The Lunar Highlands

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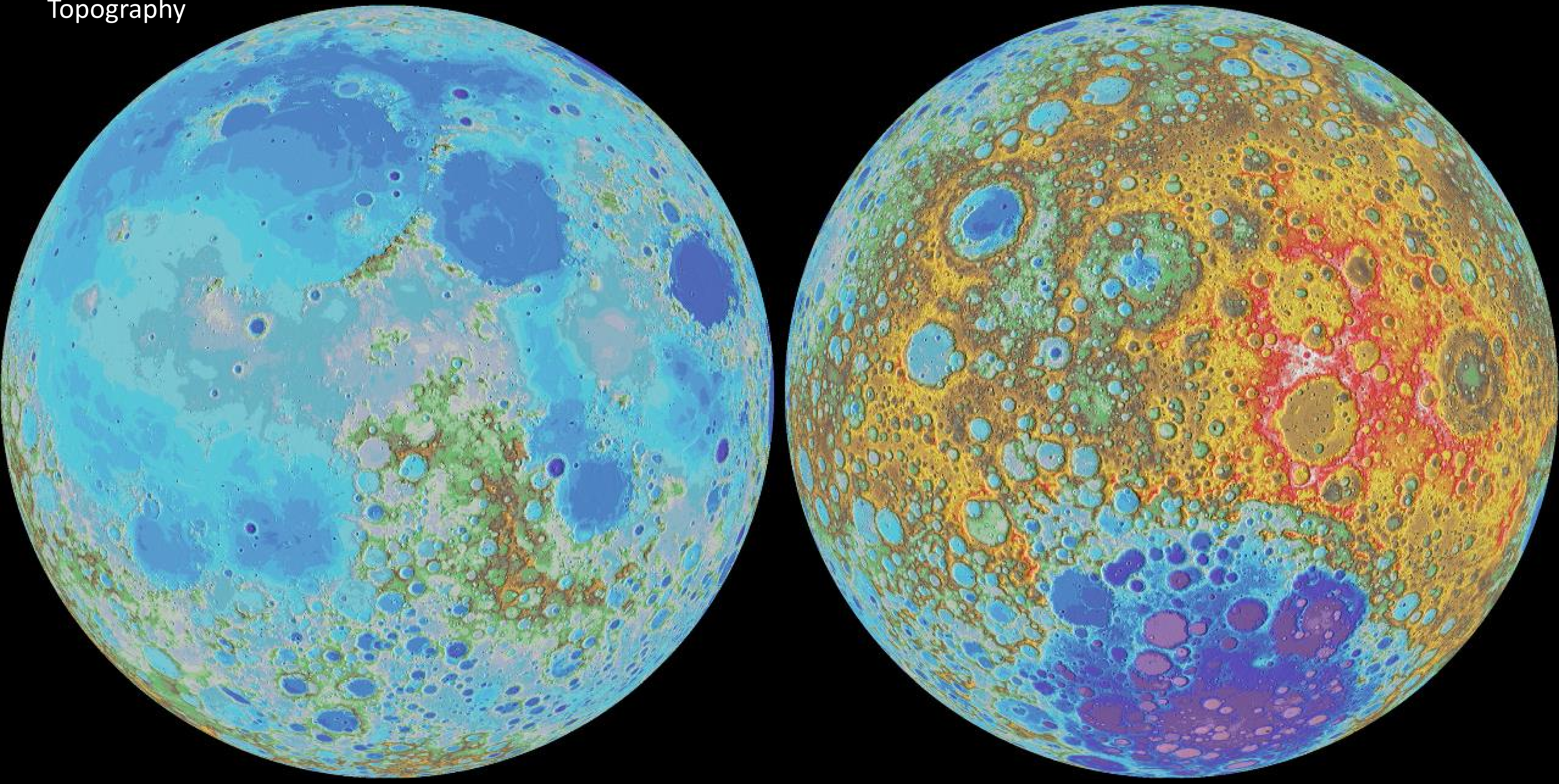
Post-magma ocean evolution of the lunar highlands

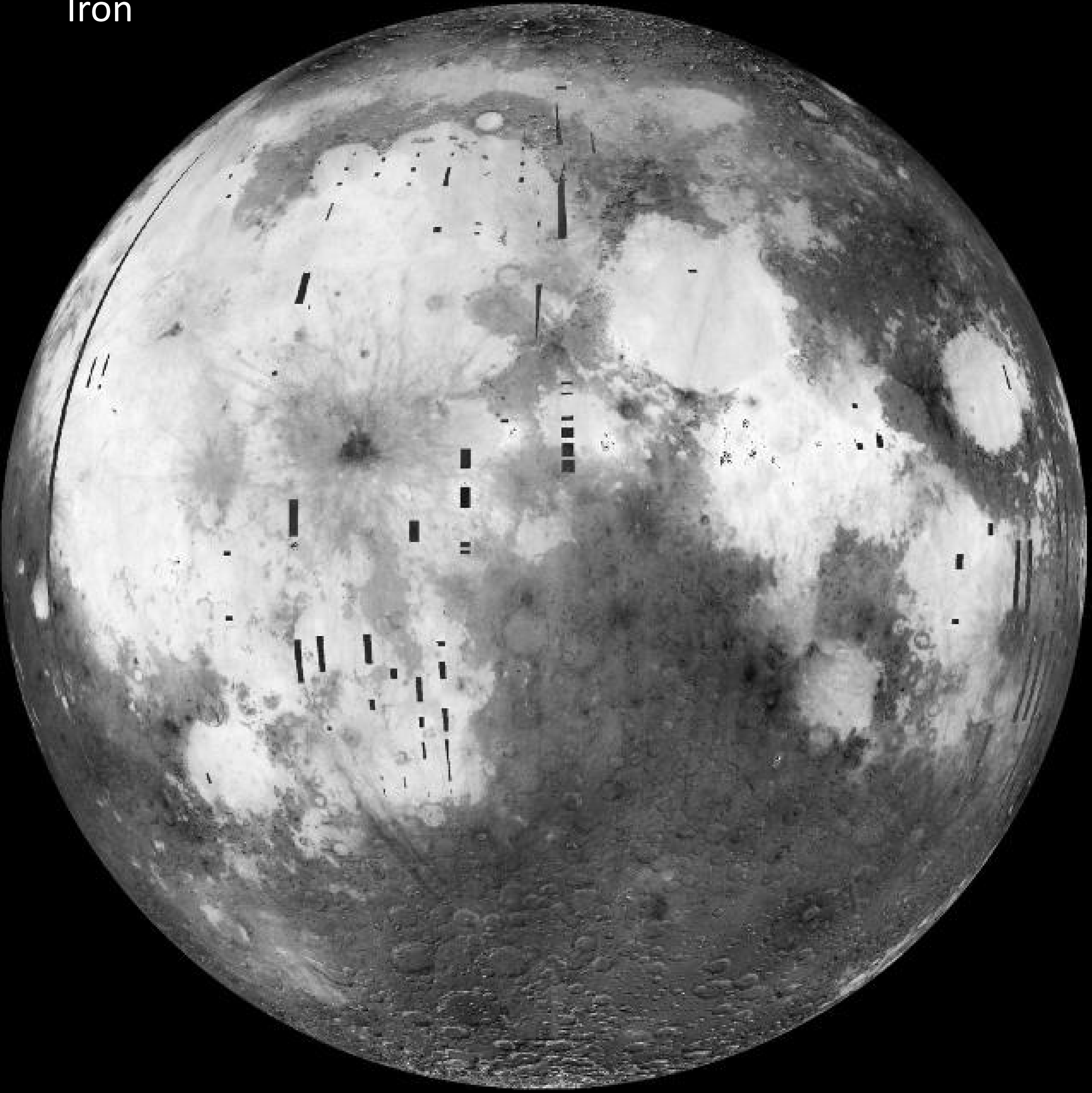
Topics

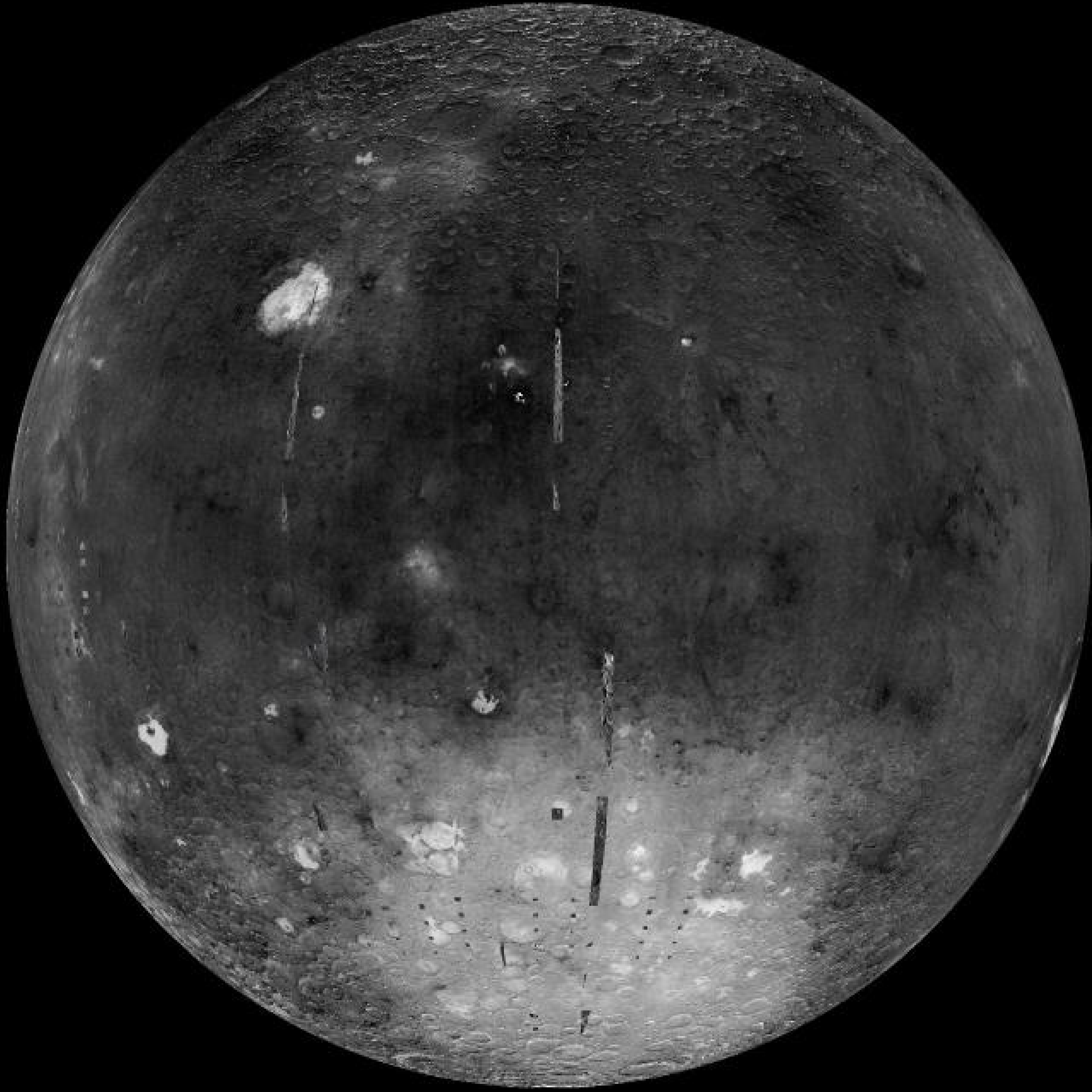
- Highland crust, mineralogy, rock types
- The regolith: definition, production, crater saturation, mixing
- Highlands at the poles

Topography

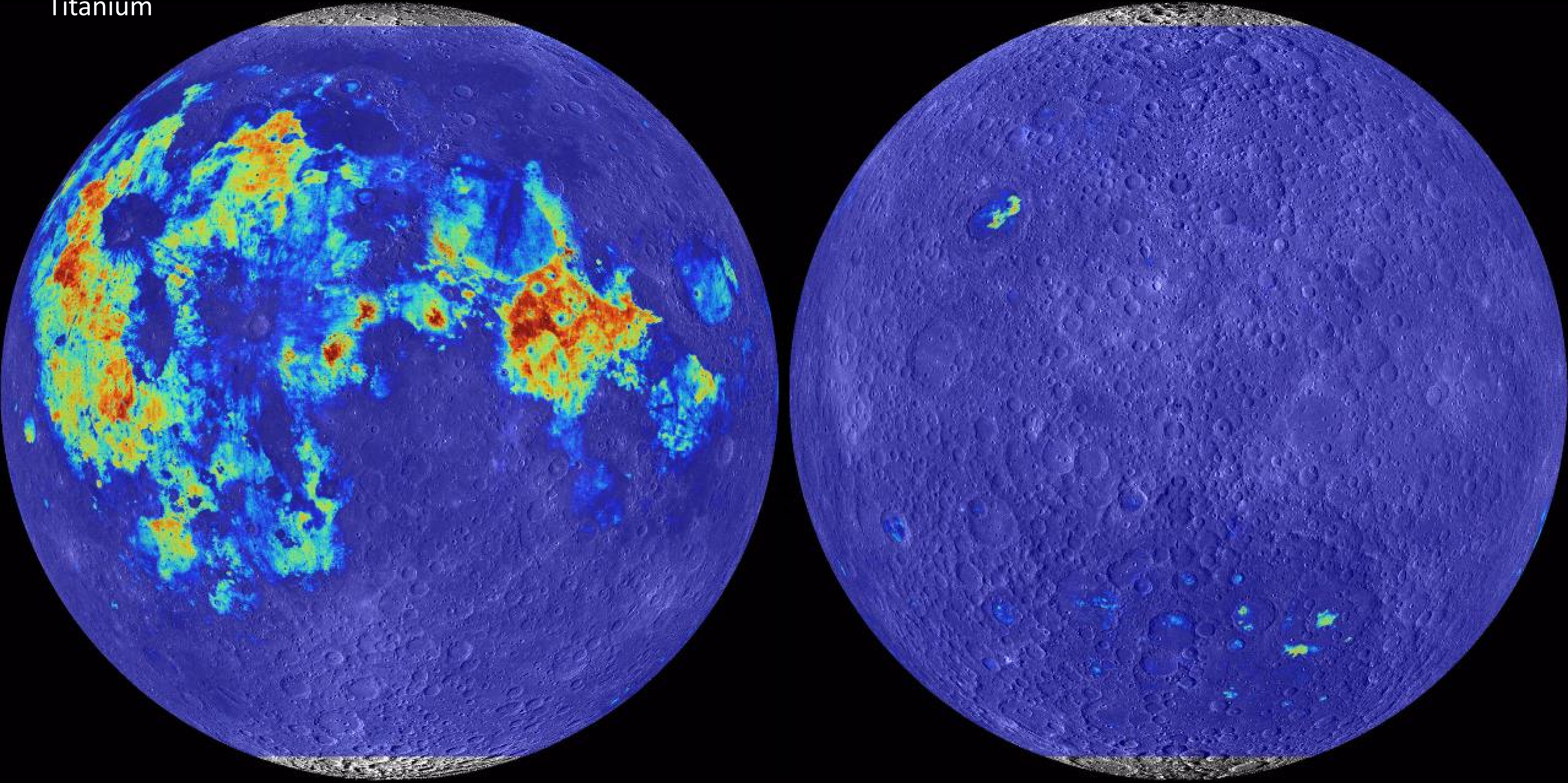


Iron

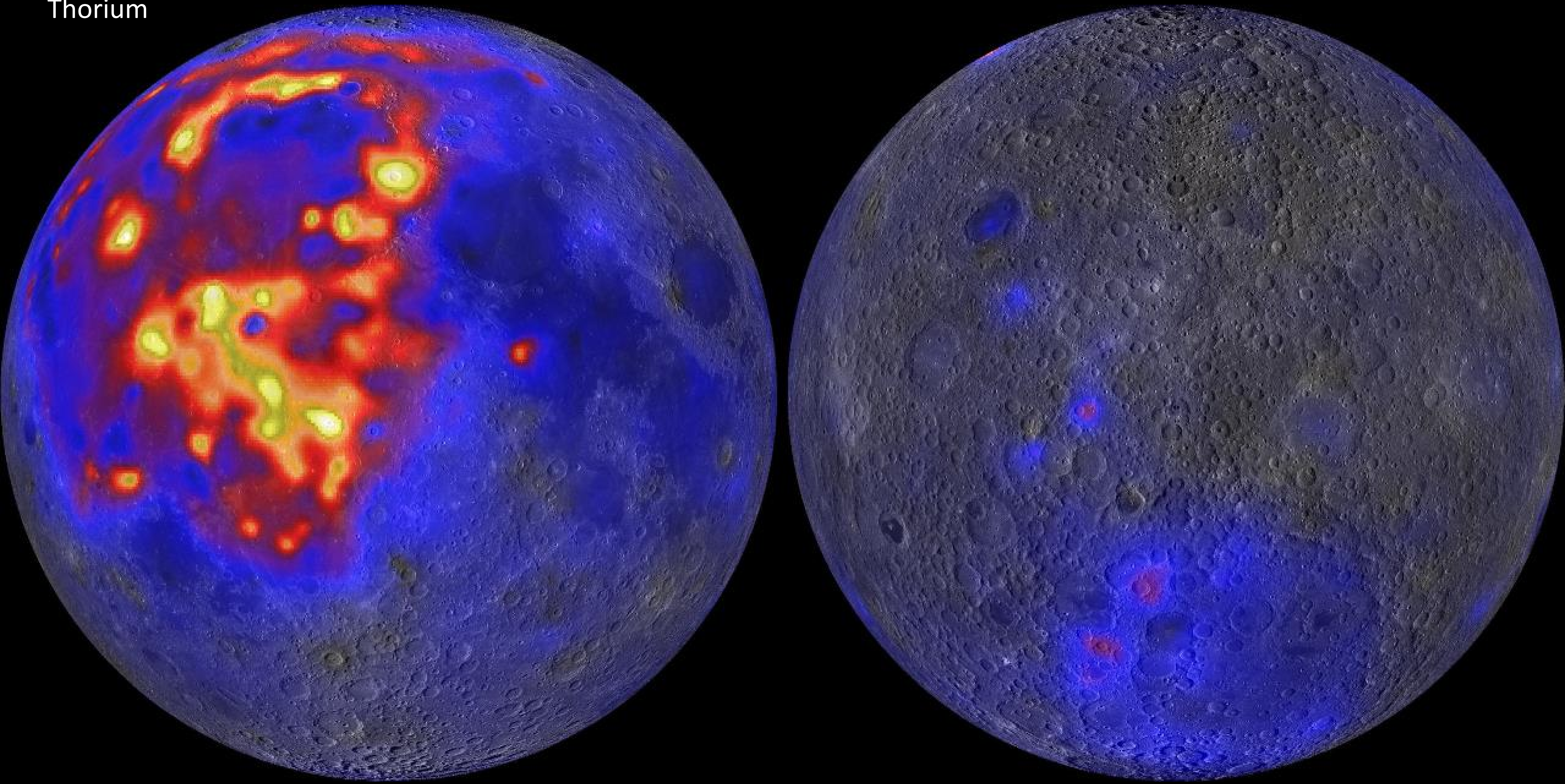




Titanium



Thorium



Lunar Terranes

Feldspathic Highlands Terrane:

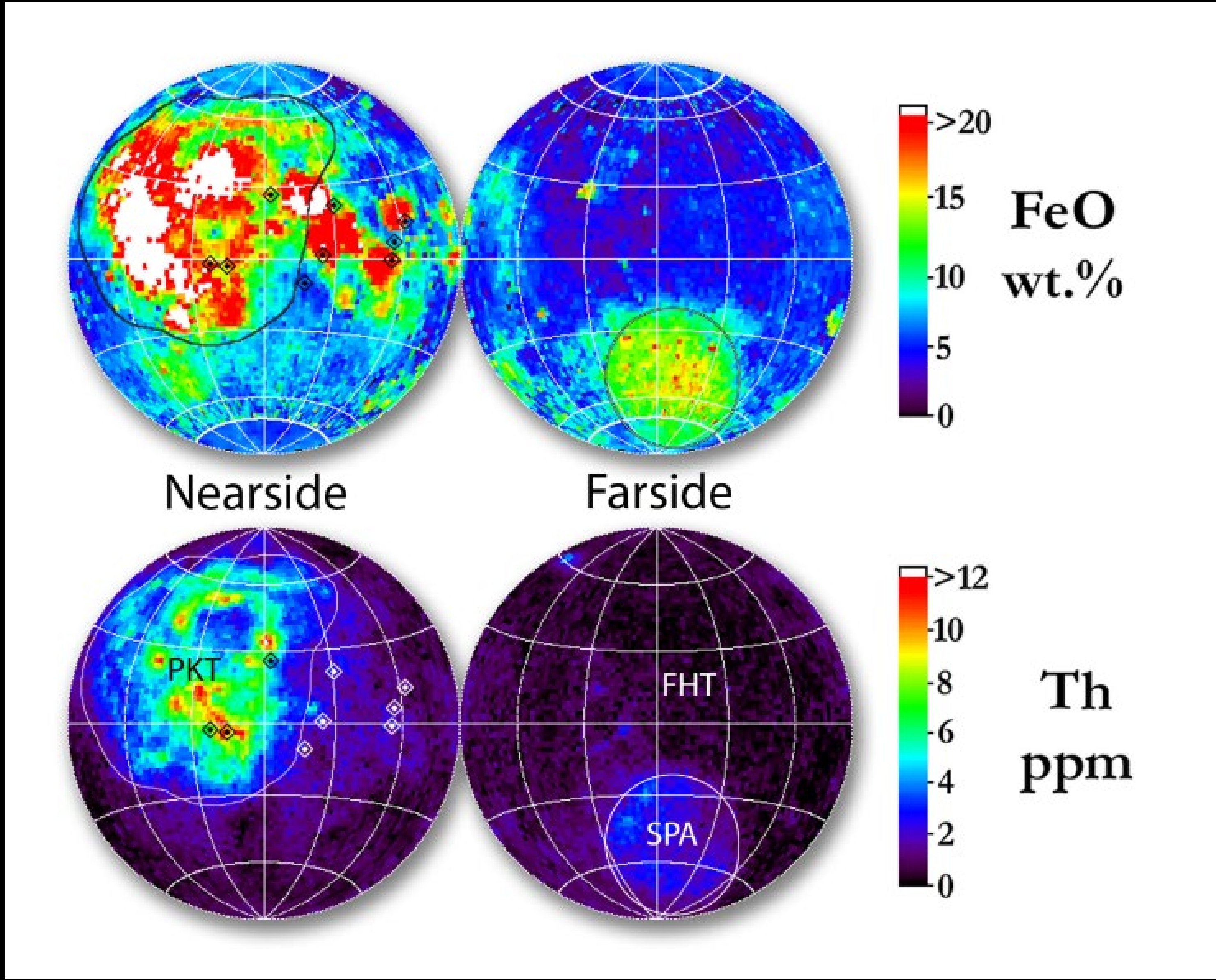
- 4-6 wt% FeO
- Low Thorium consistent with cumulates

Procellarum KREEP Terrane

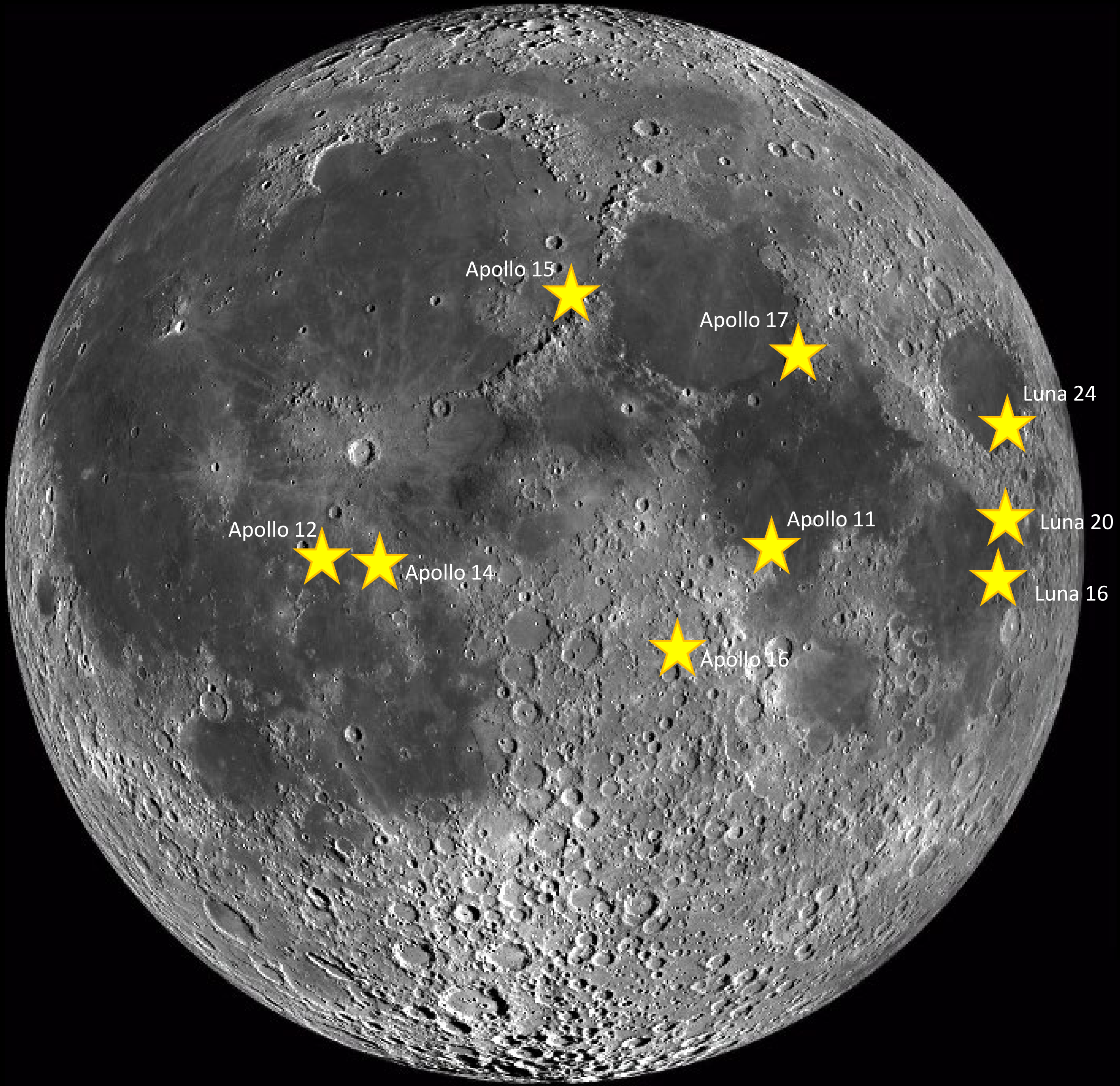
- Mostly basalts from internal Moon
- Very high FeO, TiO_2, and Thorium
- But, on one side of the Moon – does this suggest KREEP is asymmetric internally?

South-Pole Aitken Basin

- Higher FeO
- Moderate Thorium
- Further support internal asymmetry?

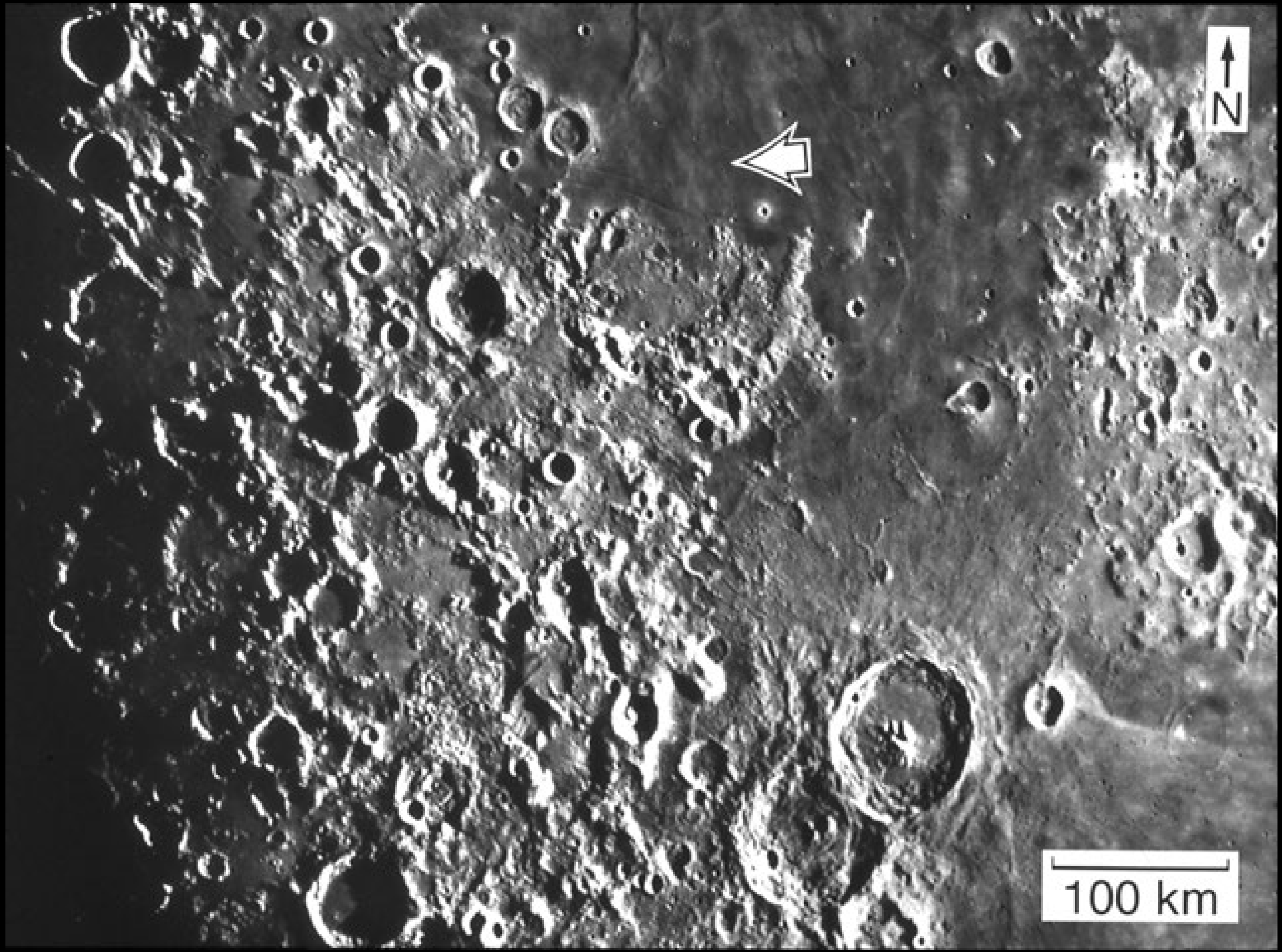


Jolliff et al., 2000


Apollo 15
Apollo 17
Luna 24
Apollo 11
Luna 20
Apollo 12
Apollo 14
Luna 16
Apollo 16

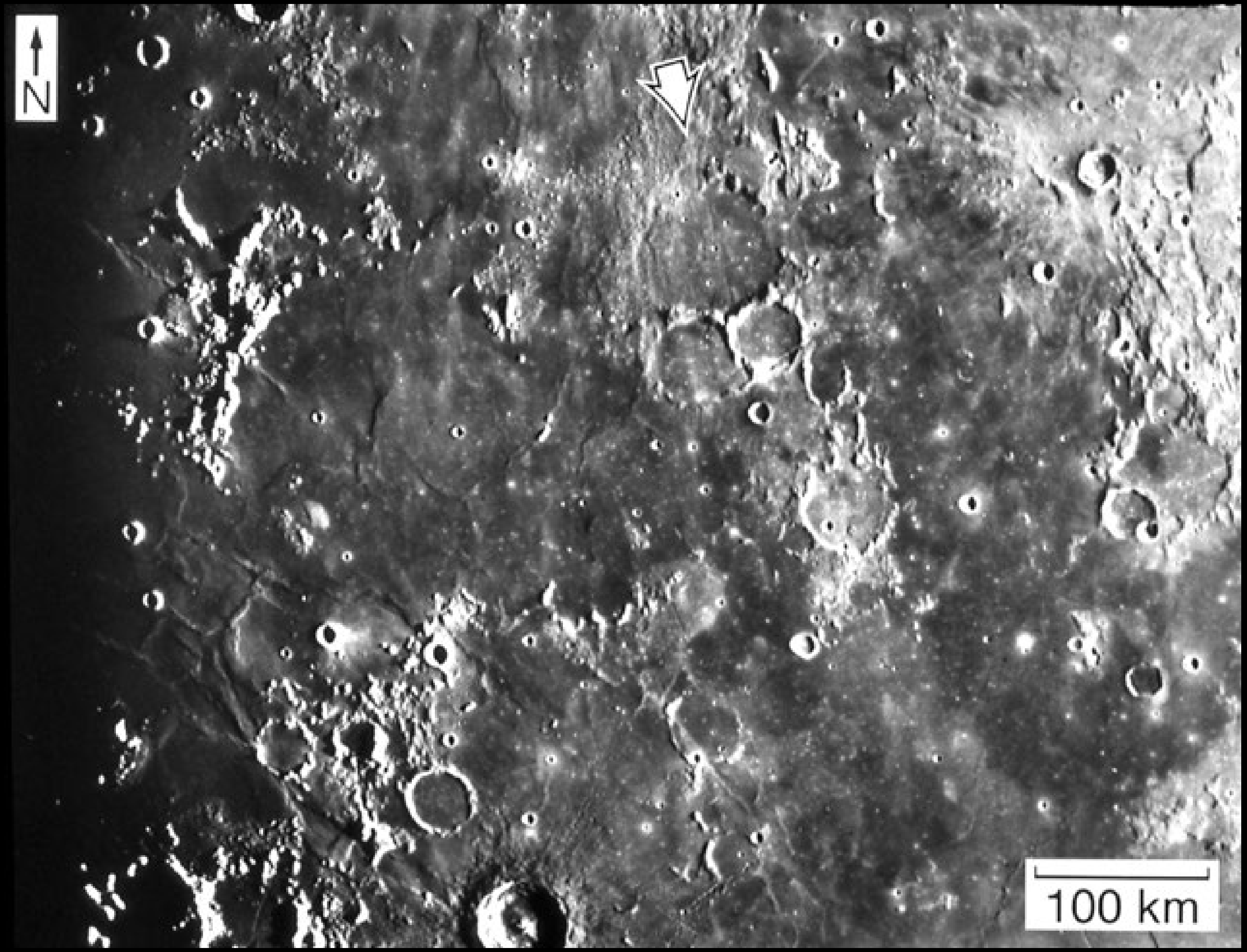
Apollo 11 Landing Site

- Mare Tranquillitatis
- First look at lunar maria, located 40 km from nearest highlands
- Still: first samples of anorthosite led to the magma ocean hypthesis



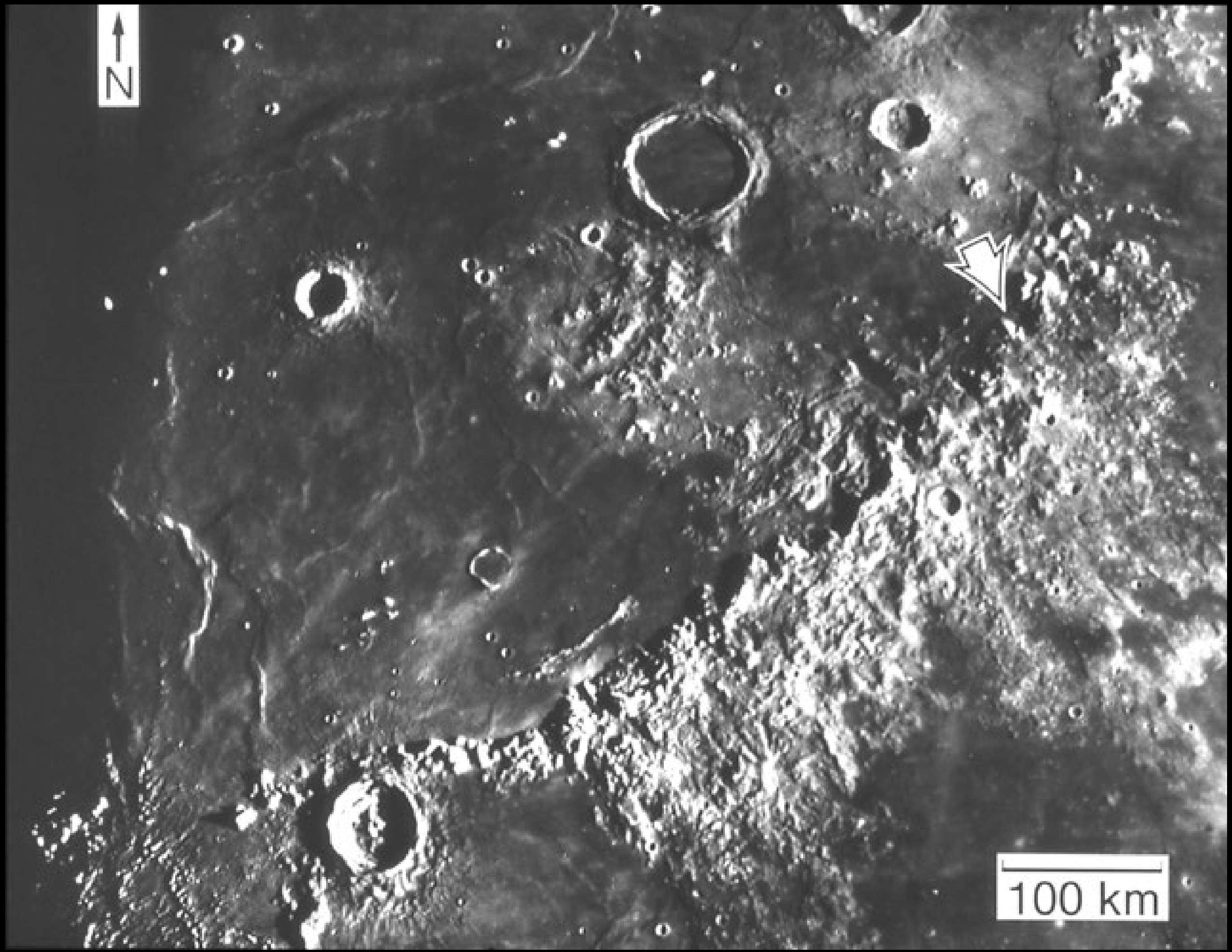
Apollo 14 Landing Site – The Fra Mauro Highlands

- First Apollo mission to land in rugged terrain of the highlands
- Landed on Fra Mauro Formation, thought to be ejecta from formation of the Imbrium basin
- But, this is still part of the Procellarum KREEP terrane, not "typical" highlands



Apollo 15 Landing Site – Exploring a Mountain Range

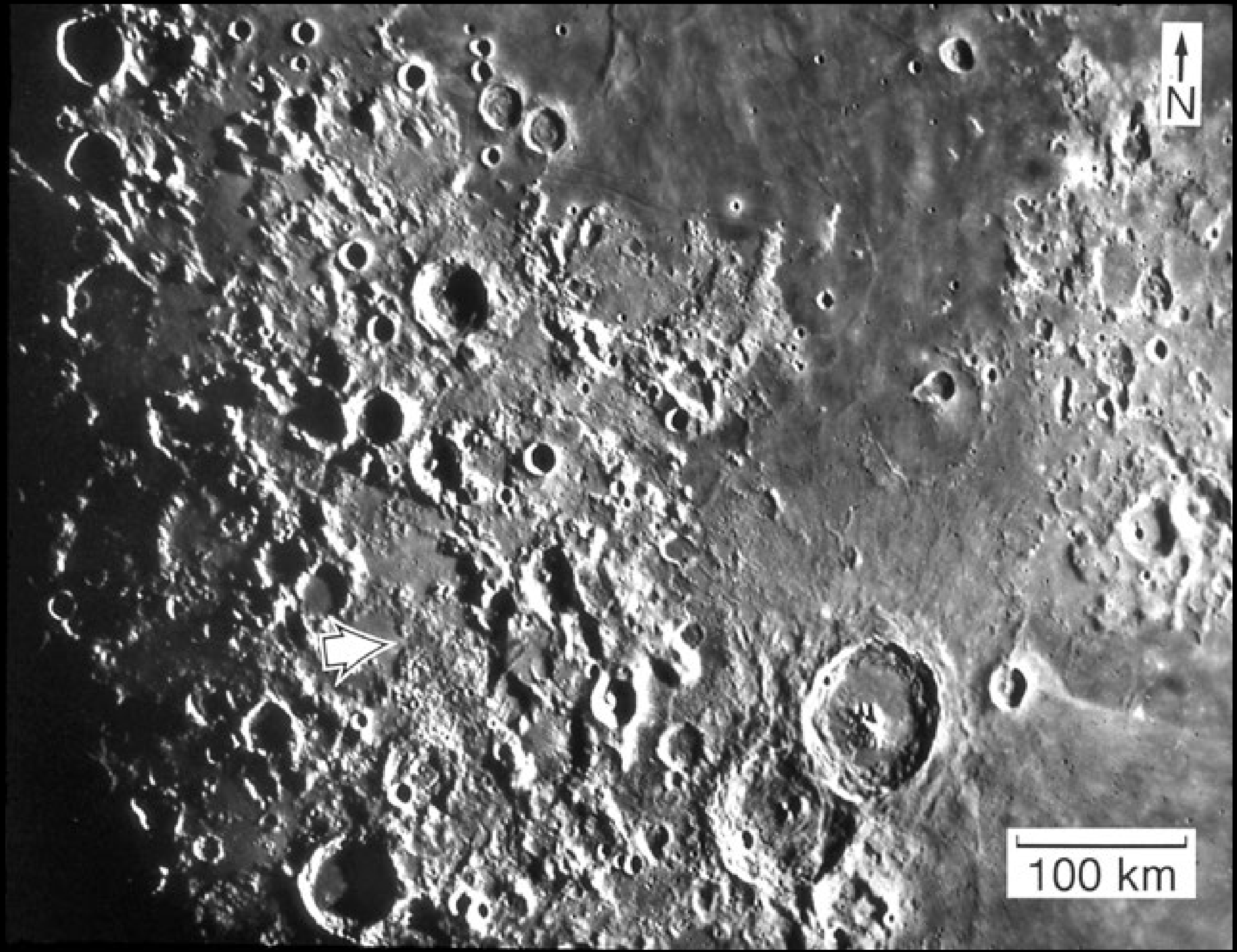
- Edge of Mare Imbrium close to the Apennine mountains
- Complex site to study the highland massifs (Imbrium basin rim), mare, and an impressive rille in the mare.
- First anorthosite collected directly from the highlands
- Variety of magnesium suite rocks occur as clasts in breccias
- Small samples of KREEP basalts found in regolith and as clasts in breccias.

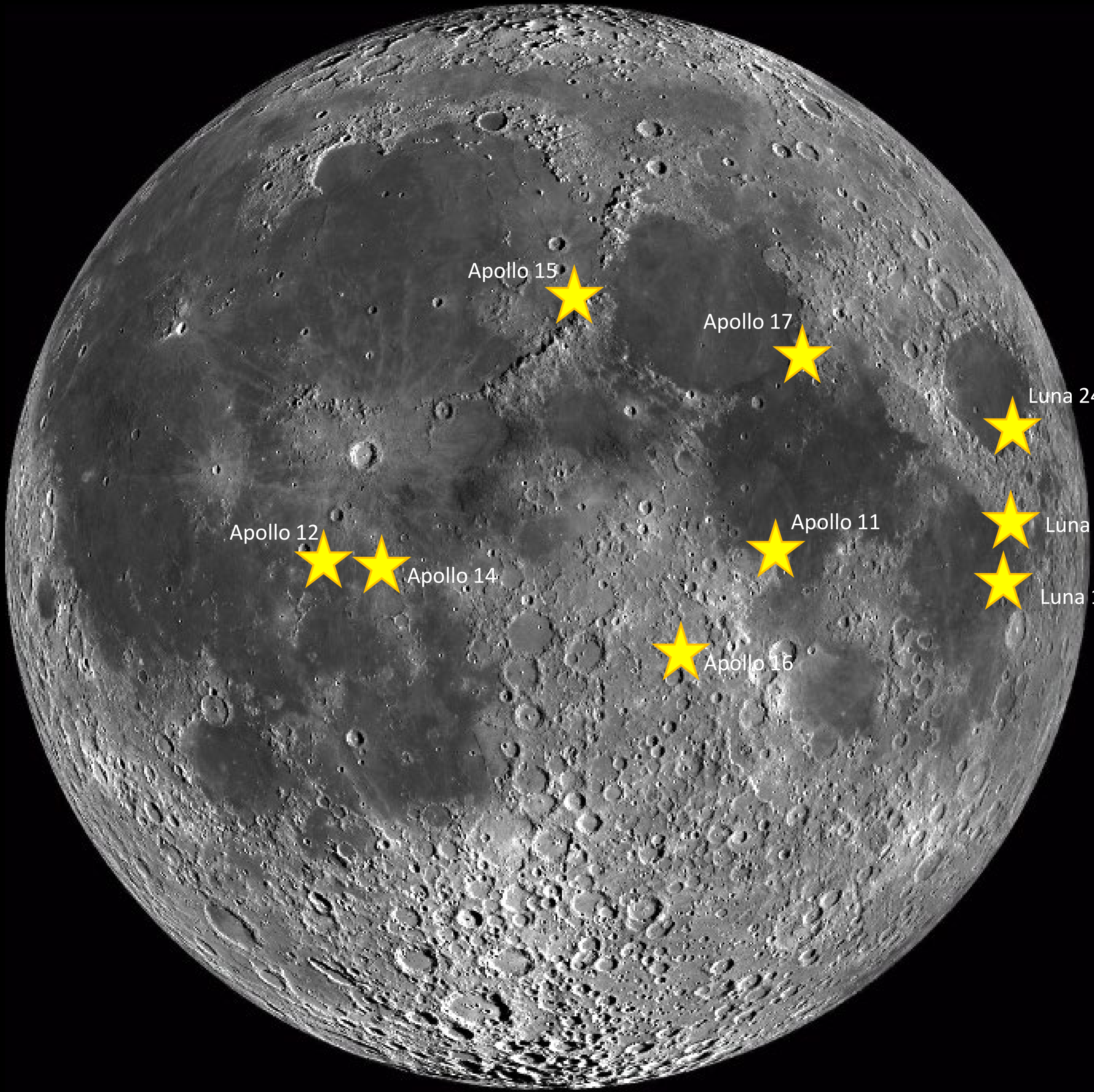



15415 – The Genesis Rock

Apollo 16 Landing Site: Descartes Highlands

- Sampled the relatively smooth Cayley Plains and the hilly and furrowed Descartes highlands
- Cayley Plains were thought to be volcanic, but the in fact was impact deposit – Imbrium ejecta mixed with local material during the impact event
- Numerous large samples of anorthosite were collected

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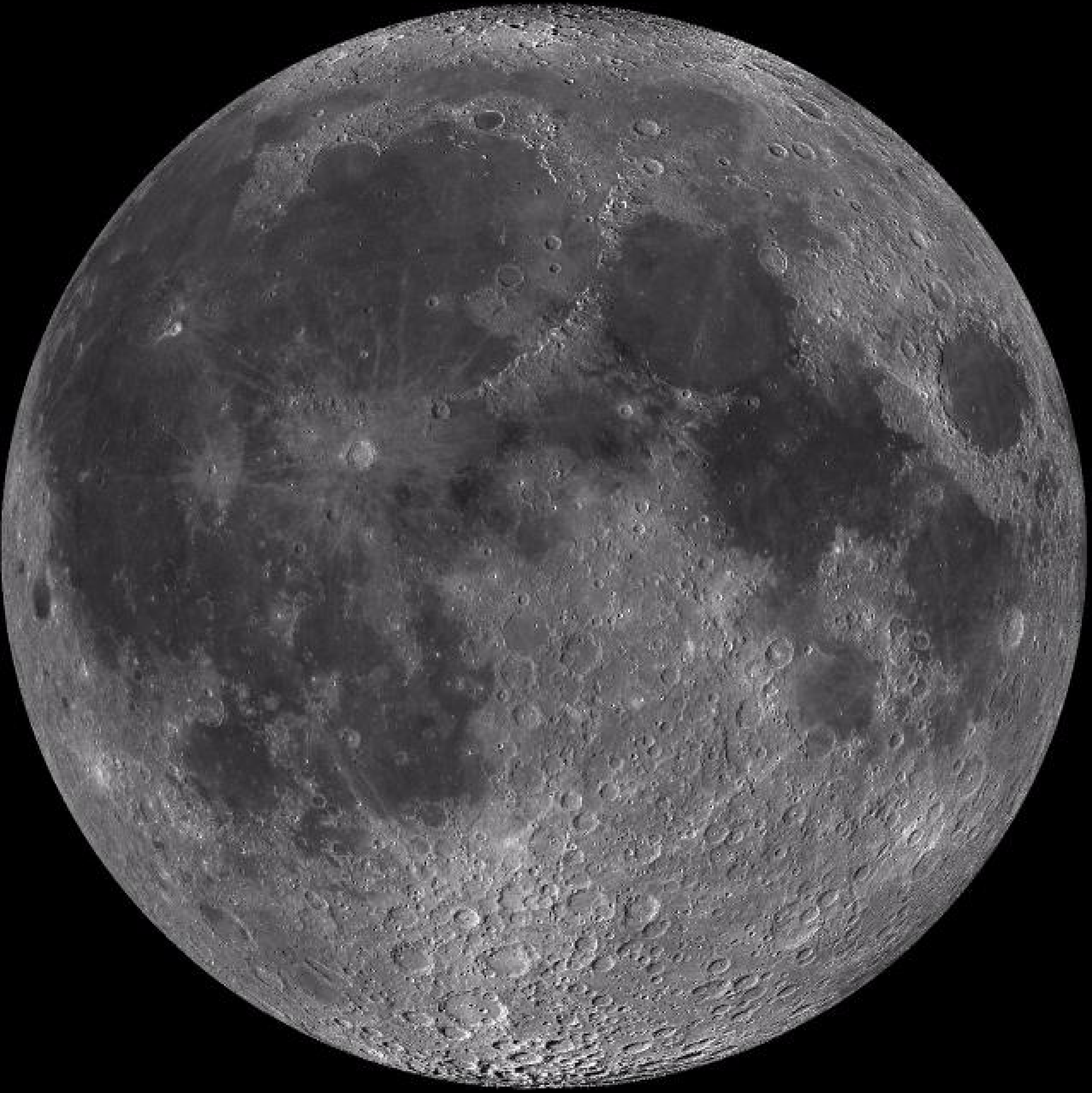
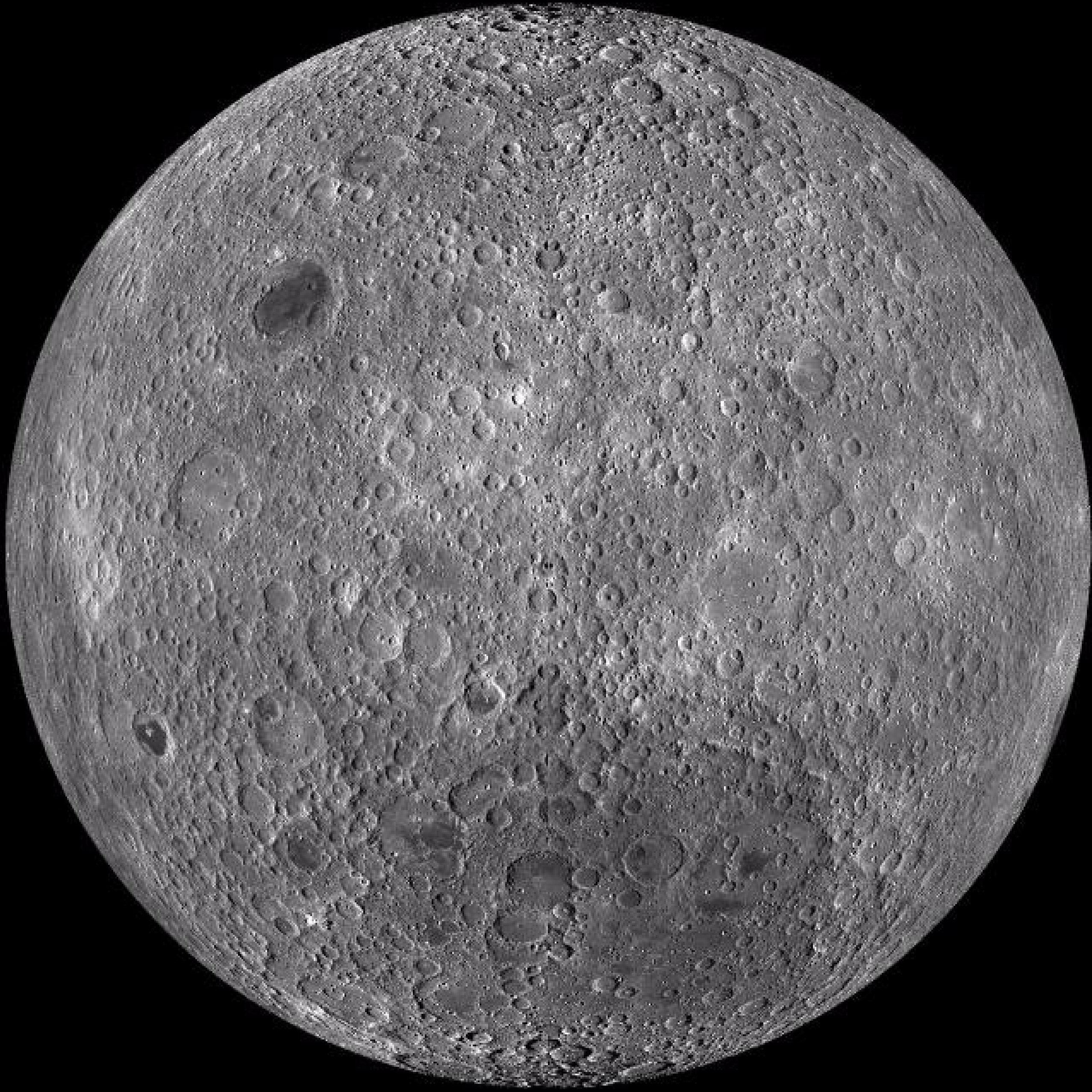
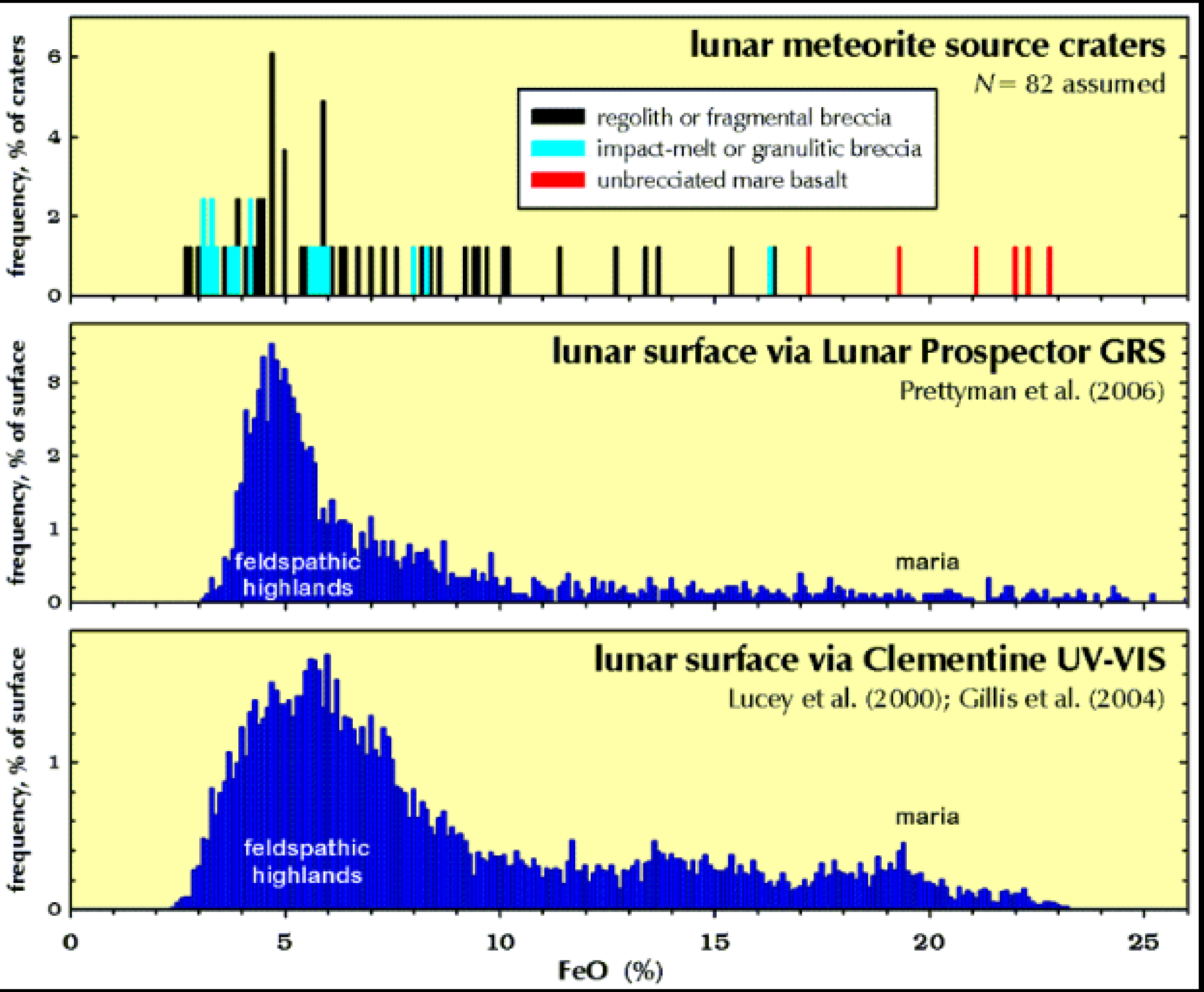
Luna 16
Apollo 16

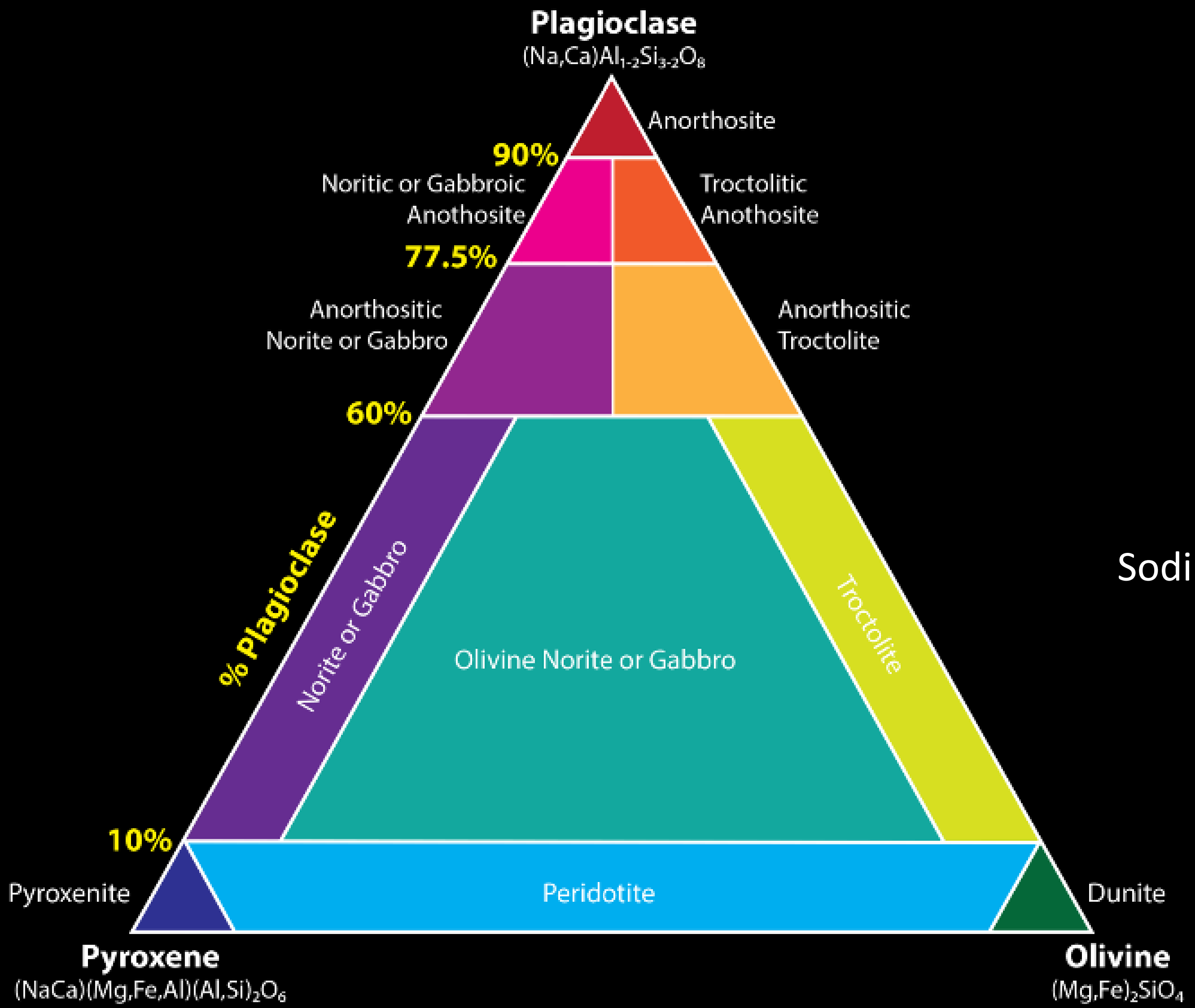



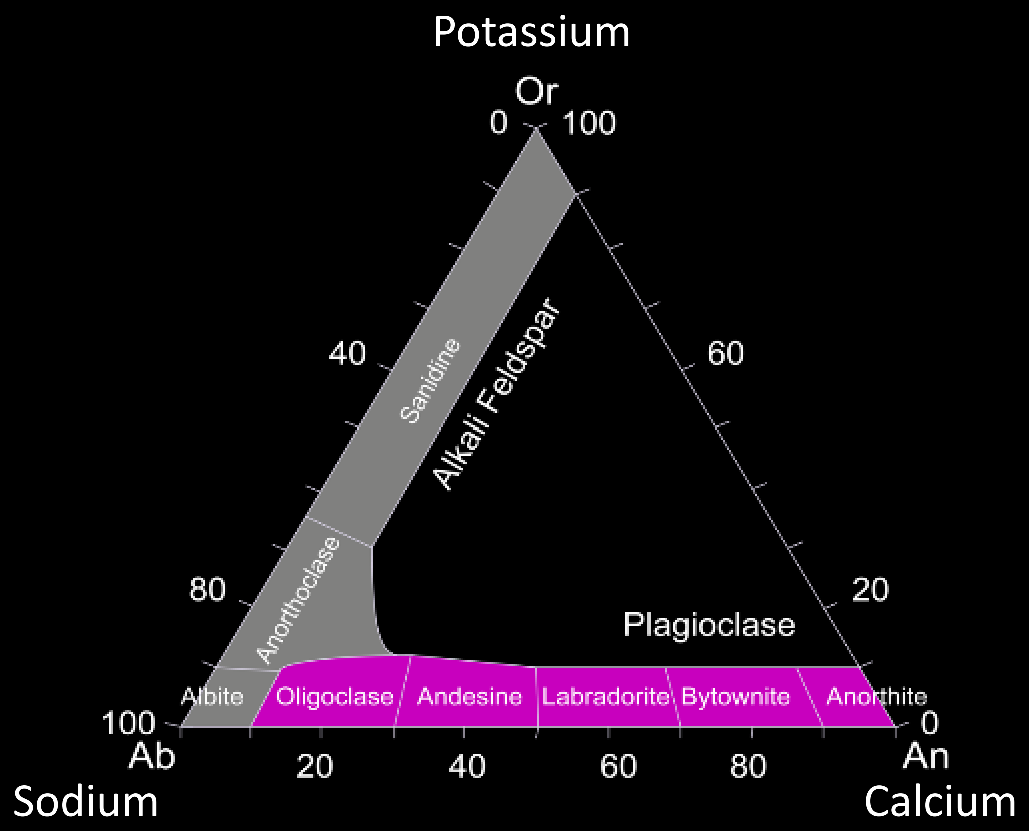


Korotev: http://meteorites.wustl.edu/lunar/moon_meteorites.htm

Types of Pristine Highland Rocks

- Ferroan anorthosite suite
- Mg suite
  - Troctolites
  - Norites
  - Gabbro-norites
  - Others
- Evolved Lithologies (Alkali suite)
  - KREEP basalts
  - Alkali anorthosites and other rocks
  - “Granites” (felsites)

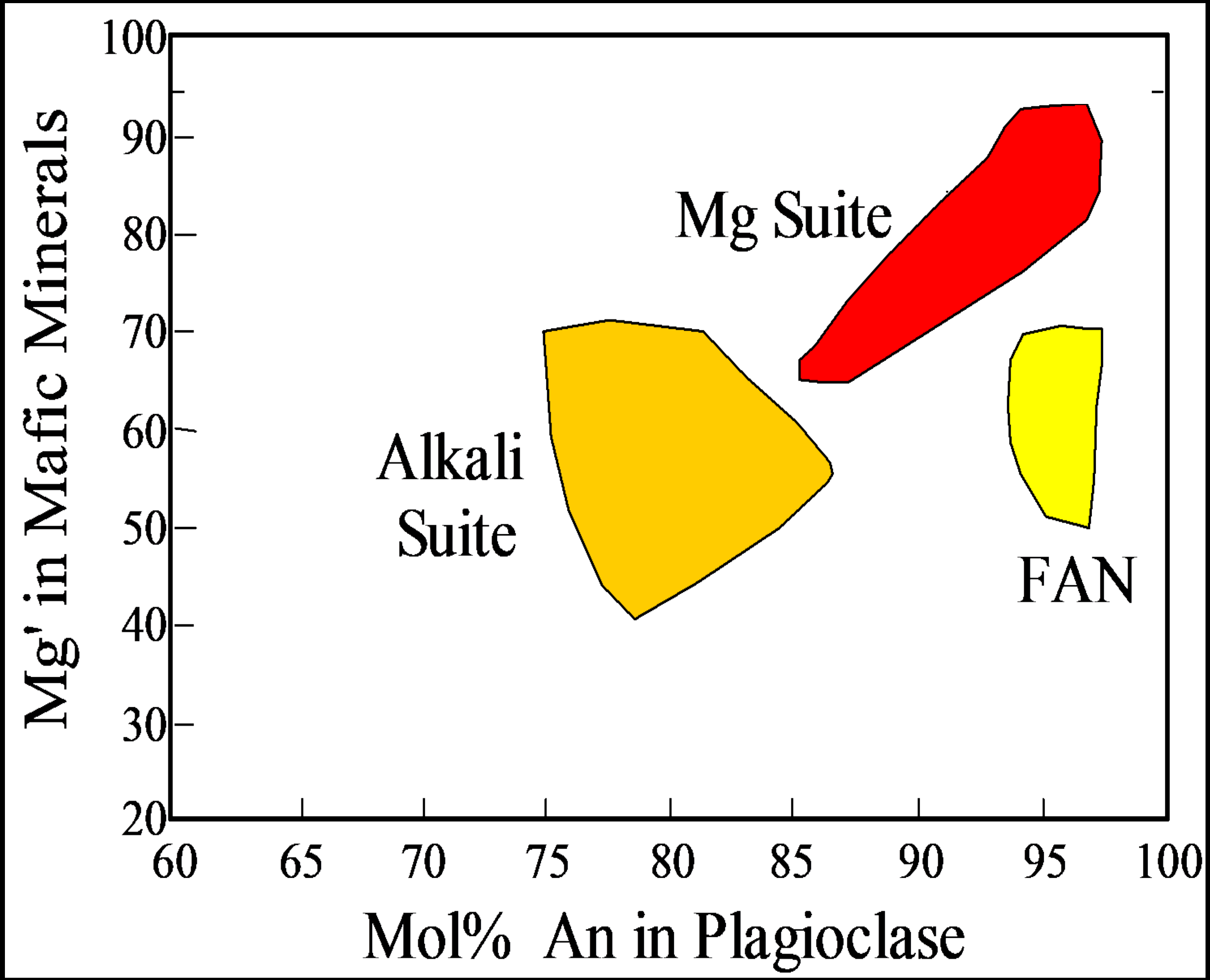




Slide courtesy Kerri Donaldson Hanna

Three Suites of Highland Igneous Rocks

- Distinctive groups of rocks when comparing
  - Mg#: molar Mg/(Mg + Fe) in mafic minerals and
  - An#: molar Ca/(Ca + Na + K) in plagioclase
- Ferroan Anorthosties (FAN)
- Magnesium Suite
- Alkali Suite

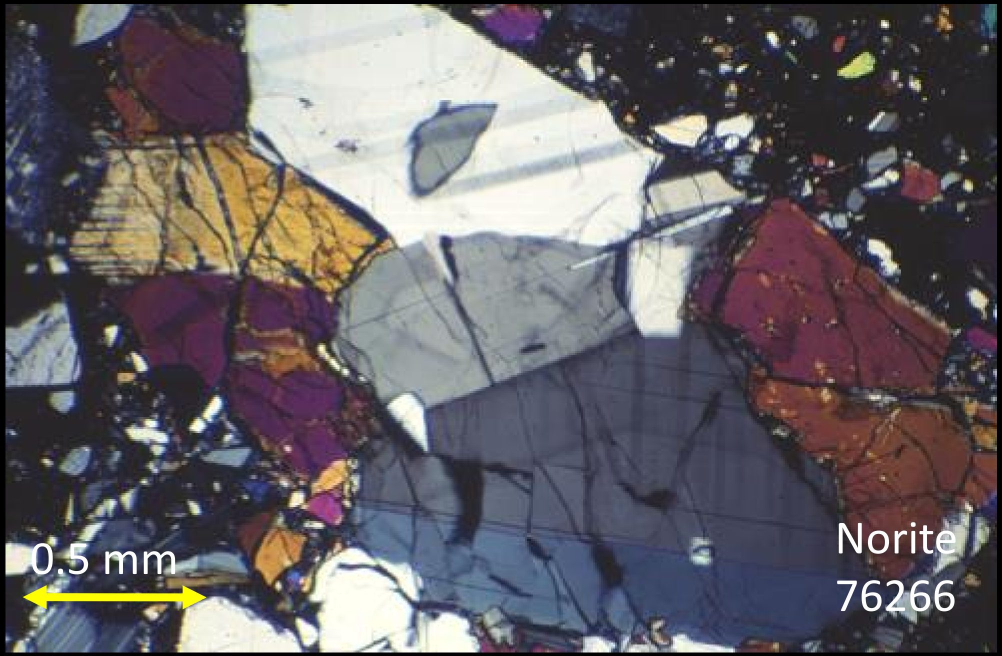


Ferroan Anorthosite Suite

- Most > 85 vol% plagioclase
  - Some 99 vol%
- Ferroan anorthosites because Mg# < 75 (most < 65)
- Plagioclase very rich in Ca (high An#)
- Ancient ages (4.4–4.56 billion years)
- Flotation crust of the magma ocean

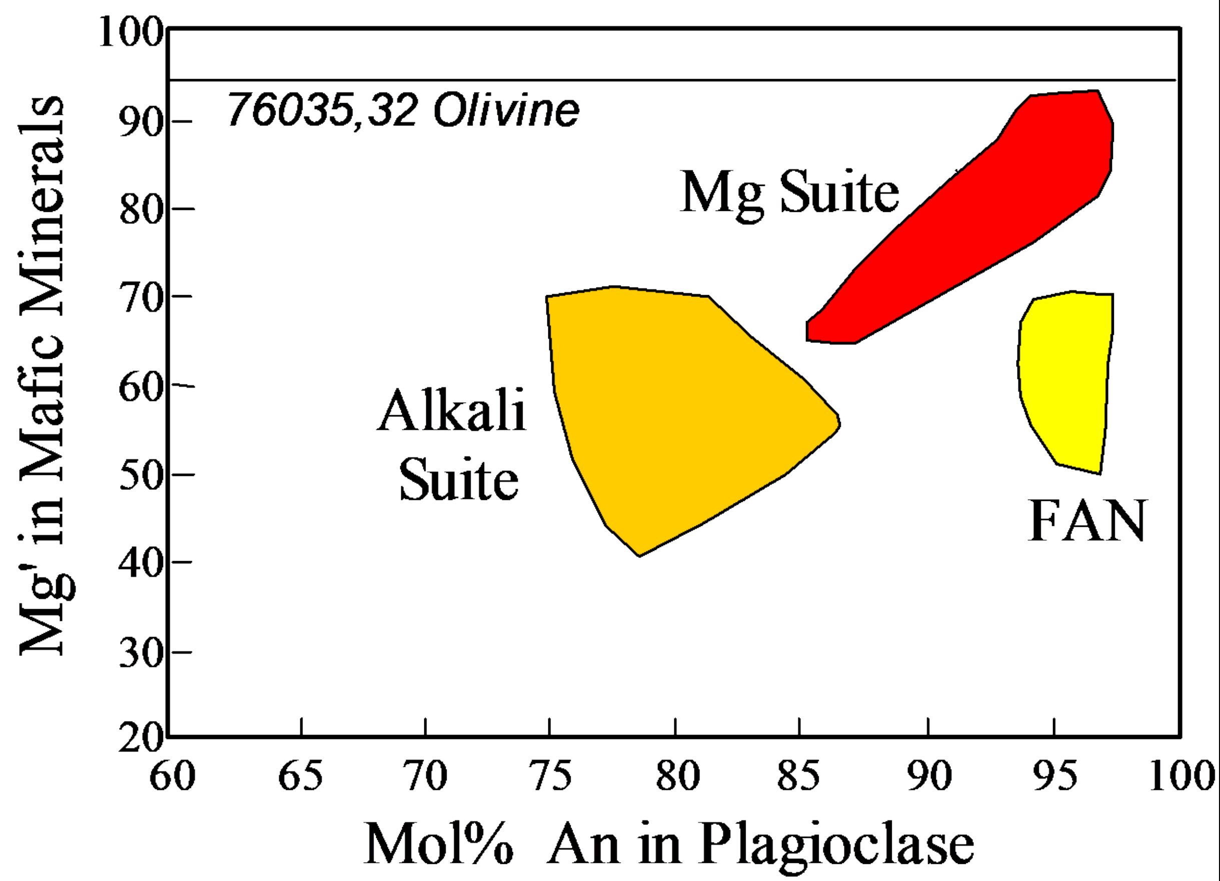
Mg Suite

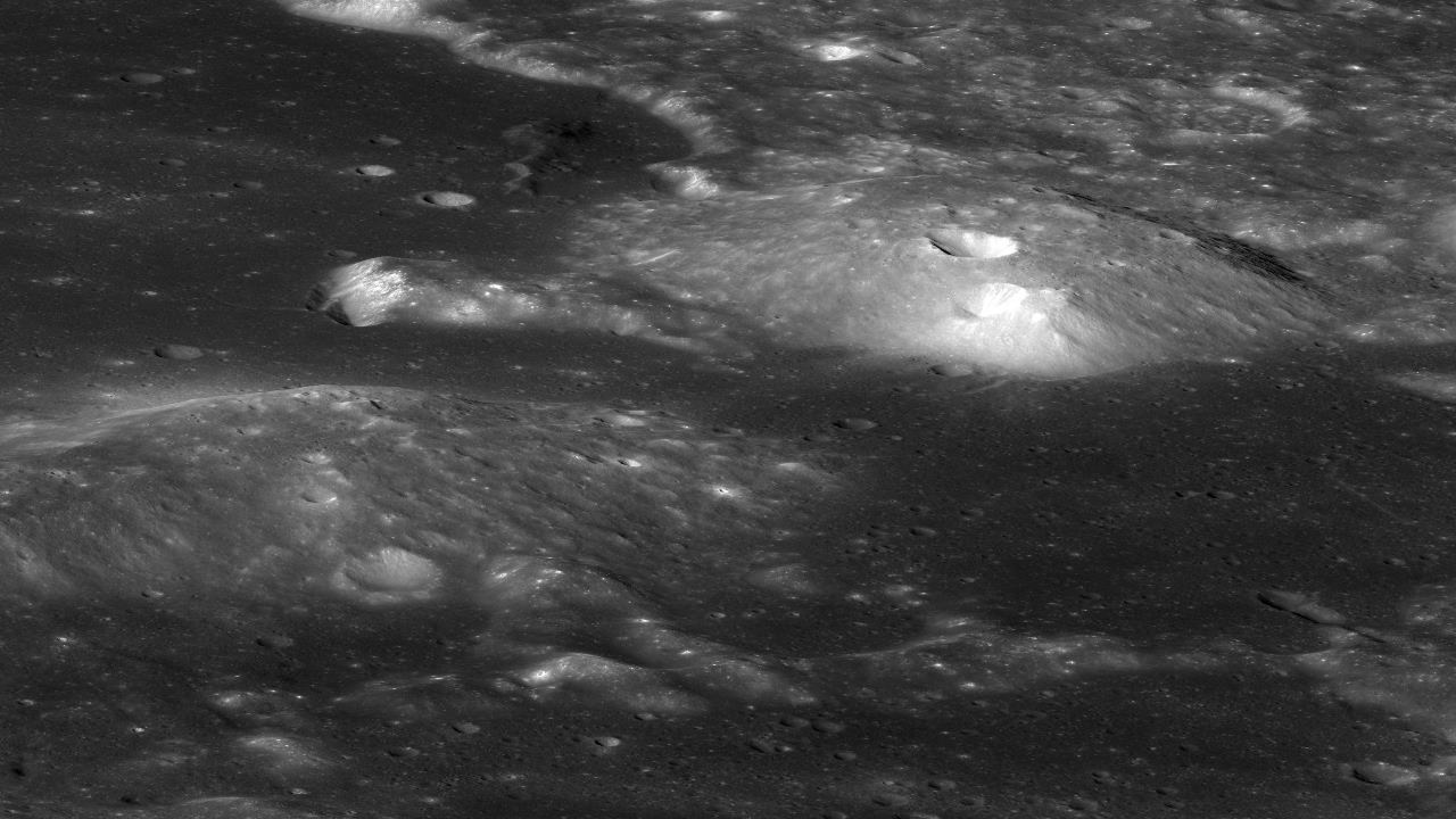
- More mafic than ferroan anorthosite suite, higher Mg#
- Diverse rock types:
  - Dunite: >90% olivine
  - Troctolites: 50% olivine, 50% plagioclase
  - Norites: 50% low-Ca pyroxene, 50% plagioclase
  - Gabbro-norites: ~half plagioclase, half pyroxene
- High KREEP abundance - nearside Procellarum KREEP terrane
- Early, intrusive volcanism (4.1+ billion years)



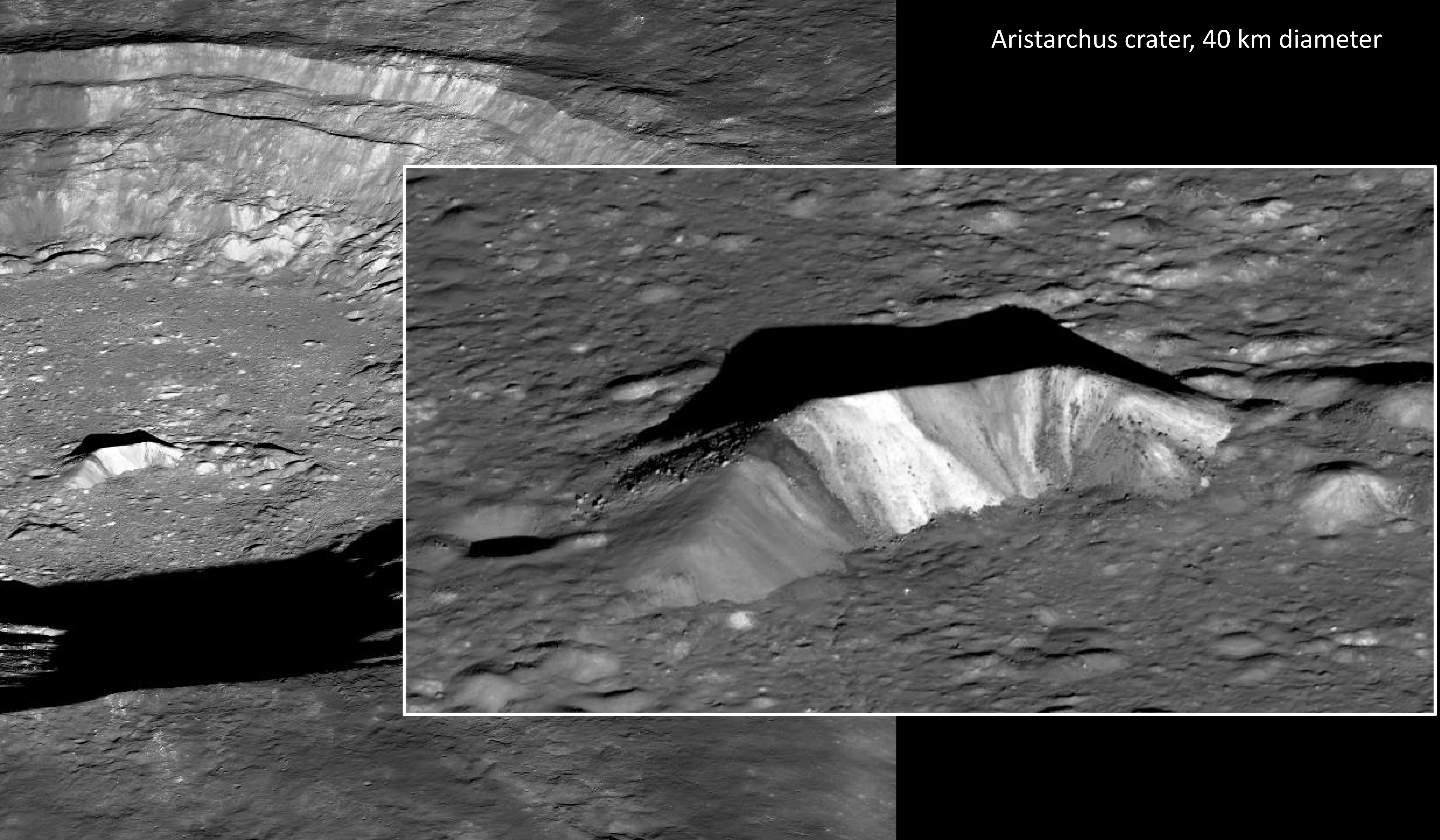
Alkali Suite

- More sodic (alakline) plagioclase
- KREEP rich – nearside Procellarum KREEP terrane rocks
- Include sodic alkali anorthosites, norites, gabbro-norites, KREEP basalts, granitic rocks
- Similar ages to Mg Suite, but extending to as young as 3.8 Gy

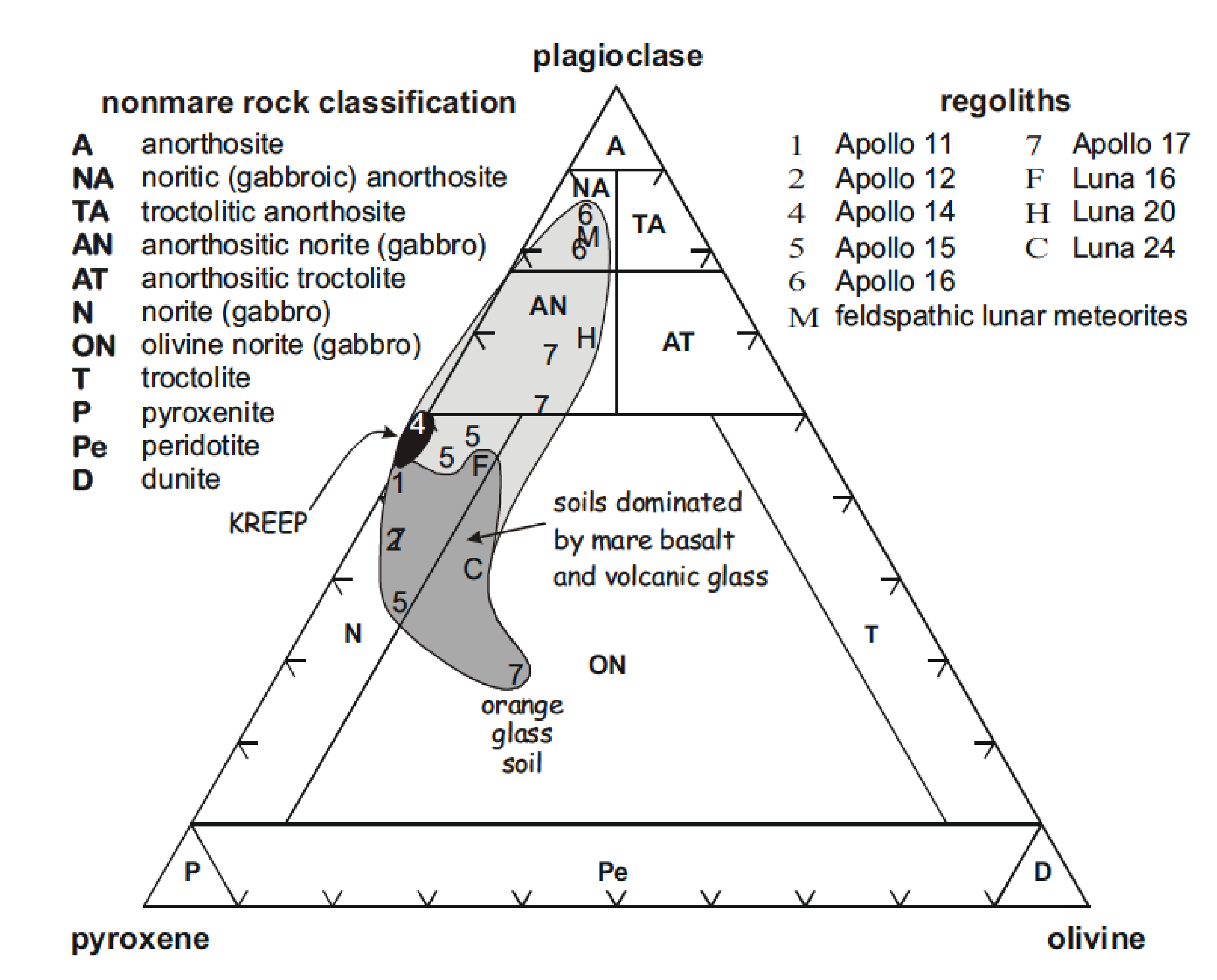




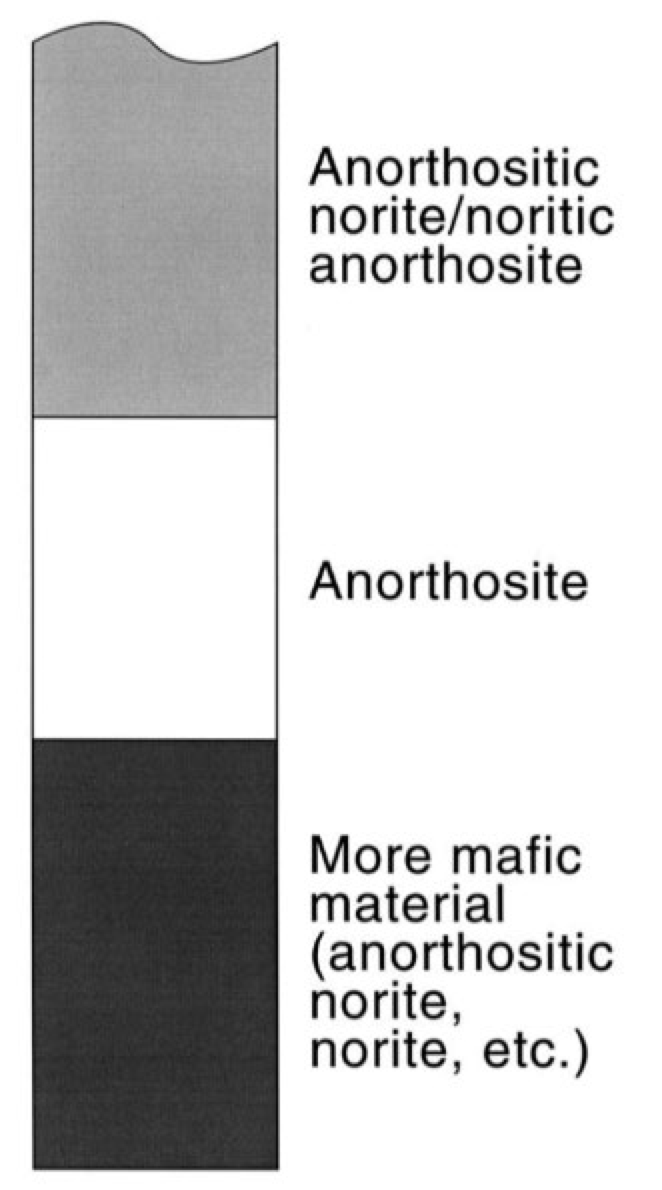
Aristarchus crater, 40 km diameter



Lunar Soils



Lucey et al. 2006

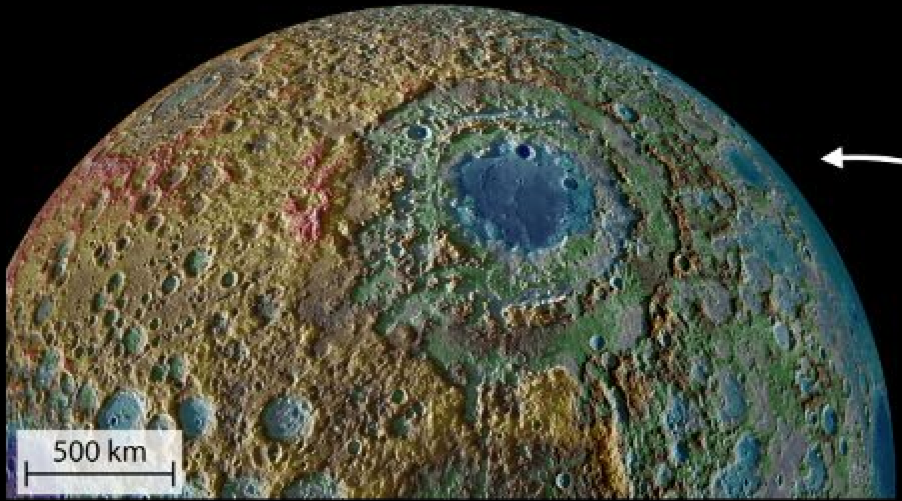


Hawke et al., 2003

The Regolith

- Entire mantle of unconsolidated material, whatever its nature or origin, it is proposed to call the regolith. –Merrill (1897)
- Adapted to Moon at Surveyor III site: Layer of fragmental debris of relatively low cohesion overlying a more coherent substratum. –Shoemaker et al. 1967
- In the highlands there may be no clear bedrock layer for reference – the local definition becomes “more philosophical in nature.” – Cintala and McBride (1995)

Regolith Generation

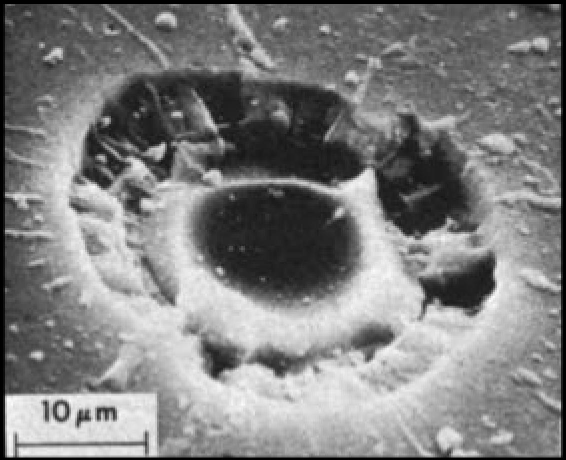


Orientale basin (~950 km)

Impacts of all sizes

Early, big: kilometers of megaregolith

Small, frequent: fine-grained regolith

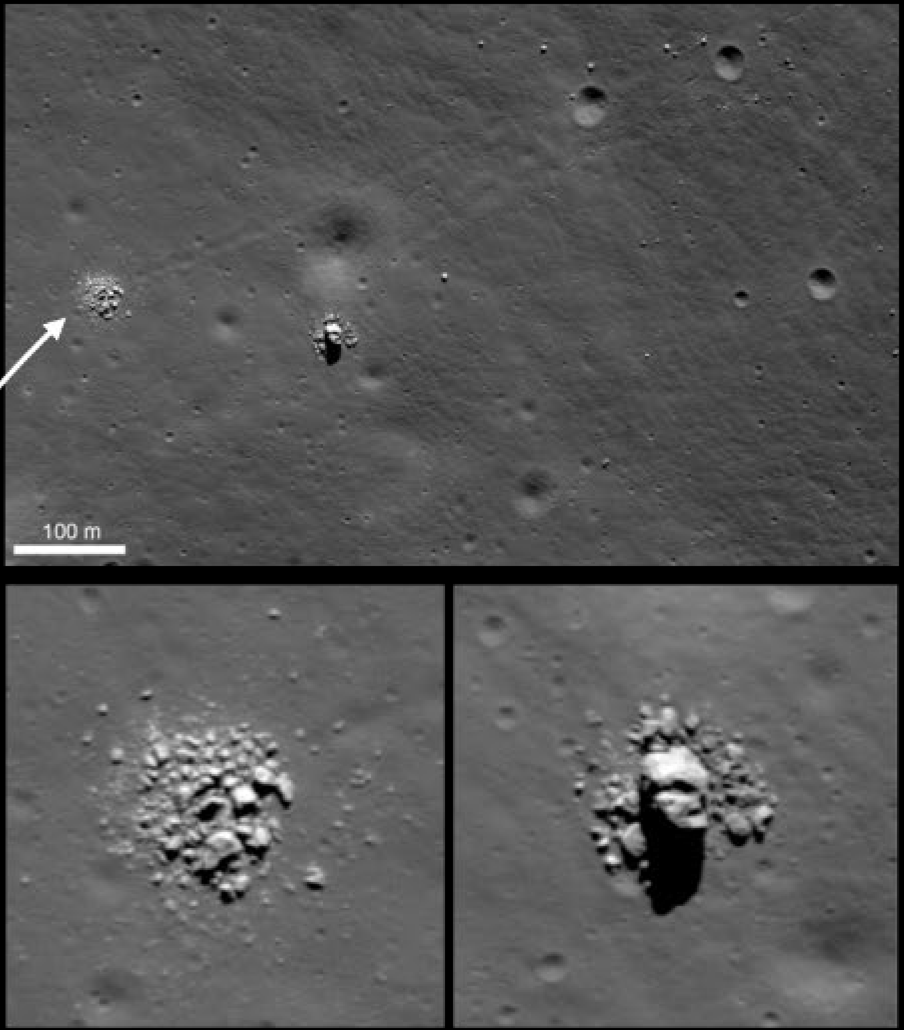


Hörz et al. (1975)

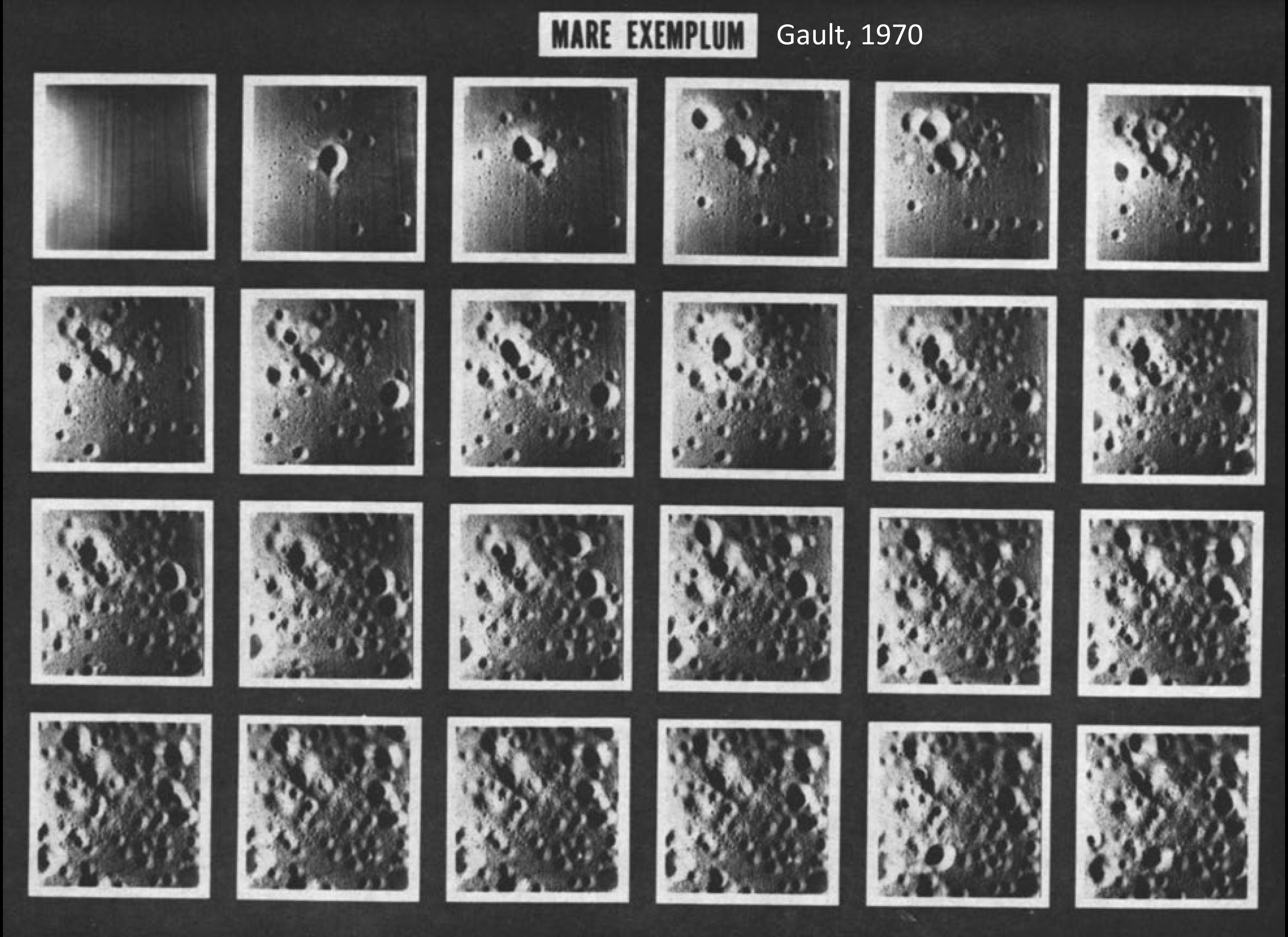
Thermal fatigue?

Molaro et al. (2015)

Extreme temperature cycling



Plescia et al. (2016)



Gault, 1970

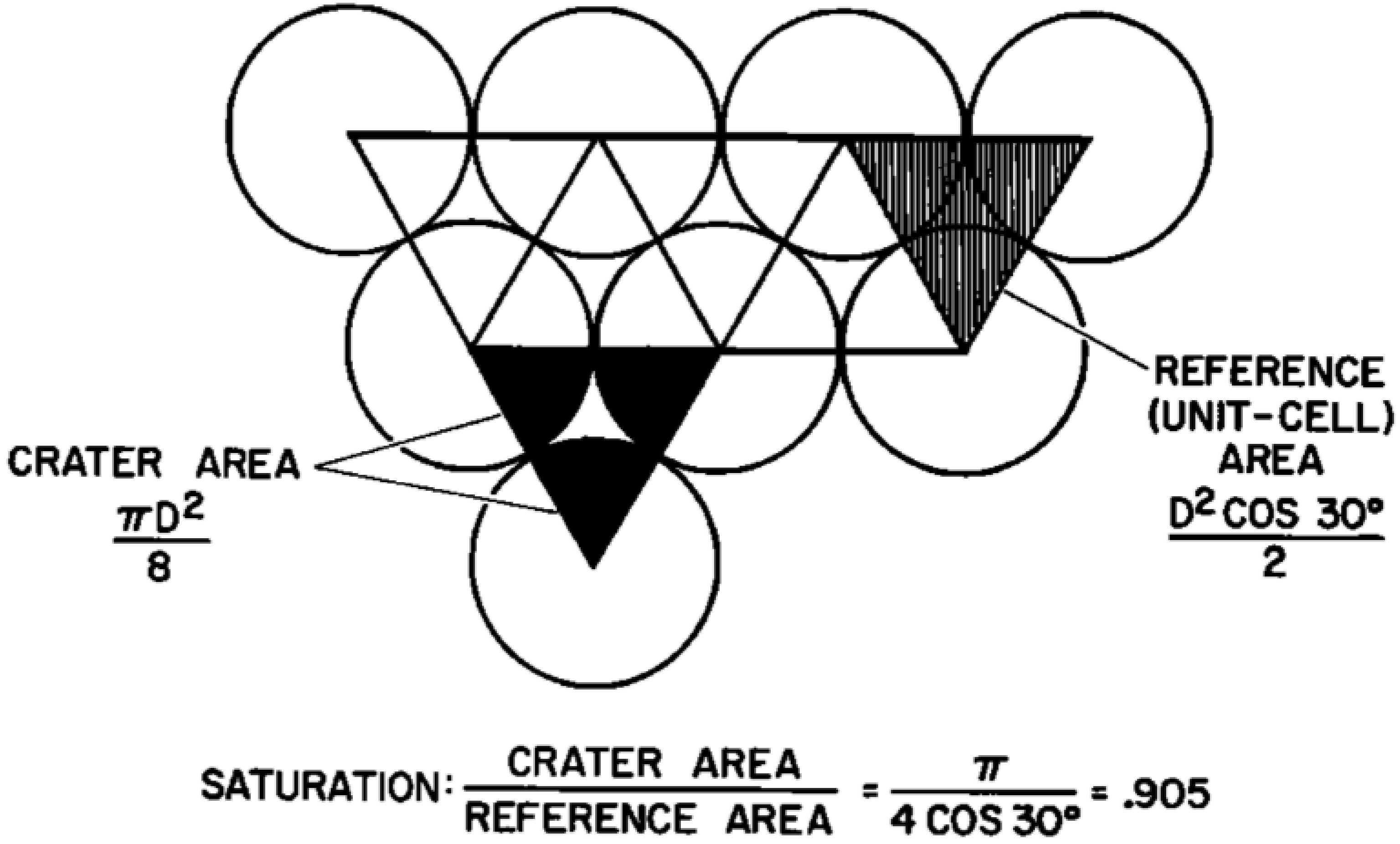


Fig. 6. Definition of the term 'saturation.'

Gault, 1970

Equilibrium: on average, one crater destroyed for each new crater produced. Occurs at ~10% of saturation

Craters smaller than ~50 km are in equilibrium in the lunar highlands (Povilaitis et al., 2016)

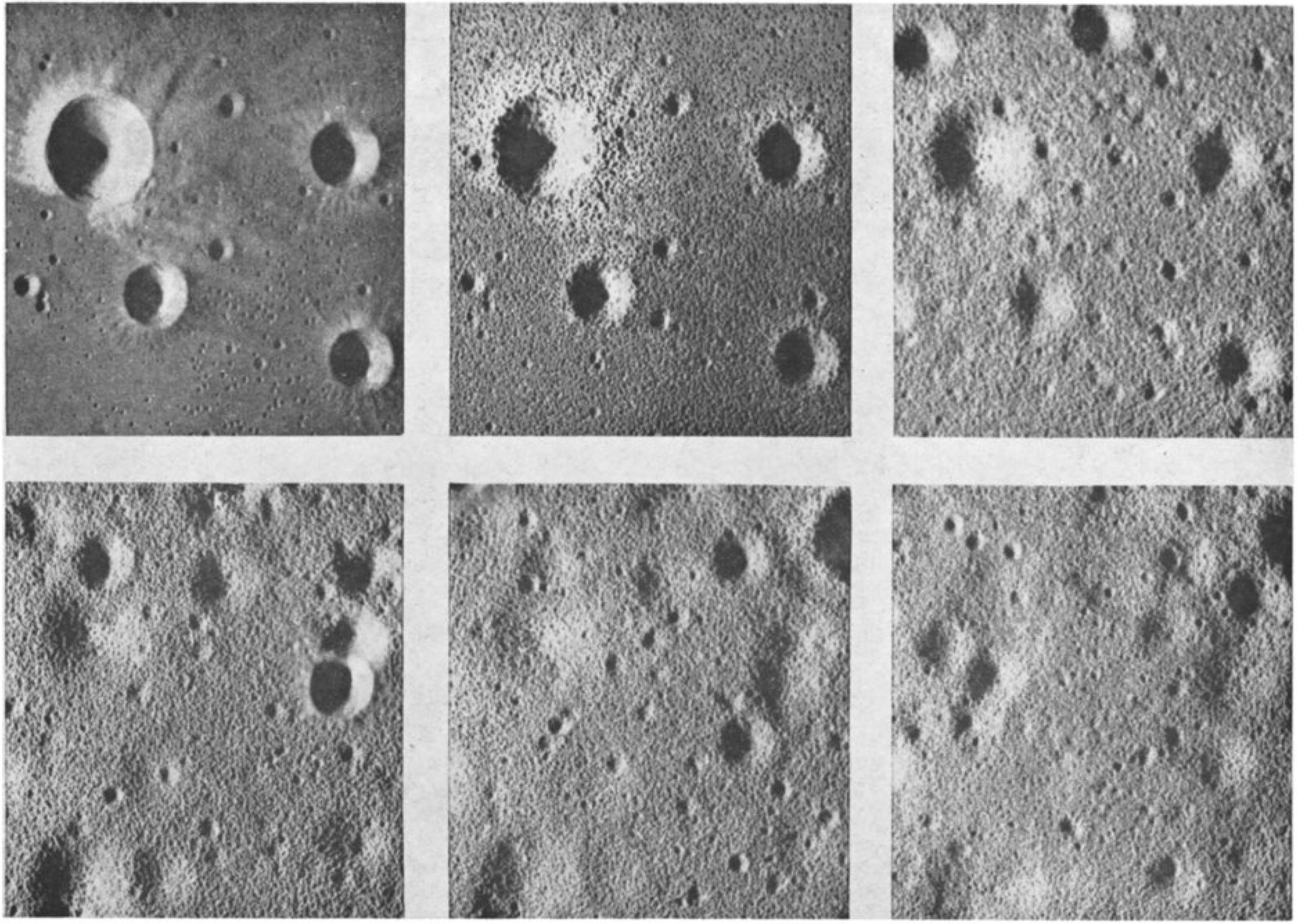
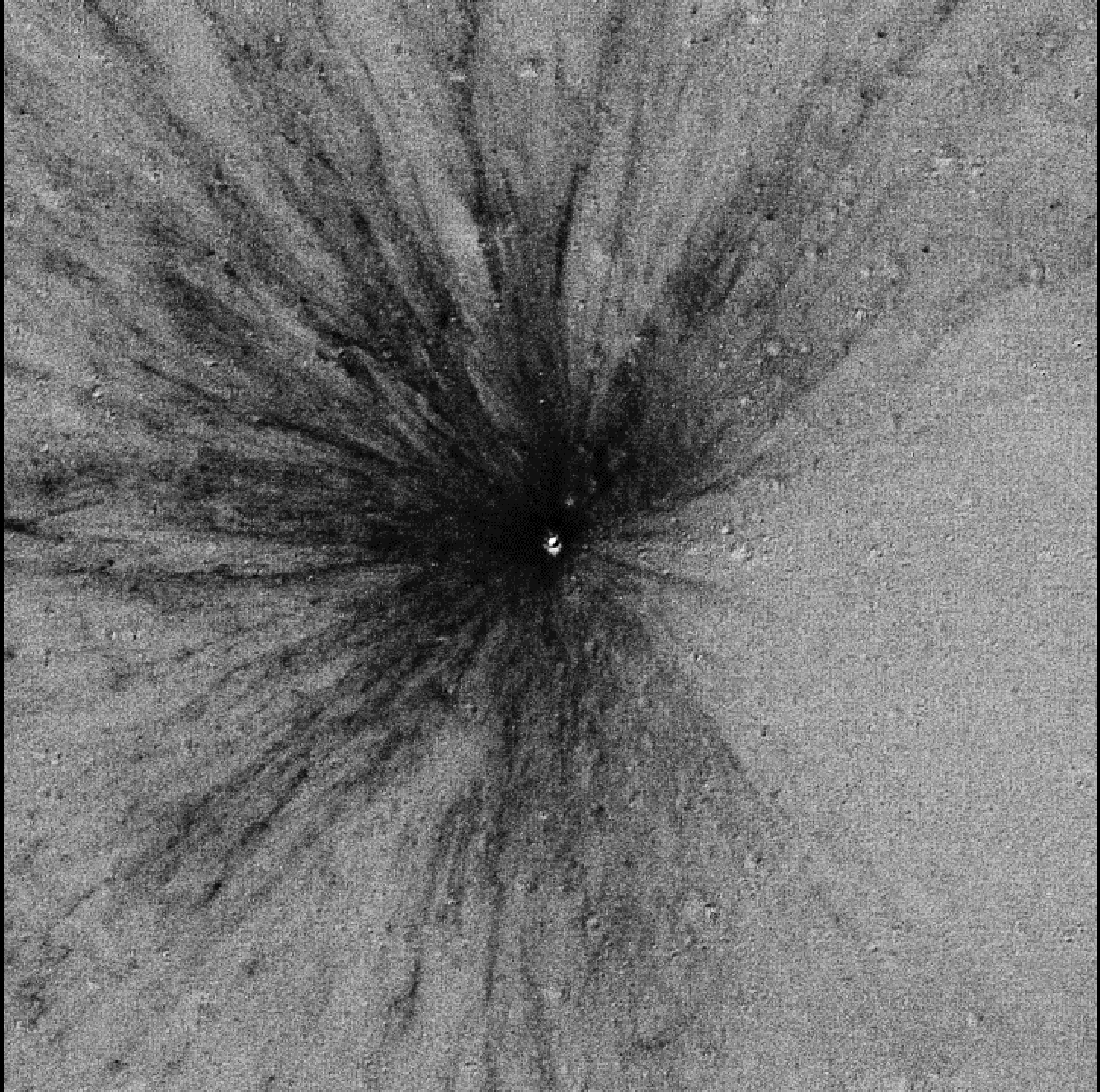
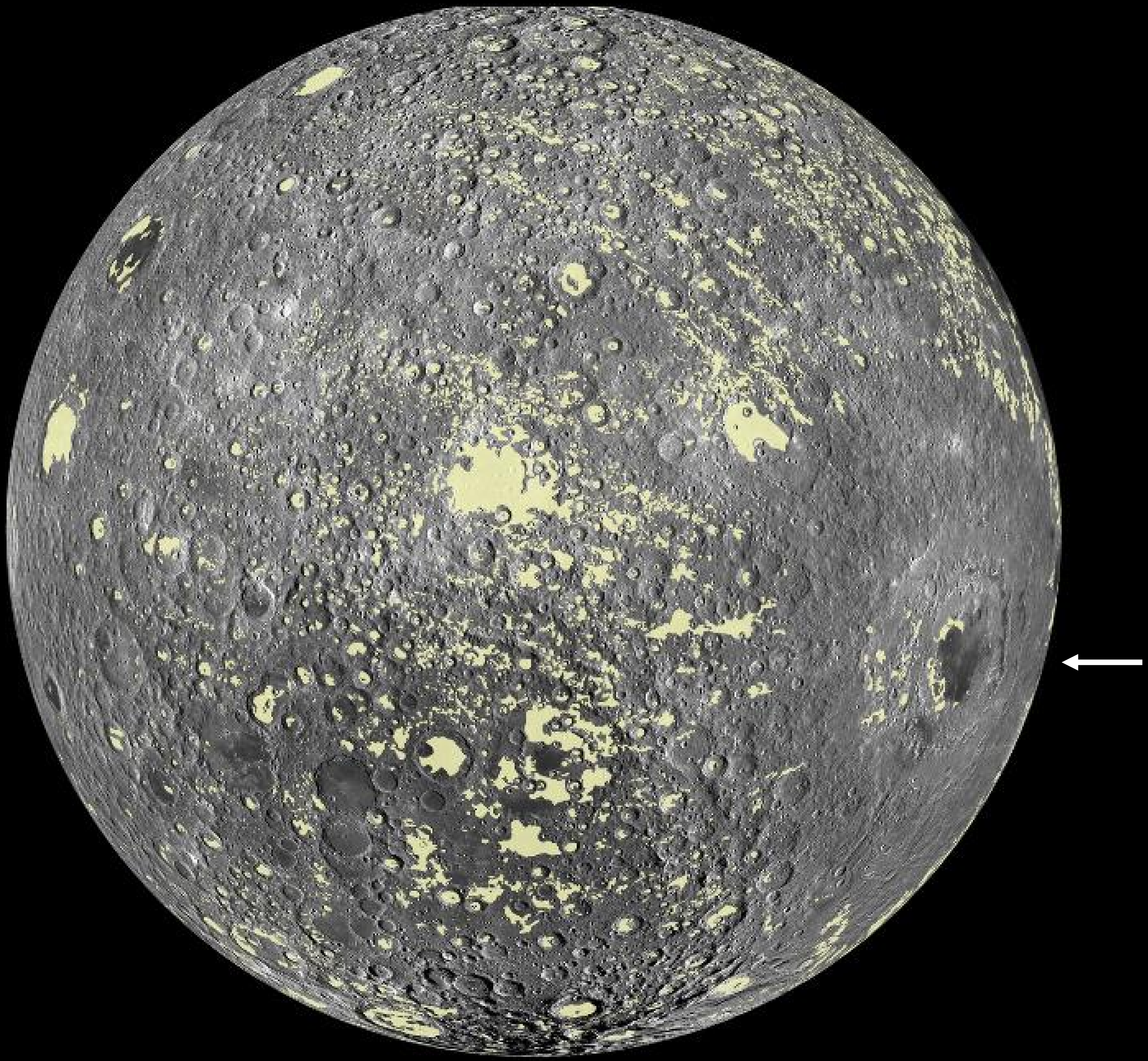


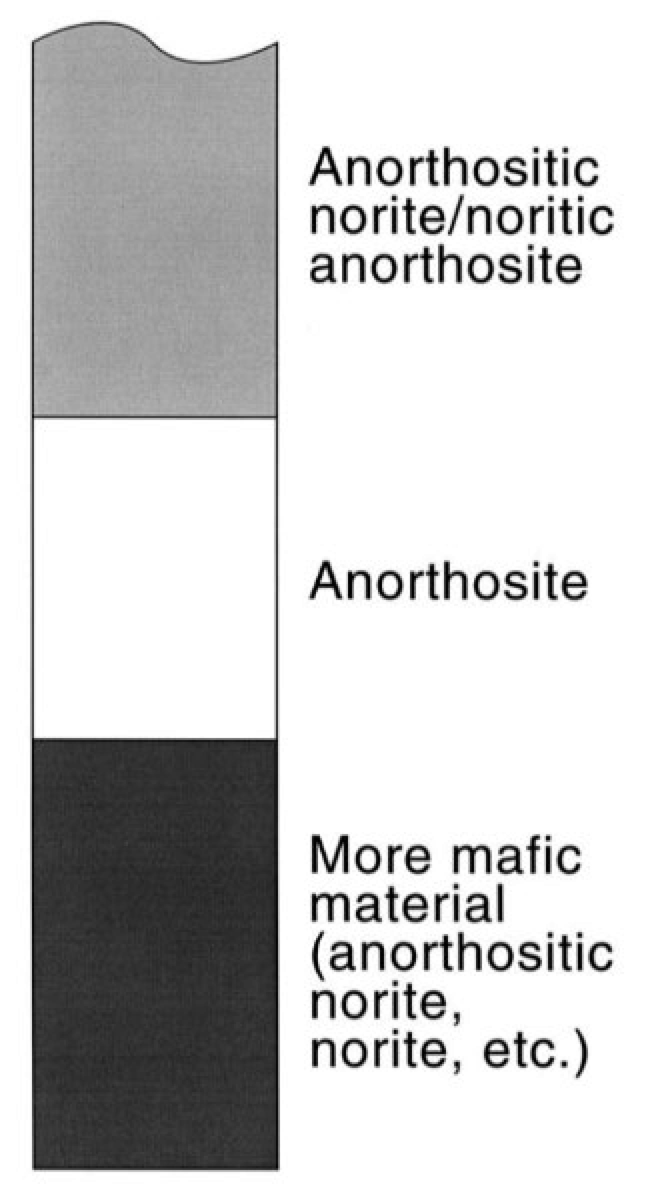
Fig. 7. Time-lapse sequence from the laboratory simulation Mare Nostrum illustrating the gradual modification and final destruction of craters by the cumulative effect of impact erosion and sedimentation.

Gault, 1970

New 12-m crater







Hawke et al., 2003

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Planets

RESEARCH ARTICLE

10.1002/2016JE005160

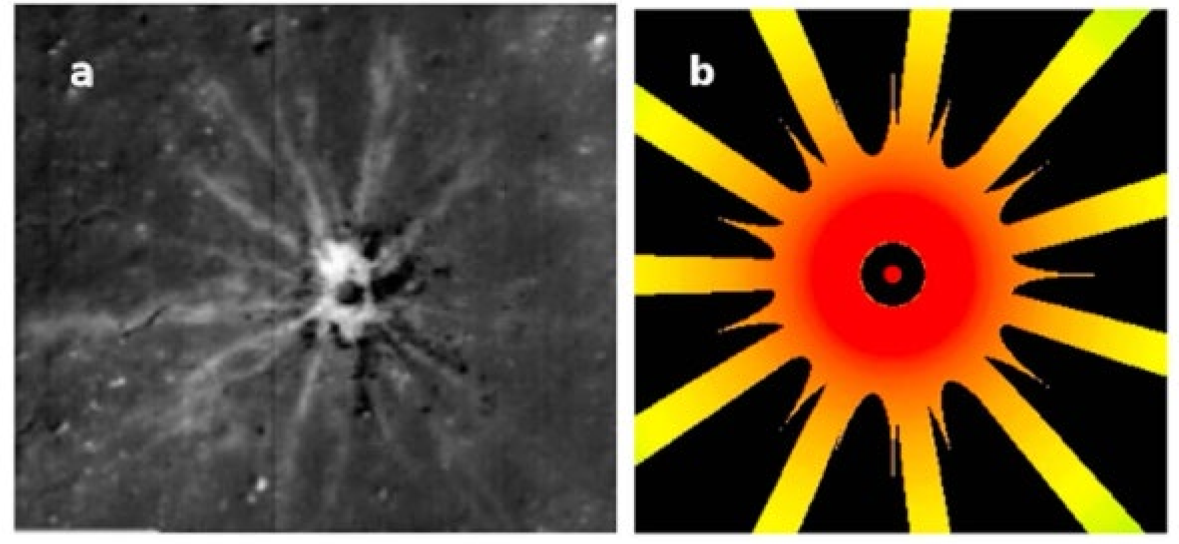
Key Points:
- Both local and distal material transports by impacts play an important role in mixing across mare/highland contacts
- The variation in the abundance of exotic material in lunar mare soil hand samples can be accounted for by the patchy nature of crater rays
- Our result supports a Copernicus Crater provenance for ray material at the Apollo 12 landing site

Heterogeneous impact transport on the Moon

Ya-Huei Huang[1], David A. Minton[1], Masatoshi Hirabayashi[1], Jacob R. Elliott[1], James E. Richardson[2], Caleb I. Fassett[3,4], and Nicolle E. B. Zellner[5]

[1]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, Indiana, USA, [2]Planetary Science Institute, Tucson, Arizona, USA, [3]Department of Astronomy, Mount Holyoke College, South Hadley, Massachusetts, USA, [4]Now at NASA Marshall Space Fligh ... on, Michigan, USA

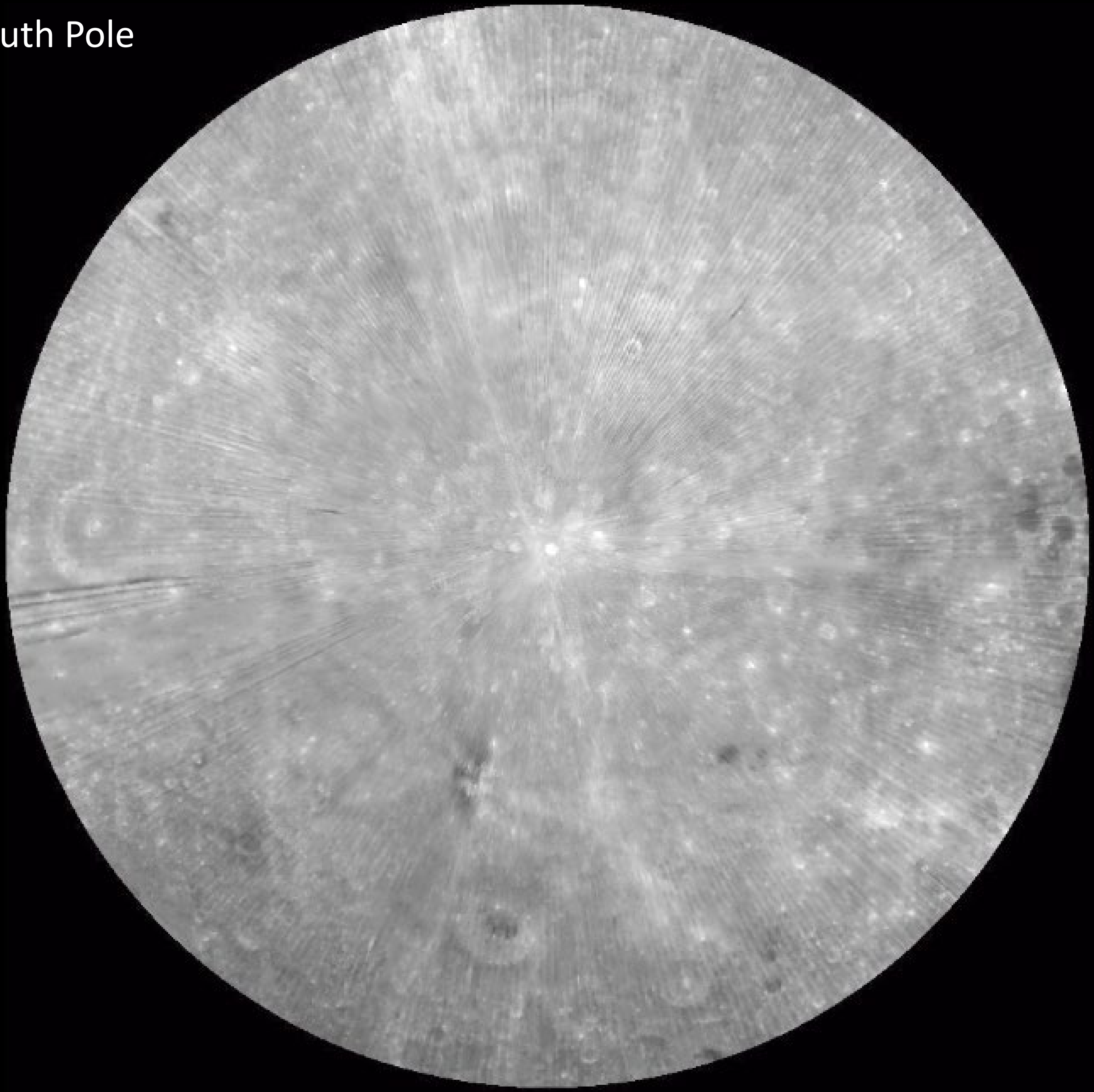
Abstract Impact cratering is the ... An impact transports both proximal m... h larger distances. Quantifying the rel... es understandings of lunar regolith ev... n



LOLA reflectance

Lemelin et al., 2016

Orthographic view of the South Pole
from LOLA reflectance



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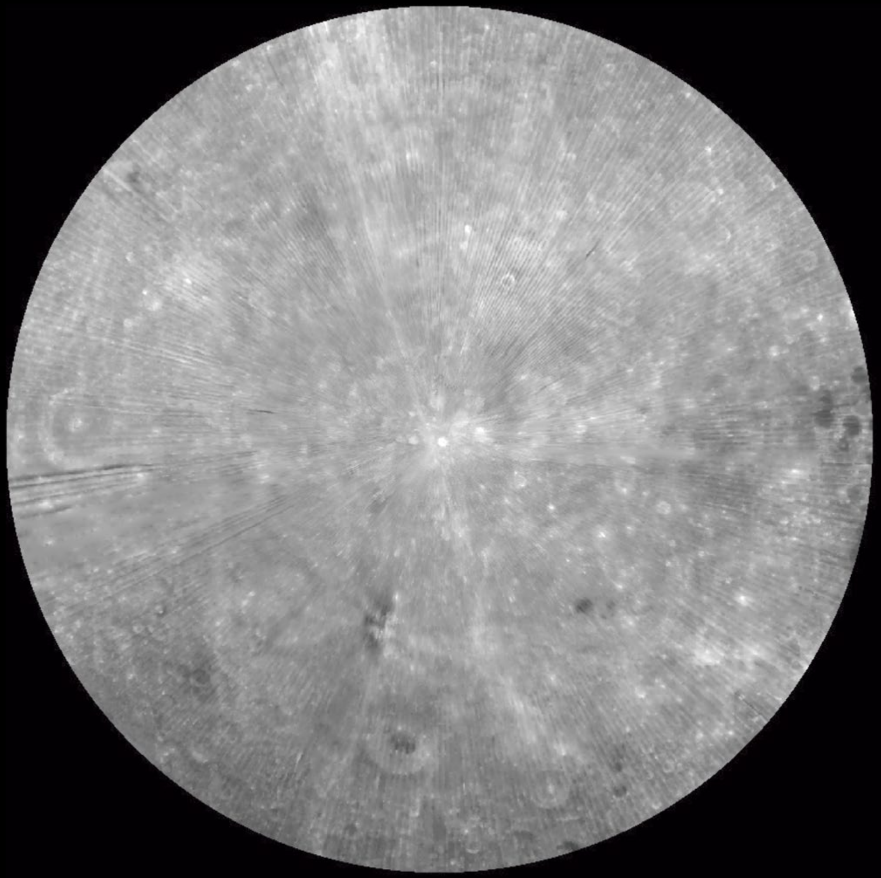

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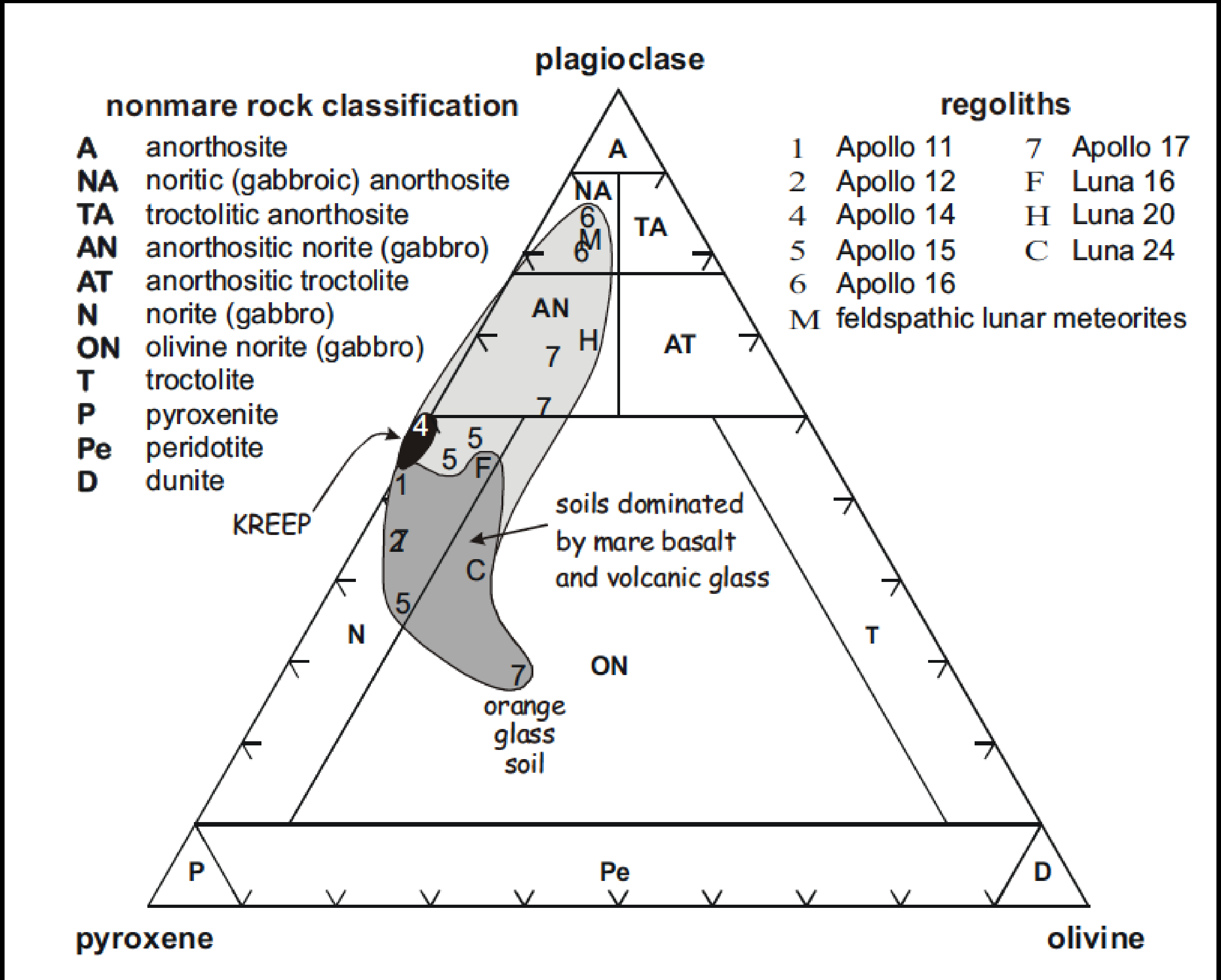
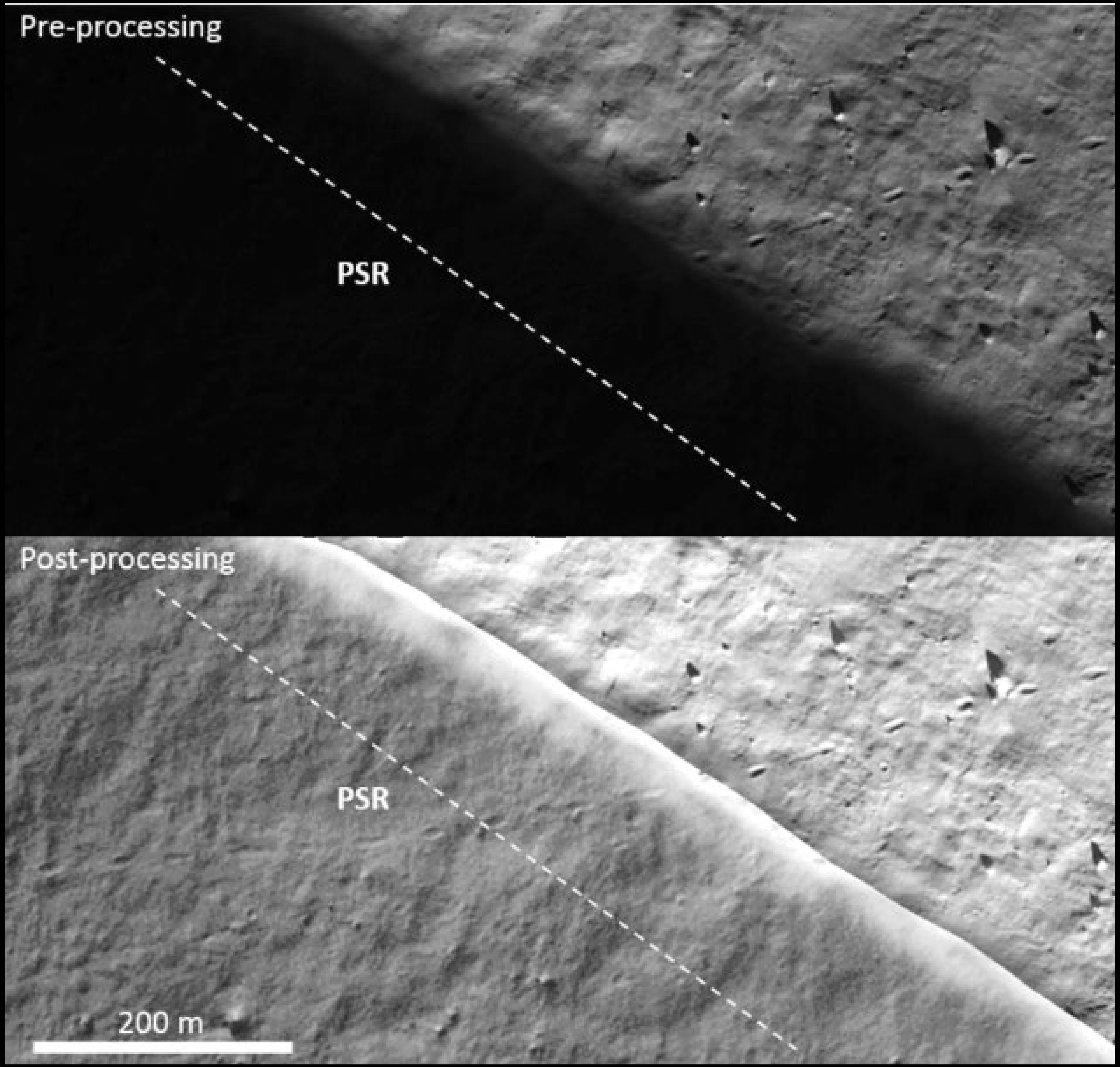


Lucey et al. 2006



Sargeant et al. 2020

Resource potential of highland soils

- O_2 extraction from soils
- Construction materials
- ??