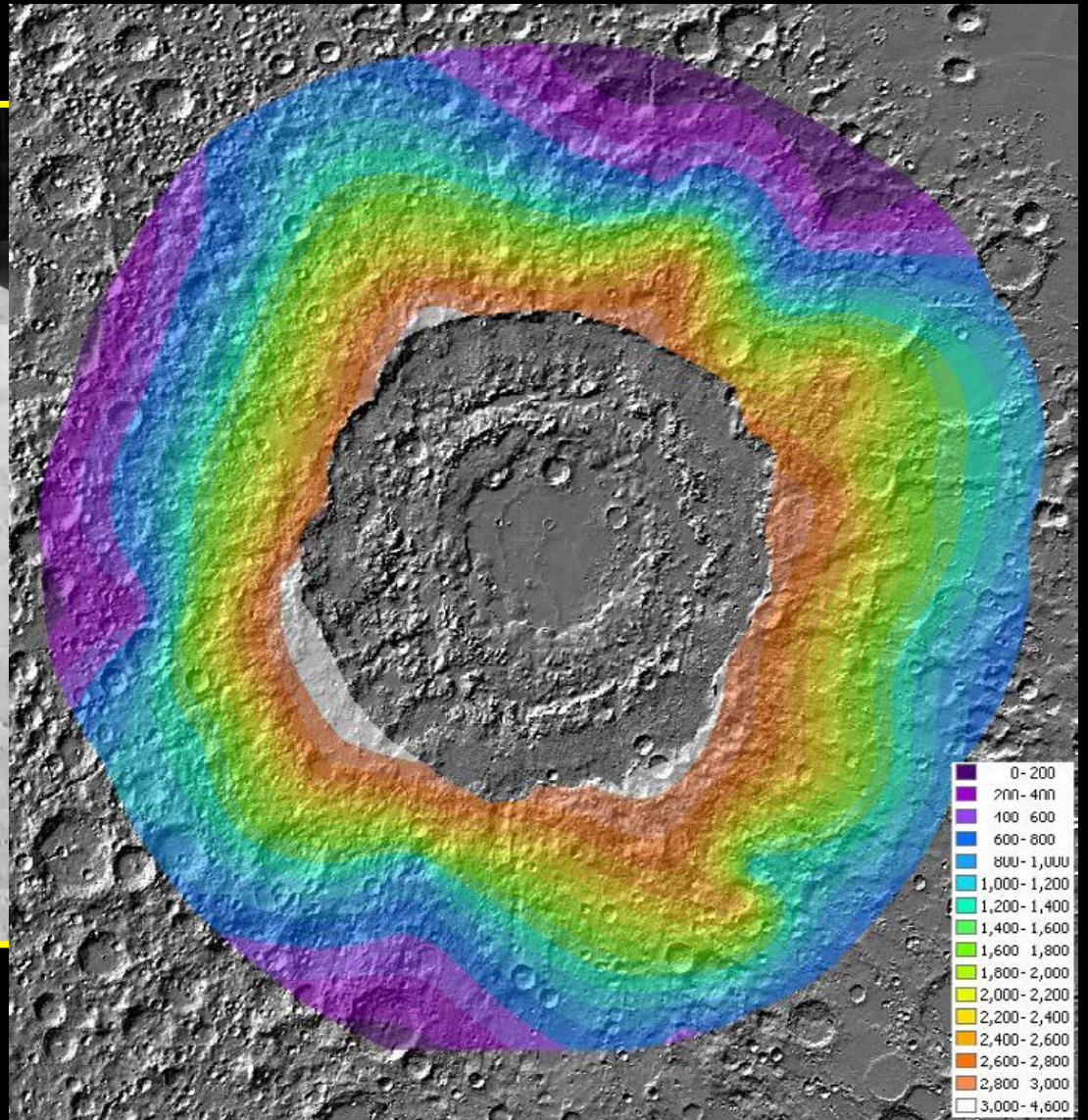
**Maunder Formation  
(Basin Impact Melt Deposit)**

(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**

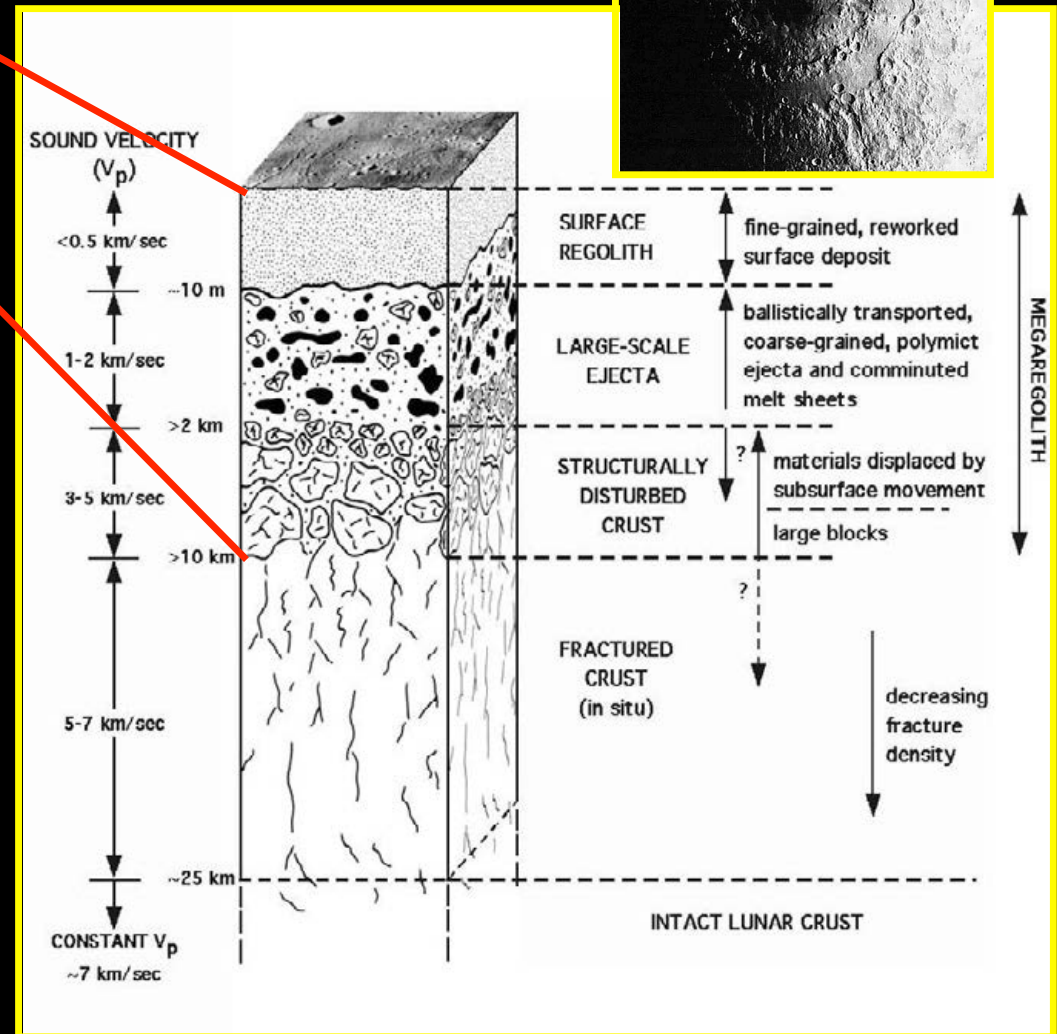
## 6. Structure and Composition of the Lunar Crust: The Magma Ocean Model



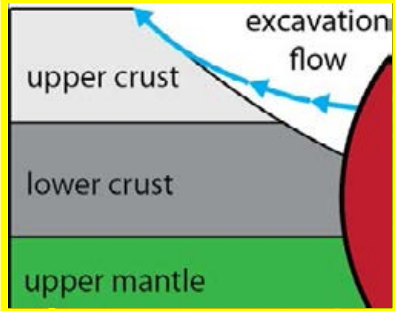
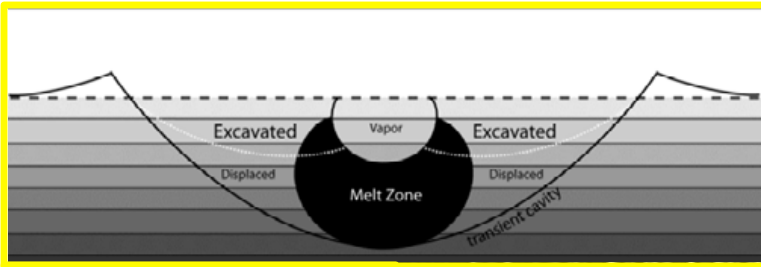
Megaregolith  
(~10 km thick)

Upper Anorthositic Crust  
(~15 km thick)

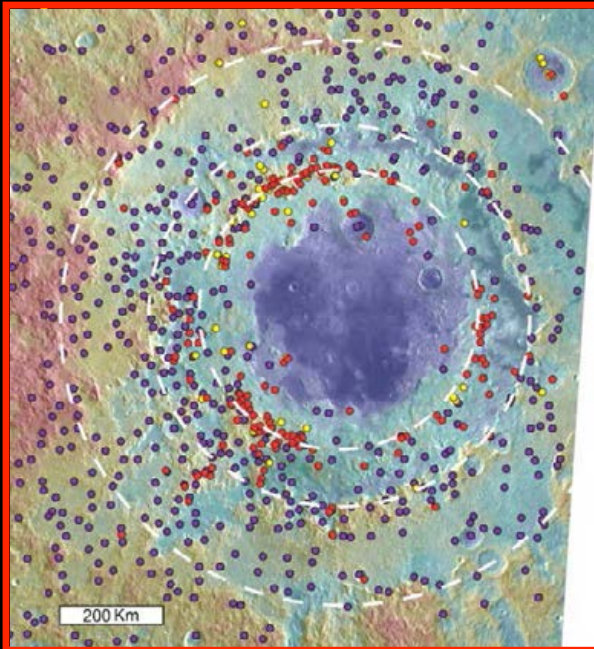
Lower Noritic Crust  
(~25 km thick)



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



Moon Mineralogy Mapper (M3)



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



## Oriente 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:

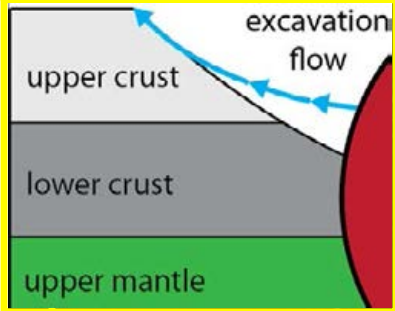
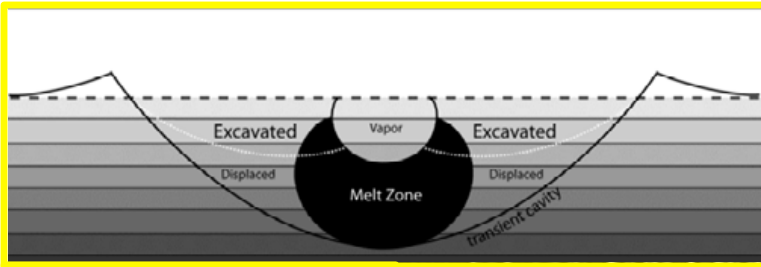
Norites, noritic anorthosite  
and anorthosite; more crystalline  
blocks.

### Inner Rook Mountains:

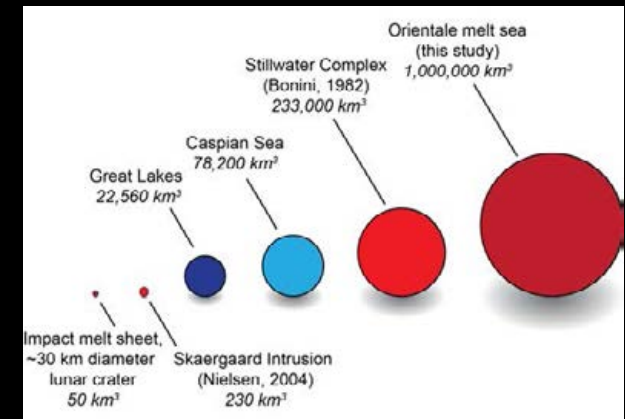
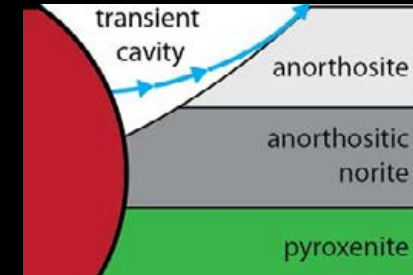
Massifs are crystalline anorthosite;  
discrete peaks and clusters of peaks.

### Maunder Formation (Basin Impact Melt Deposit)

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



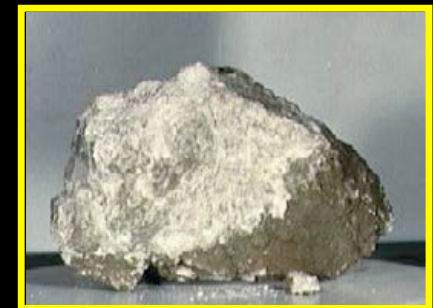
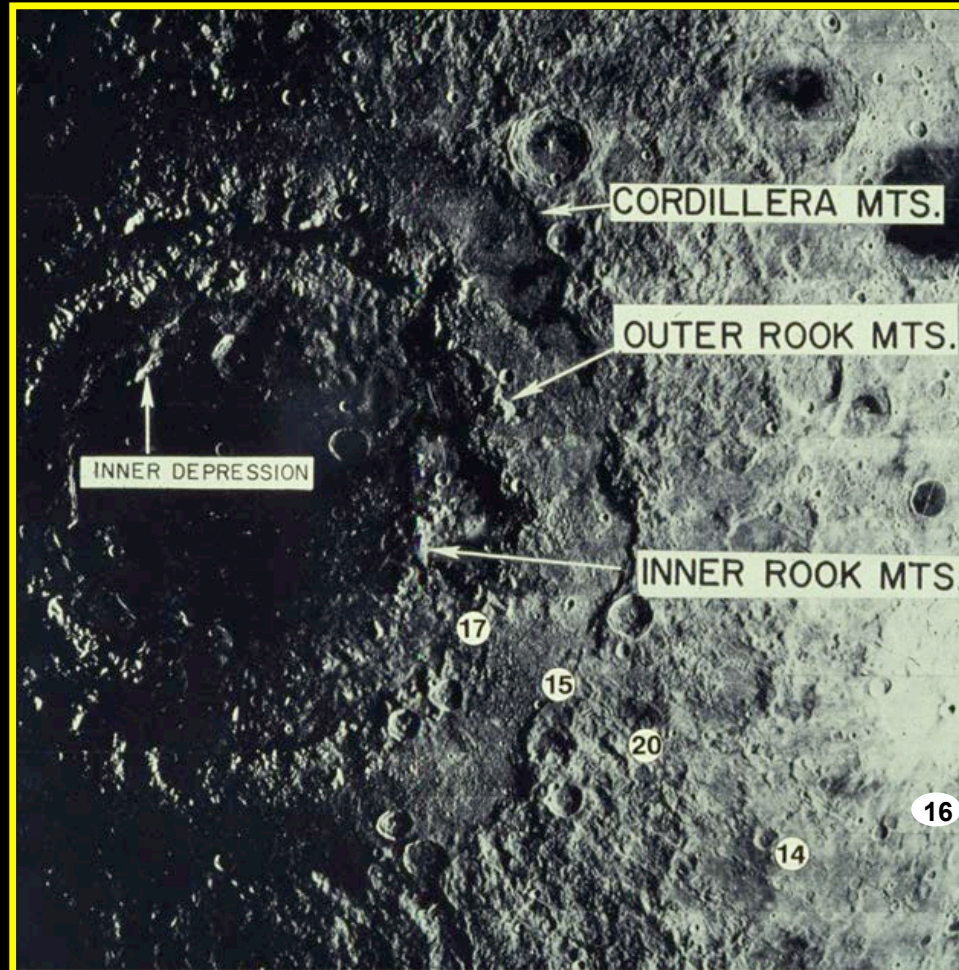
## 7. Orientale Impact Melt Sea



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

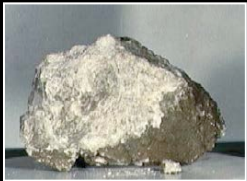
(Wilson and Head, 2010;  
Vaughan et al, 2011, 2012)

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





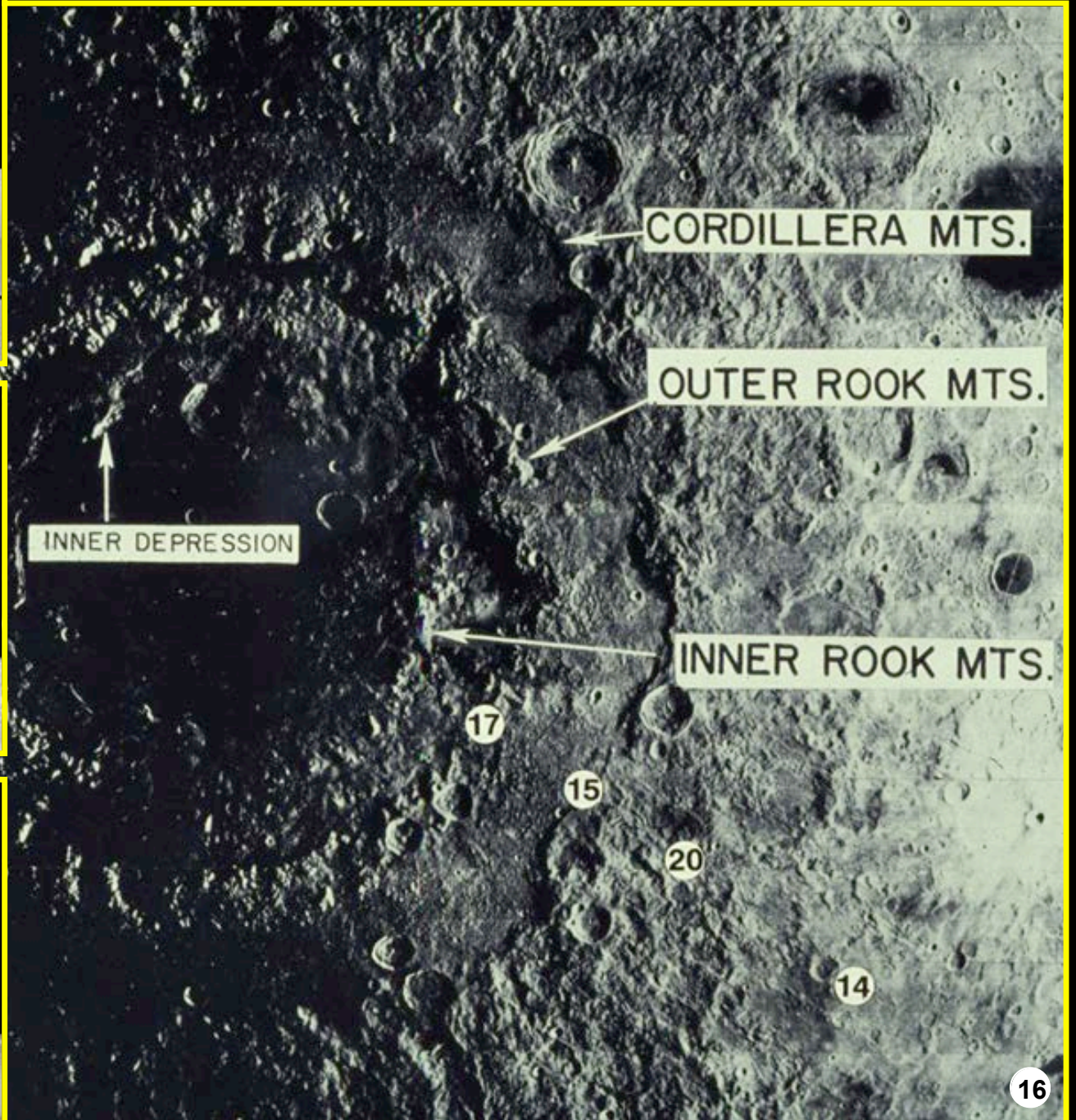
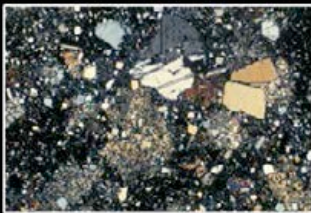
## APOLLO 17



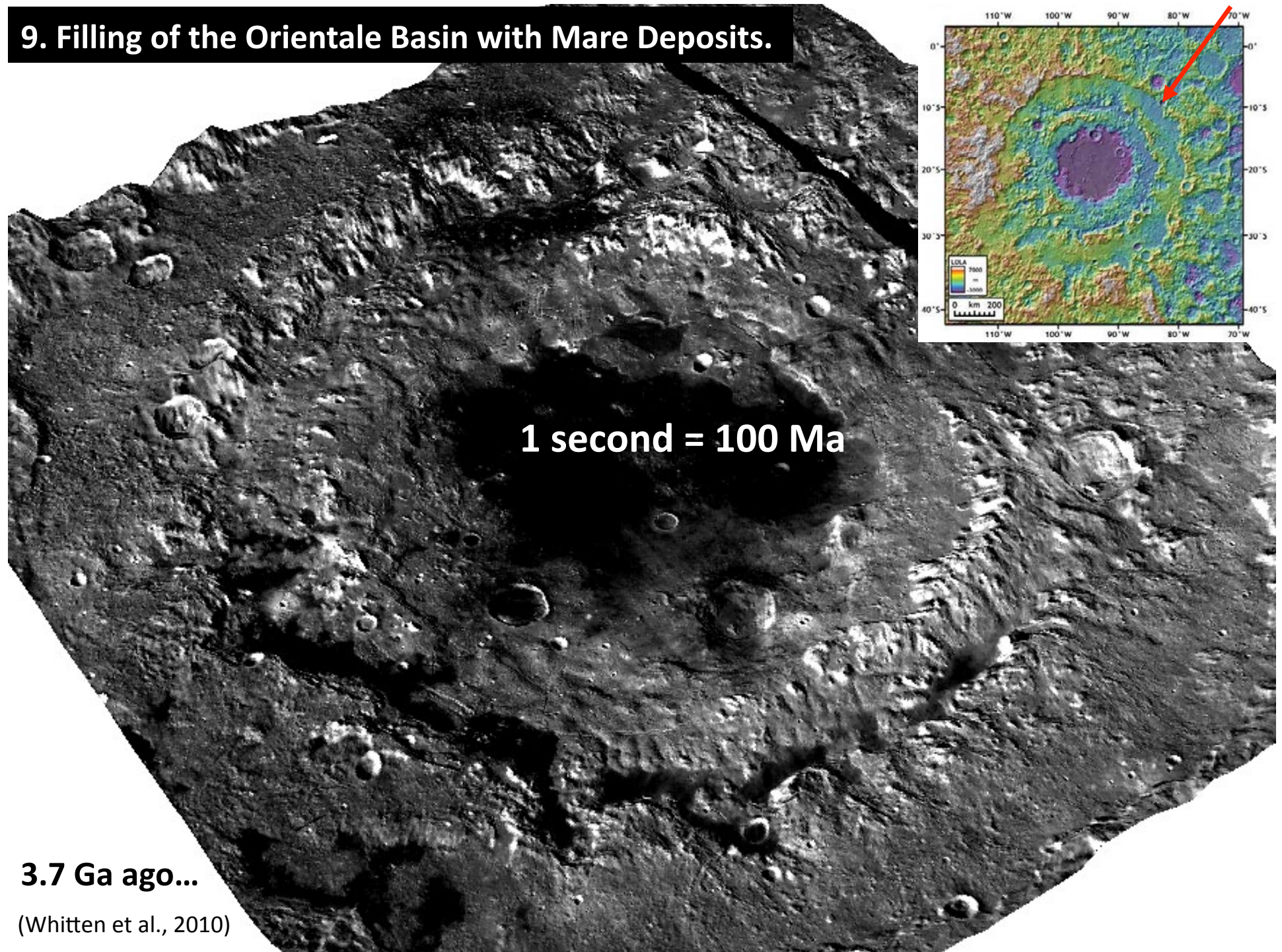
## APOLLO 15



## APOLLO 16



## 9. Filling of the Orientale Basin with Mare Deposits.



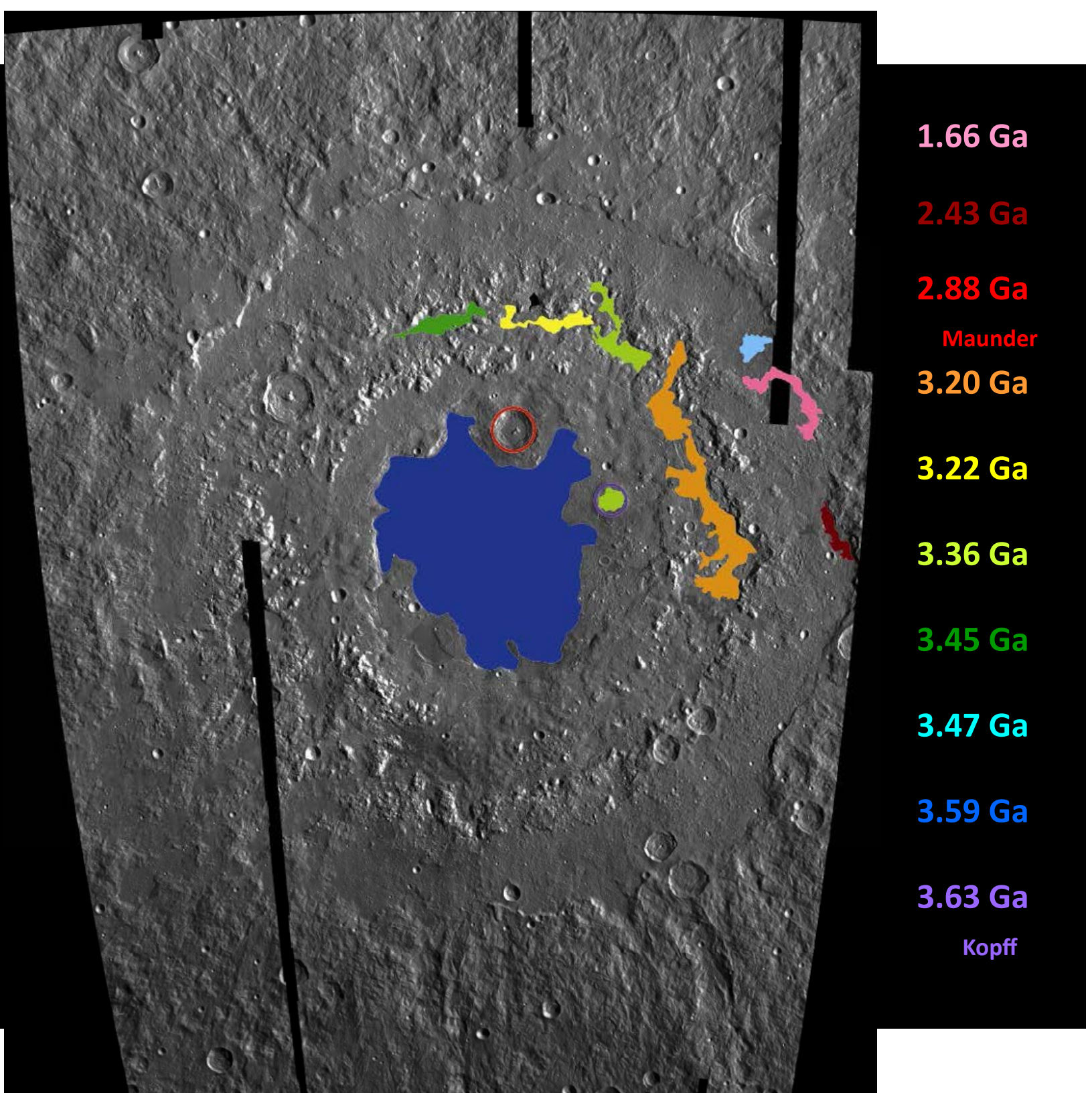
**3.7 Ga ago...**

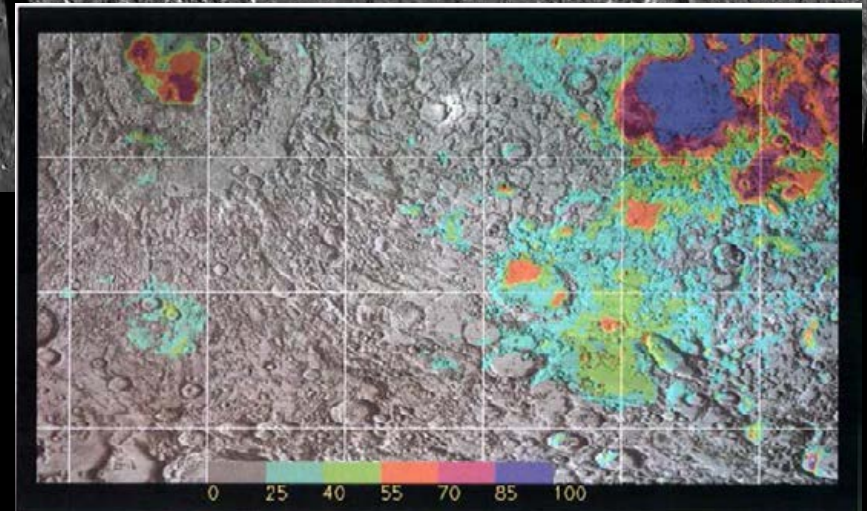
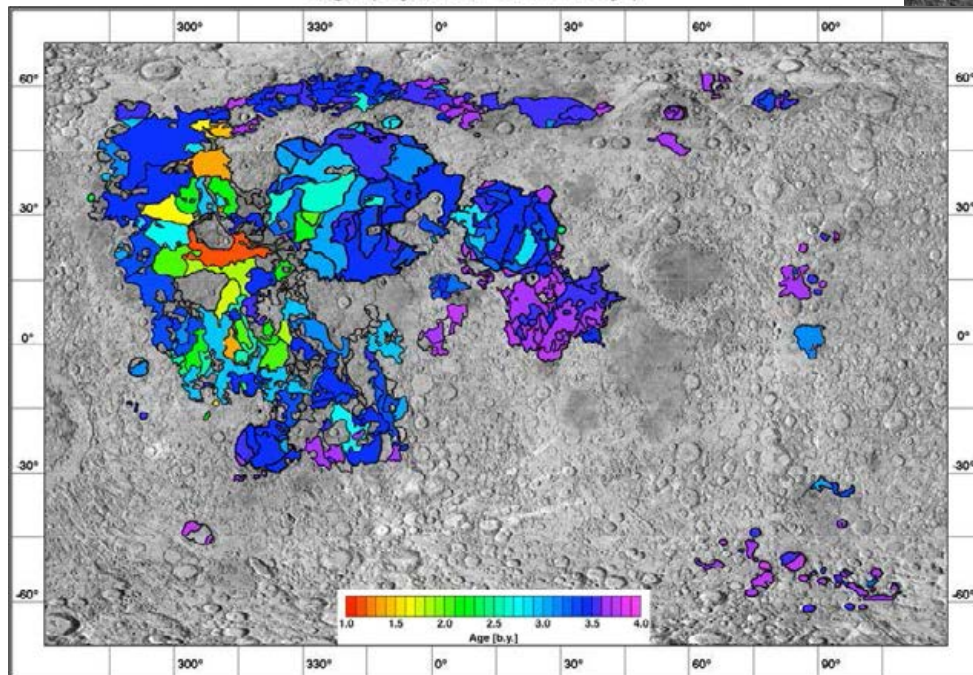
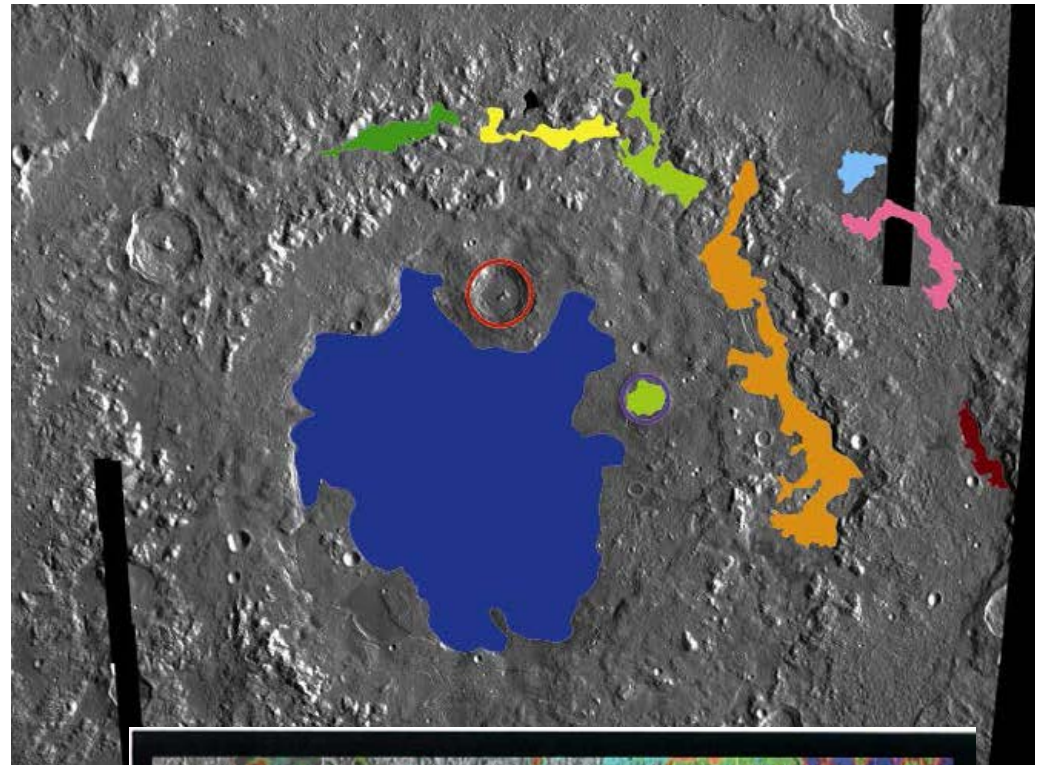
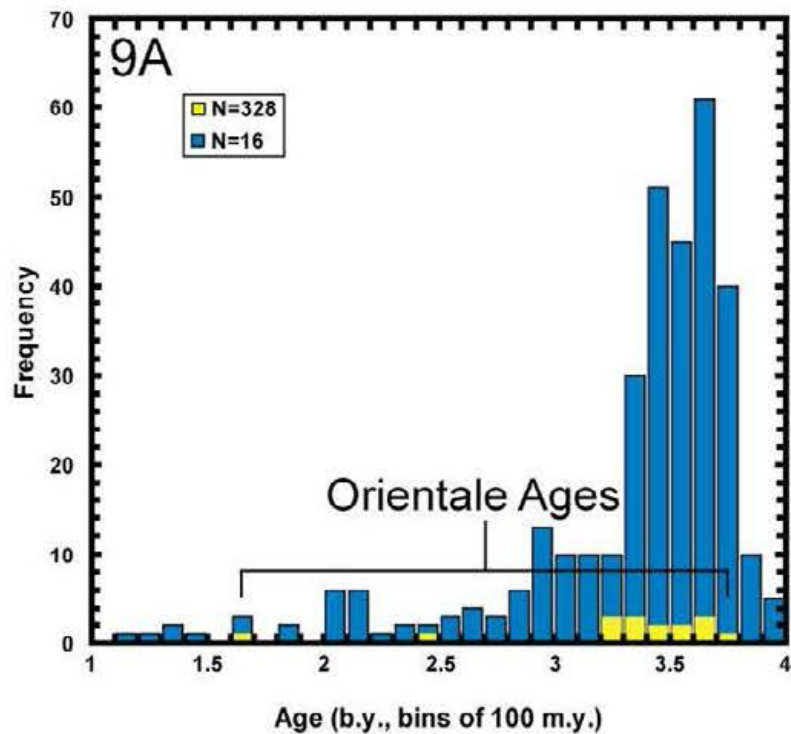
(Whitten et al., 2010)



**1 second = 100 Ma**

**3.7 Ga ago...**

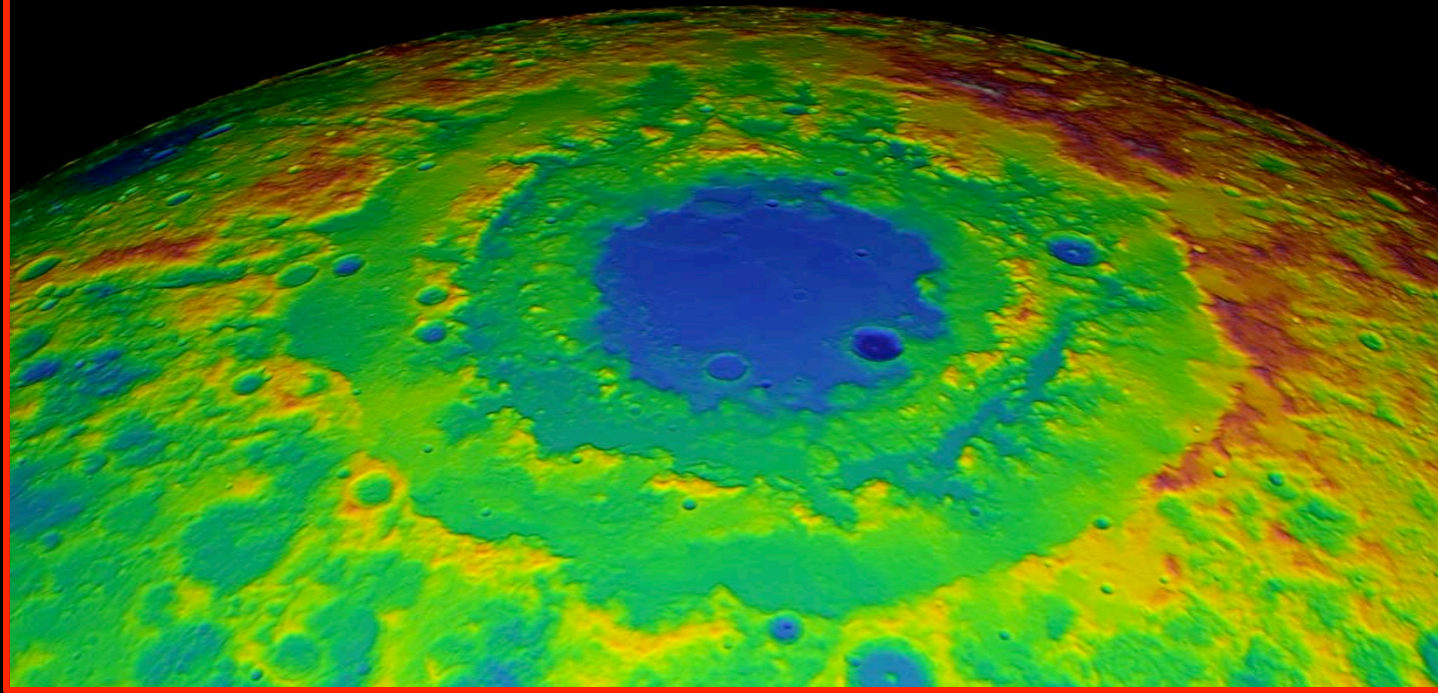




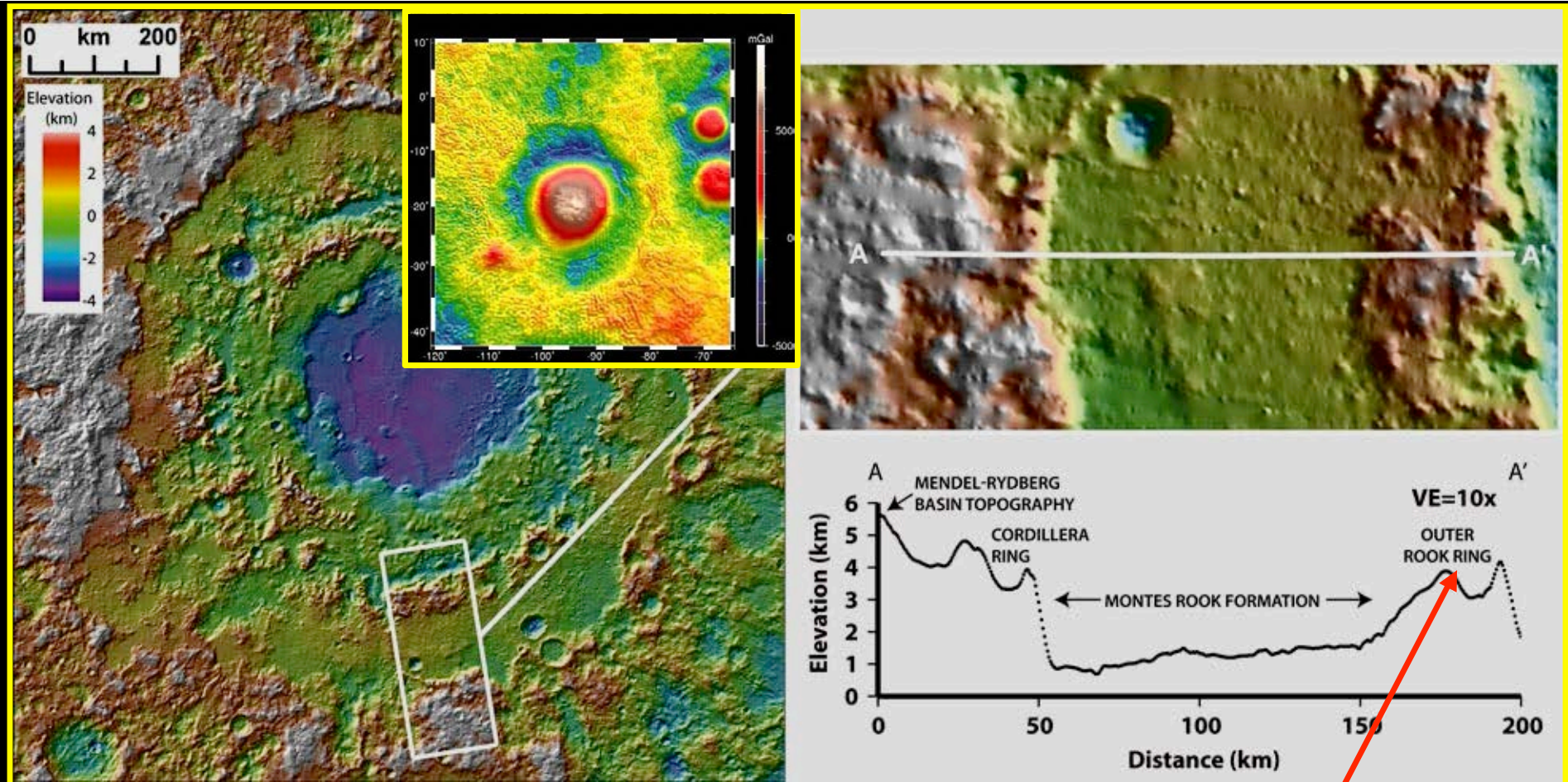
Summary of Orientale Maria  
Lessons for South Pole-Aitken Basin

(Whitten et al., 2010)

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

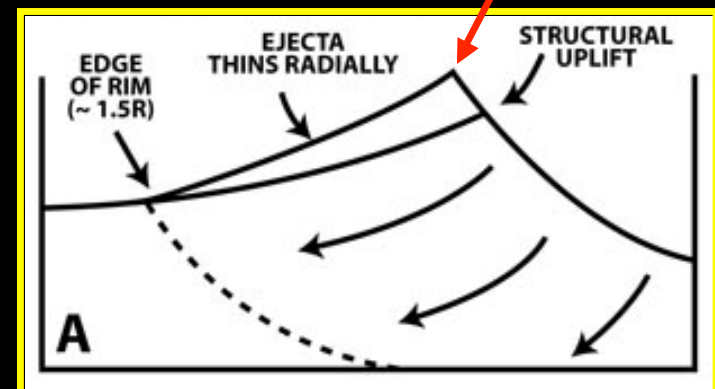


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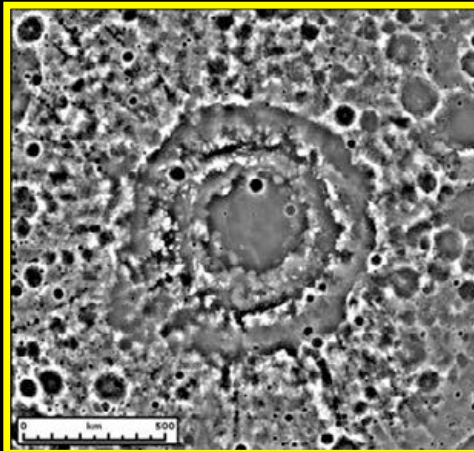
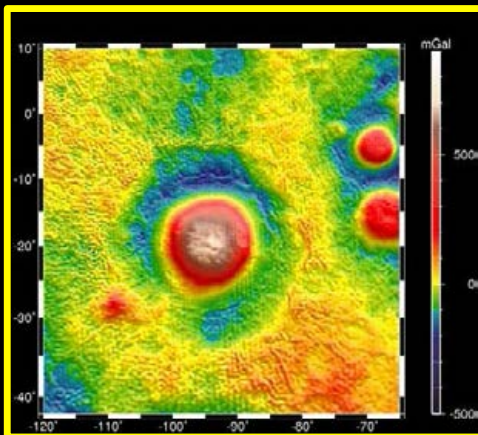
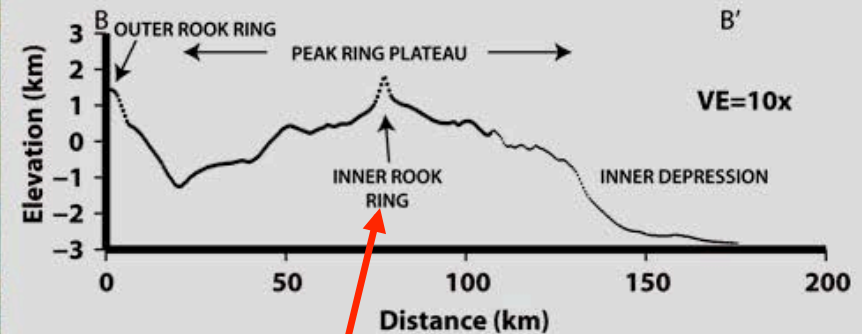
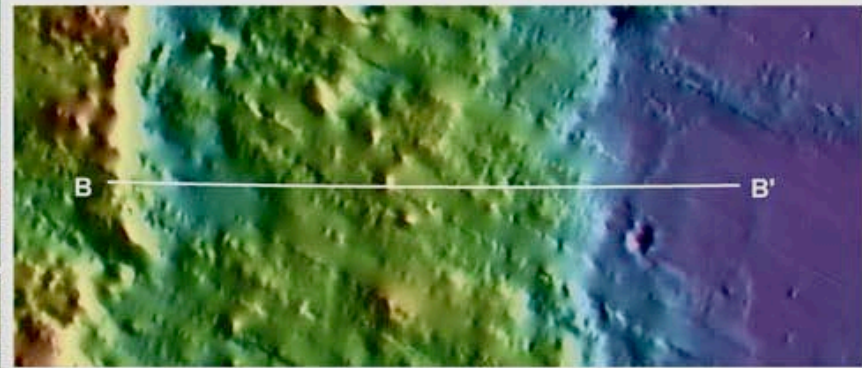
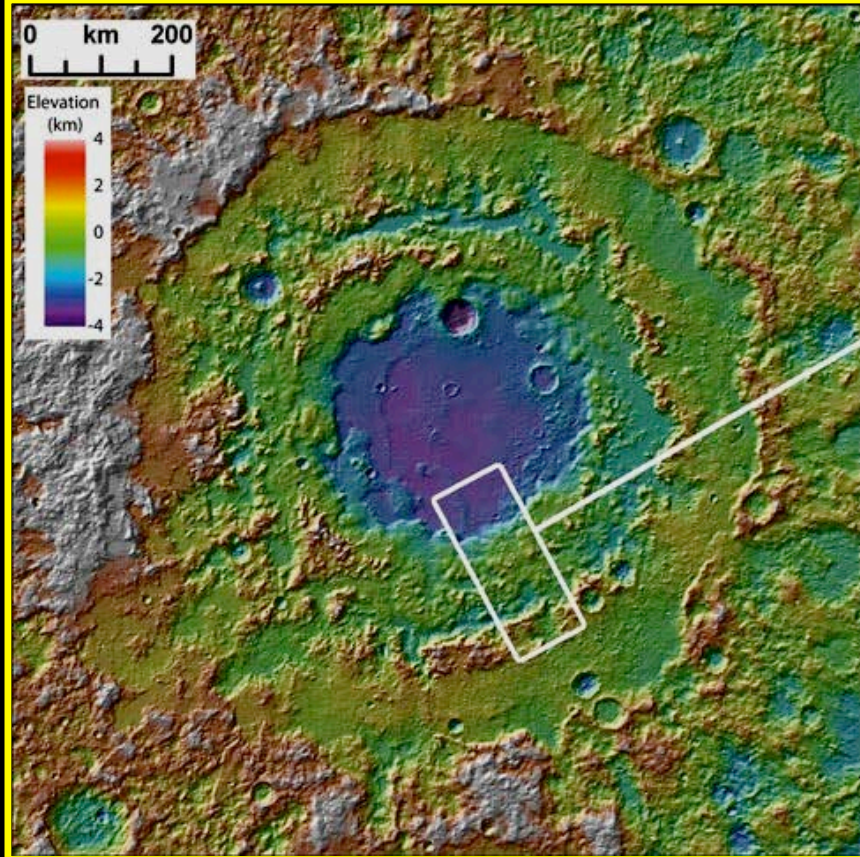


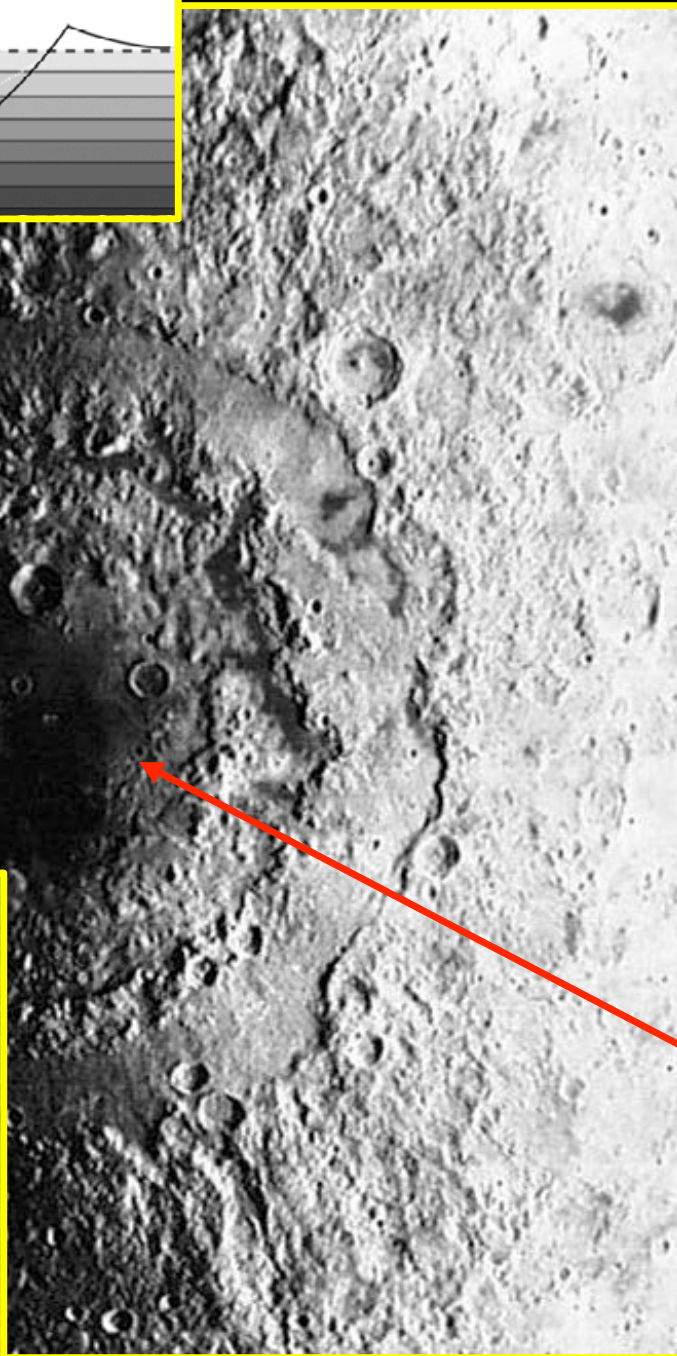
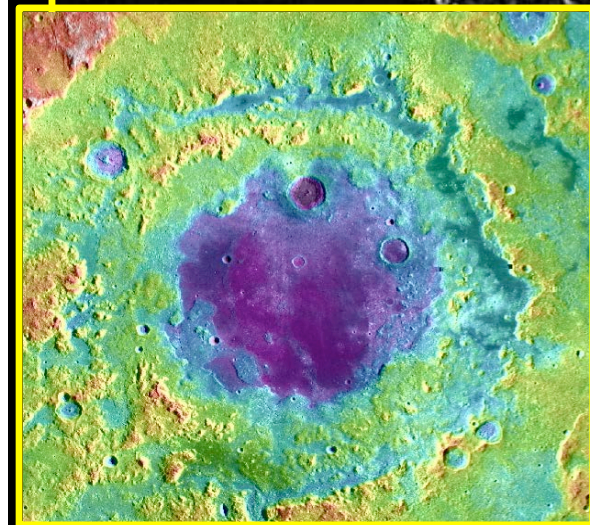
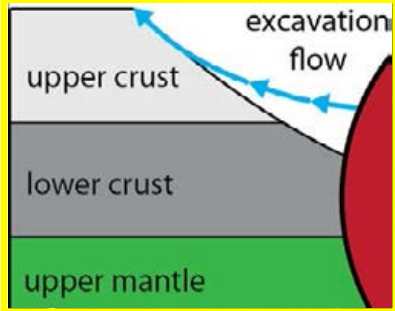
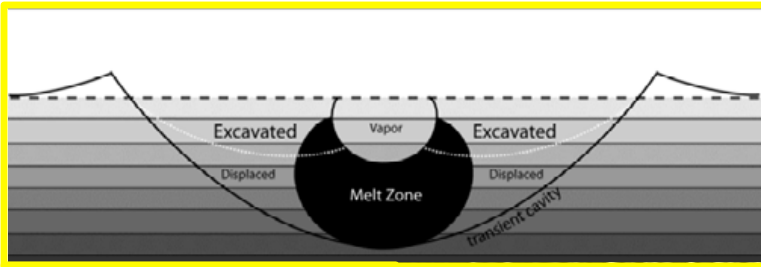
## Region of Interest (ROI) 1: Origin of Basin Rings/Crustal Structure

-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?

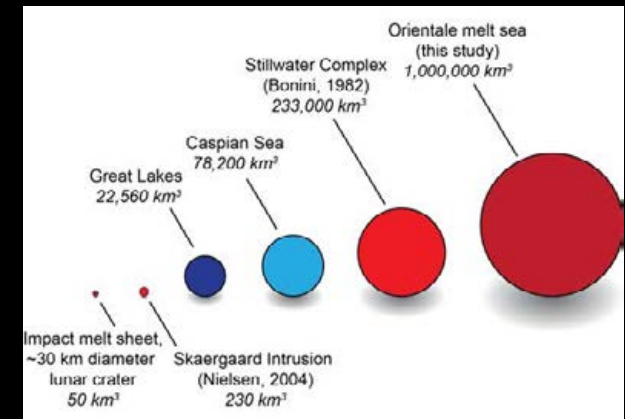
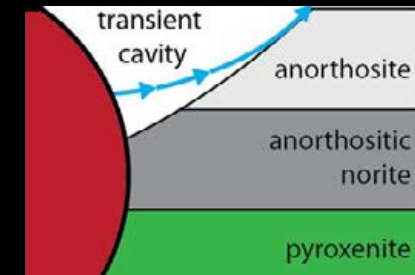


## ROI 2: What is the Origin of the Inner Rook Mountains?



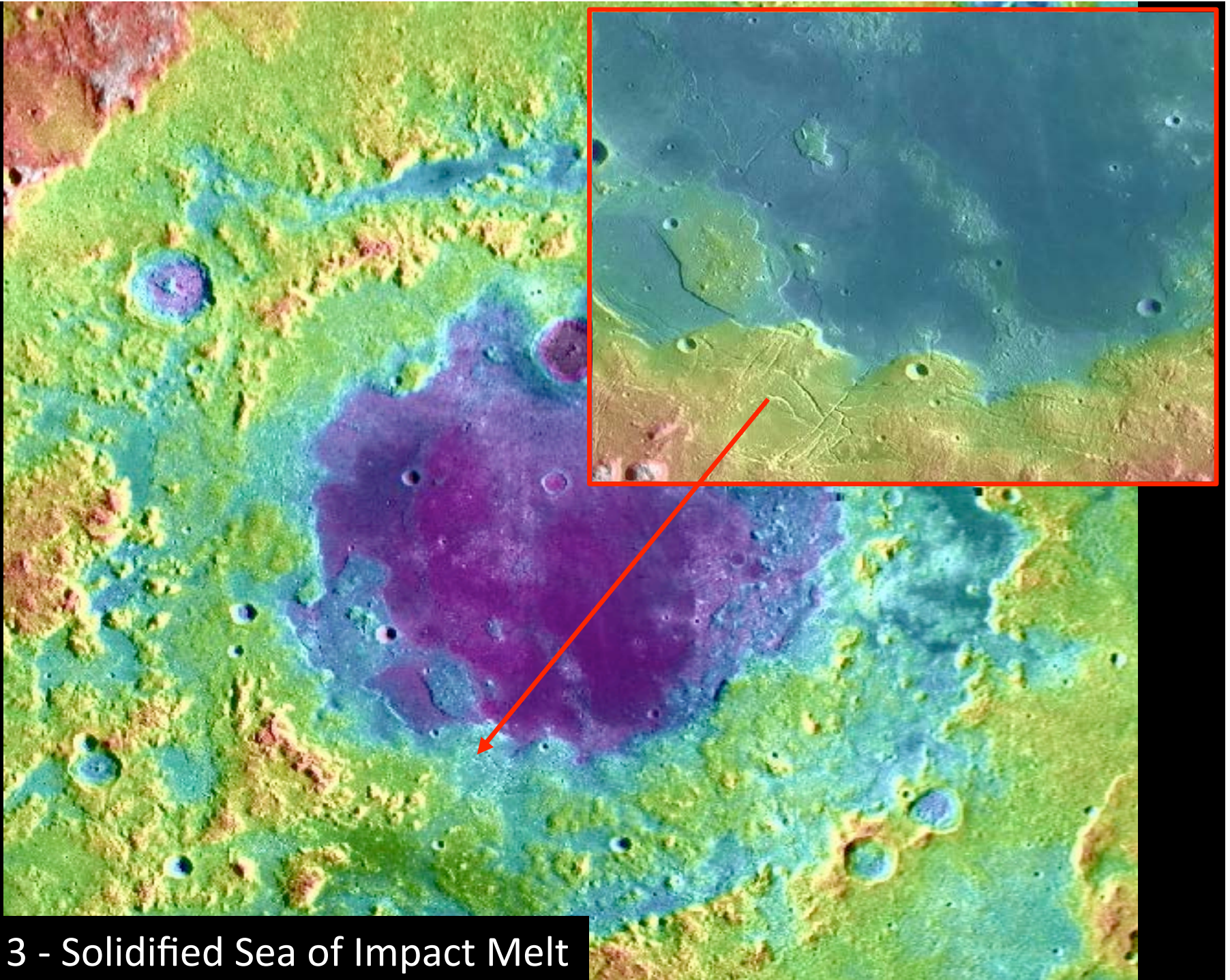


## ROI 3-Orientale Impact Melt Sea



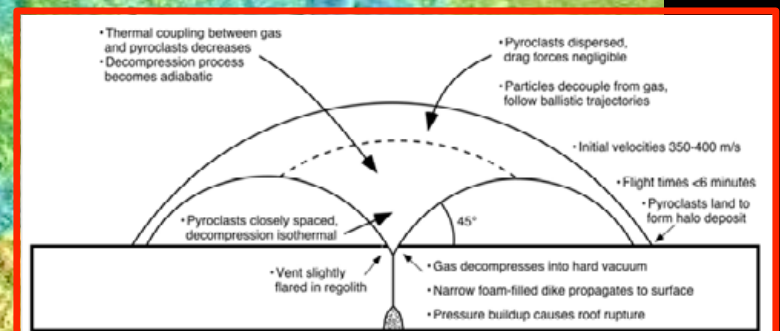
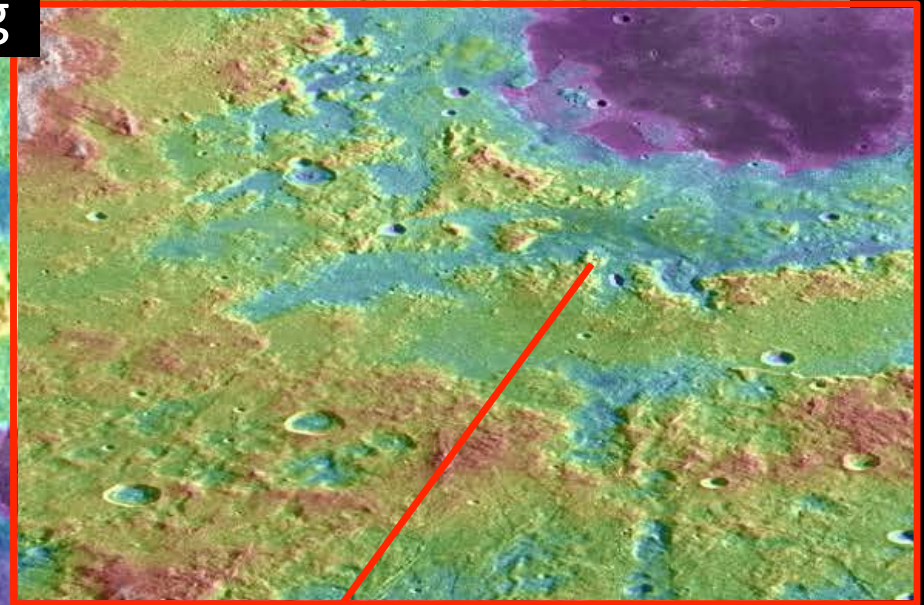
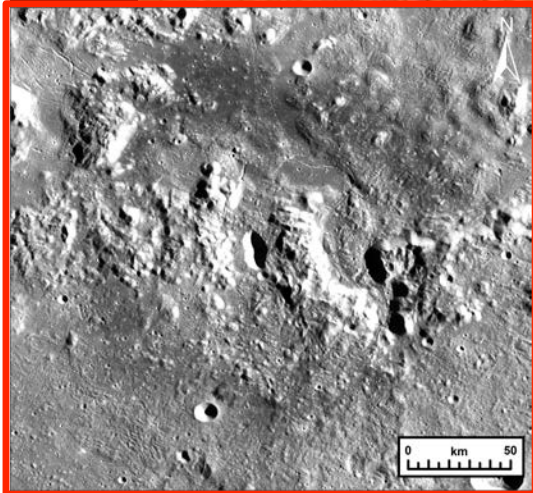
**Maunder Formation  
(Basin Impact Melt Deposit)**

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

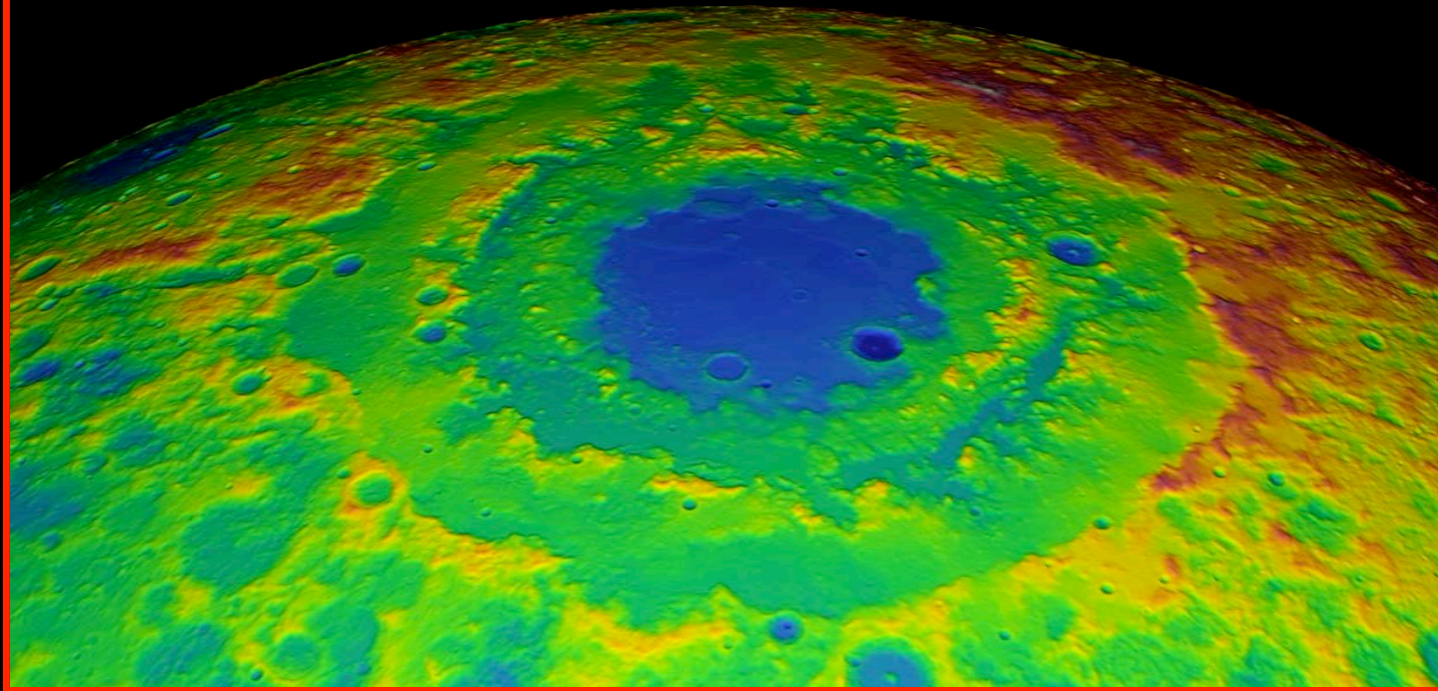


ROI 3 - Solidified Sea of Impact Melt

## ROI 4-Explosive Volcanic Ionian Ring

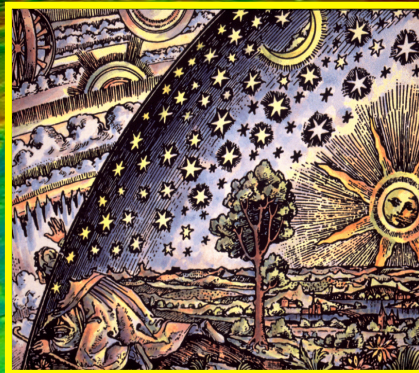


# Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin



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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P. Senthil Kumar: CSIR-NGRI, Hyderabad, India

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# Brown-Vernadsky Microsymposia: Thematic Science Workshops for the Community



SSSERVI Evolution and Environment of Exploration Destinations



## Microsymposium 57

Polar Volatiles on the Moon & Mercury:  
Nature, Evolution & Future Exploration



March 19-20, 2016

The Woodlands Marriott - The Woodlands, TX

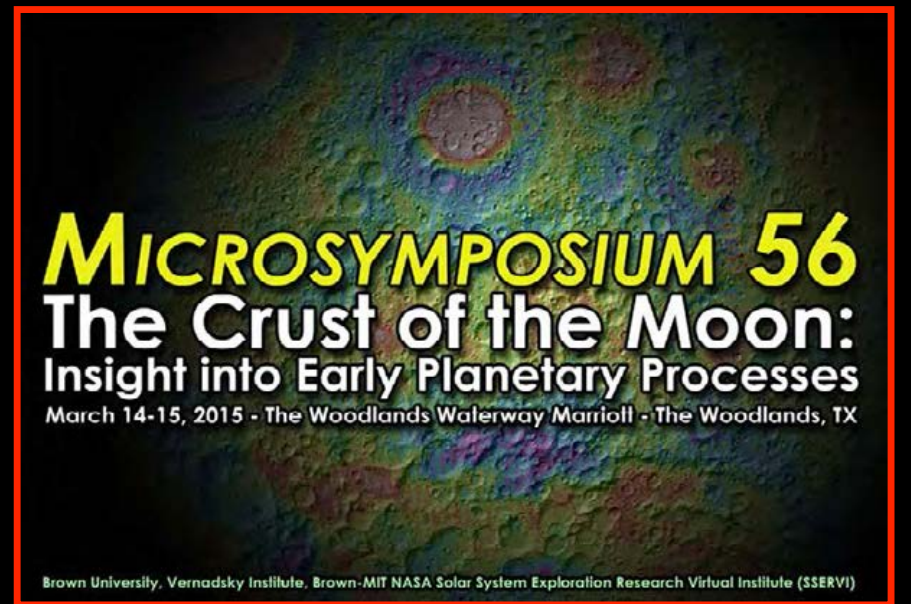
Brown University, Vernadsky Institute,  
Brown-MIT NASA Solar System Exploration Research Virtual Institute (SSSERVI)



## Microsymposium 55

Scientific Destinations for Human Exploration

March 15-16, 2014 - The Woodlands Waterway Marriott - The Woodlands, TX  
Brown University, Vernadsky Institute, Brown-MIT NASA Solar System Exploration Research Virtual Institute (SSSERVI)



## MICROSYMPOSIUM 56

### The Crust of the Moon: Insight into Early Planetary Processes

March 14-15, 2015 - The Woodlands Waterway Marriott - The Woodlands, TX

Brown University, Vernadsky Institute, Brown-MIT NASA Solar System Exploration Research Virtual Institute (SSSERVI)

