

Origin and Evolution of the Moon's Procellarum KREEP Terrane

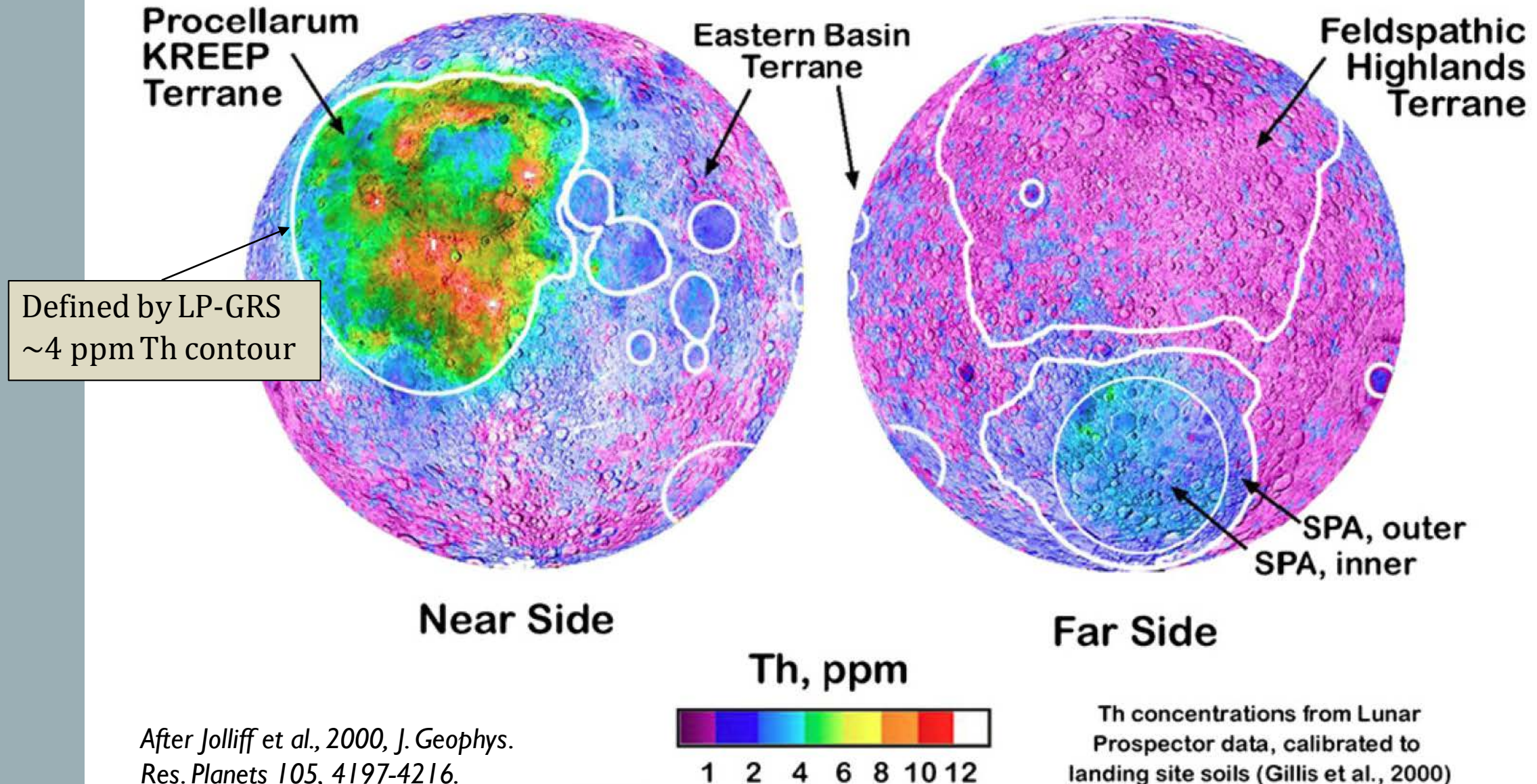
A White Paper submitted to the
2023 Planetary Science Decadal Survey

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The Procellarum KREEP Terrane on the lunar nearside is a unique province that produced volcanism over an extended period of the Moon's history.

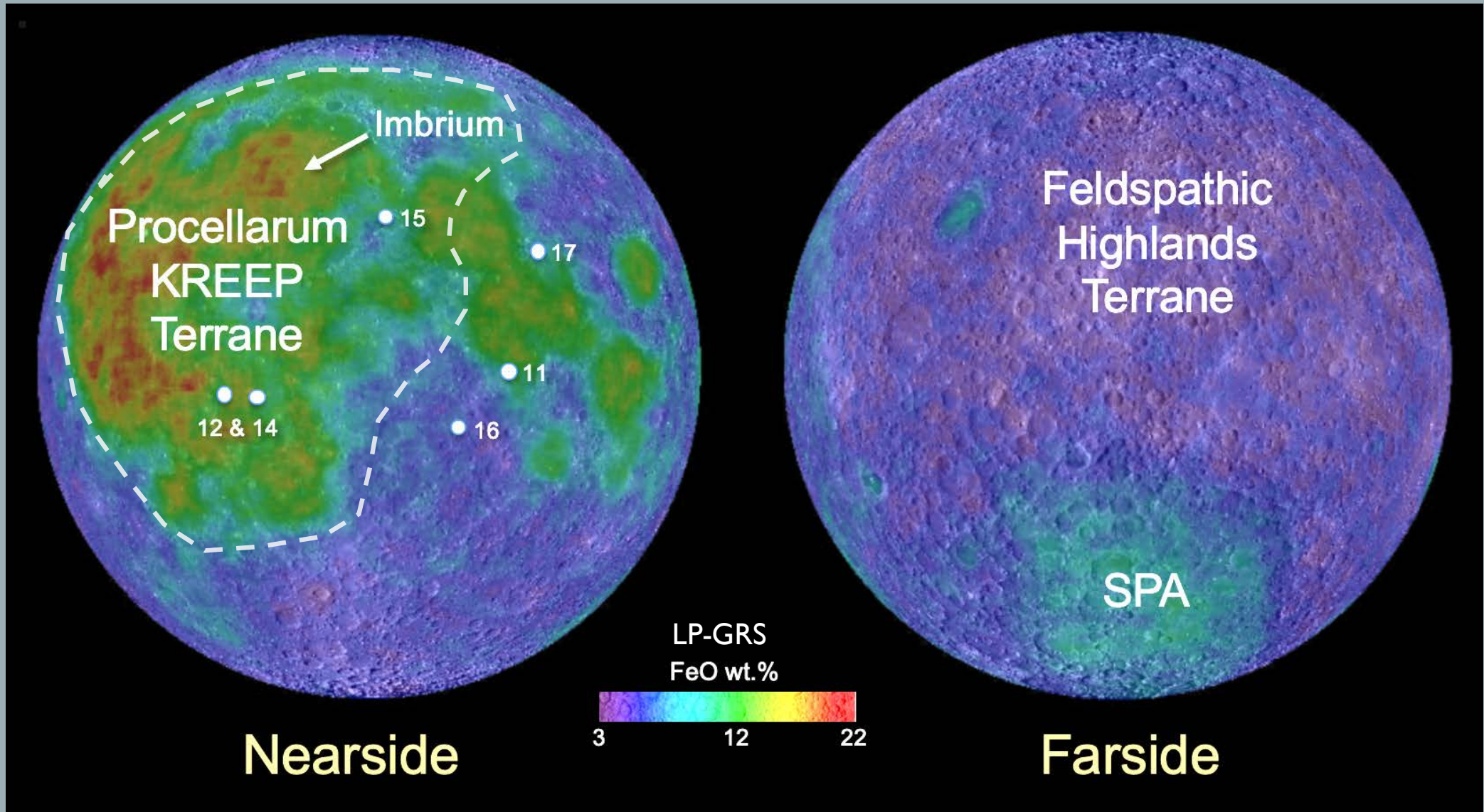
- Thermal evolution of the lunar mantle in this region possibly driven by high concentration of radiogenic heat-producing elements.
- Key to unlocking thermal evolution of the Moon and may have implications for understanding extensive volcanism on other inner Solar System bodies such as Mercury and Mars.
- Major volcanic features of this terrane could be explored by a long-distance rover in a New Frontiers class mission to answer questions about how this planetary asymmetry formed, why volcanism was so voluminous in this region, and how it persisted for over 3 billion years.

What is the Procellarum KREEP Terrane?



After Jolliff et al., 2000, *J. Geophys. Res. Planets* 105, 4197-4216.

What is the Procellarum KREEP Terrane?

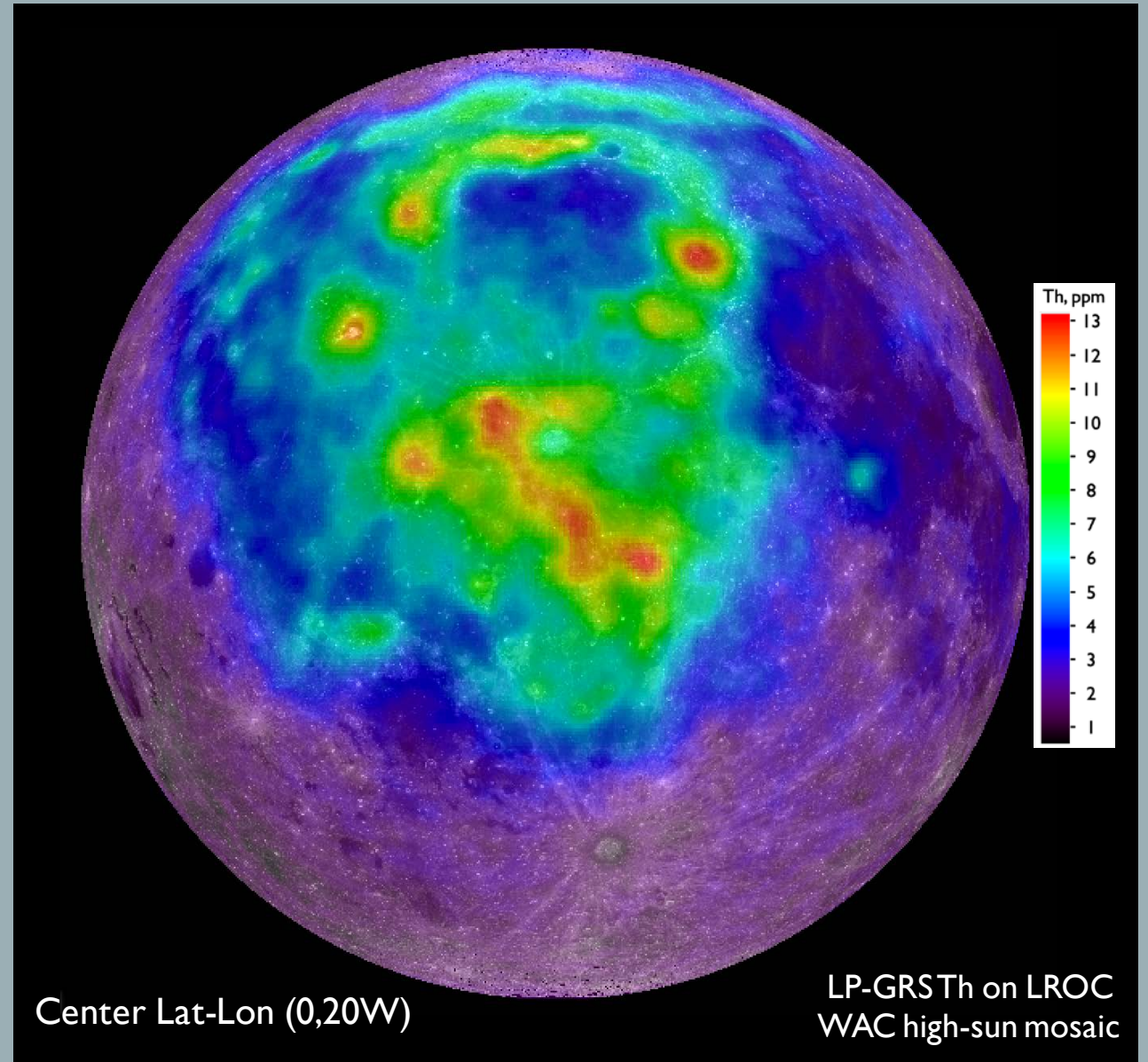


Significance of the Procellarum KREEP Terrane

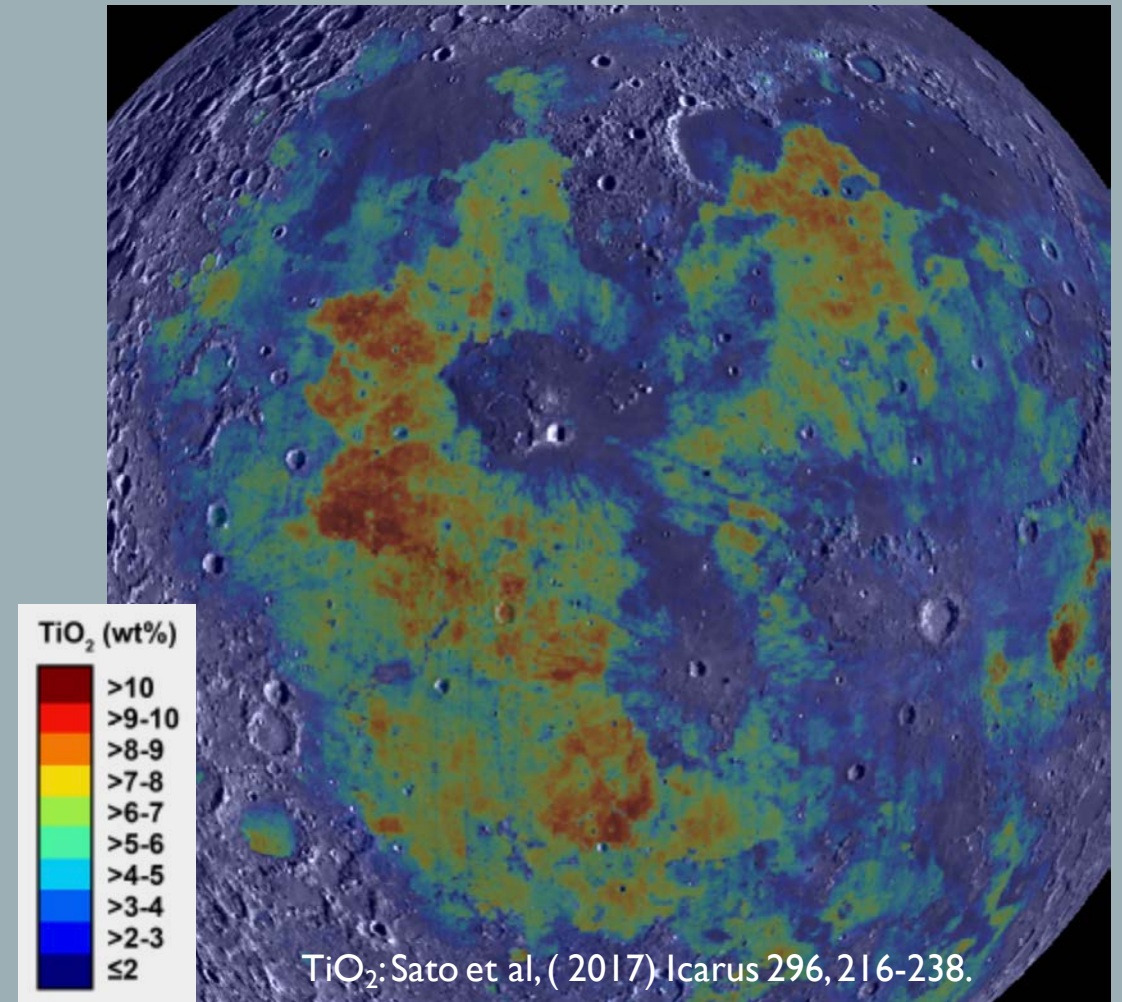
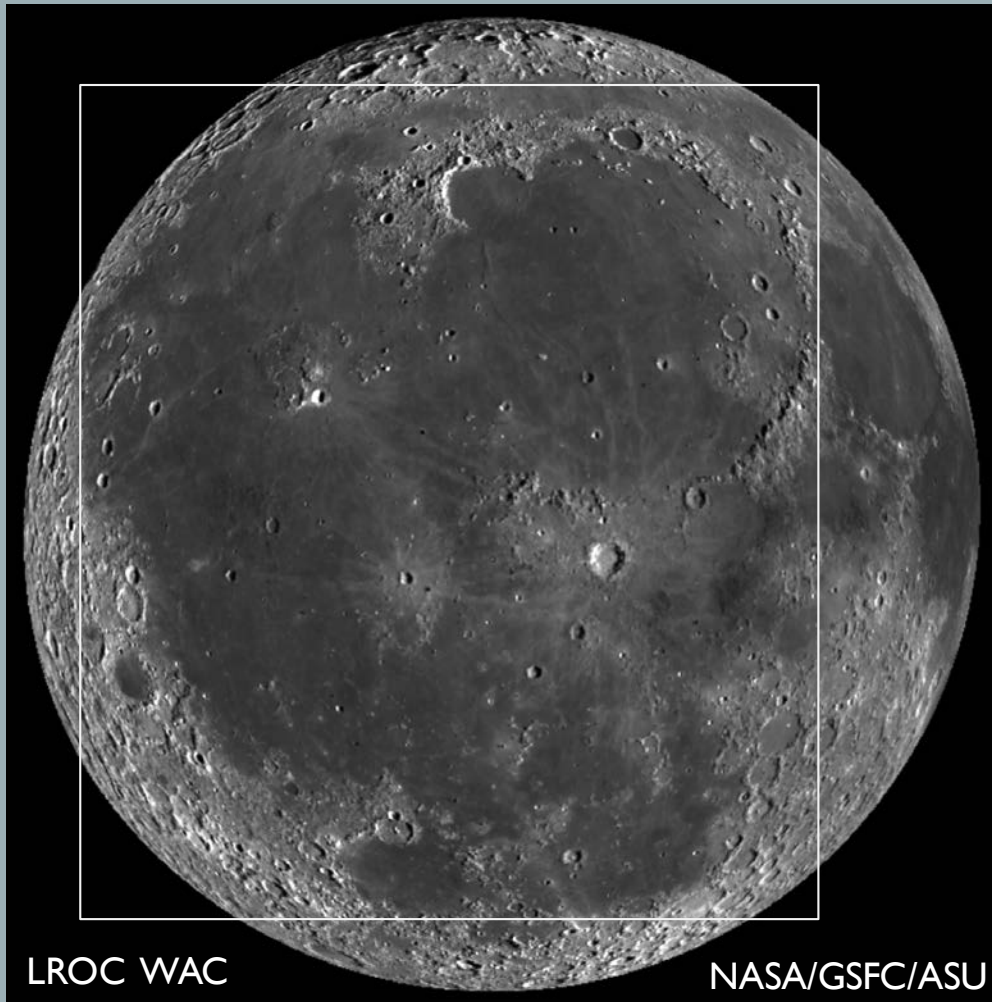
Terrane: geochemical provinces of the Moon that share a common geologic history.

Procellarum KREEP Terrane (PKT):

- Mafic province, ~16% of Moon's surface area
- Coincident with extensively resurfaced Procellarum-Imbrium region
- Vast majority of mare basalts erupted within or adjacent to the PKT
- Highly enriched in U, Th, K, and by inference other KREEP elements
- Includes most sites of rare silicic volcanism
- Represents strong global asymmetry in composition and thermal evolution
- Site of early degree-1 mantle overturn?
- How was KREEP concentrated in the PKT?



Procellarum KREEP Terrane: Extensive Basaltic Volcanism

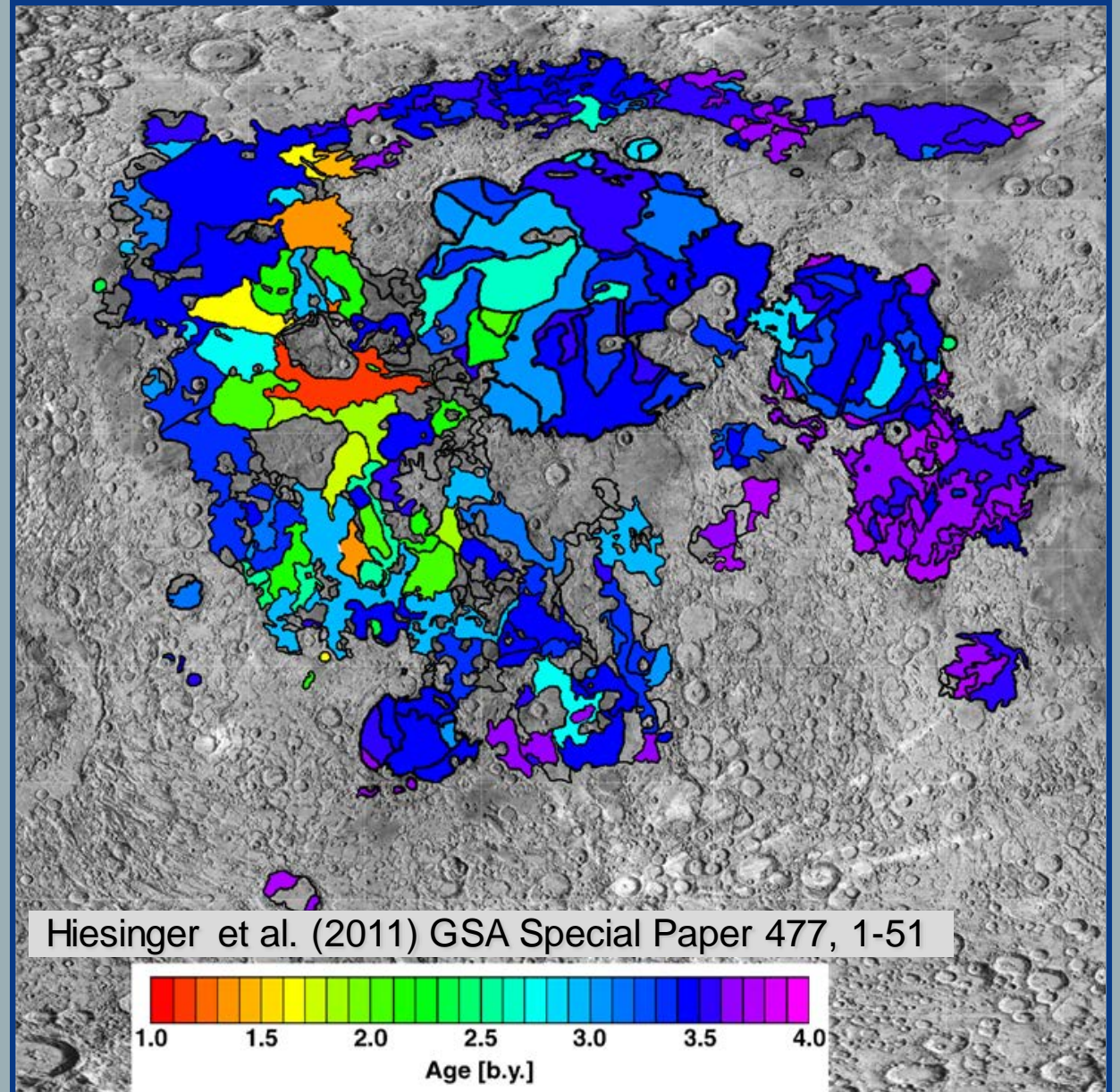


Basaltic volcanism occurs extensively throughout the Procellarum KREEP Terrane. Basalts exhibit a large range of Ti concentrations → reflecting variety of mantle sources.

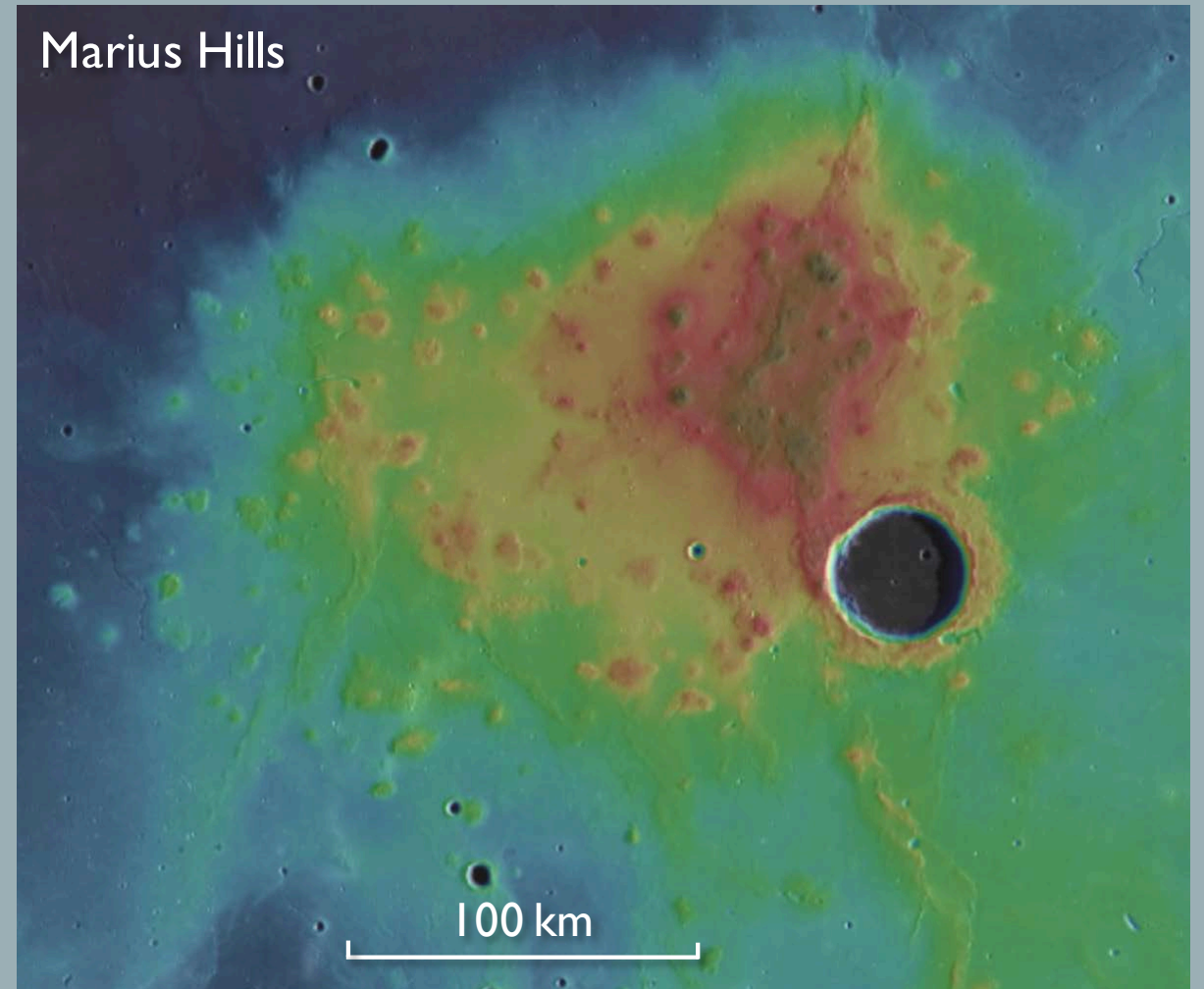
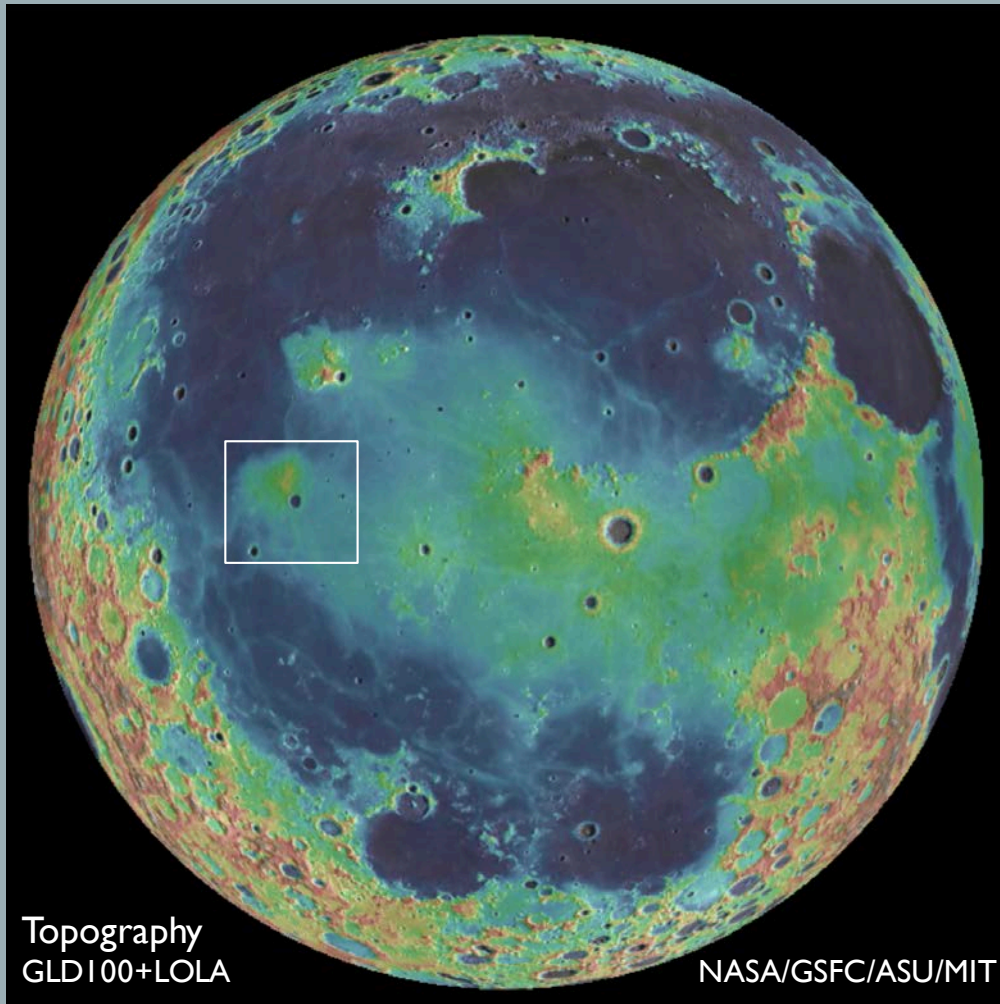
Procellarum KREEP Terrane: Volcanism extended over time



Basalt ages range from ~1.0 to 3.6 Byrs.
What sustained this extended basalt production?



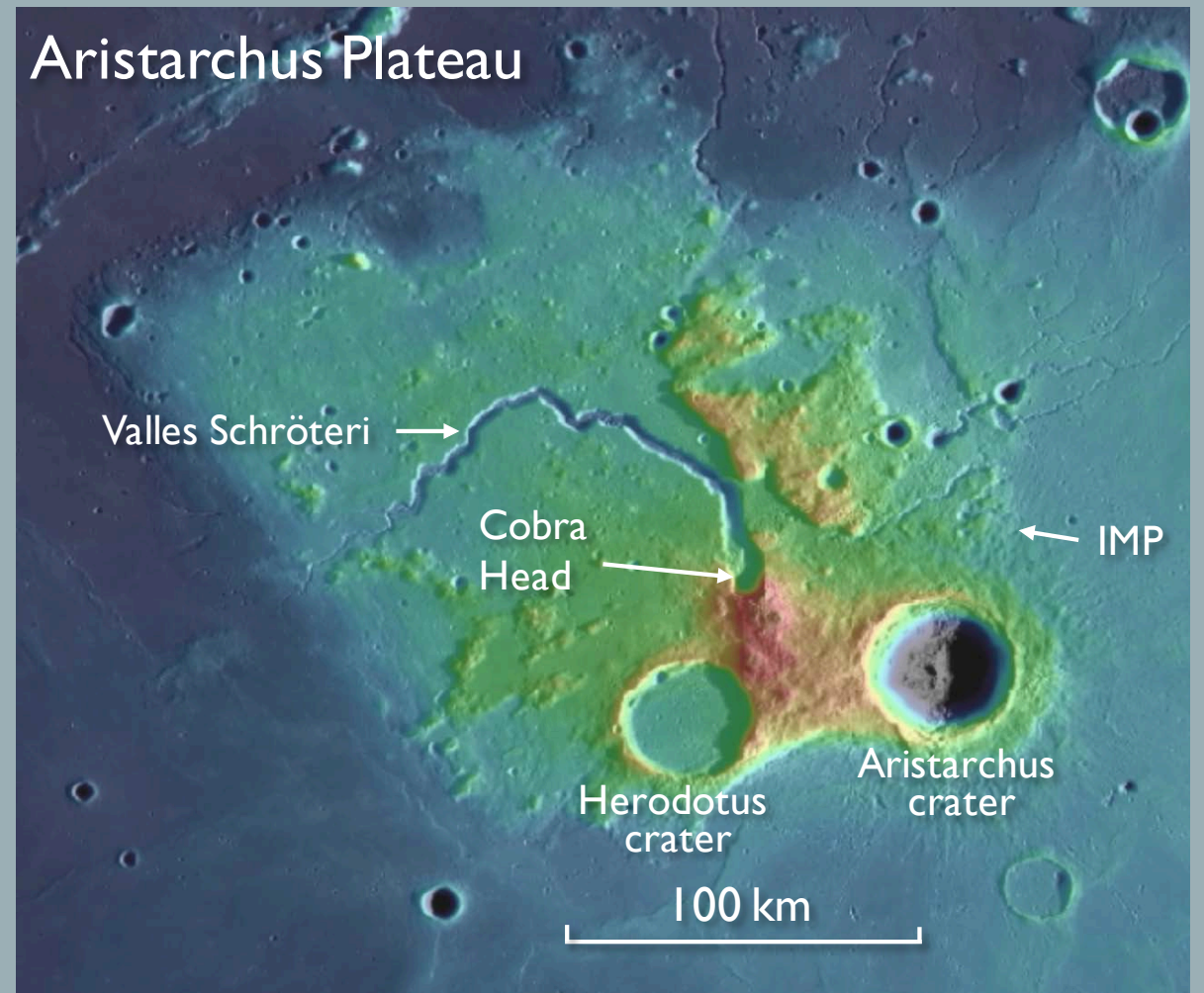
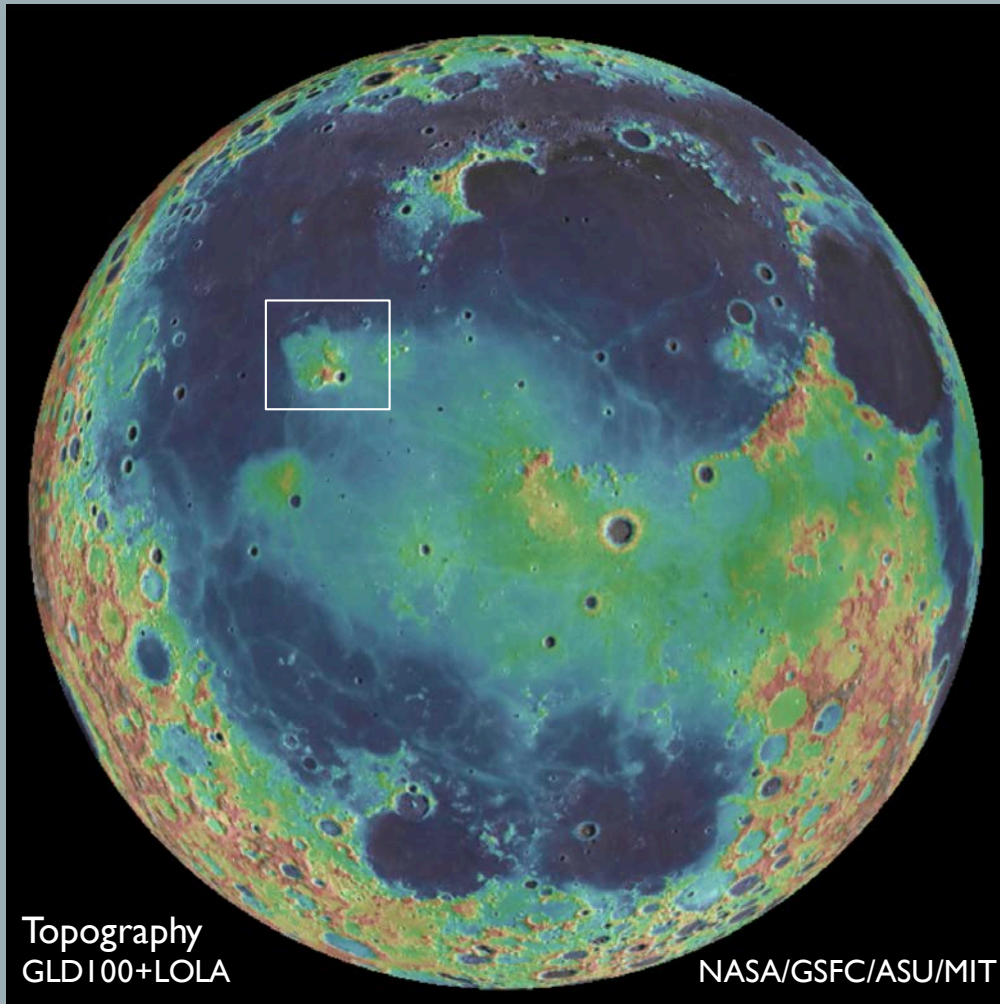
Procellarum KREEP Terrane: Volcanism extended over time



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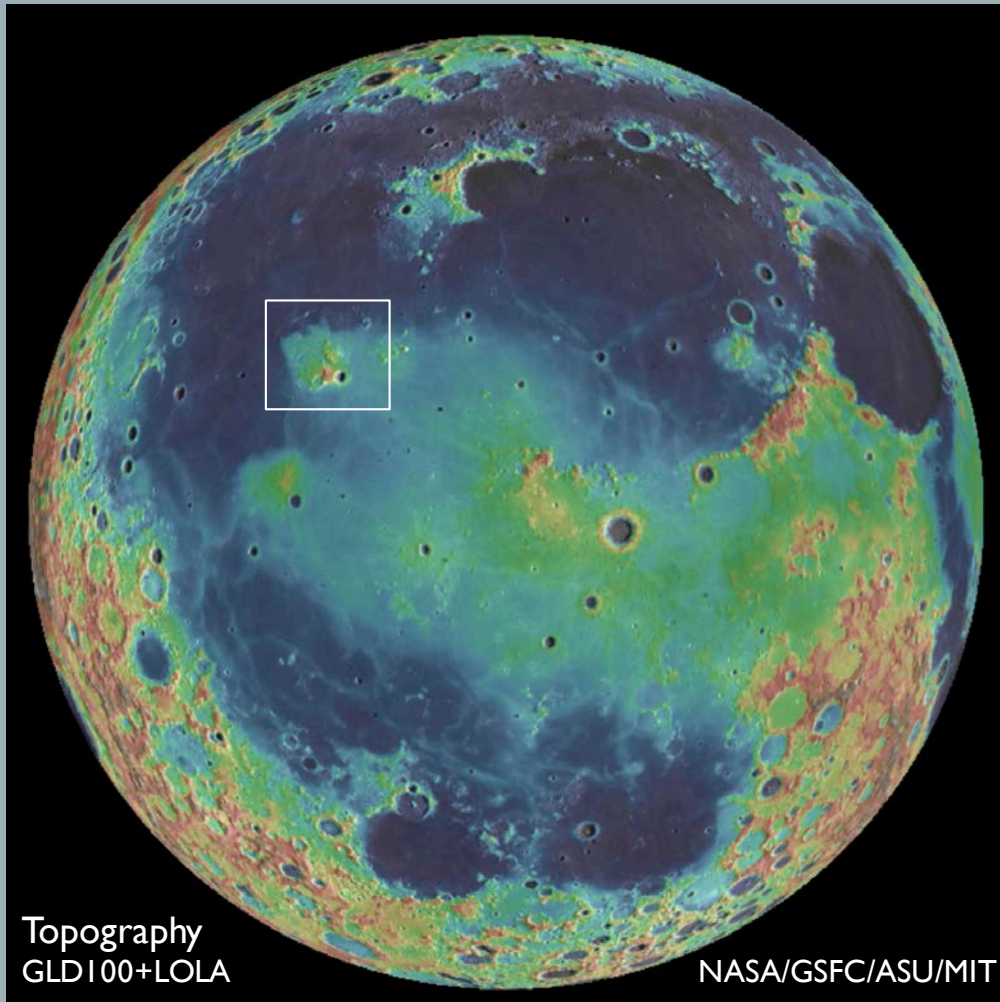
Huang, J., et al., 2011, *J. Earth Sci.* 22, 601.
Hiesinger, H., et al., 2016, *Lunar Planet. Sci.* 47, #1877.

Aristarchus Plateau: A Solar-System-class pyroclastic deposit

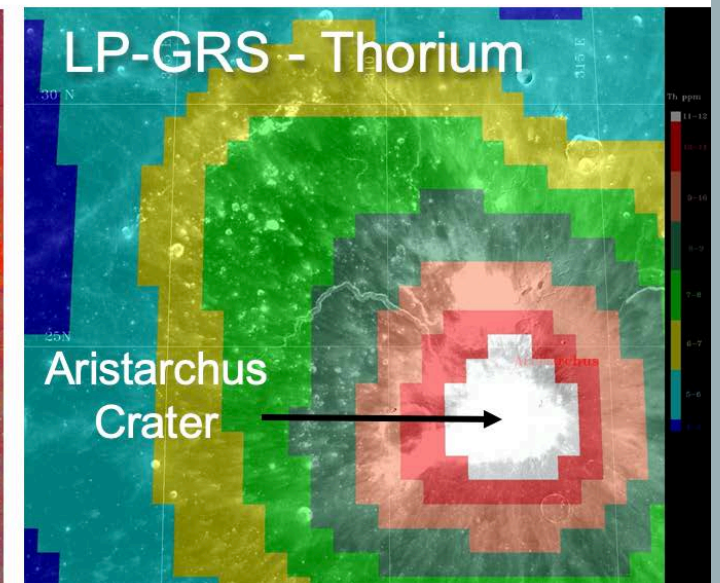
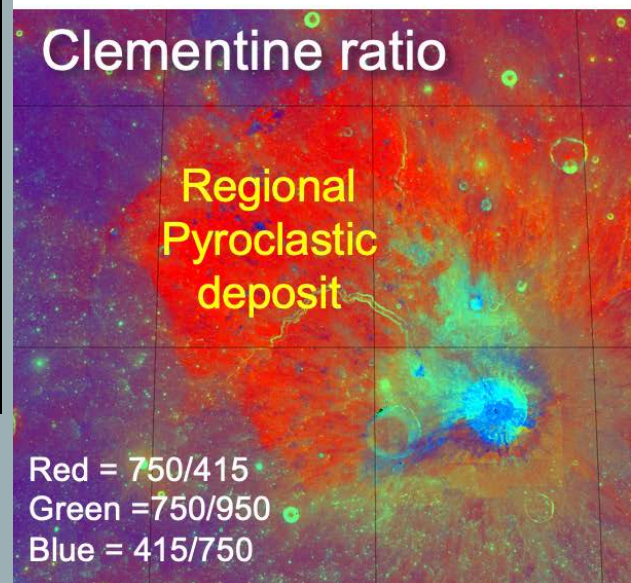
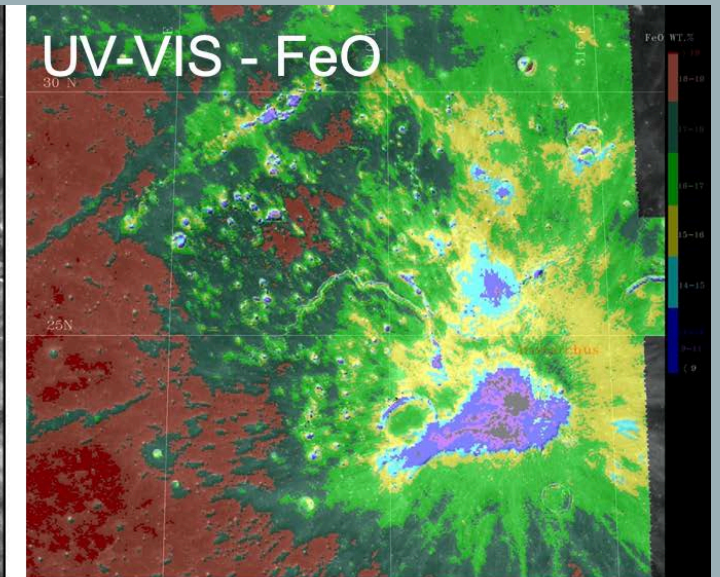
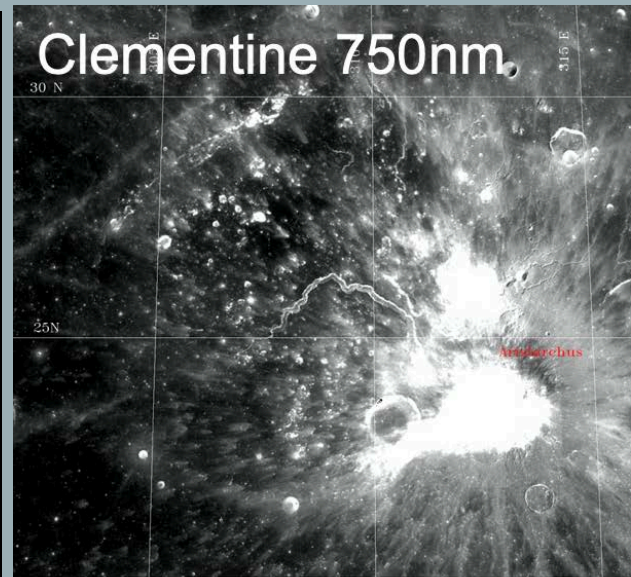


Aristarchus Plateau contains the largest pyroclastic deposit on the Moon, a huge lava channel, Valles Schröteri, beginning at the “Cobra Head” vent, an IMP, and possibly bimodal volcanism.

Aristarchus Crater: An extraordinary compositional anomaly



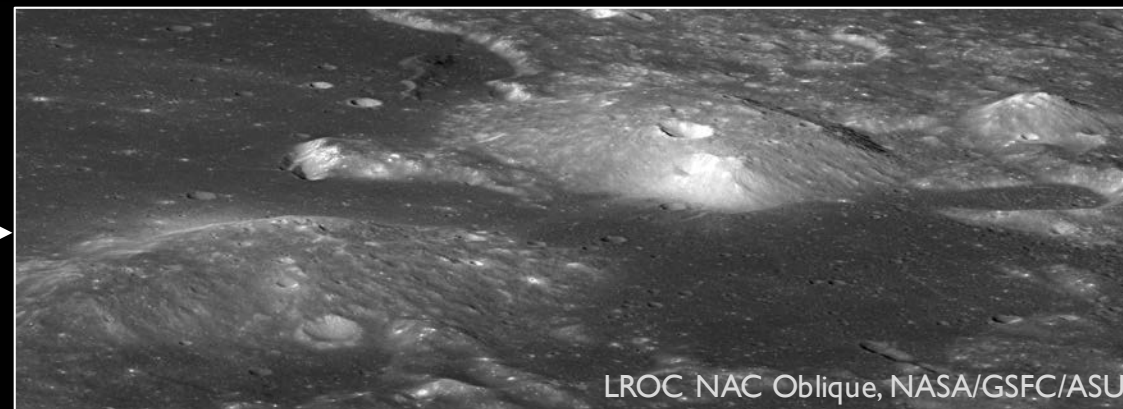
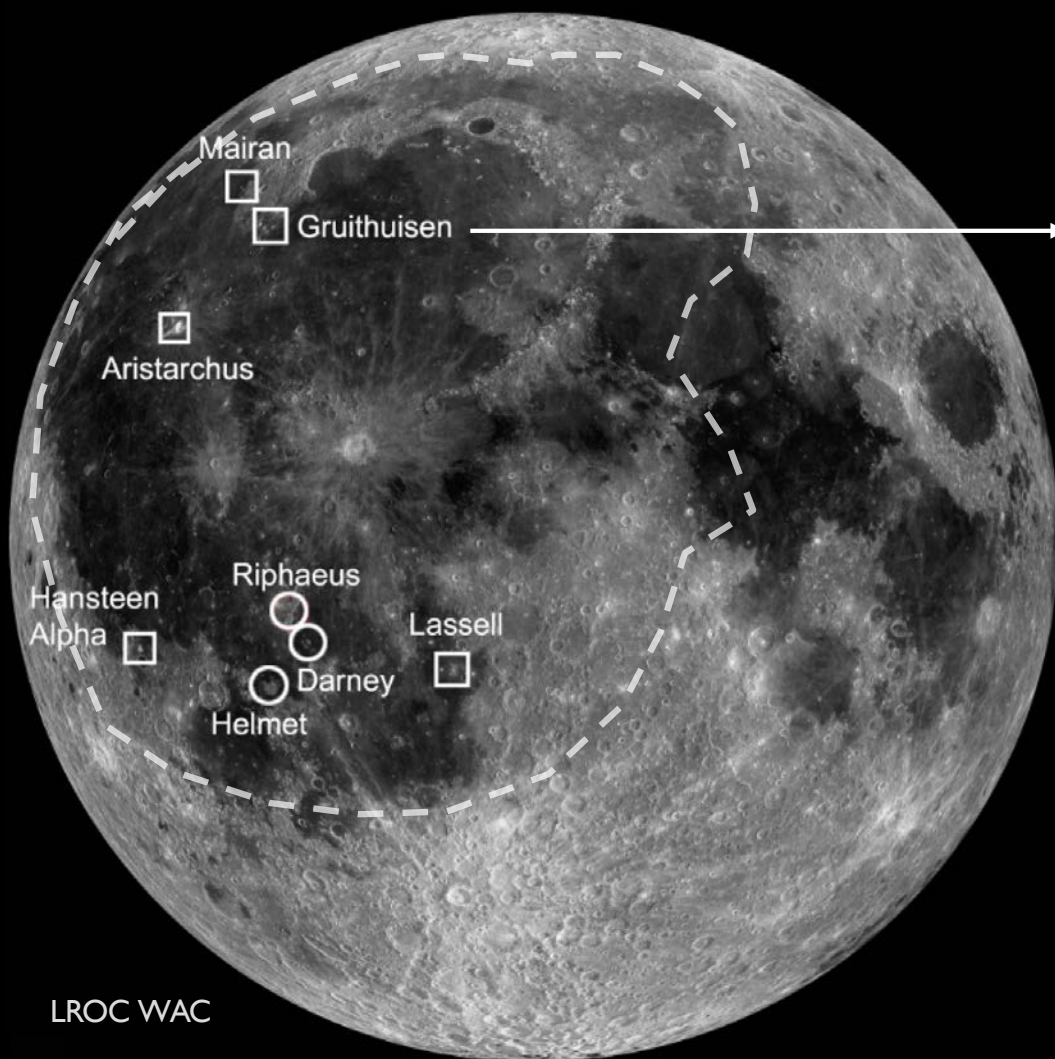
Aristarchus impact excavated silicic intrusive-extrusive complex and ejected material widely.



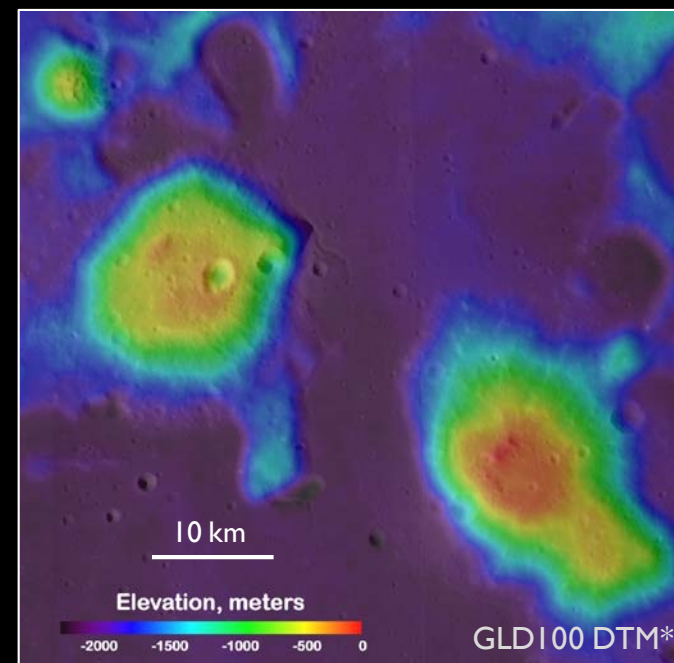
Sites of silicic volcanism save one occur within the PKT



Sites of silicic volcanism: Gruithuisen Domes

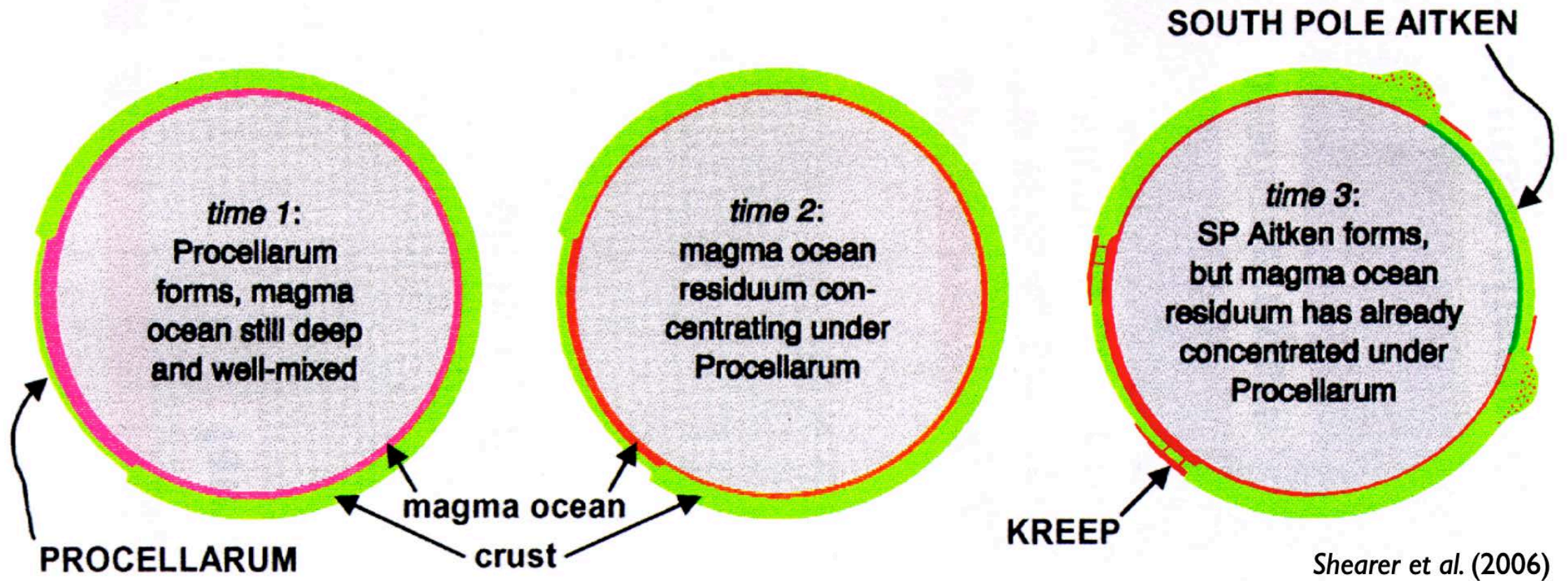


Gruithuisen
Domes



*Scholten et al., 2012

How did KREEP become concentrated in the PKT?



Hypothesis: A very early Procellarum impact basin formed, thinning the early crust, and LMO residuum (urKREEP) concentrated beneath the Procellarum basin.

Was cumulate overturn enhanced in mantle beneath the PKT?



Earth and Planetary Science Letters 201 (2002) 473–480

EPSL

Gravitational differentiation due to initial chemical stratification: origin of lunar asymmetry by the creep of dense KREEP?

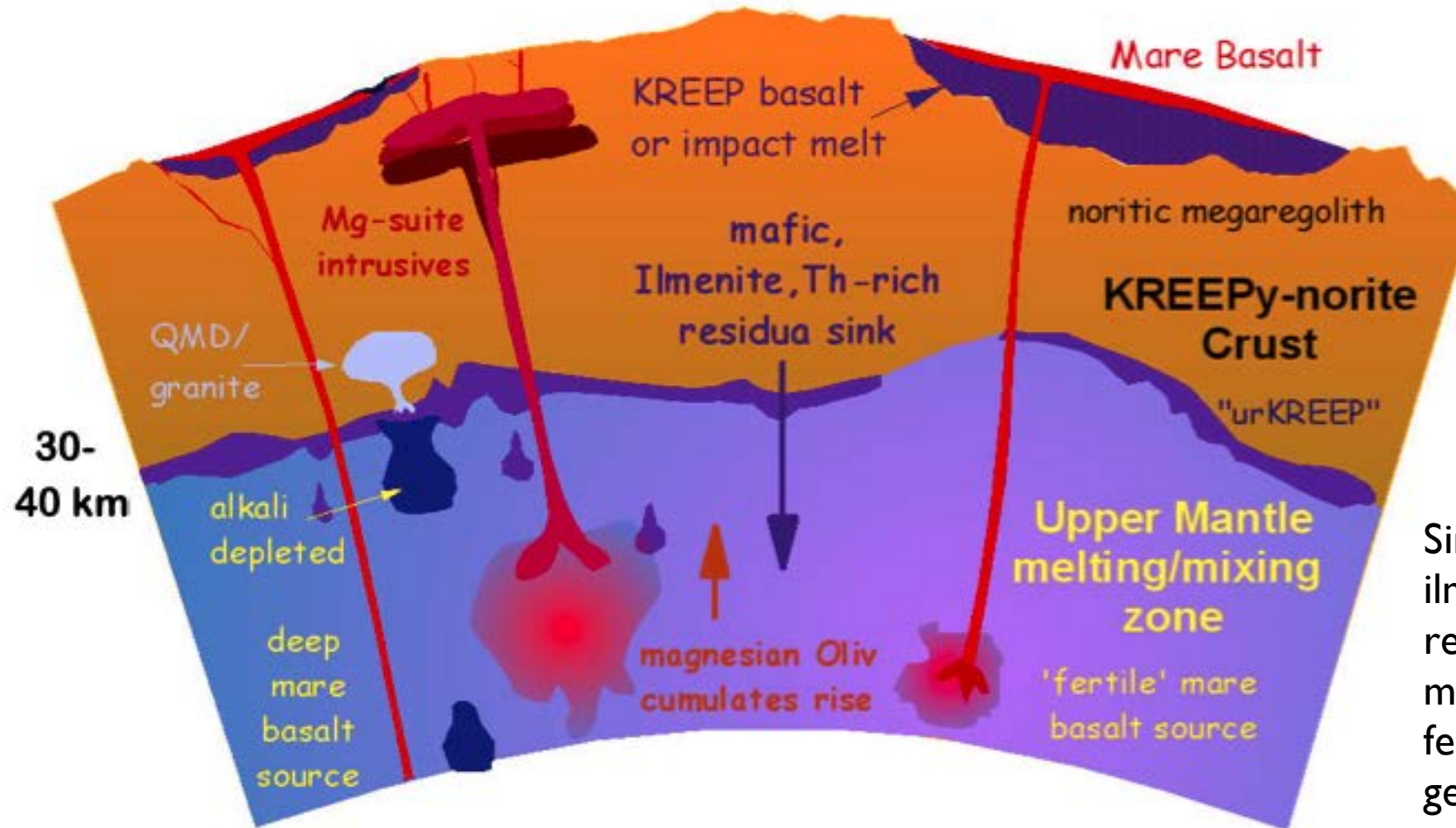
E.M. Parmentier^{a,*}, S. Zhong^b, M.T. Zuber^c

Models for the evolution of the Moon must explain the emplacement of mare basalts primarily on one side of the Moon, and in a region of the surface roughly correlating with high subsurface concentrations of KREEP.

Hypothesis: A long-wavelength, degree-1 instability led to sinking of ilmenite-rich cumulates, which mixed into the upper mantle, providing enrichment also in heat-producing U, Th, and K, and contributing to the production of voluminous mare basalts in the Procellarum KREEP Terrane.

Schematic cross section of crust and upper mantle beneath the PKT

Procellarum KREEP Terrane

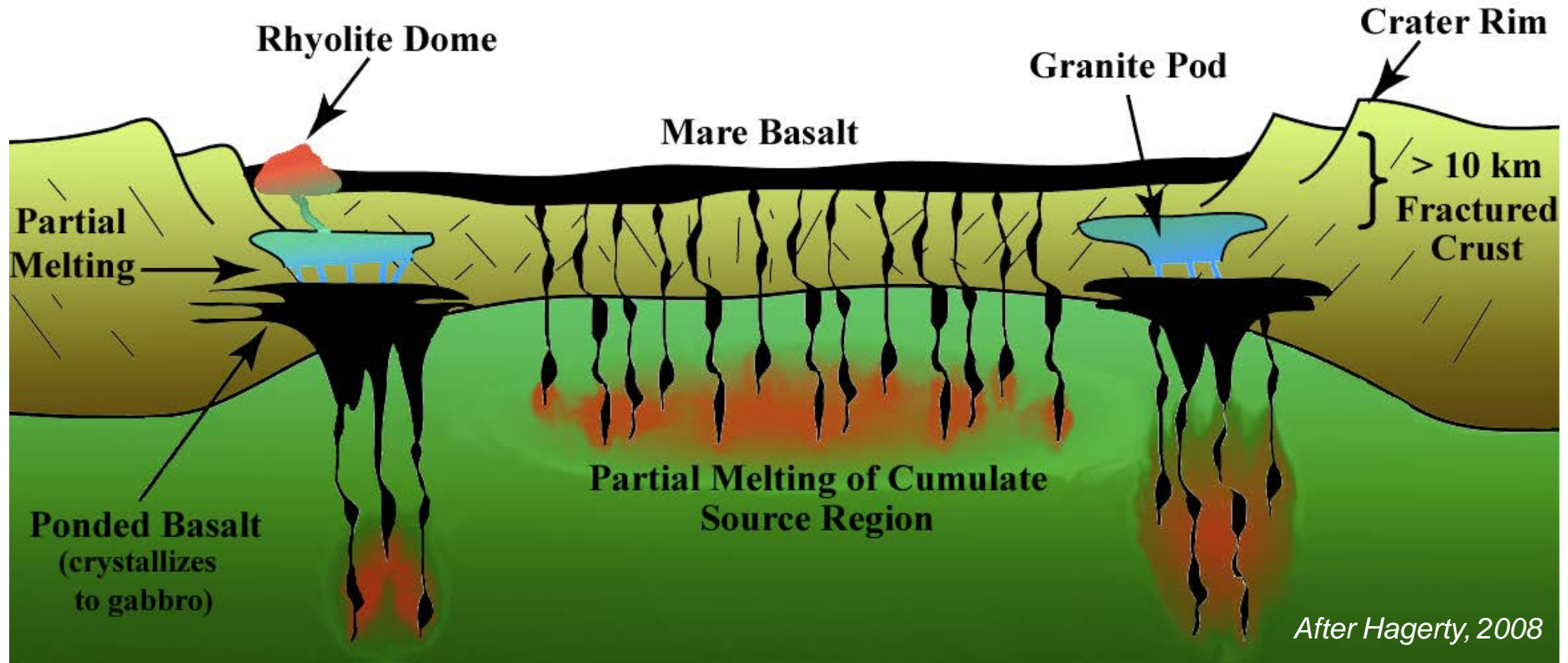


Magmatic and volcanic processes were enhanced in the PKT and led to a unique crustal province.

No evidence in remote sensing data and samples for anorthositic crustal materials that dominate the Moon's feldspathic highlands.

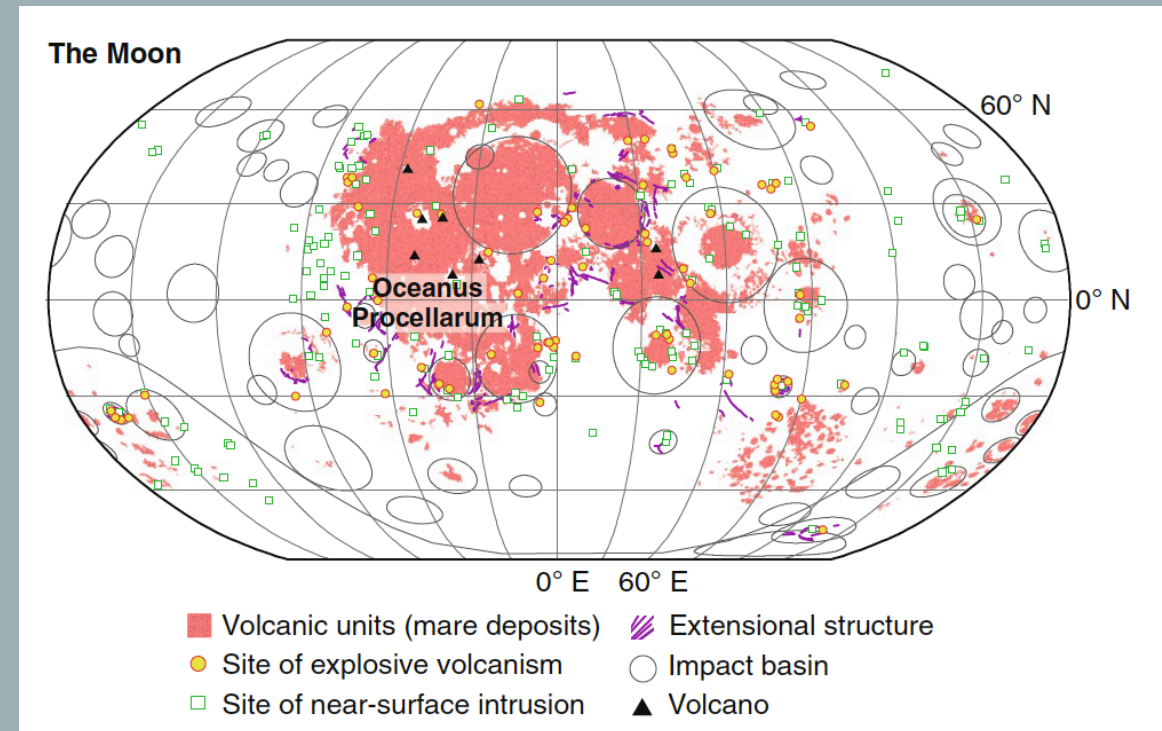
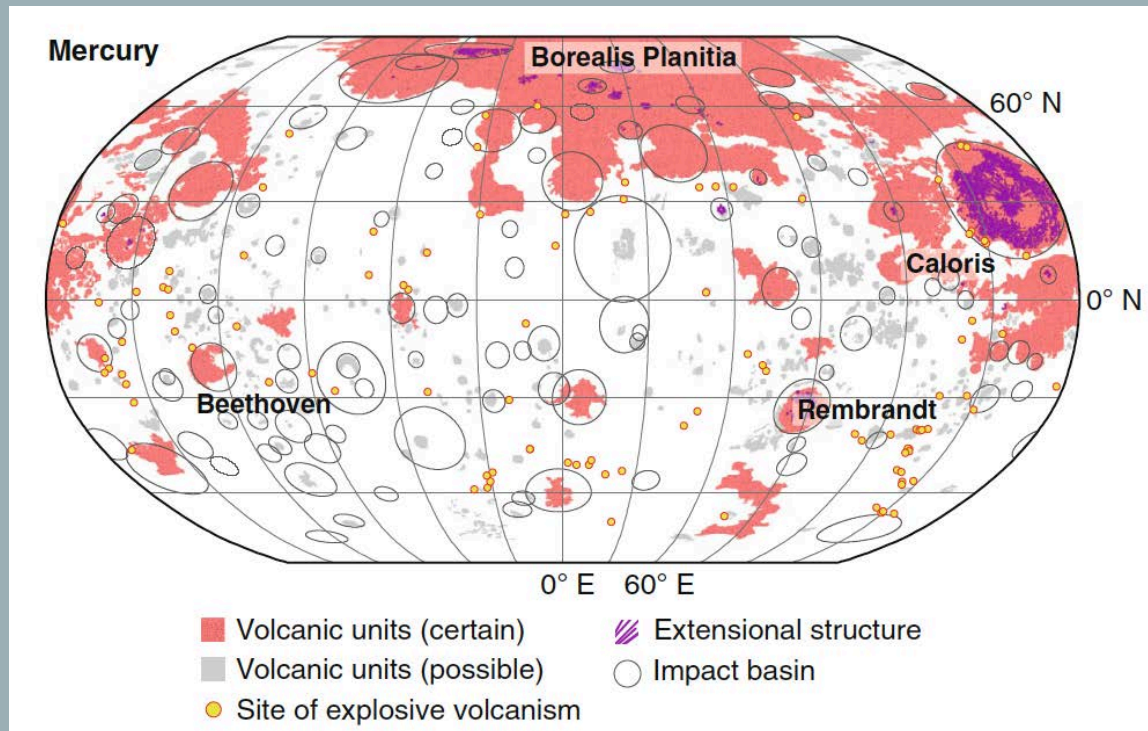
Sinking and mixing of ilmenite- and KREEP-rich residua into the upper mantle created hybrid, fertile sources for generation of mare basalts.

Basaltic underplating to generate silicic partial melts?



Basaltic underplating and partial melting of “fertile” (KREEP-rich) crustal rocks for alkali suite and granite petrogenesis (Hagerty et al., 2006, JGR 111; Gullikson et al., 2016, Am. Min. 101).

Relevance to other rocky planets: Mercury: Smooth Plains Deposits



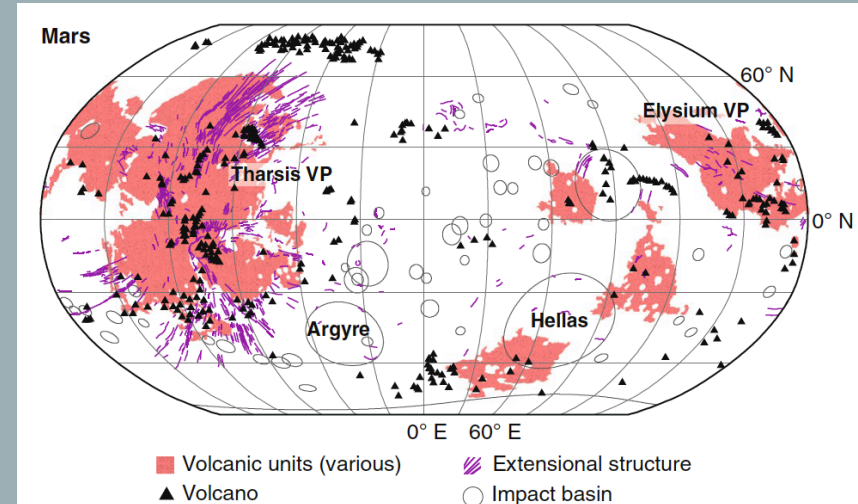
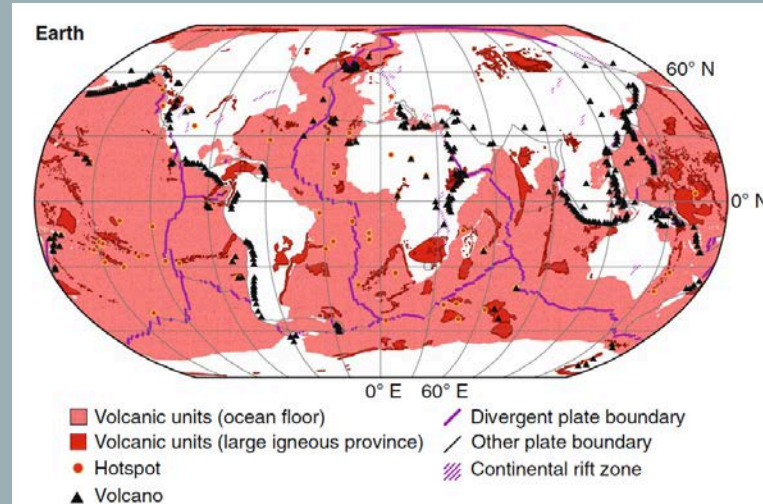
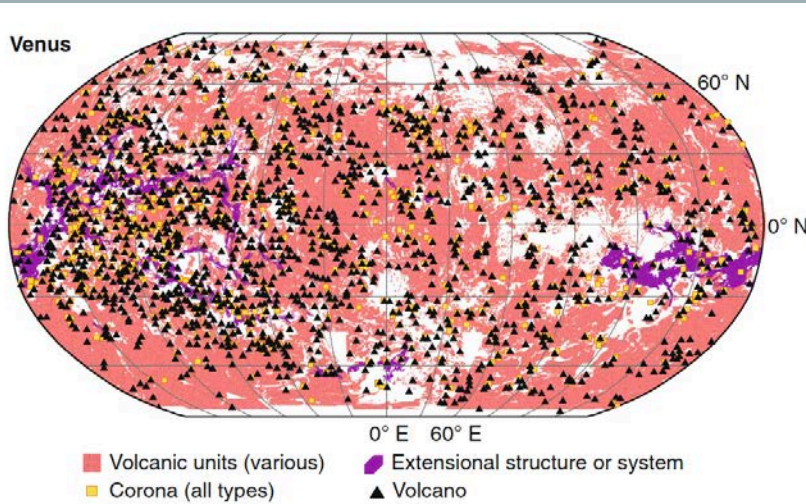
Byrne, 2019, *Nature Astronomy*

Volcanic Plains on Mercury

- Northern Volcanic Plains (Borealis Planitia)
 - Extensively resurfaced “terrane”
 - Ages: 3.8 Byrs and older
- Basin-associated volcanic plains
 - Span a greater range of ages 1-3.5 Byrs

Are there any parallels between Borealis Planitia on Mercury and PKT on Moon?
How do large volcanic provinces develop and evolve on small rocky bodies?

Comparisons to Large Volcanic Provinces on Mars, Venus, Earth



Byrne, 2019, Nature Astronomy

What are the similarities and differences in large volcanic provinces among the terrestrial planets?

- Hesperian to Late Amazonian basalts on Mars
- Regional and lobate plains on Venus
- Large igneous provinces and ocean floors on Earth
- Northern Volcanic Plains (Borealis Planitia) on Mercury
- Procellarum KREEP Terrane on Moon

Making the case for exploration of the Procellarum-KREEPTerrane

Crawford, Fagents, and Joy (2007) Exploring the Basaltic Lava Flows of Oceanus Procellarum: Valuable (non-polar) lunar science facilitated by a return to the Moon. *Astronomy & Geophysics* **48**, 3.18-3.21.

ABSTRACT

The Moon is a promising science target, made a priority in recent space exploration plans. So far, polar landing sites have been preferred, but many promising scientific objectives lie elsewhere. Here we summarize the potential value of one such scientific target, northern Oceanus Procellarum, which includes basalts of a wide range of ages. Studying these would allow refinement of the lunar stratigraphy and chronology, and a better understanding of lunar mantle evolution. We consider how exploration of such areas might be achieved in the context of lunar exploration plans.

Full Moon exploration

Ian Crawford, Sarah Fagents and Katherine Joy make the case for exploring the basaltic lava flows of Oceanus Procellarum: valuable (non-polar) lunar science facilitated by a return to the Moon.

Chang'e-5 sample return from the Procellarum KREEP Terrane

Qian et al. (2018) Geology and scientific significance of the Rümker region in northern Oceanus Procellarum: China's Chang'E-5 landing region. *J. Geophys. Res.* 123, 1407–1430.



Journal of Geophysical Research: Planets

RESEARCH ARTICLE

10.1029/2018JE005595

Special Section:

Science and Exploration of the Moon, Near-Earth Asteroids, and the Moons of Mars

Key Points:

- The Rümker region is located in the northwest of the Procellarum KREEP Terrane, experiencing a long and complex geological history
- We carried out a detailed geological study and defined and dated 14 geological units
- The Em4 is the science-rich unit and suitable for landing. It is proposed as the first priority for sample return

Geology and Scientific Significance of the Rümker Region in Northern Oceanus Procellarum: China's Chang'E-5 Landing Region

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Abstract The Rümker region (41–45°N, 49–69°W) is located in northern Oceanus Procellarum of the Moon.

Key Scientific Questions

- Are the basalts of Oc. Procellarum themselves enriched in Th and other heat-producing elements compared to basalts sampled by Apollo, Luna, and lunar meteorites?
- Or is the apparent Th enrichment merely the result of vertical and horizontal mixing with an underlying KREEP-rich substrate?
- What relationship between ages of basalt units and their compositions?
- What factors led to very different expressions of volcanic morphologies such as shield volcanos, domes and cones, pyroclastic deposits, and irregular mare patches?
- What were the effects of impact craters such as Aristarchus that ejected Th-rich material over large portions of the basaltic plains?
- What was the nature of the Th-rich rock excavated by Aristarchus crater?
- What is the petrologic relationship between the basaltic rocks and the enriched crustal materials?
- How and why did volcanism persist in this region over nearly 3 Byrs?
- How much of the distribution of KREEP-rich material was caused by the Imbrium basin impact?
- What caused the great concentration of KREEP in this region of the Moon?
- Were Oc. Procellarum basalts erupted into an ancient, large impact basin that formed while the crust was still too hot to retain structures commonly associated with such basins?