

Volcanogenic Resources for a Sustained Human Presence on the Moon*

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Abstract

The Moon has a wide variety of volcanogenic features that contain an array of metals, rare-earth elements, and energy resources for long-term, sustained human habitation. These resources occur in (1) regional basin-fill basalt flows, (2) small (<15 km) silica-rich igneous domes such as Mons Gruithuisen and Compton-Belkovich, and (3) patchy exhalative deposits such as Ina and Maskelyne that may be less than 100 million years old. Recent mapping missions by the Lunar Reconnaissance Orbiter have provided background surveys of the lunar surface. Future investigations will be needed to target areas of concentrated resources.

High values of titanium-oxide (up to 11 wt. %) occur in Oceanus Procellarum. Detailed mapping of small pyroclastic volcanic vent deposits has identified a suite of volcanogenic elements that include iron, zinc, cadmium, mercury, lead, copper, and fluorine. Rare metals and platinum-group elements may also reside in low concentrations in regolith breccias, highland impact breccias, and possibly in layered mafic intrusives. Thorium is relatively abundant in Oceanus Procellarum, associated with late-stage melts rich in KREEP (Potassium/Rare-Earth-Elements/Phosphorus) constituents. Exhalatives and some impact breccias contain volatiles such as nitrogen and carbon, the building blocks of plastics and foodstuffs. Other volatiles, including water, also occur in lunar pyroclastic glasses and in cold, permanently shadowed areas near the poles. Lunar orbital depots for fuel and life-support materials have benefits for mission economics and can serve as temporary accumulation areas for transport of materials derived from volcanogenic sources to Earth's surface. Future advances in technology and planetary engineering on the Moon, a perfect proving ground, will offer humans a steppingstone to Mars, ultimately leading to a sustained human presence in space.

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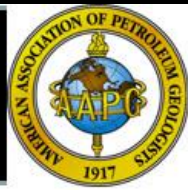
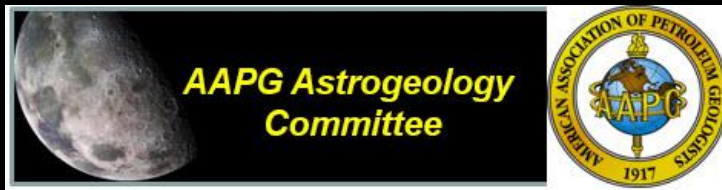
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May 23, 2018



BUREAU OF
ECONOMIC
GEOLOGY



Noel Carboni

Outline

- **Lunar Maria: Basin-Fill and Extrusives**

- Lunar Terranes*

- Maria Compositional Units*

- **Silicic Domes**

- Mons Gruithuisen and Compton-Belkovich*

- **Recent Mare Patches and Exhalatives**

- Ina*

- Maskelyne and Sosigenes IMP*

Lunar Resources

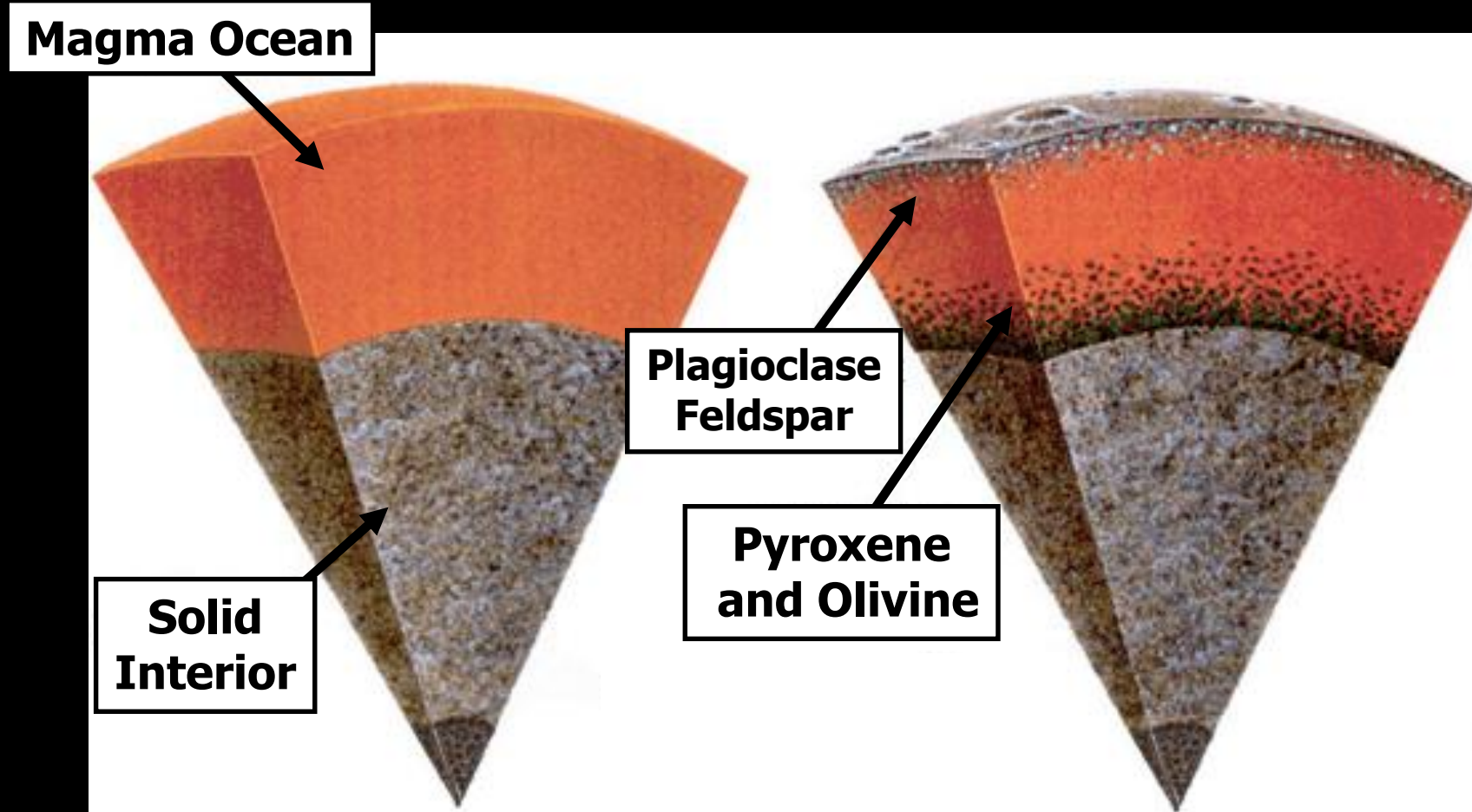
Resource	Use	Occurrence
<i>Helium-3</i>	Energy	Mature regolith
<i>Hydrogen</i>	Propellant, water	Mature regolith, poles
<i>Oxygen</i>	Propellant, air/water	Global
<i>Uranium, thorium</i>	Power generation	Silicic Domes
<i>Metals</i> Iron Titanium Aluminum	<u>Construction</u> Moon base Shielding Roads Solar power facility	Mare basalts Highland breccias

Lunar Impact Origin

- *Density differences*
- *Volatile depletion*
- *Isotopic similarities*
- *Lunar orbit inclined 5°*



Crust-Mantle Differentiation

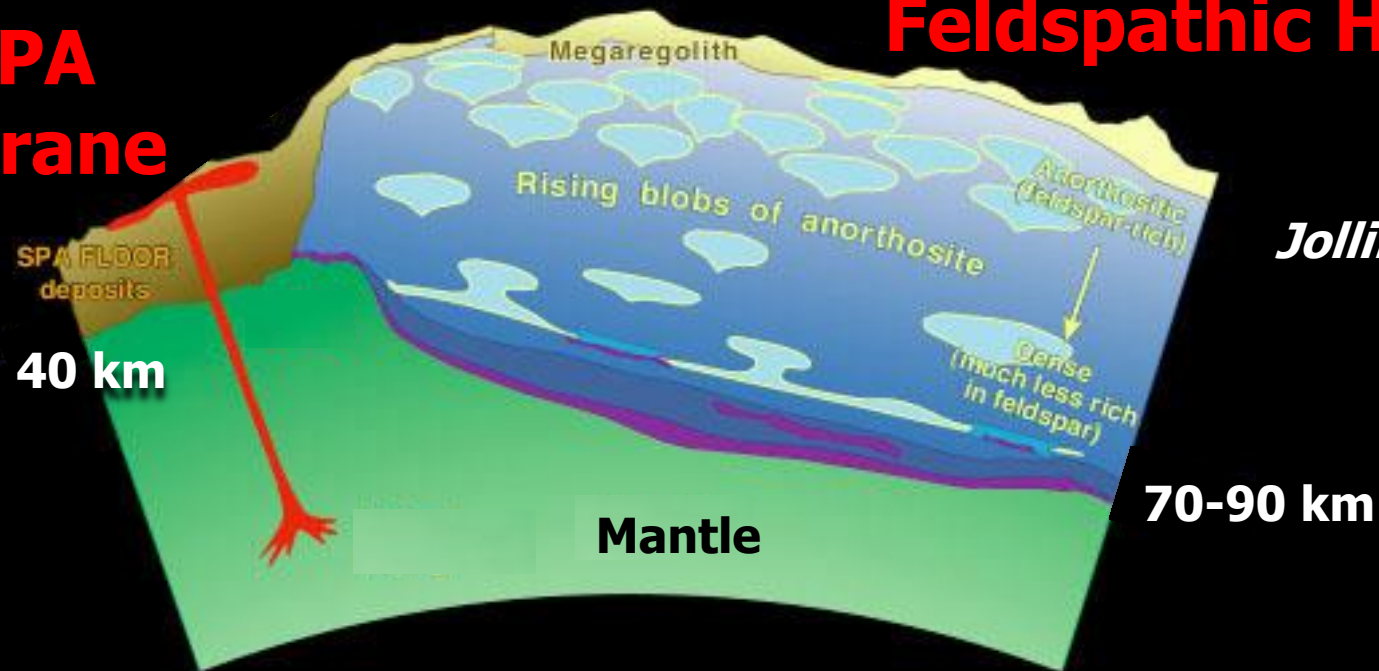


Taylor (1994)

Lunar Terranes

**SPA
Terrane**

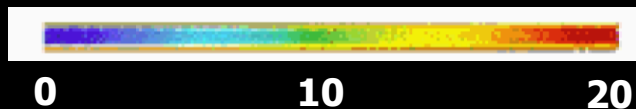
Feldspathic Highlands Terrane



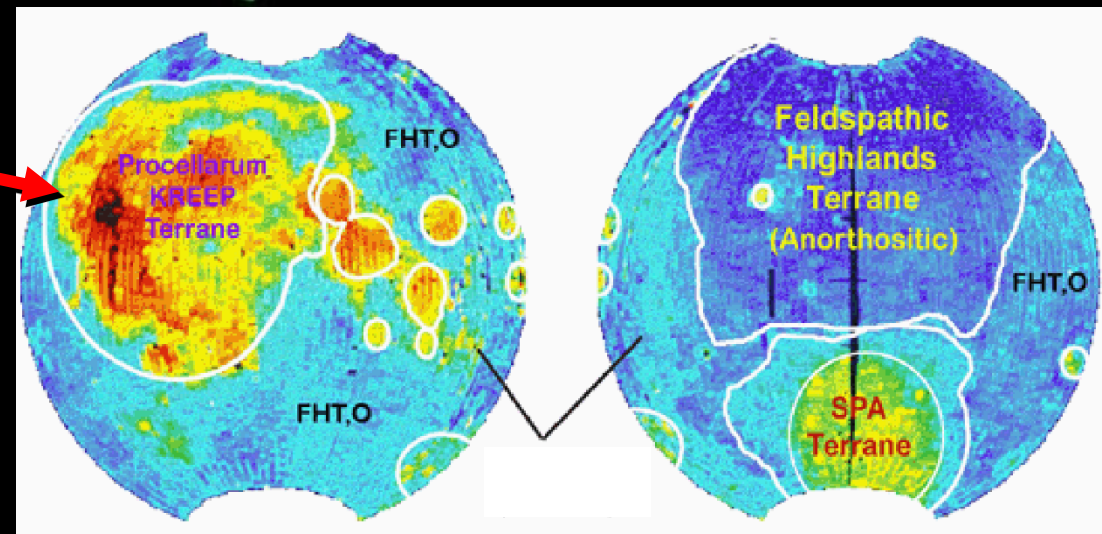
Jolliff, et al. (2000)

KREEP

FeO wt. percent

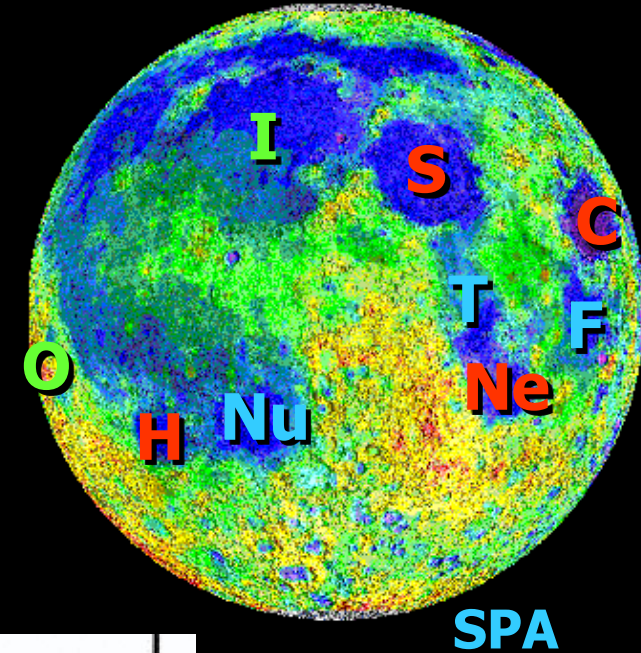
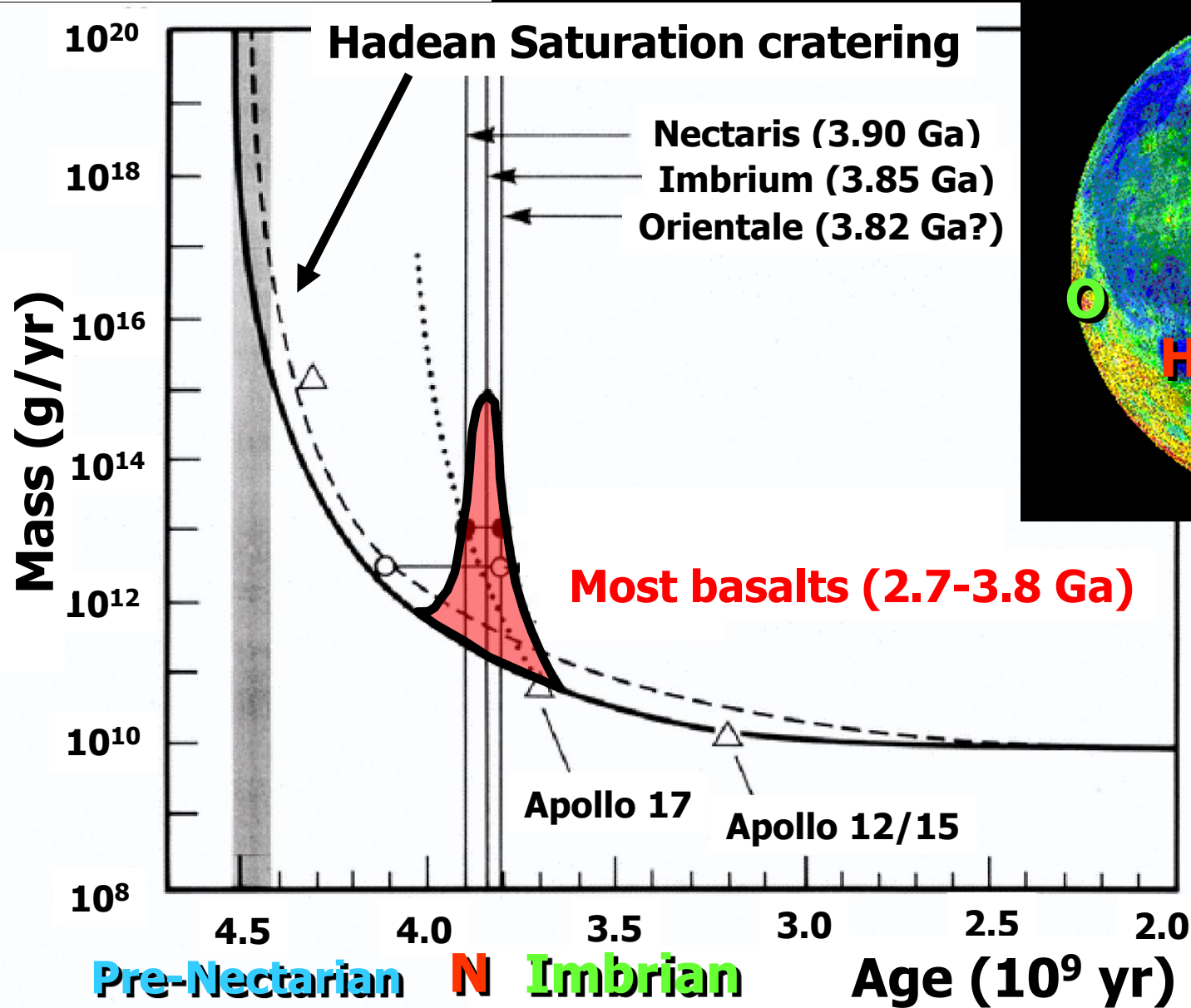


Lucey, et al. (1995)



Late Heavy Bombardment

10^{20} g/yr = $\sim 100^{12}$ tons/yr



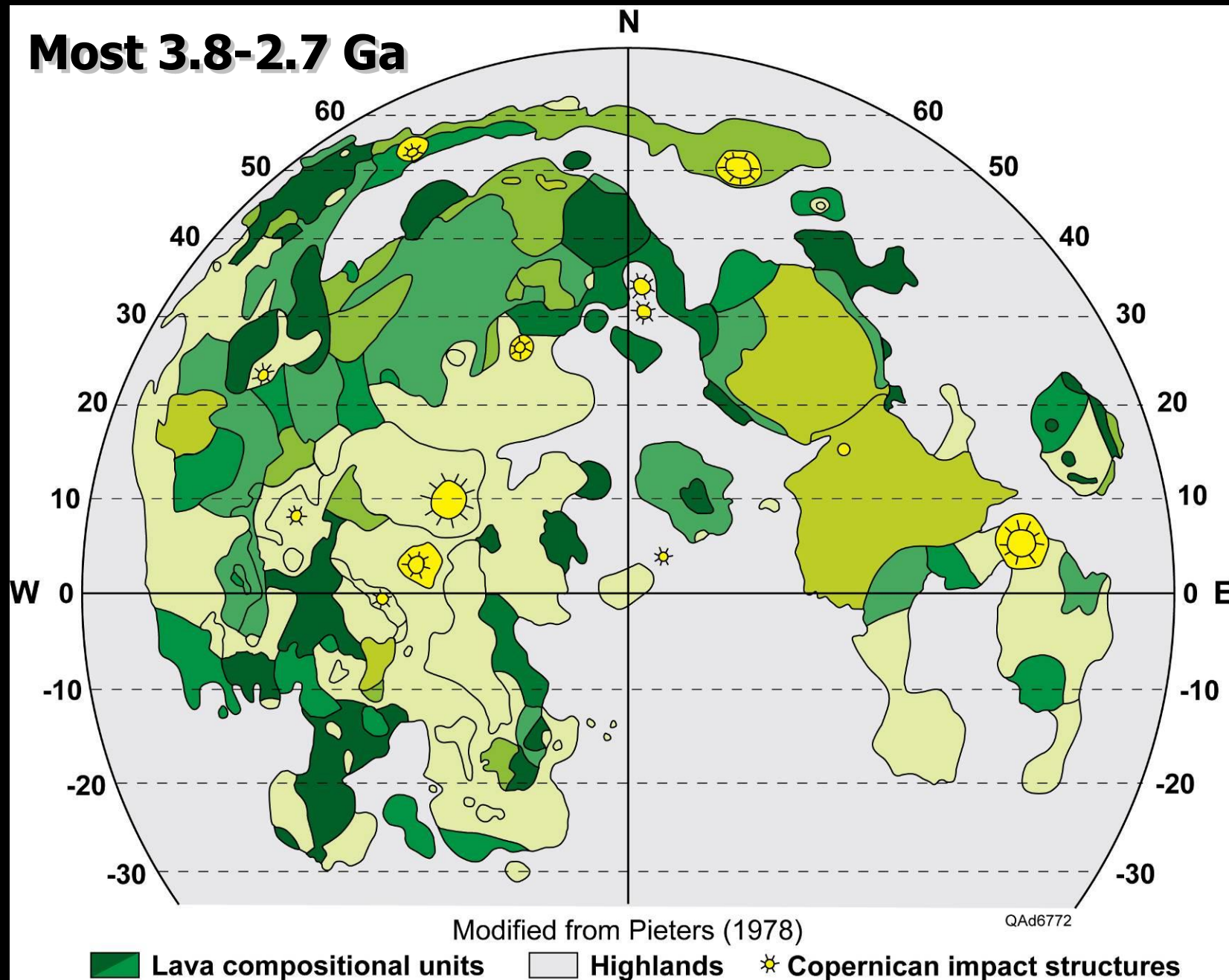
Imbrian

Nectarian

Pre-Nectarian

*Haskin,
Cohen et al.*

Nearside Compositional Units



Lunar TiO_2 Basalts

Rolf Wahl Olsen



$\text{TiO}_2 > 7 \text{ wt.}\%$



$\text{TiO}_2 3\text{-}7 \text{ wt.}\%$



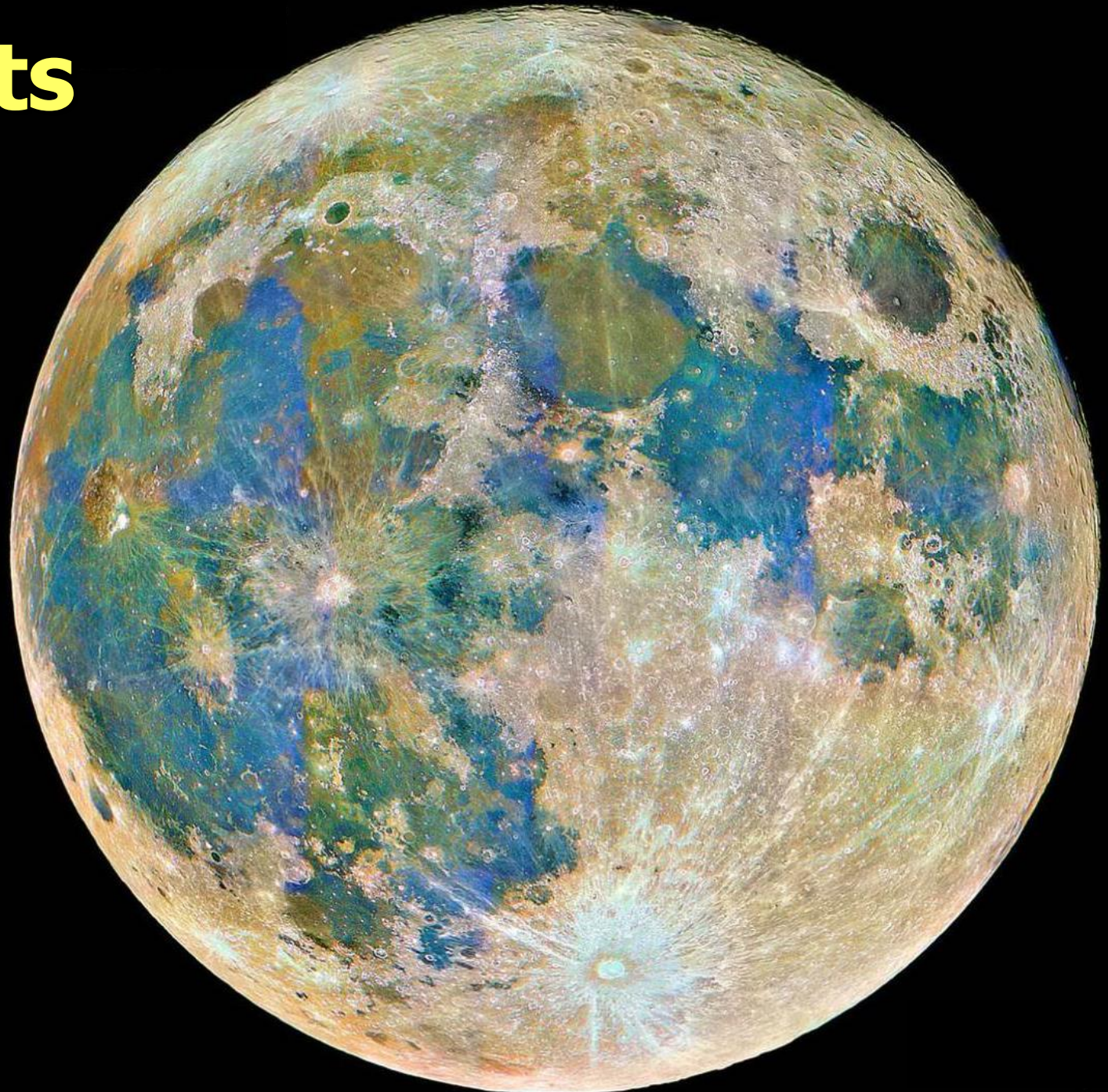
$\text{TiO}_2 < 2 \text{ wt.}\%$



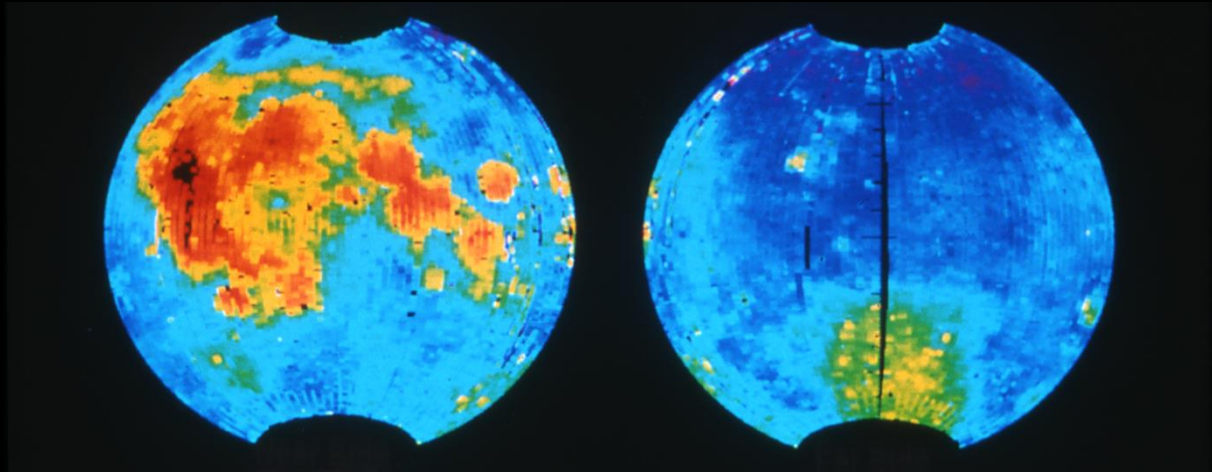
Old highlands/ejecta



Recent ejecta



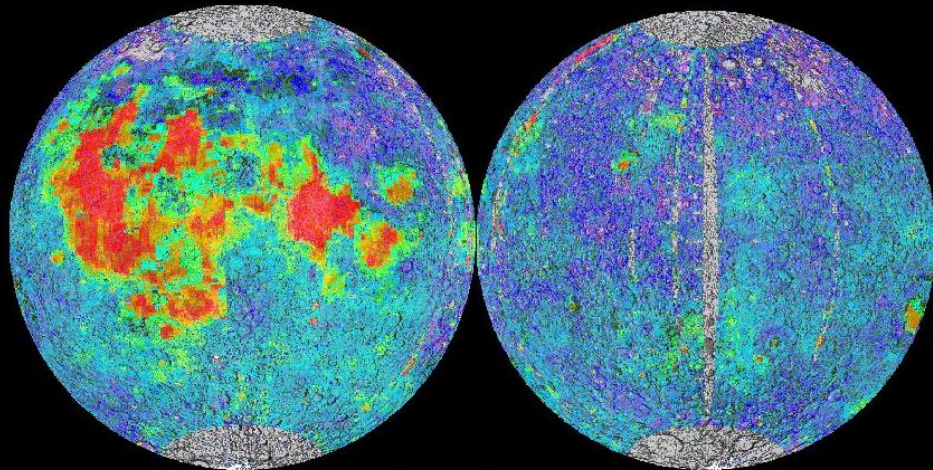
Lunar Fe and TiO₂ Abundance



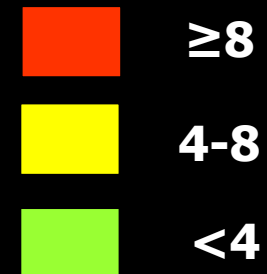
Near side

Far side

Fe wt. %



TiO₂ wt. %



Outline

- **Lunar Maria: Basin-Fill and Extrusives**

 - Lunar Terranes*

 - Maria Compositional Units*

- **Silicic Domes**

 - Mons Gruithuisen and Compton-Belkovich*

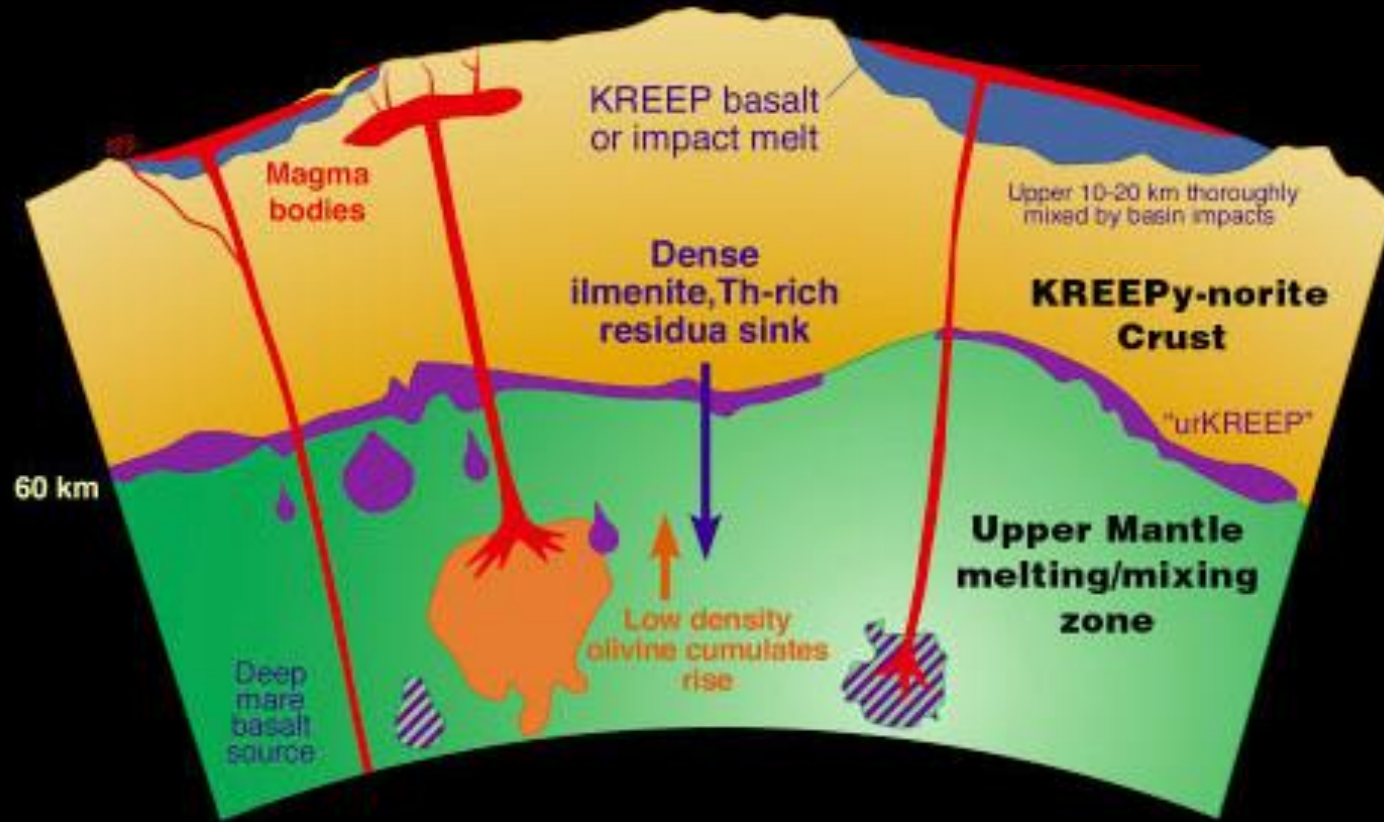
- **Recent Mare Patches and Exhalatives**

 - Ina*

 - Maskelyne and Sosigenes IMP*

Lunar Procellarum KREEP

(Potassium-REE-Phosphorus)



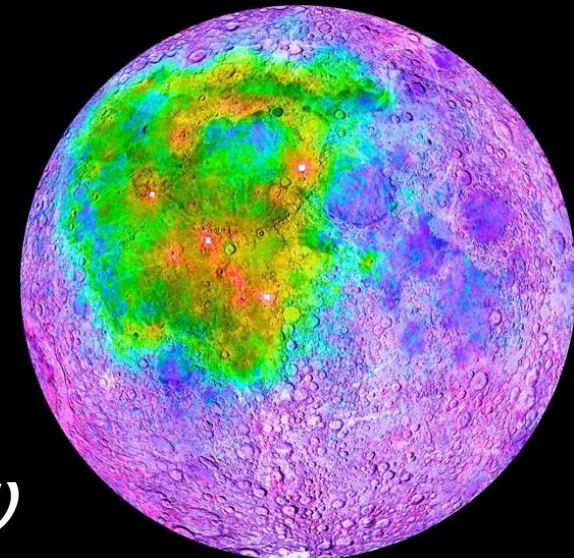
Jolliff et al. (2000)

Thorium (ppm)



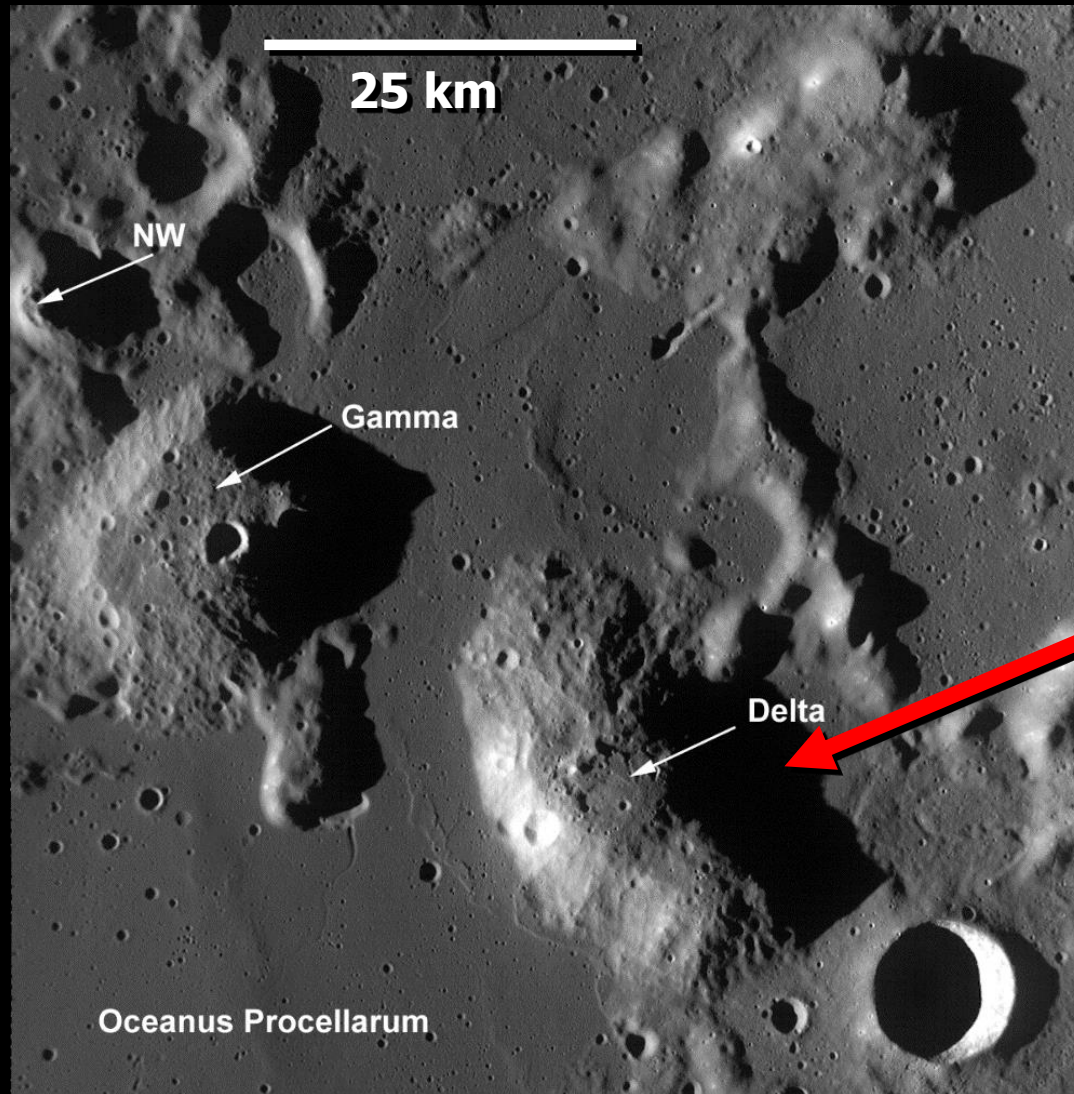
1

12



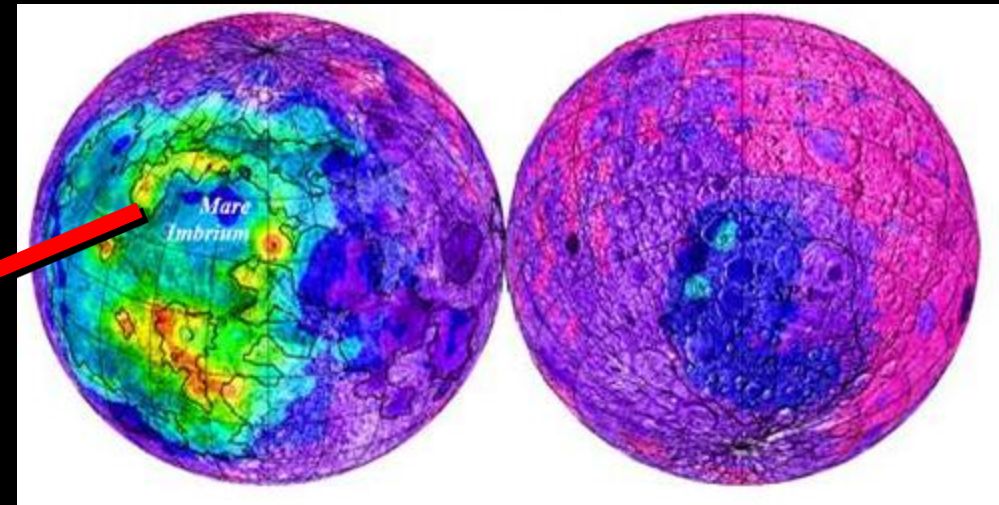
Spudis (2005)

Mons Gruithuisen



LOLA M117752970ME

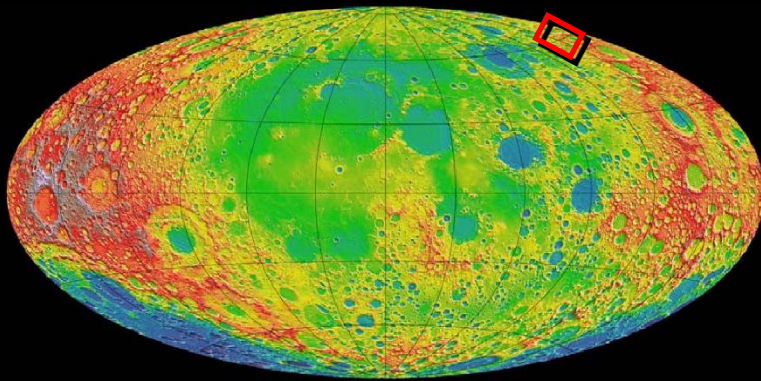
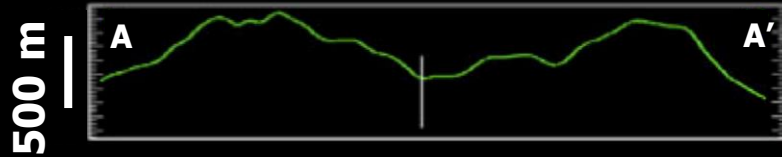
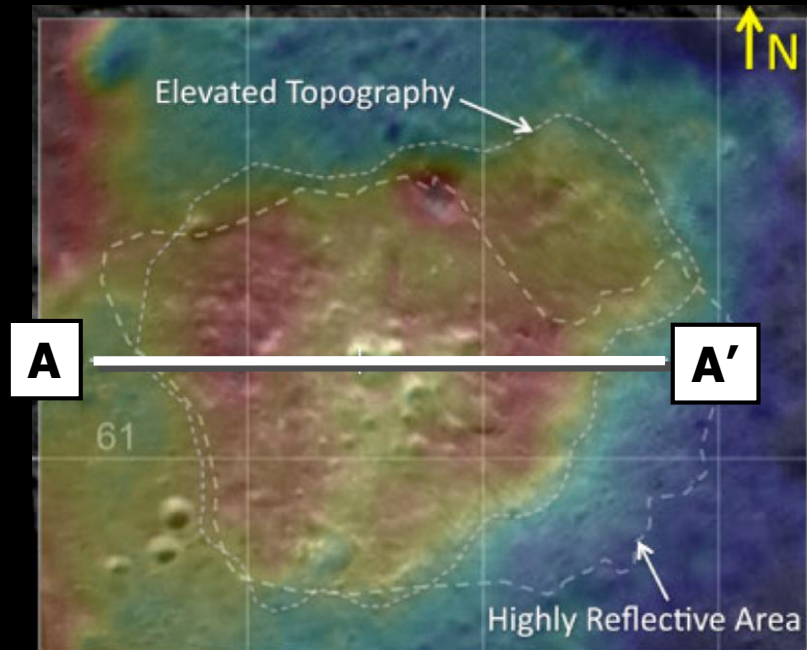
Thorium: Silicic Domes



 >90 ppm

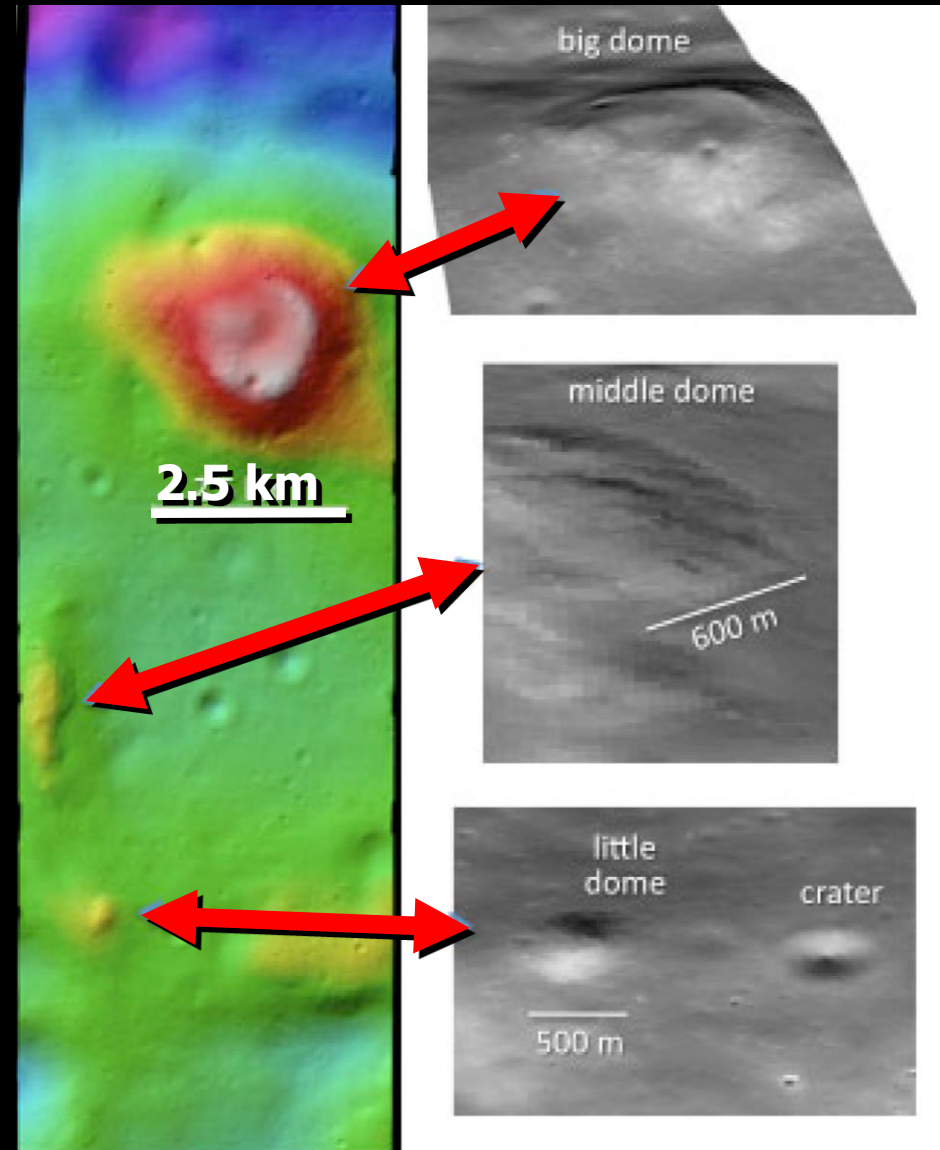
Yamashita (2009)

Compton Belkovich Lava Domes



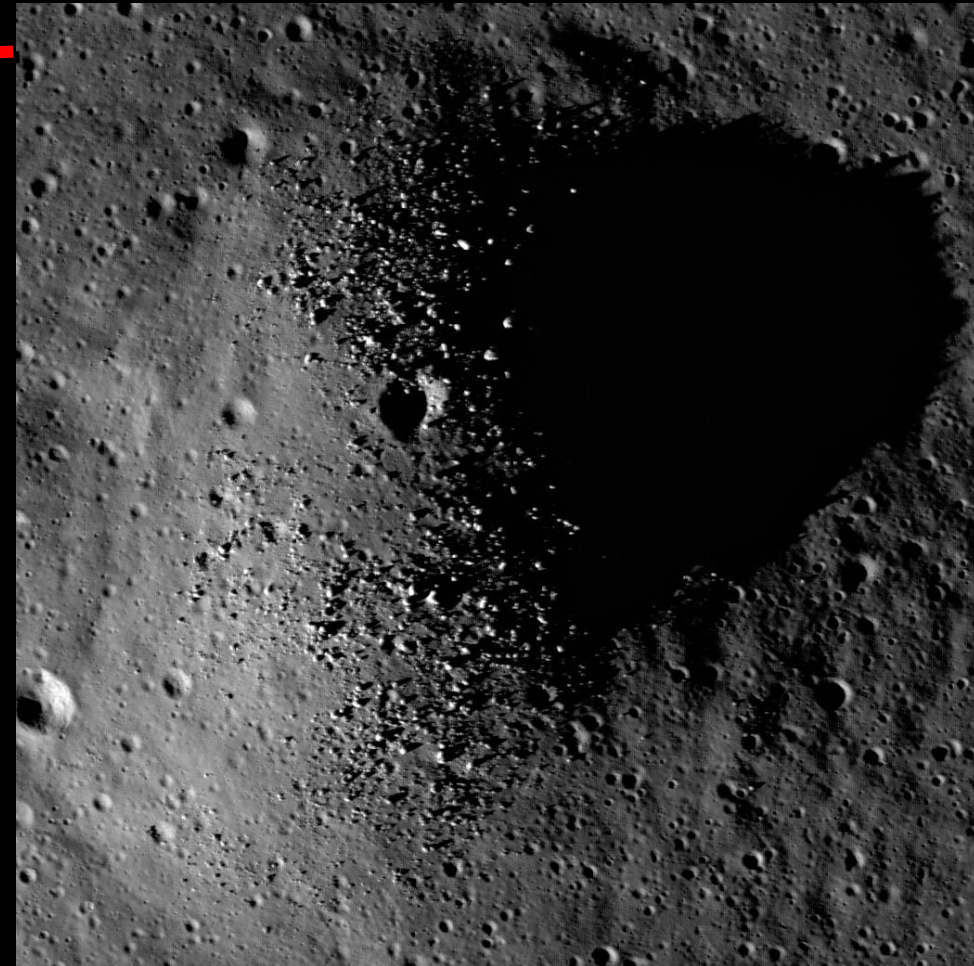
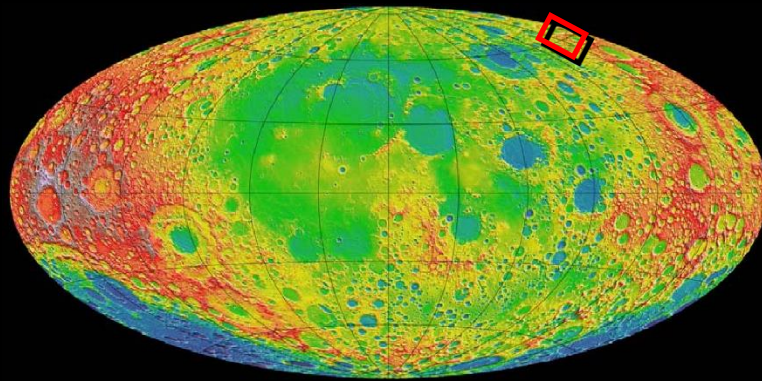
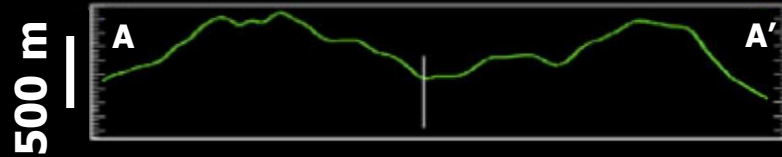
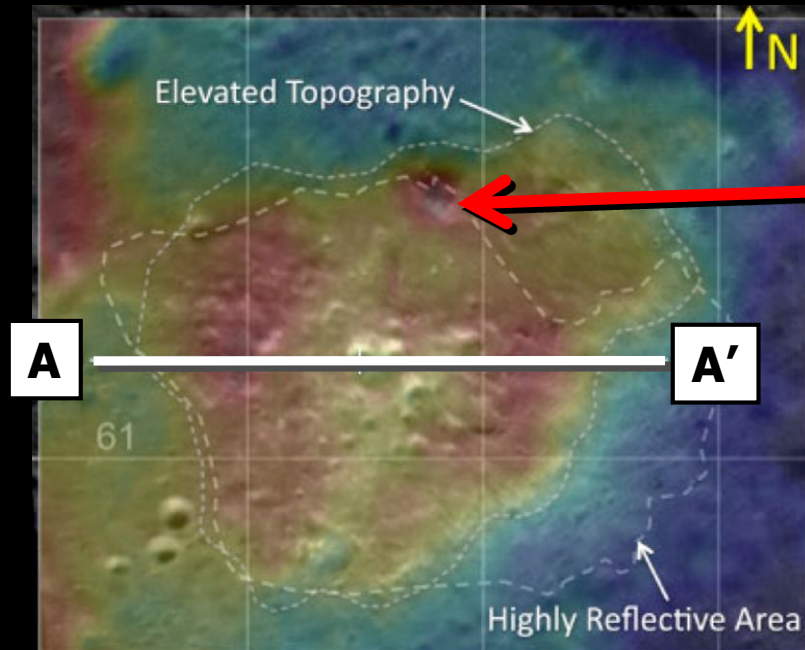
Modified from Jolliff et al. (2011)

40-55 ppm Th



Compton Belkovich Lava Domes

Modified from Jolliff et al. (2011)

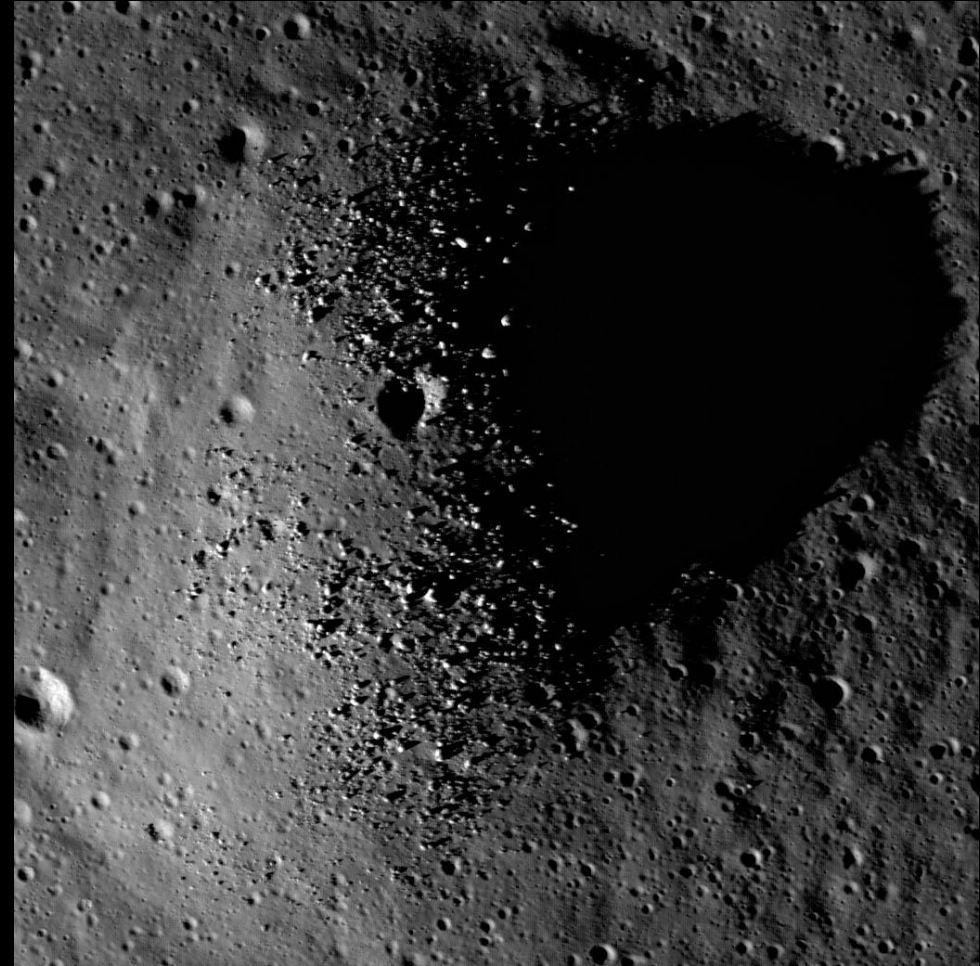


100 m

Weathering of Igneous Domes

Compton Belkovich

Musina, South Africa



100 m

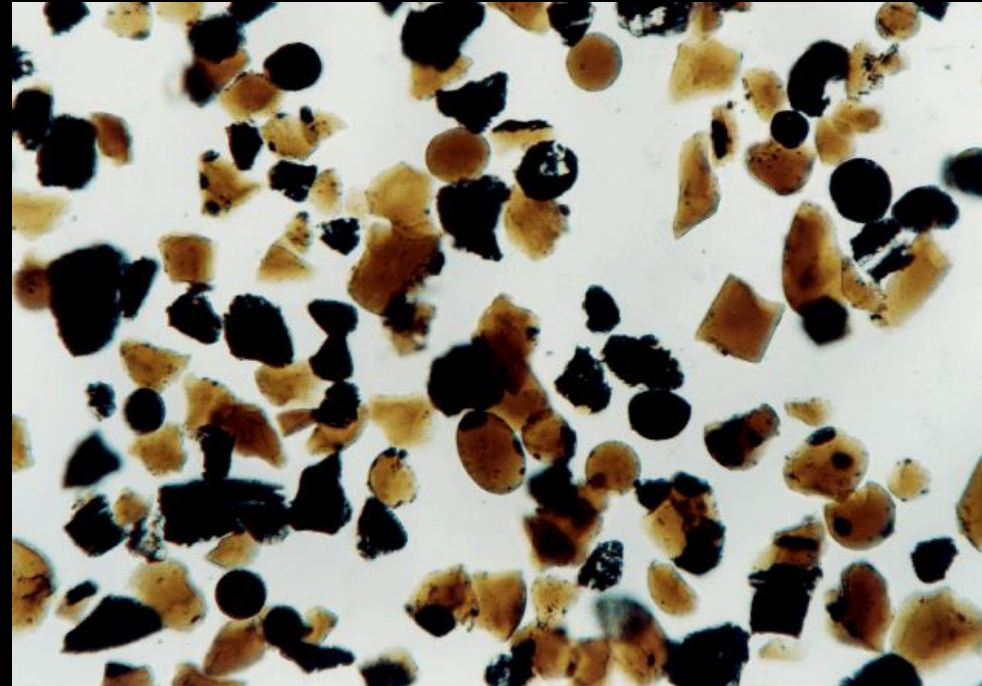
Lunar Volatiles—Endogenic

Pyroclastics: >500 ppm water in some low-Ti glasses

Saal et al. (2008)



*Pu'u O'o fire fountain
USGS (1985)*

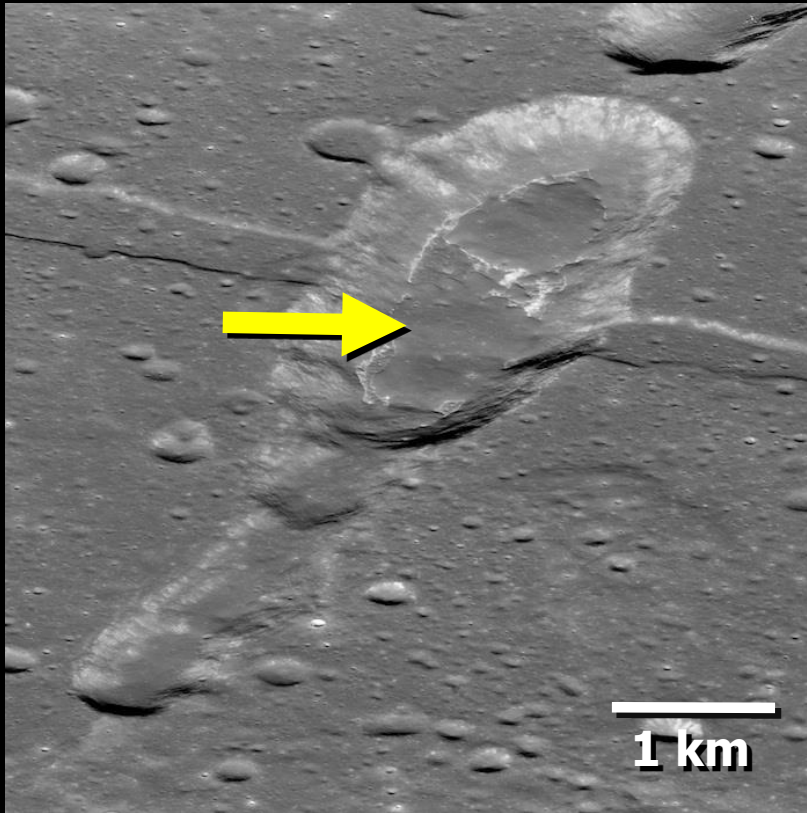


*Volcanic Glass—Apollo 17
NASA (1972)*

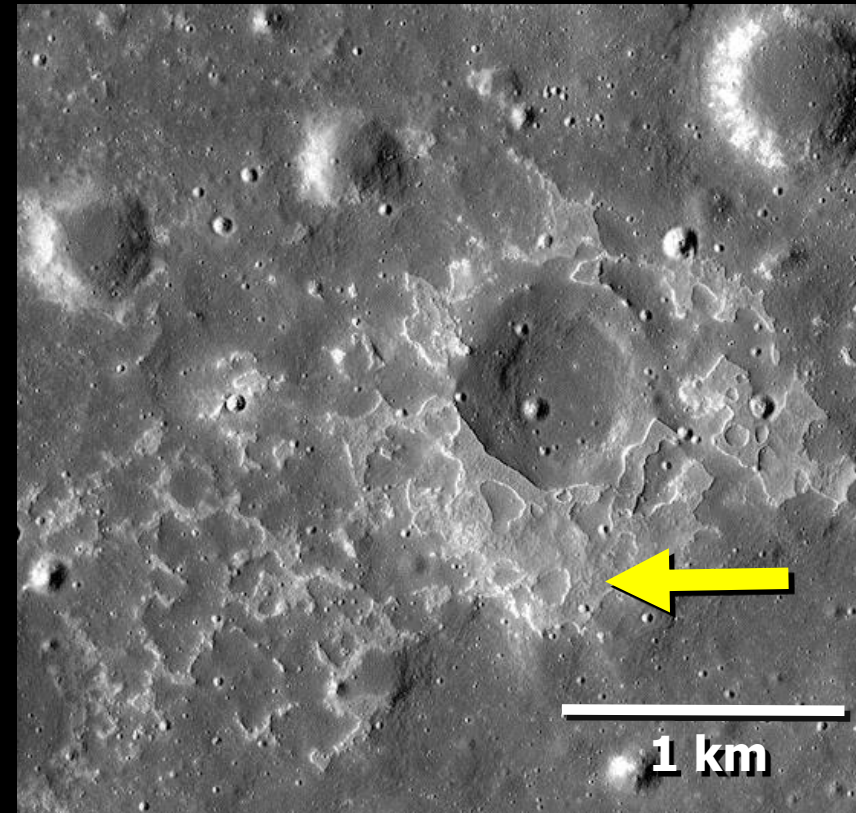
Recent Volcanism

Irregular Mare Patches: 18-50 Mya

Sosigenes IMP



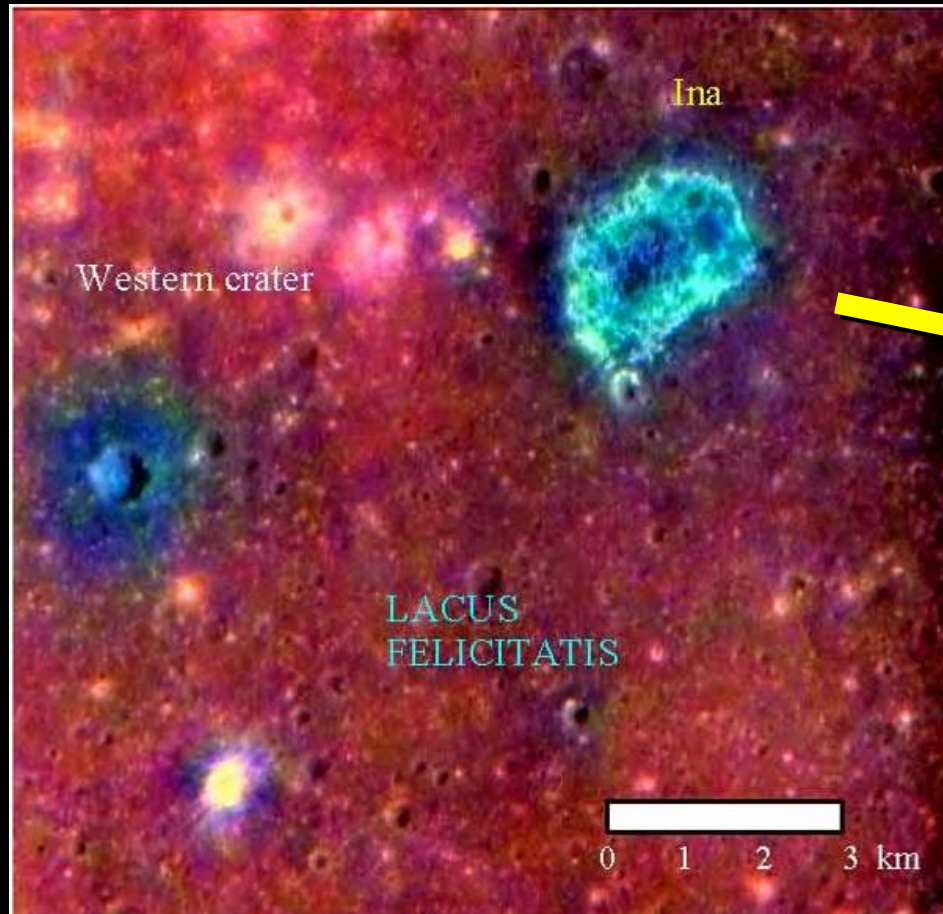
Maskelyne IMP



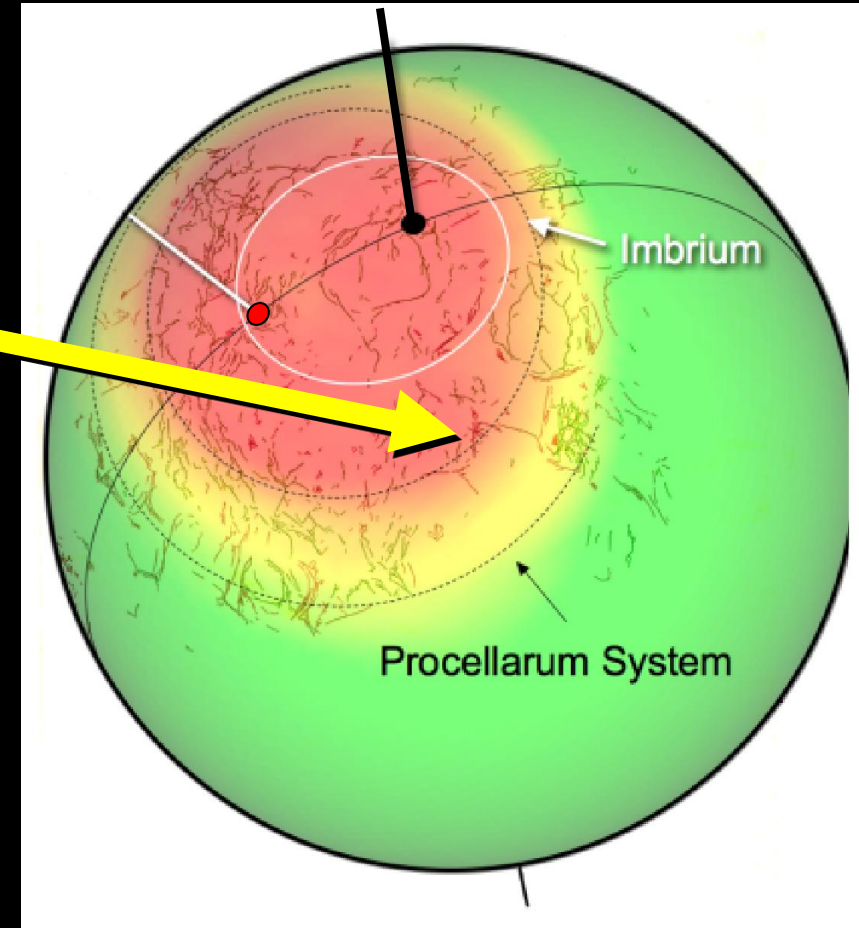
Braden et al. (2014)

Ina: Antipodal Position from SPA Basin

False Color Image



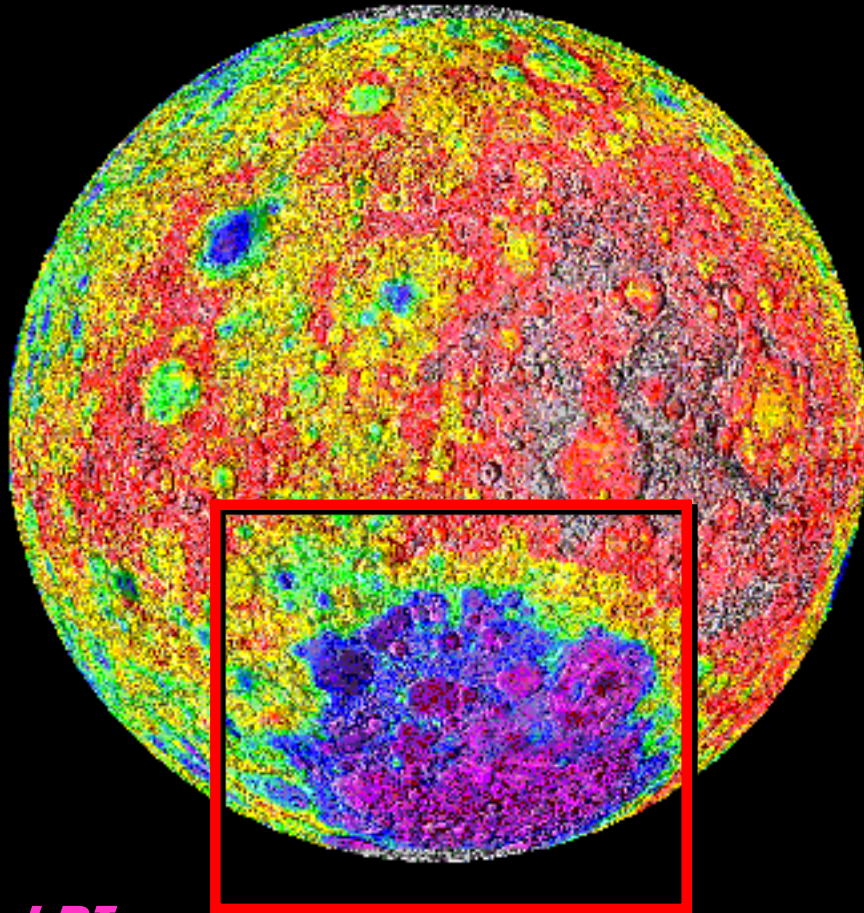
SPA antipode



Schultz et al. (2006)
Schultz and Crawford (2008)

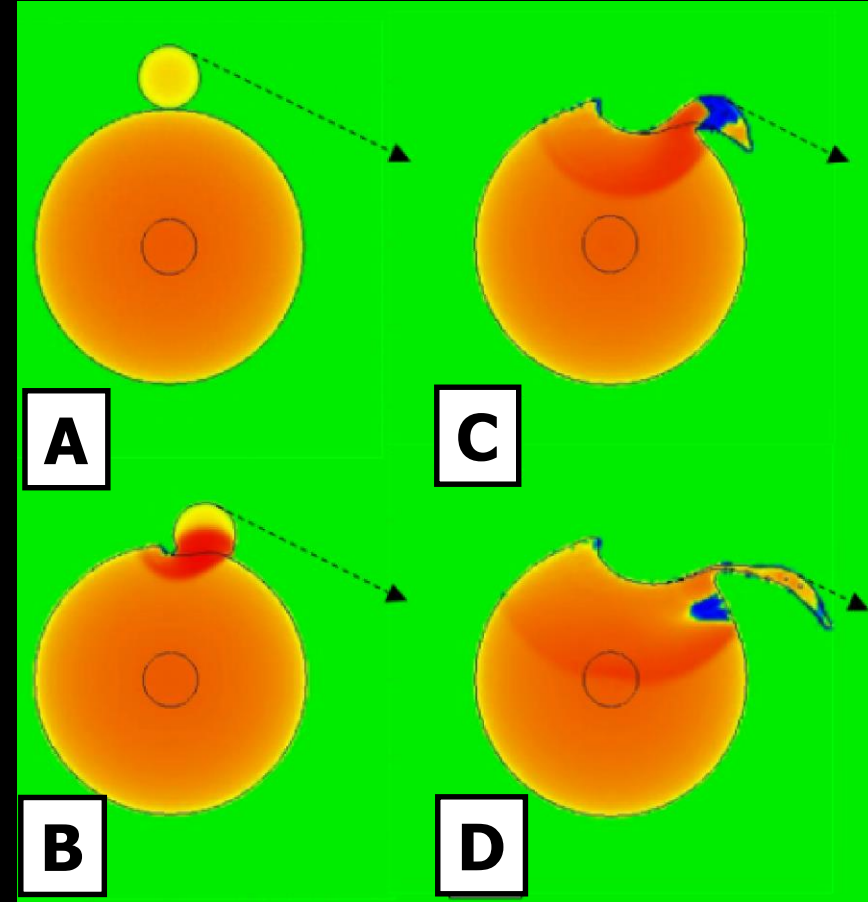
South Pole–Aitken Basin

Laser altimetry



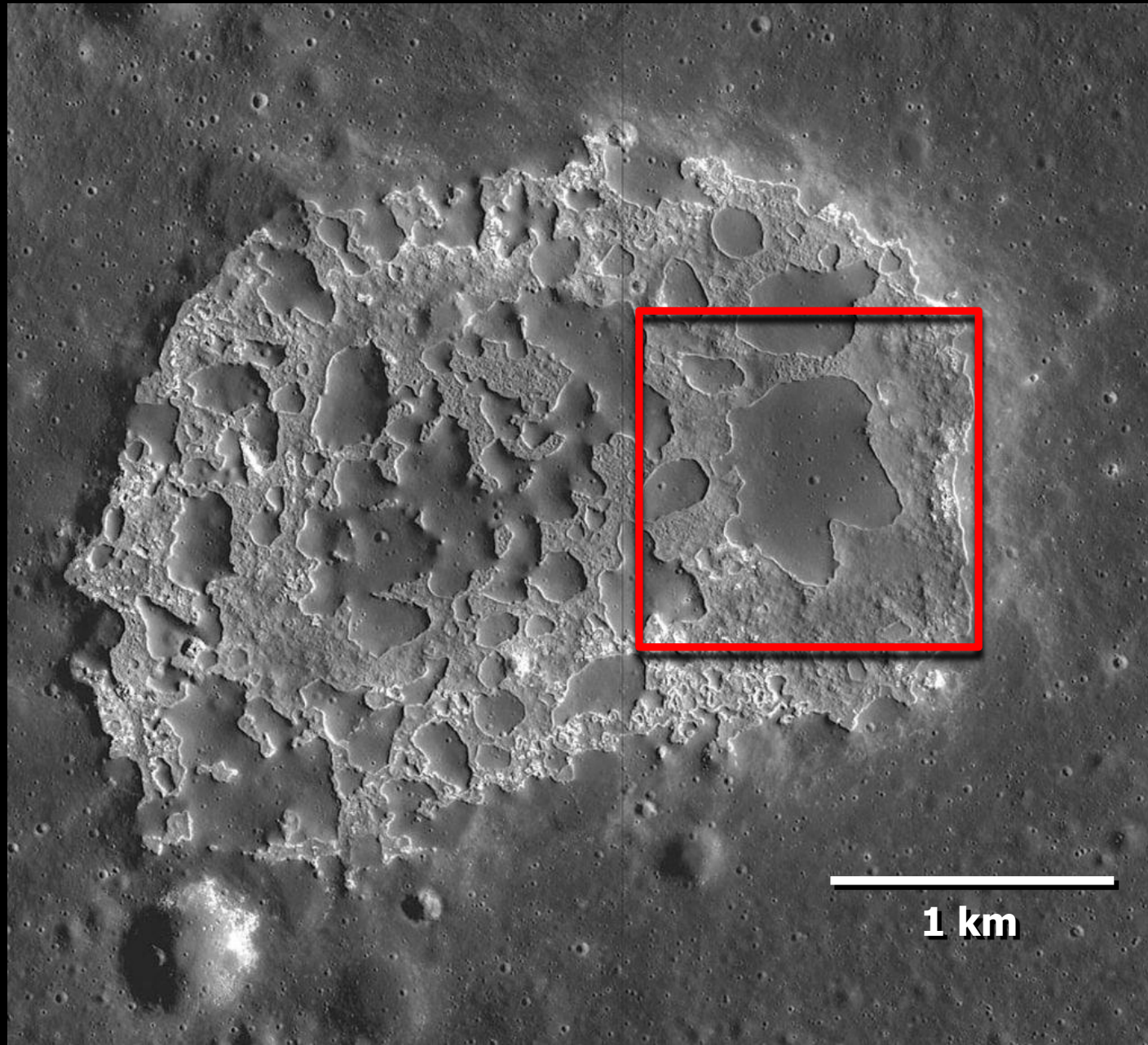
LPI

Collision model

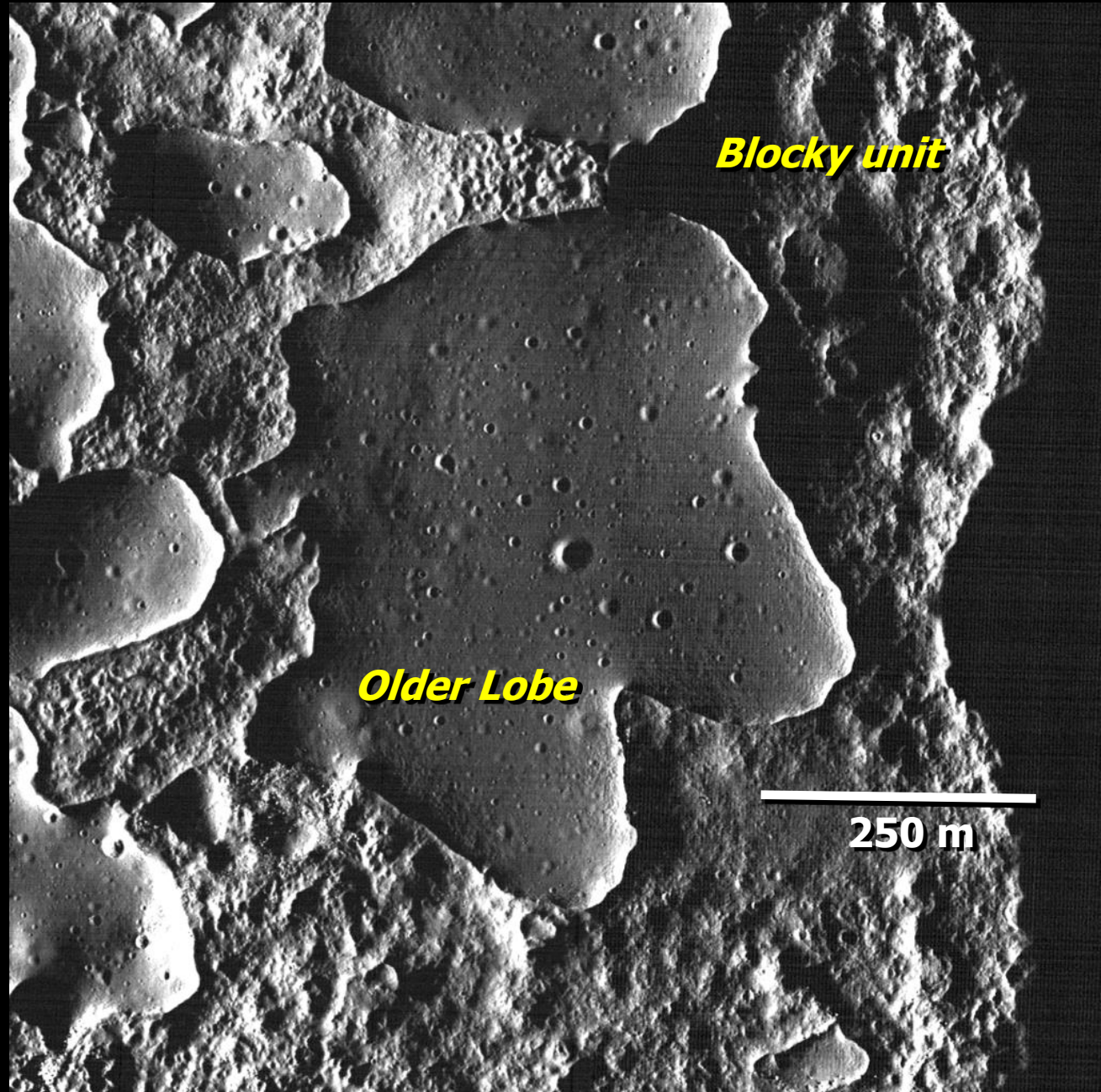
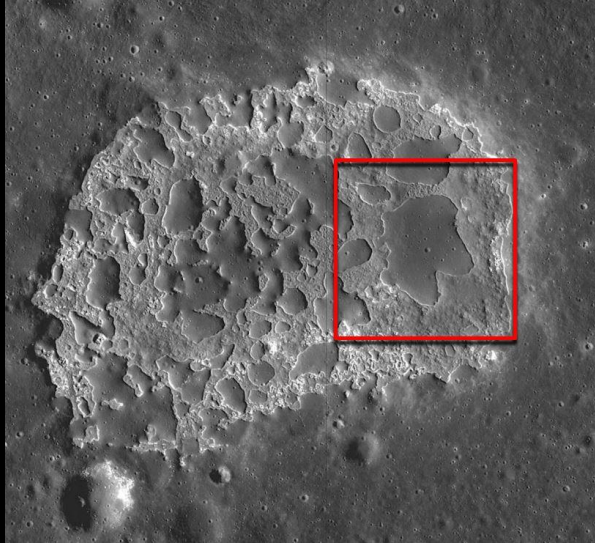


Modified from Schultz and Crawford (2008)

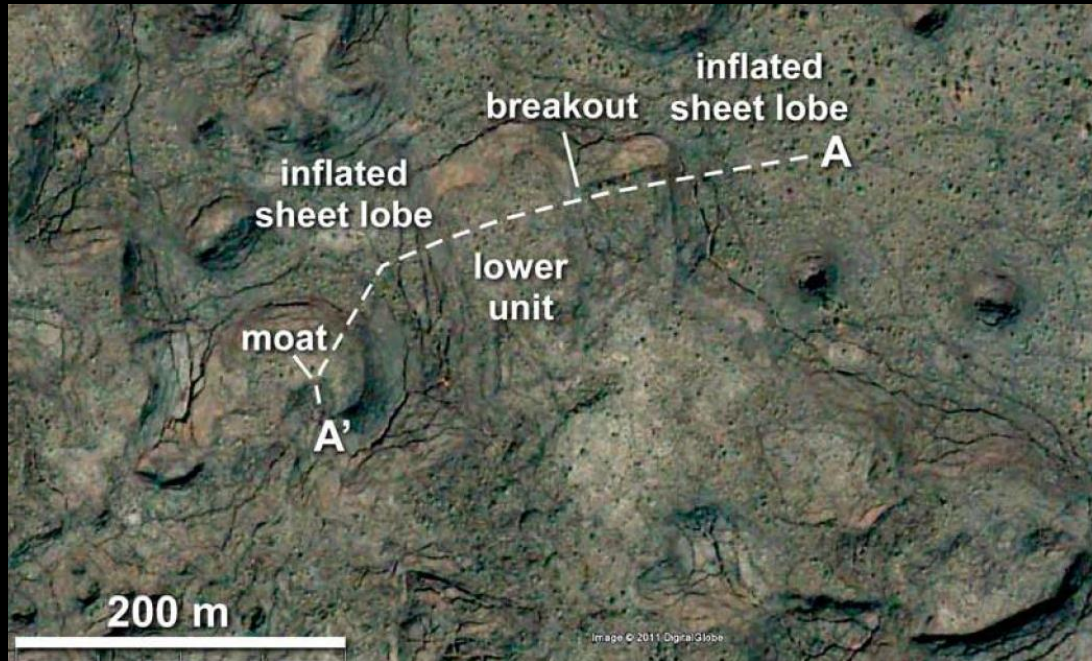
Ina: Closer View



Ina: Mons Agnes: 20-30 m tall



Inflated Lava Flows: New Mexico



***Lava injected beneath
a solid crust***

***McCartys Lava Flow
Northwest New Mexico***



Garry et al. (2012)



Summary

- **Lunar Mare: Basin-Fill and Extrusives**

- *Most 2.7 to 3.8 Ga*
- *>70 compositional nearside units*
- *Ti-rich basalts ($>10\%$ TiO_2)*
(Tranquillitatis, Procellarum)

- **Silicic Domes**

- *Late-stage emplacement: KREEP Terrane*
- *Far side: Compton-Belkovich*
- *Thorium and uranium (>50 ppm)*

- **Recent Mare Patches and Extrusives**

- *18 to 50 Mya*
- *Volatiles*



**Clementine
photograph**