# Physiography and Geology of the Moon

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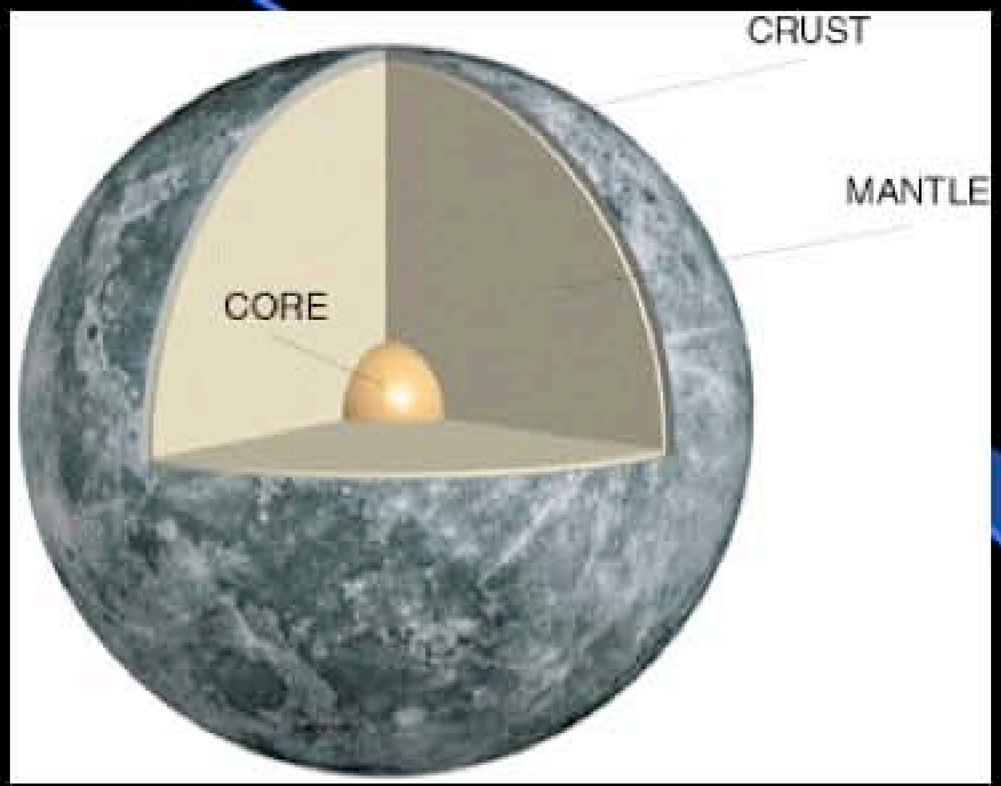
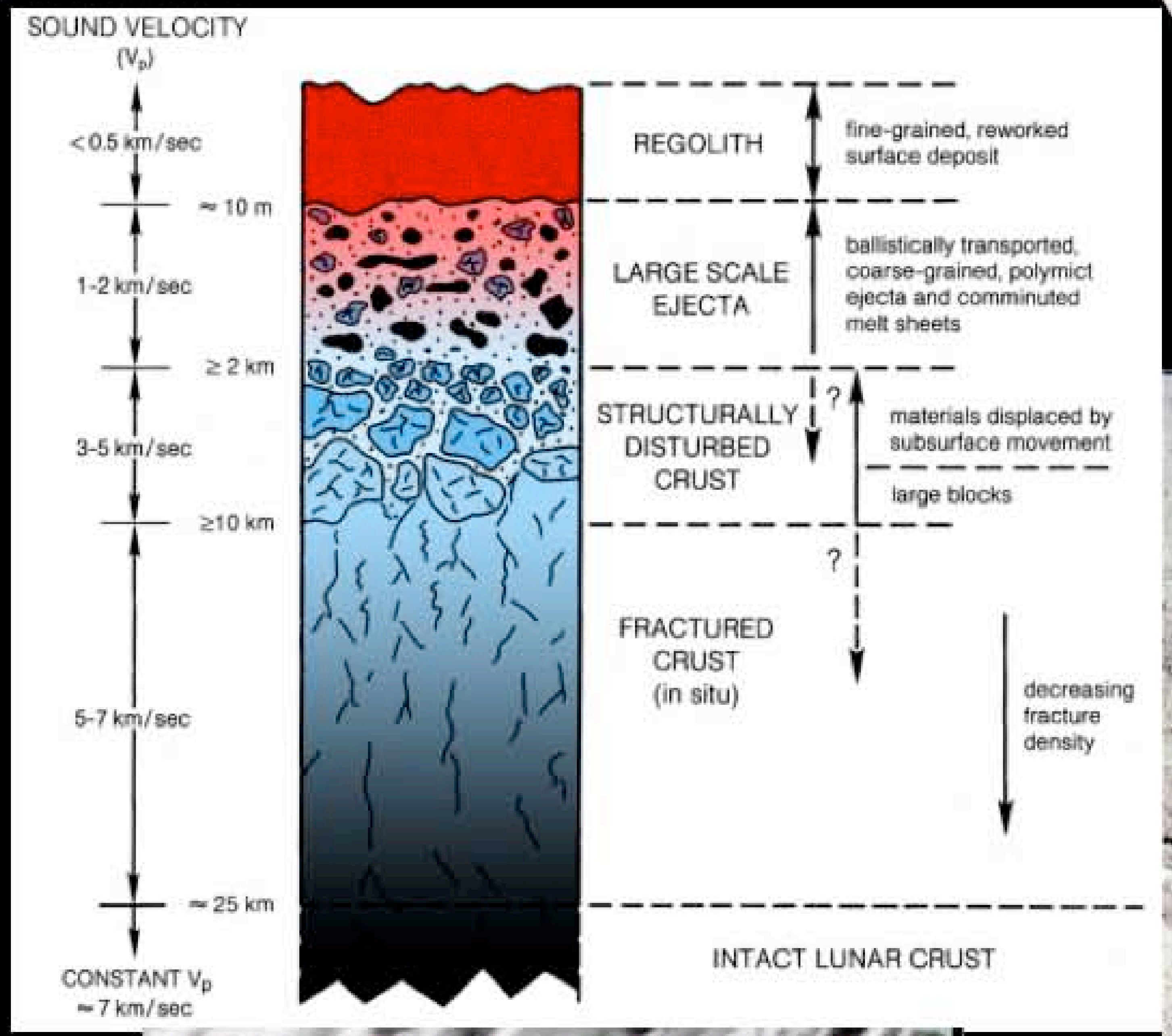
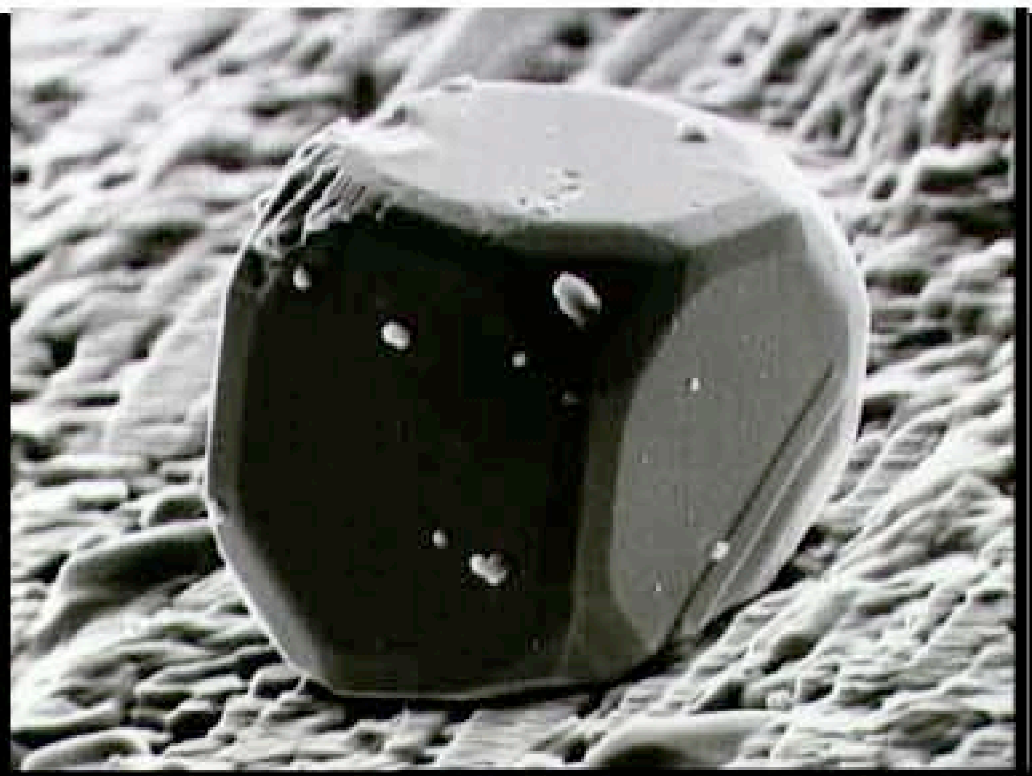
# The Nature of the Moon

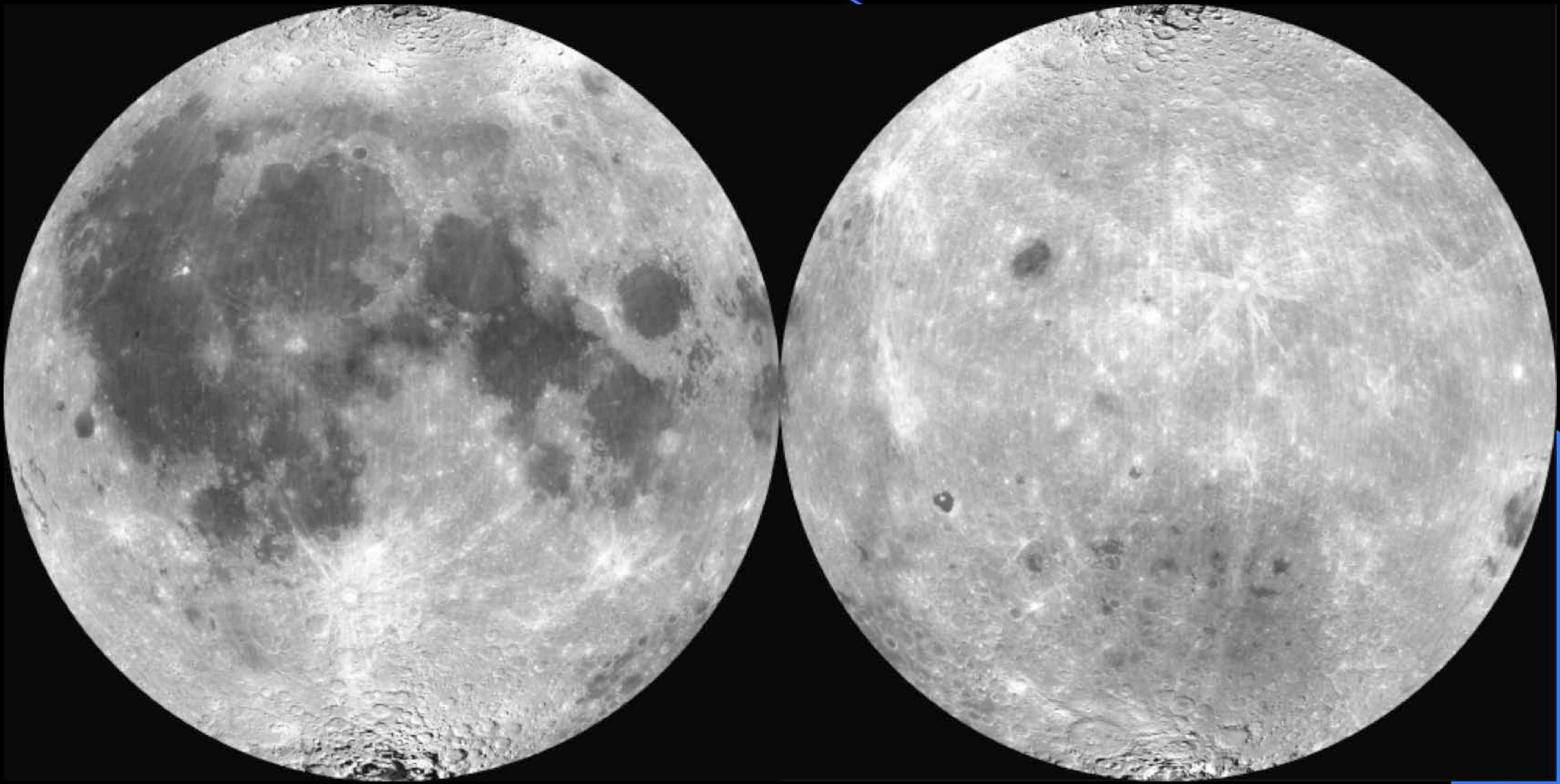
- A rocky planetary object, differentiated into crust, mantle, and core
- Heavily cratered surface; partly flooded by lava flows over 3 Ga ago
- Since then, only impacts by comets and asteroids, grinding up surface into chaotic upper layer of debris (regolith)
- Regolith is easily accessed and processed; likely feedstock for resource extraction



# Moon – Near and Far Sides

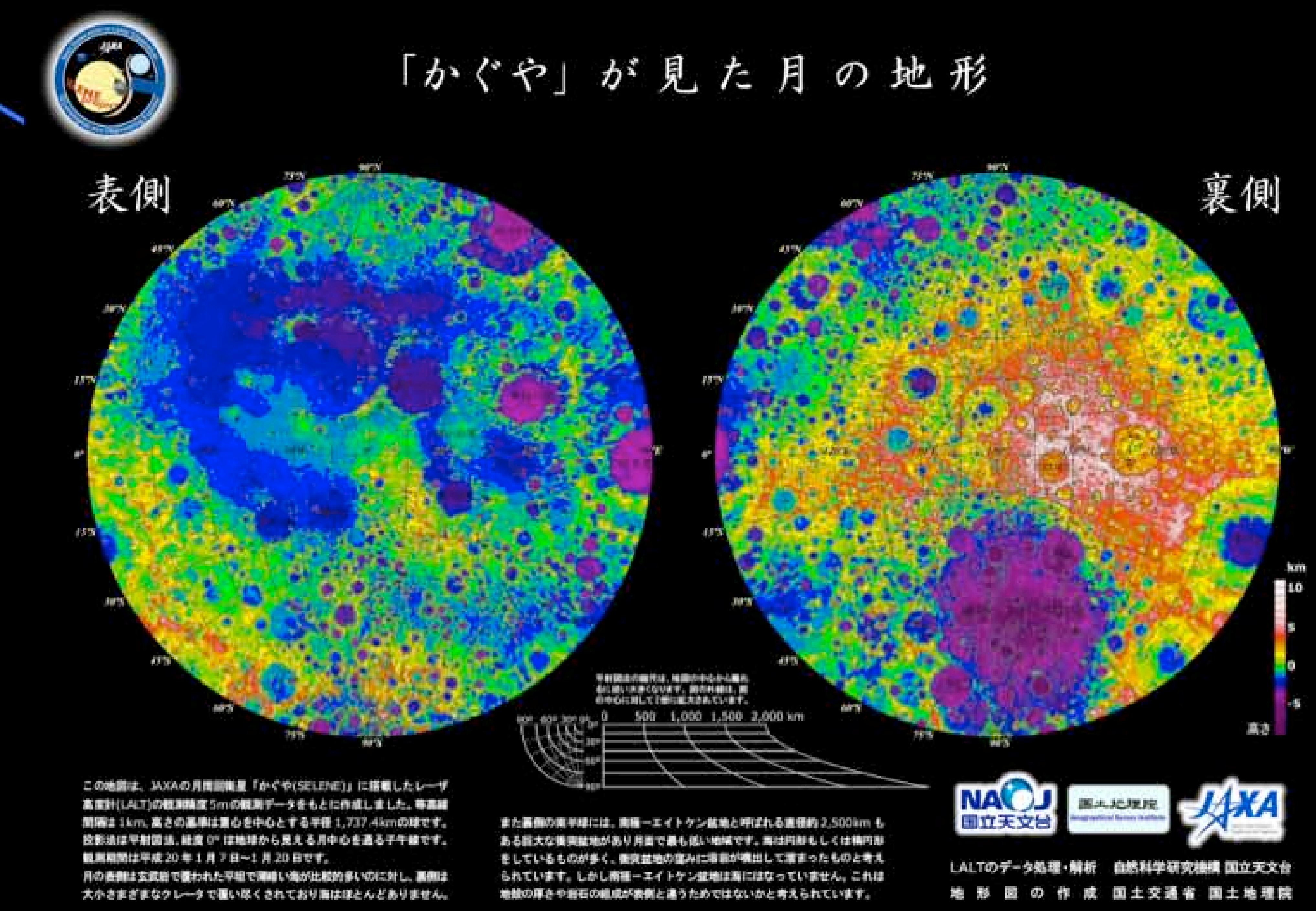


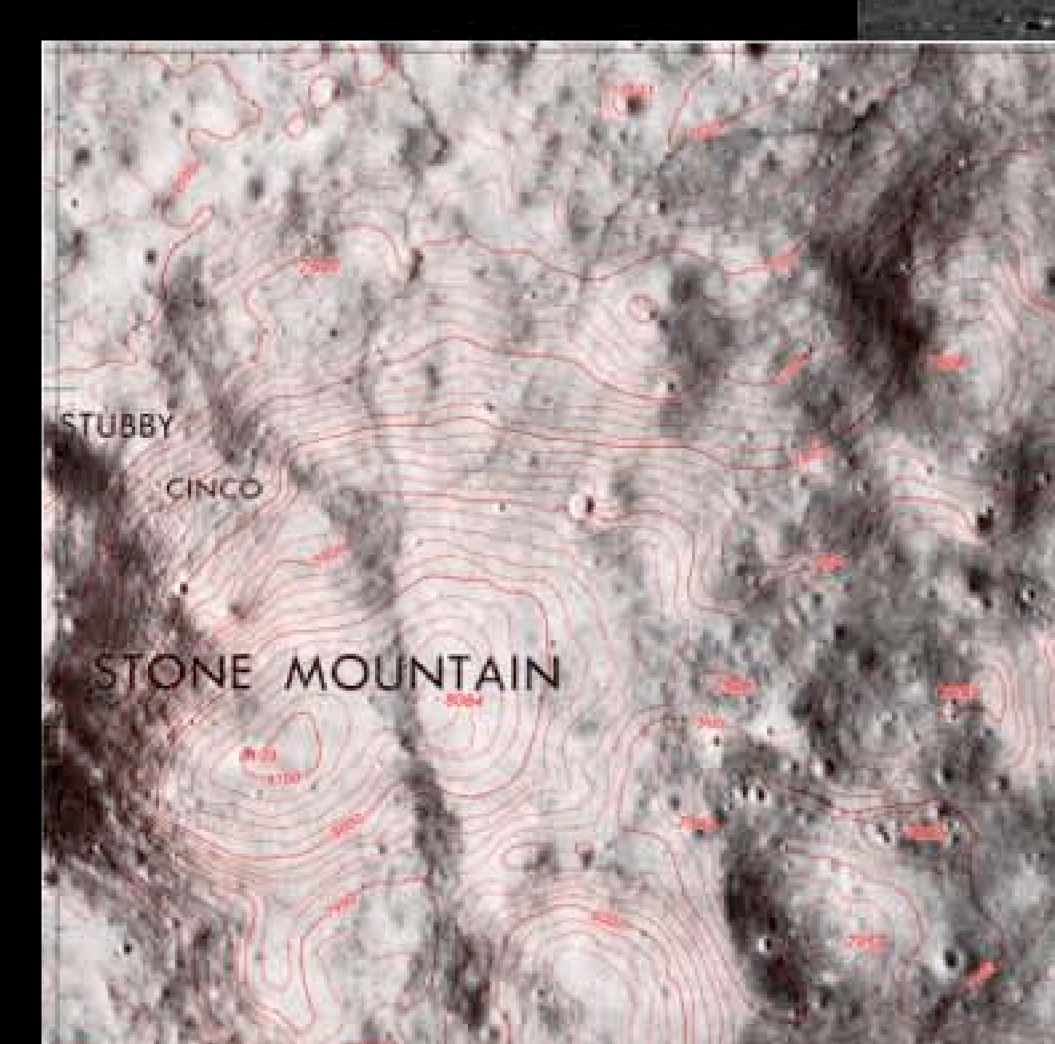
Near side

Far side

# Topography

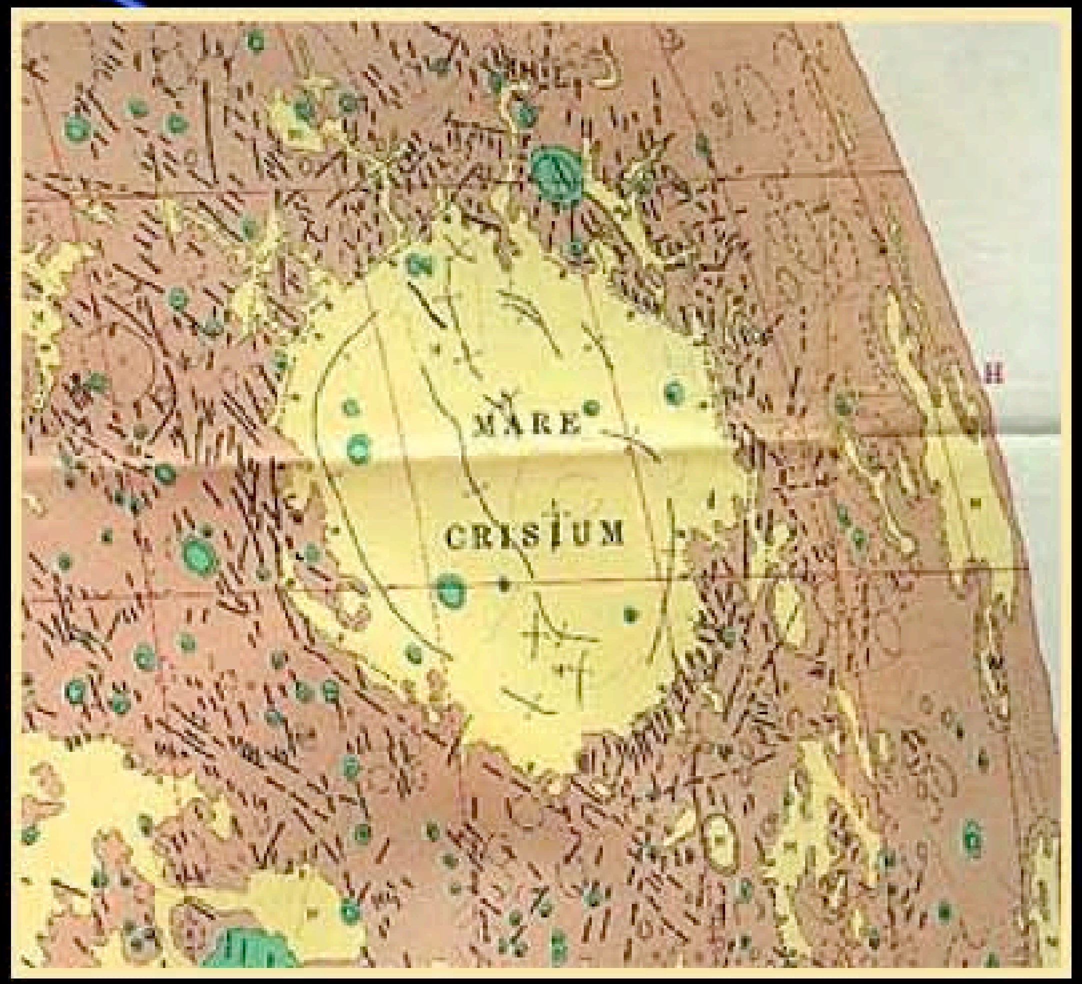
- Global figure is roughly spherical, but with major departures
  - South Pole-Aitken basin on far side is major feature
- Moon is very “bumpy”; extremes of elevation + 8 km to –9 km (same dynamic range as Earth, sea floor to mountains)
- Physiography divided into rough, complex bright highlands (terra) and relatively flat, smooth dark lowlands (maria)
- Landforms dominated by craters, ranging in size from micrometers to thousands of km across
- Smooth flat areas are rare, but occur in maria (modulated by sub-km class cratering)
- Average slopes: 4-5° in maria, 7-10° in highlands



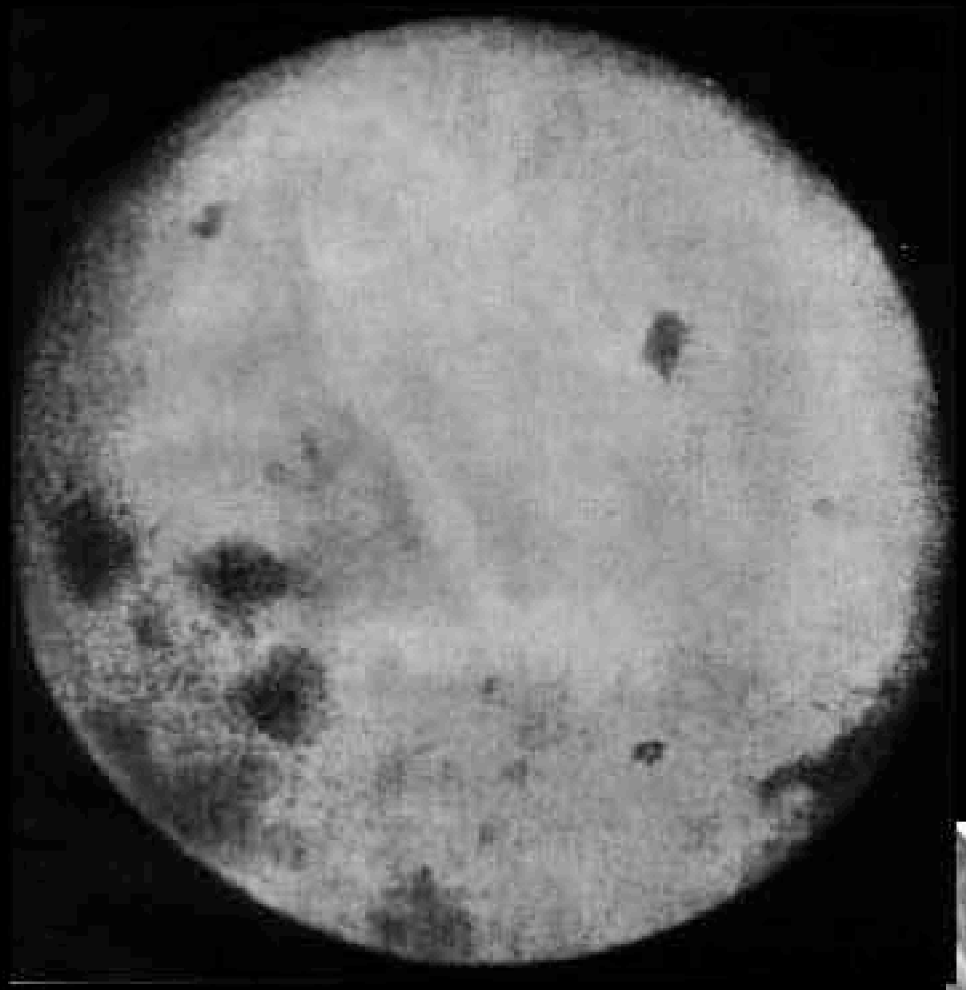



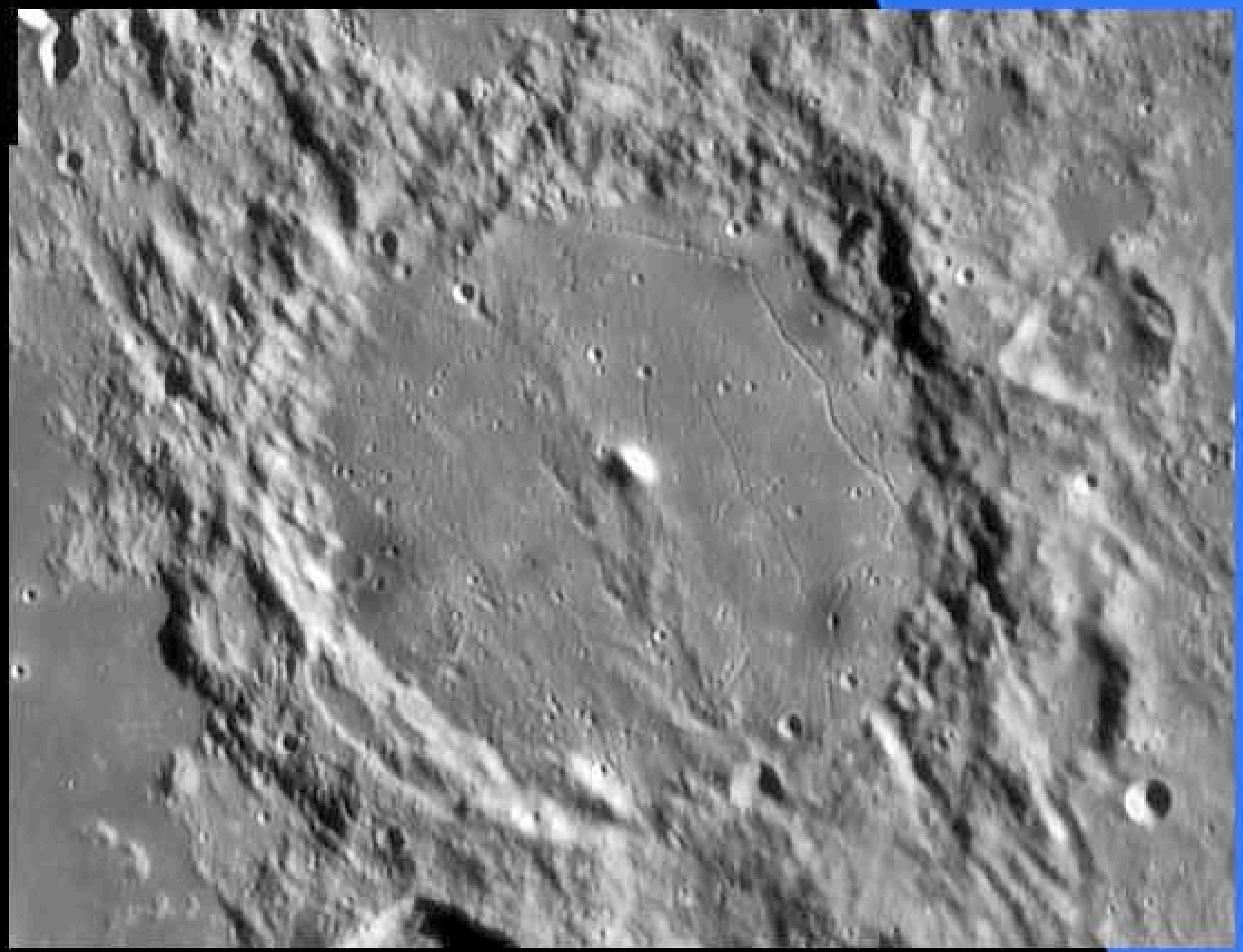
# Lunar Physiography

- Landforms and provinces that make up the Moon's surface and terrain
- Mapped originally by telescope
- Space Age showed far side has less maria
- Fundamentally, surface shaped by two processes:
  - Impact
  - Volcanism



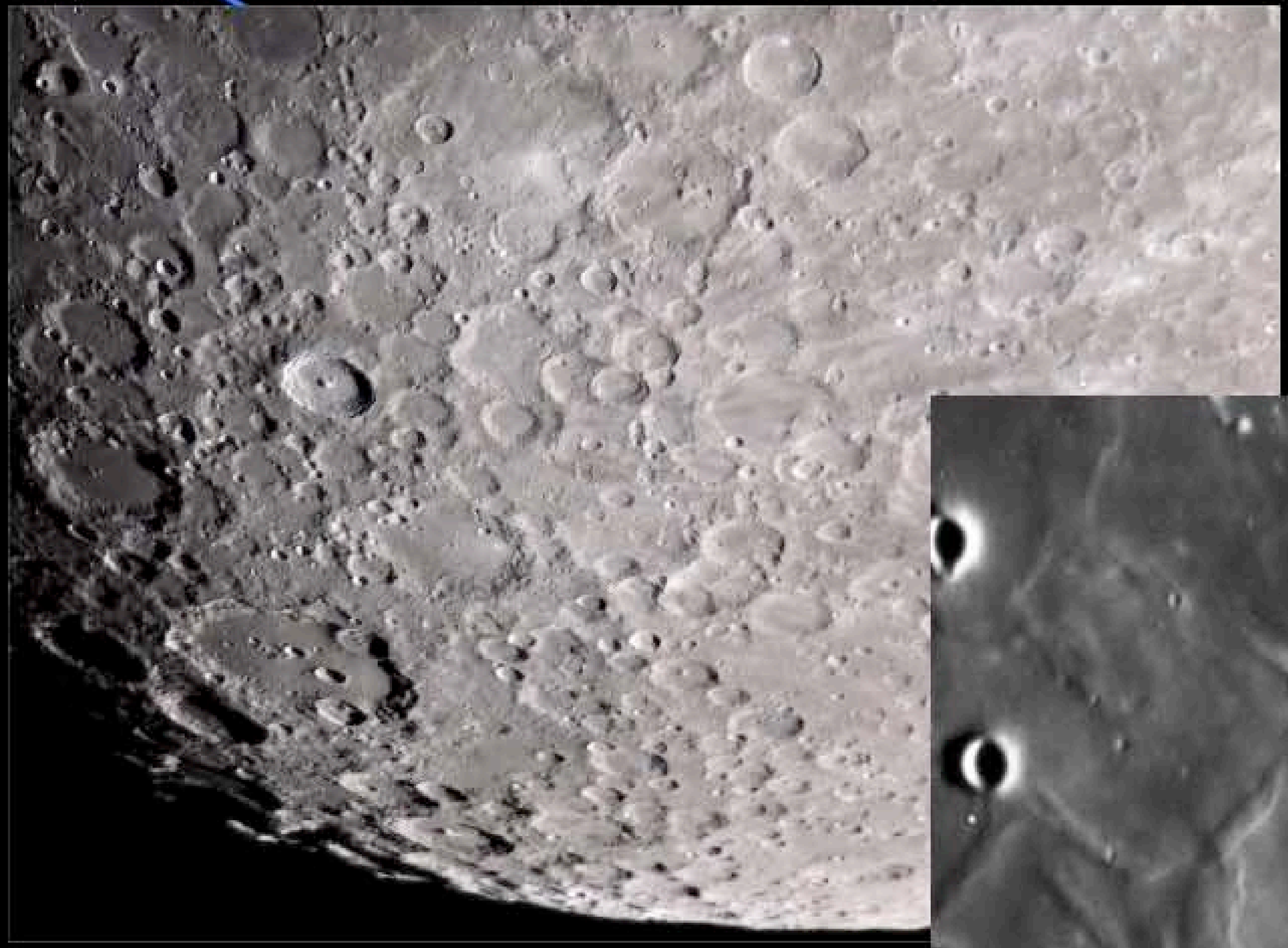


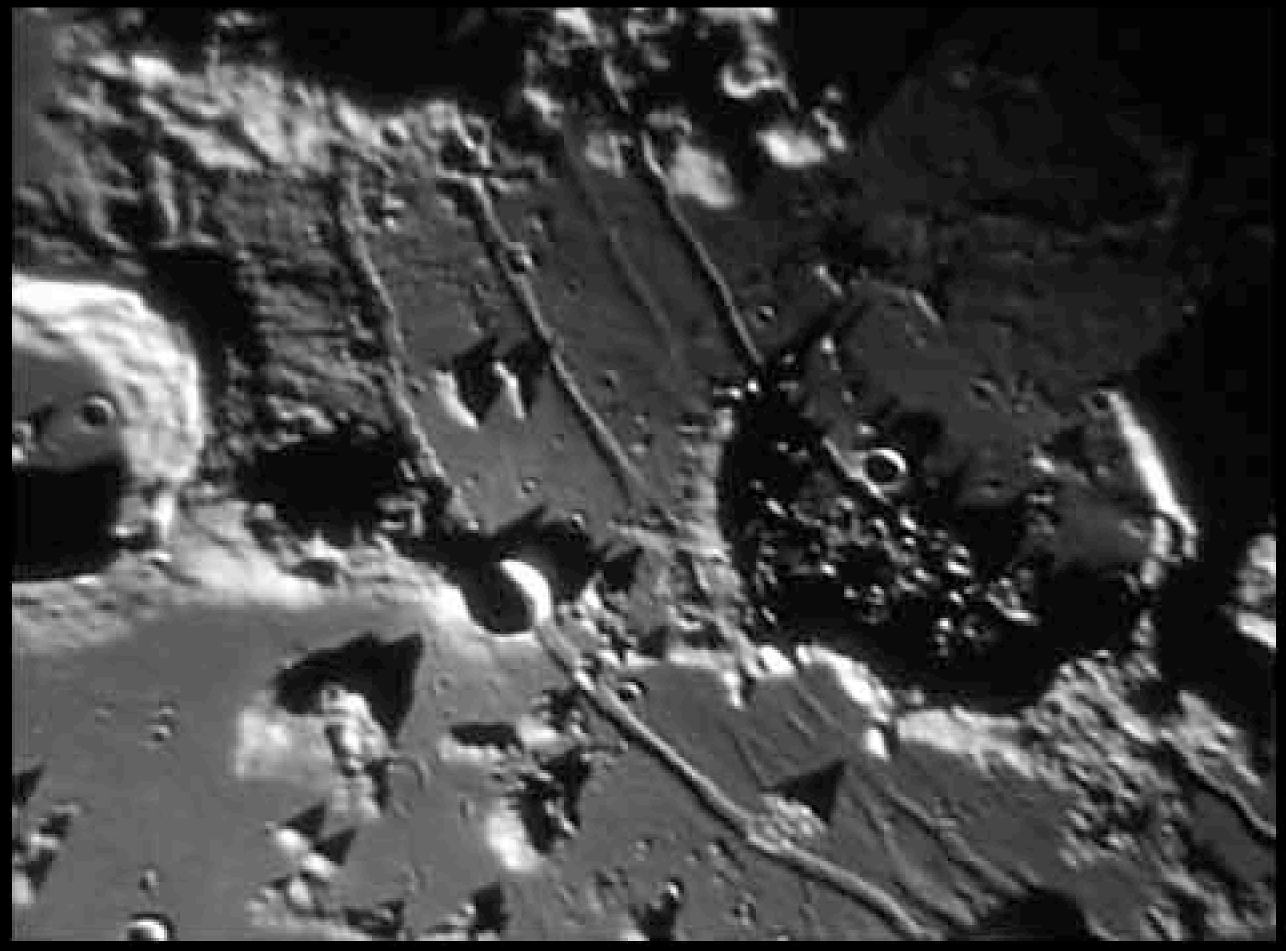


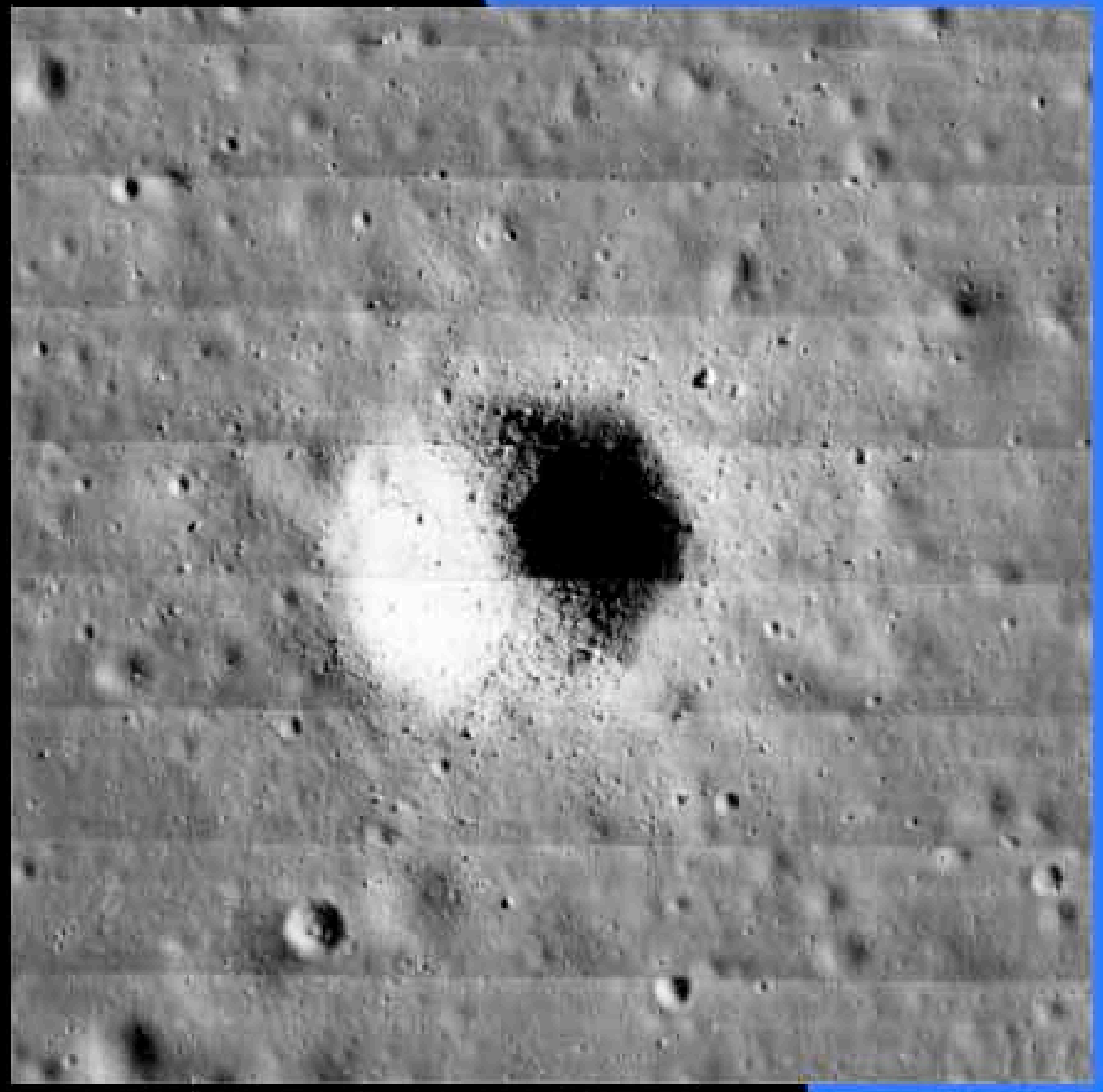


# Surface Morphology and Physiography

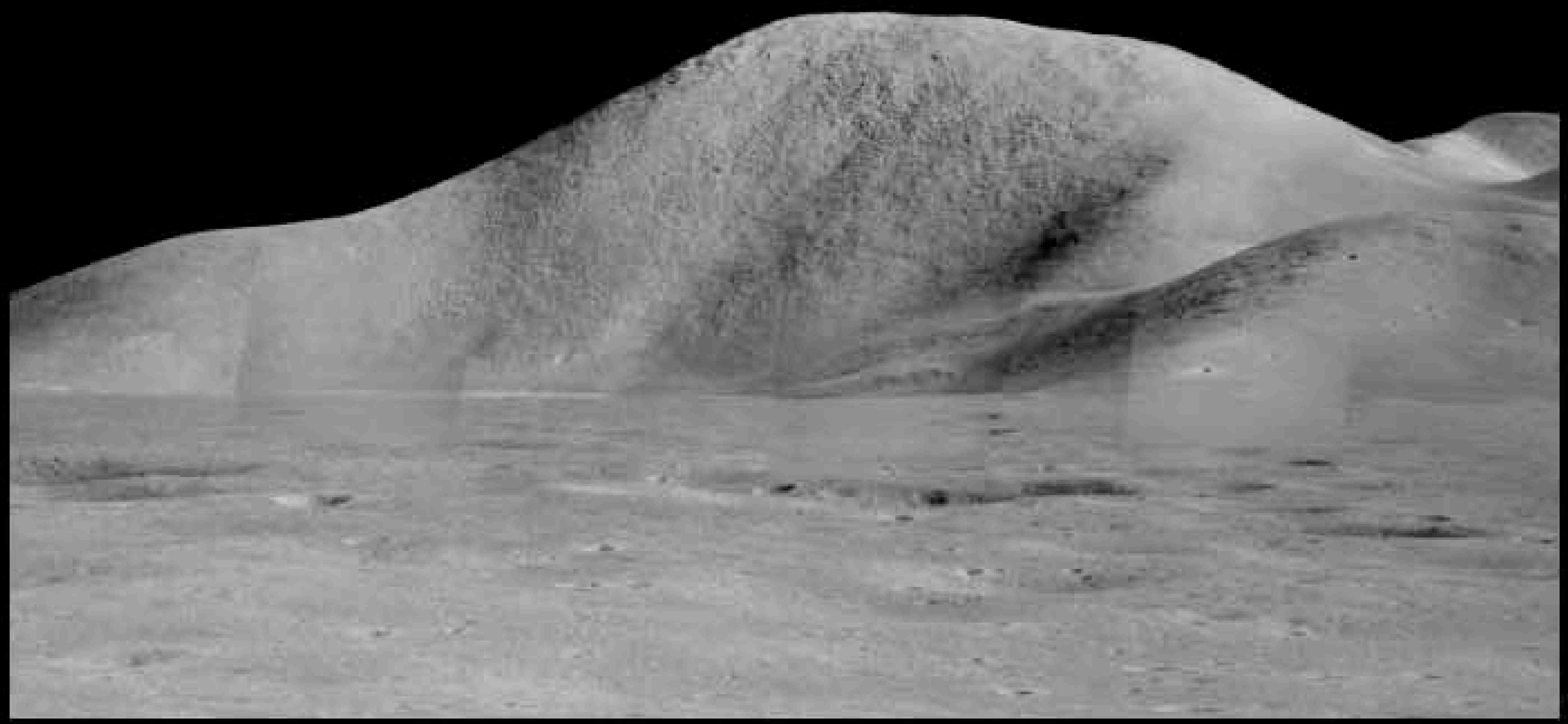
- Craters dominate all other landforms
  - Range in size from micro- to mega-meters
  - Shape and form change with increasing size (bowl shaped to central peaks to multiple rings)
- Maria are flat-lying to rolling plains, with crenulated ridges
  - Low relief, all mostly caused by post-mare craters
- Few minor landforms
  - Domes and cones
  - Faults and graben
  - Other miscellaneous features

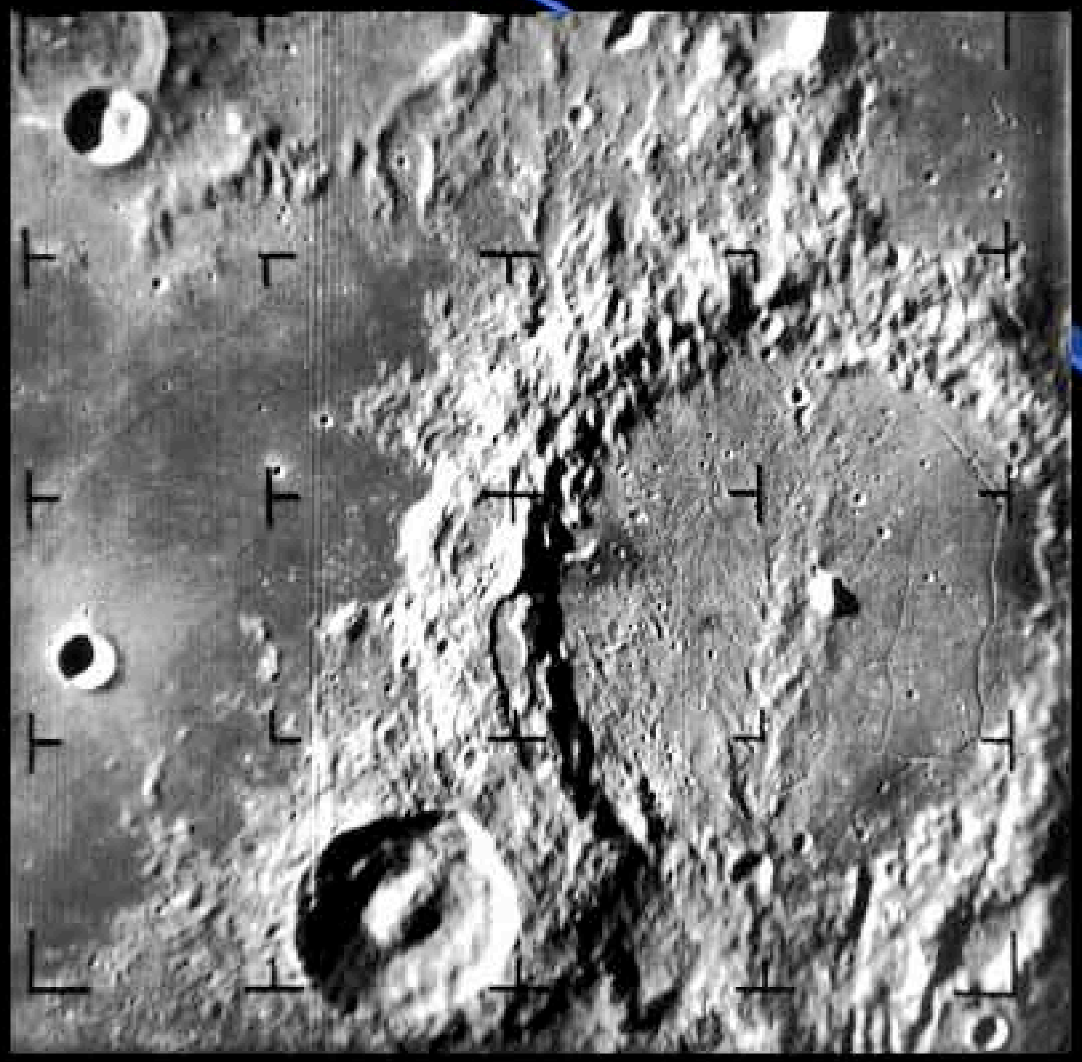


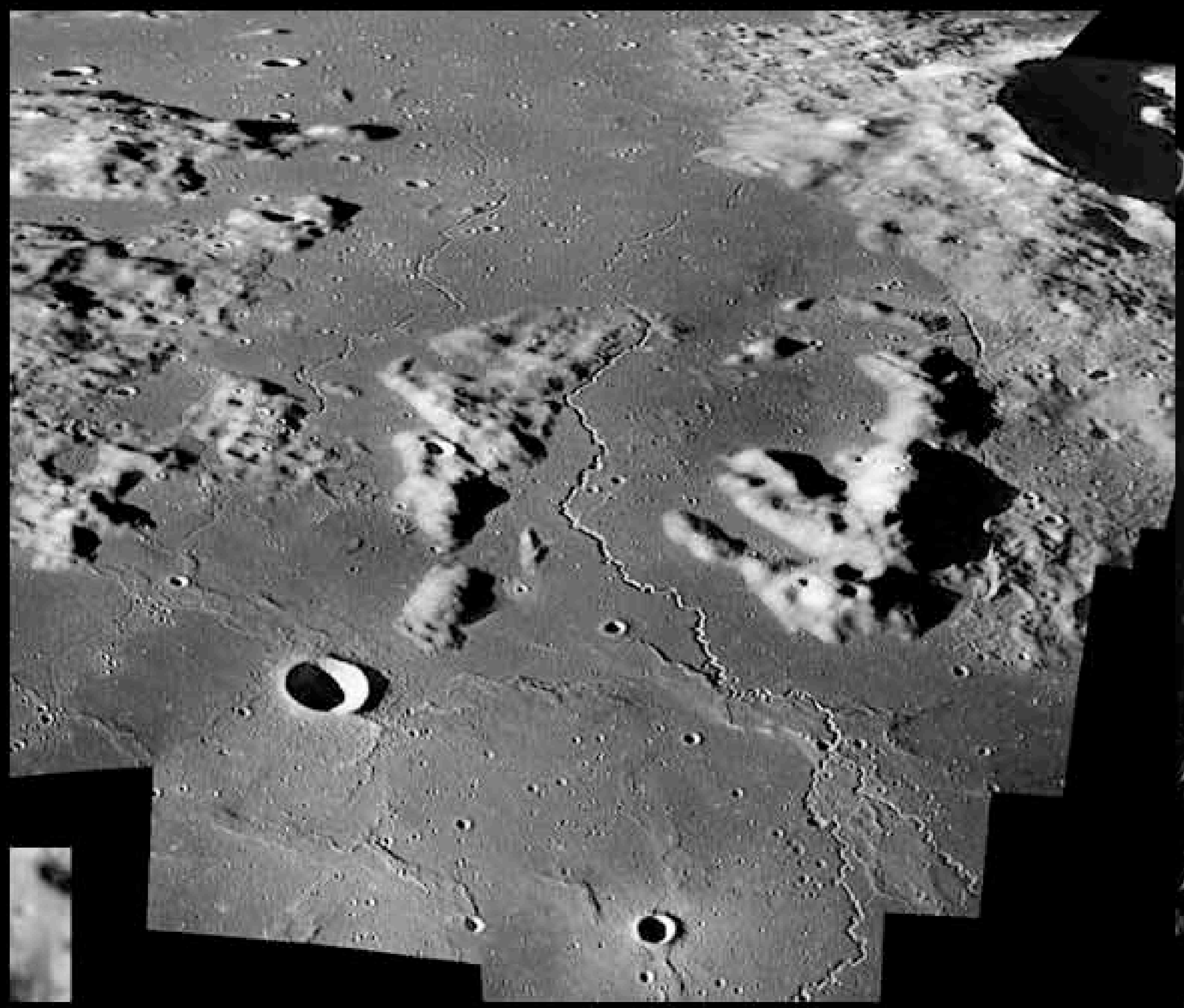


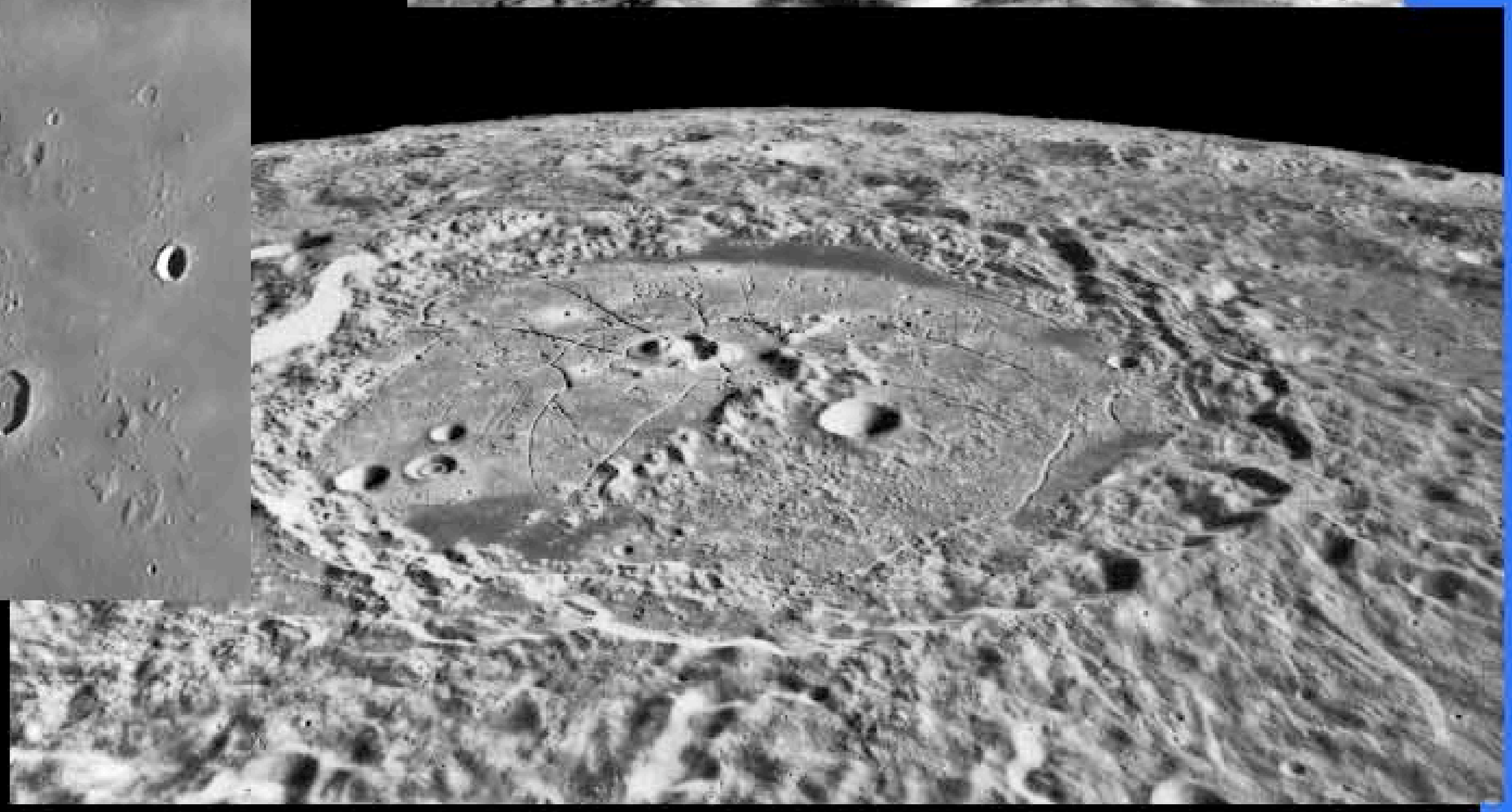


# Some Lunar Landscapes





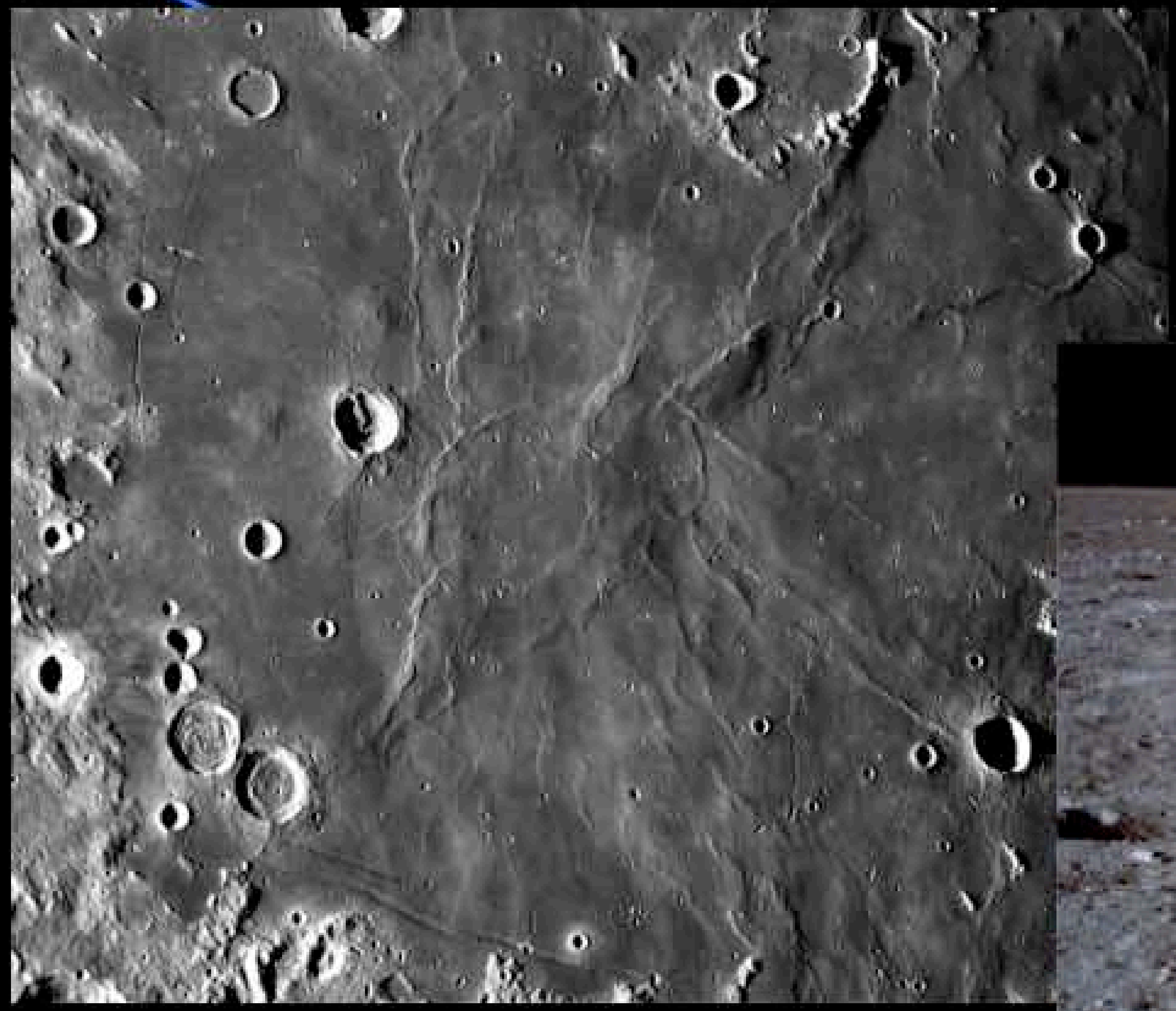




# Lunar Terrains

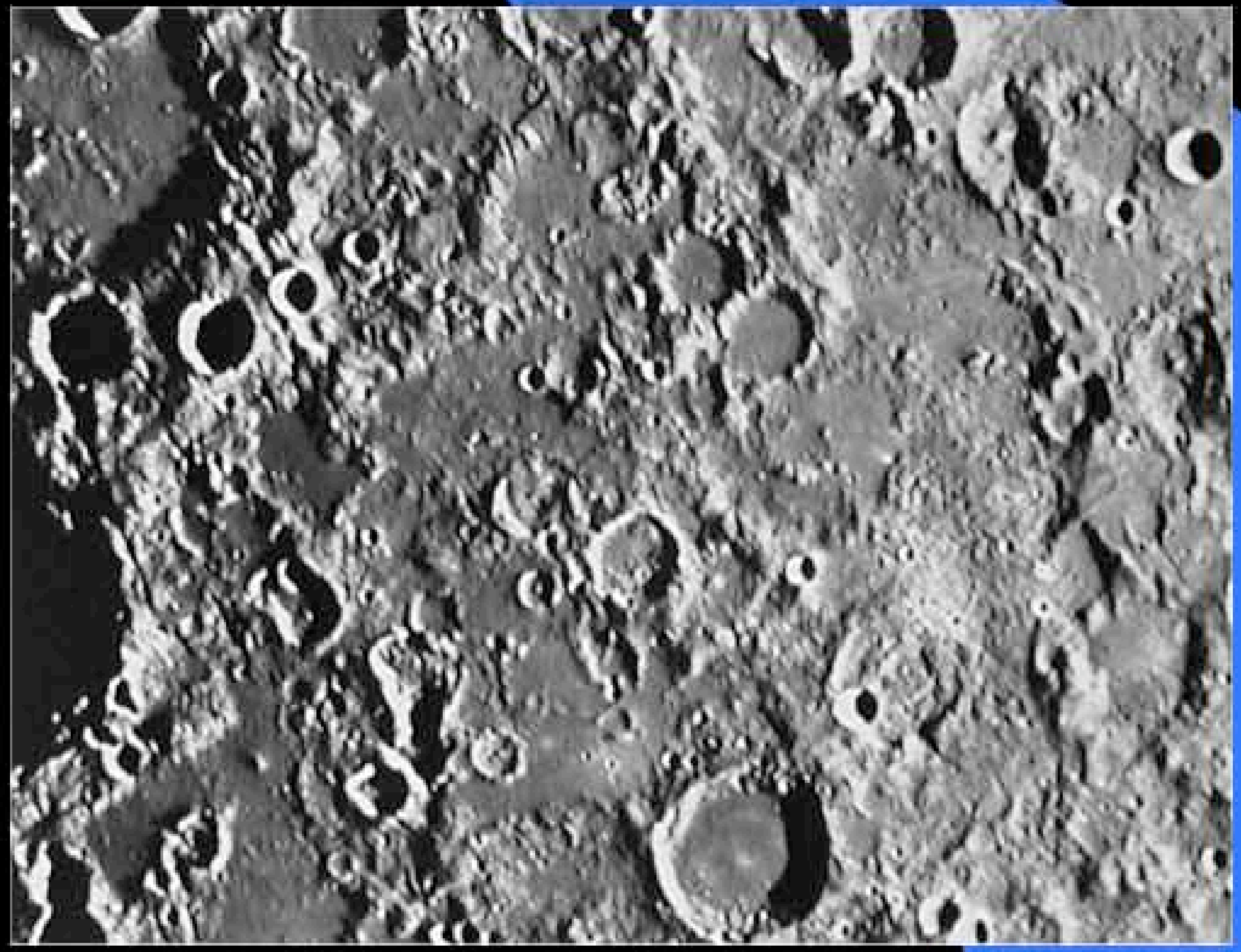
**Maria**

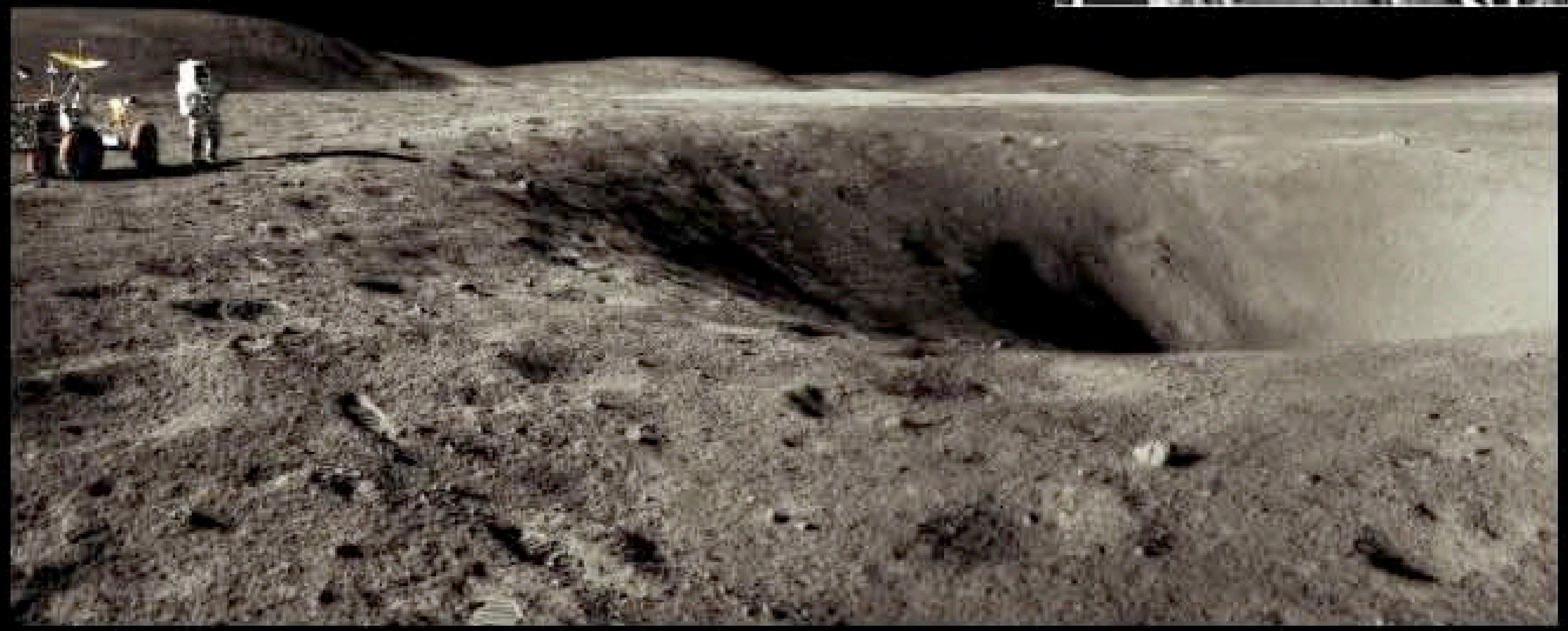
- Flat to gently rolling plains
- Numerous craters D < 20 km; larger craters rare
- Blockier (on average) than highlands (bedrock is closer to surface)
- Mean (r.m.s.) slopes 4°- 5°



**Highlands**

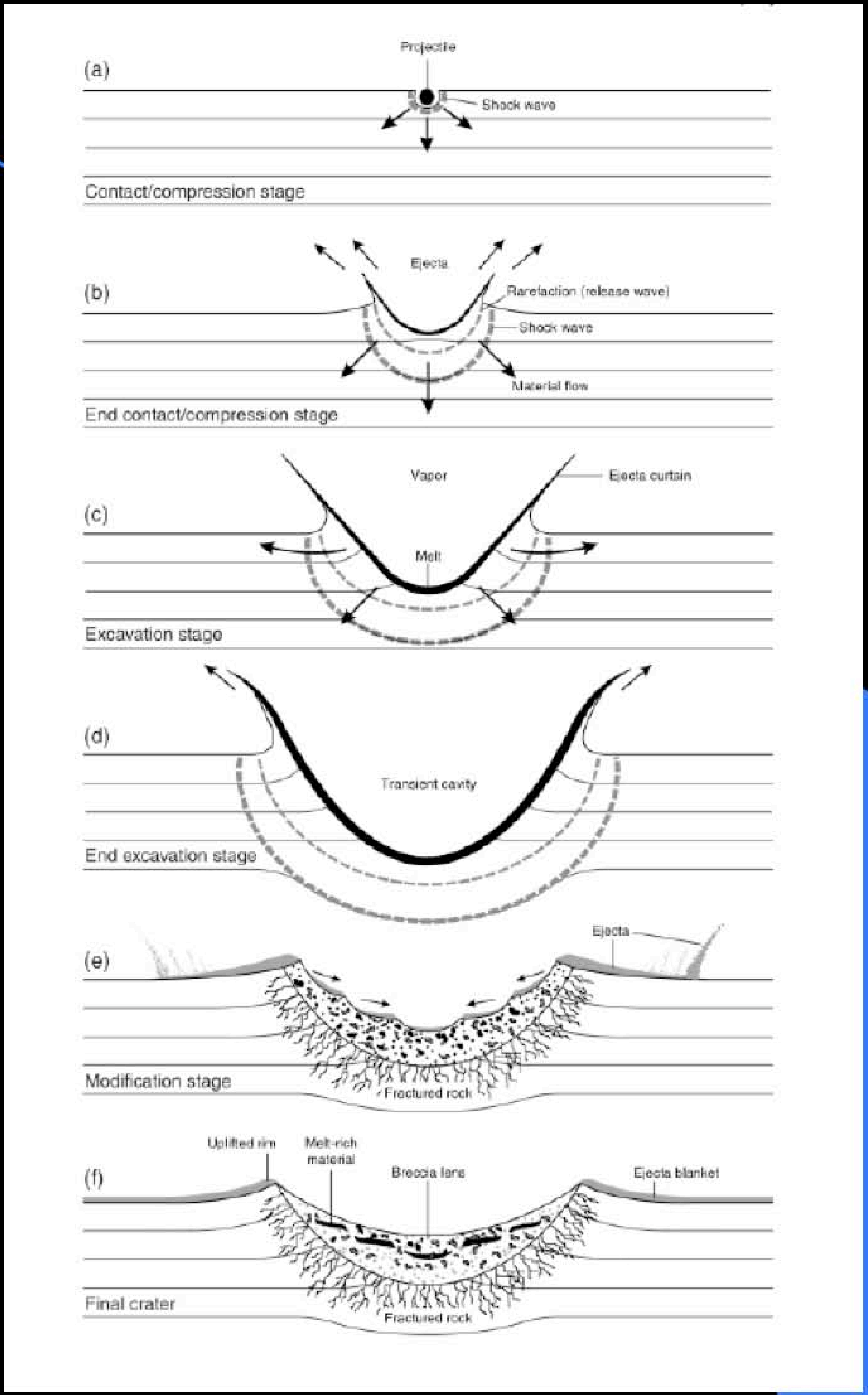
- Rugged, cratered terrain
- Smoother intercrater areas
- Numerous craters D > 20 km
- Large blocks present, but rare; “sandblasted” Moon
- Mean (r.m.s.) slopes 7°- 10°





# The Cratering Process

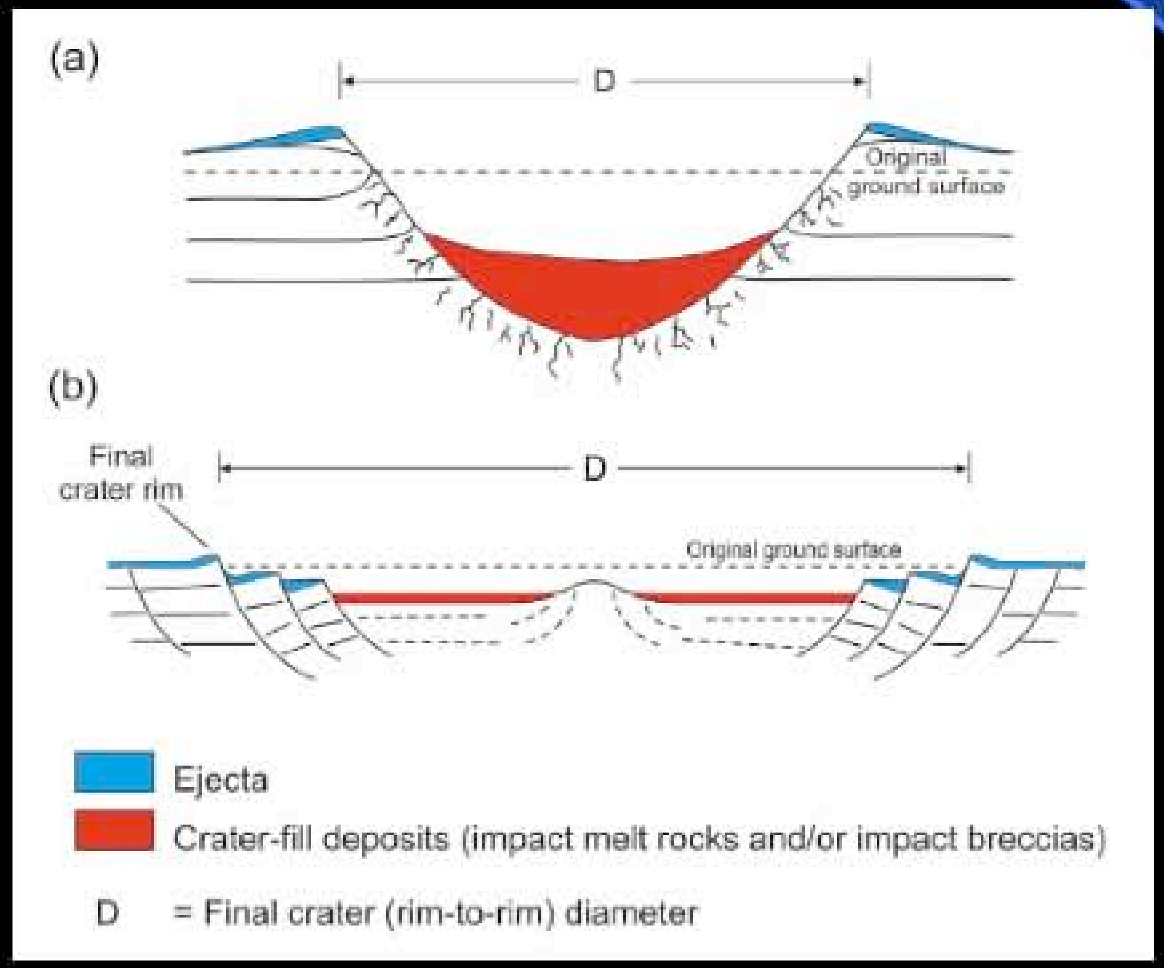
- Impacting debris
- Contact and penetration
- Vaporization and jetting
- Target compression
- Target decompression (rarefaction)
- Excavation
- Adjustment and modification
- Ejecta deposition

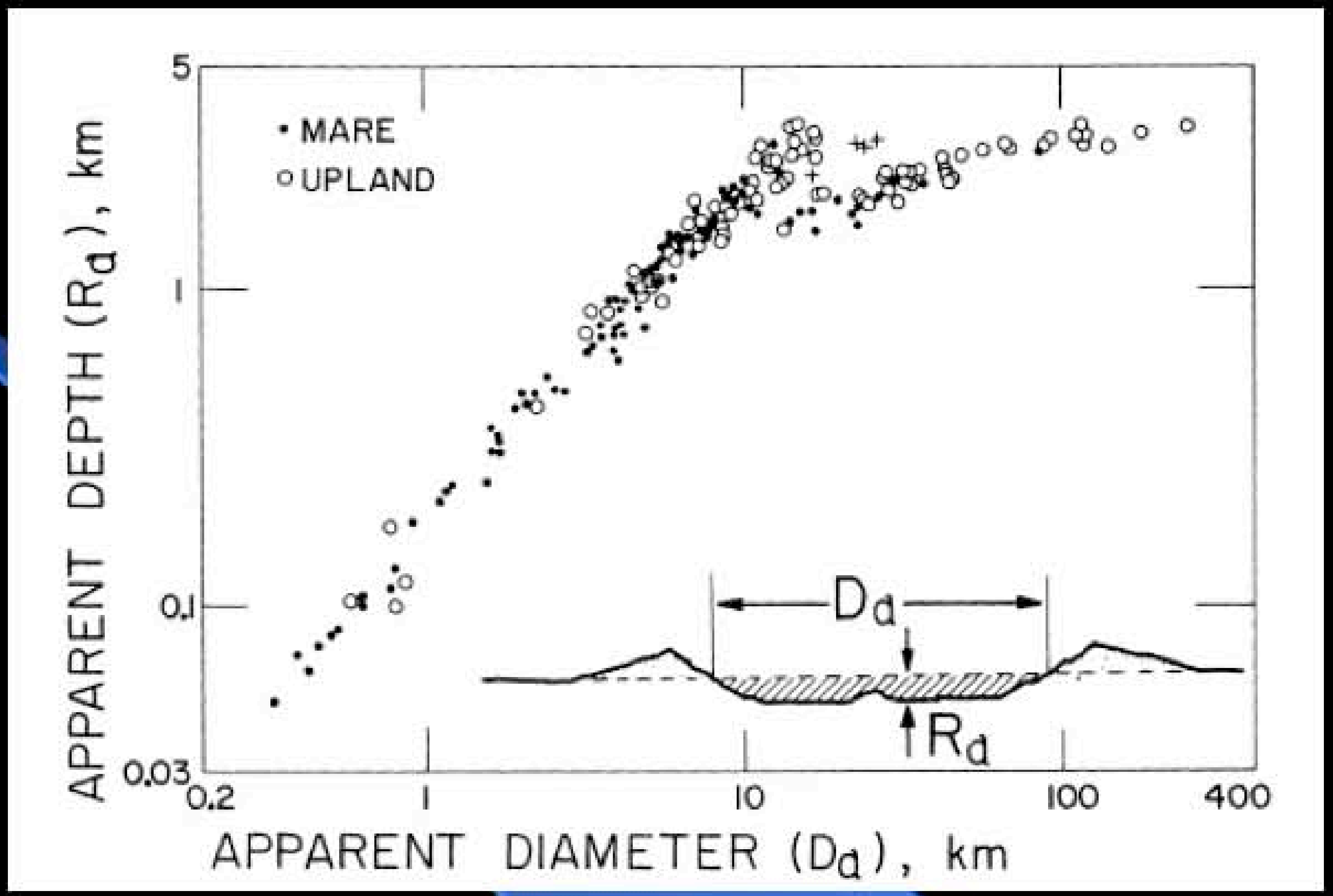


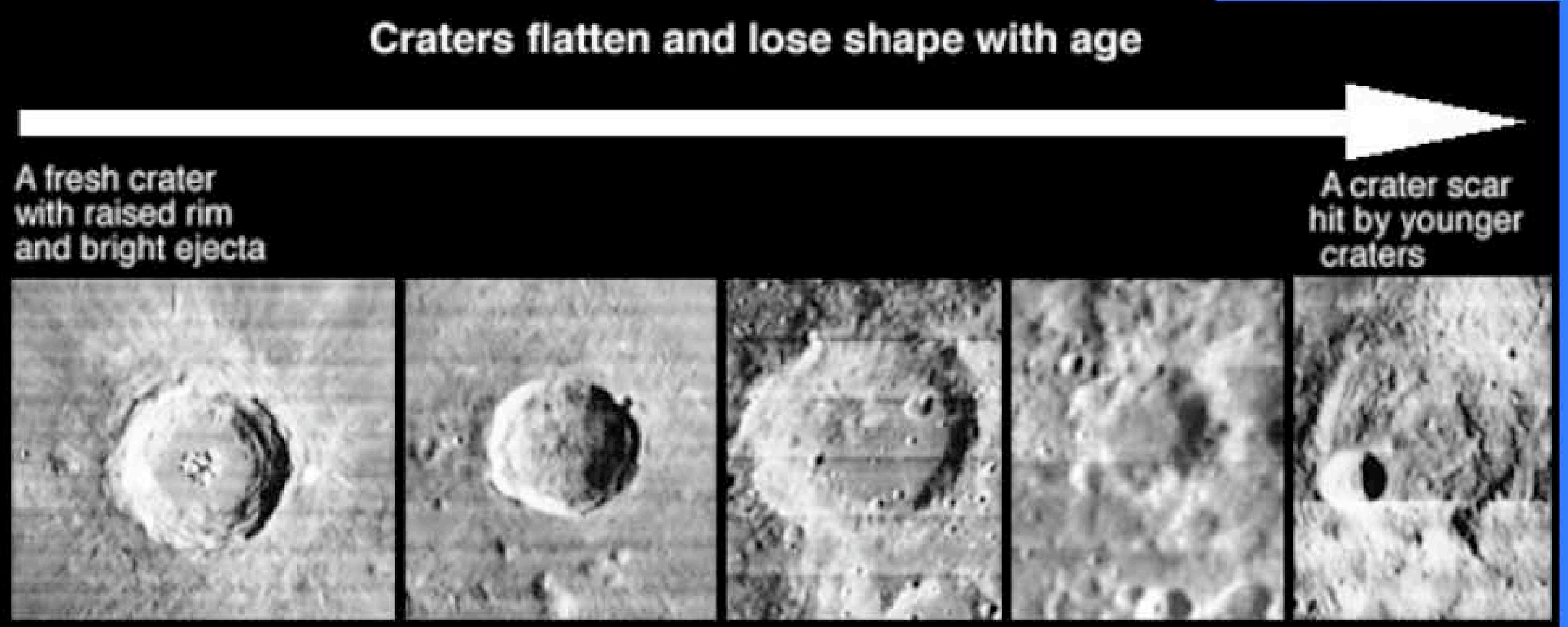
# Craters

Dependence of morphology with size
- Simple craters
- Complex craters
- Protobasins
- Two-ring basins
- Multi-ring basins

Dependence of morphology with age
- Fresh craters
- Topographic elements disappear with time
- Ancient (ghost) craters



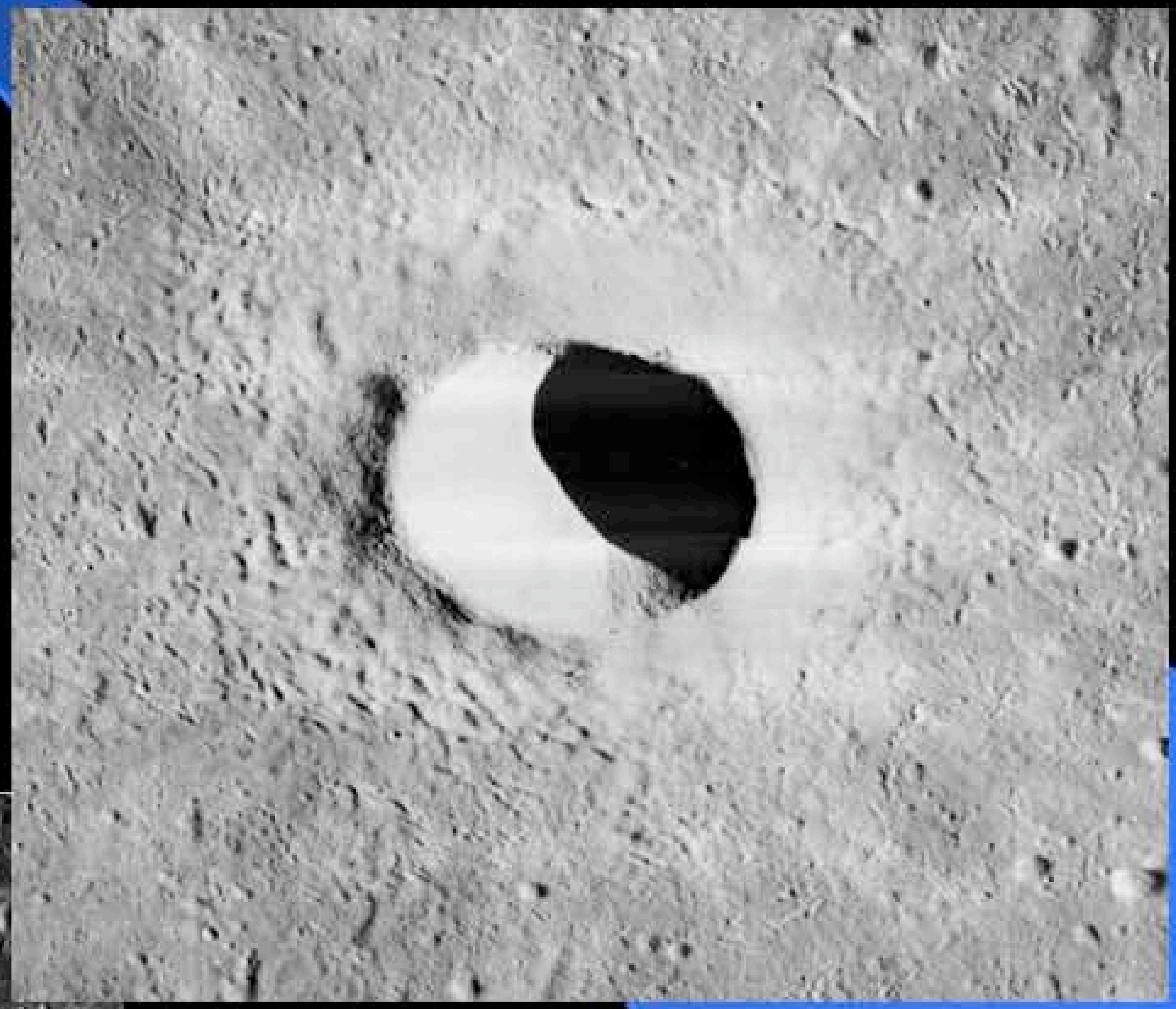



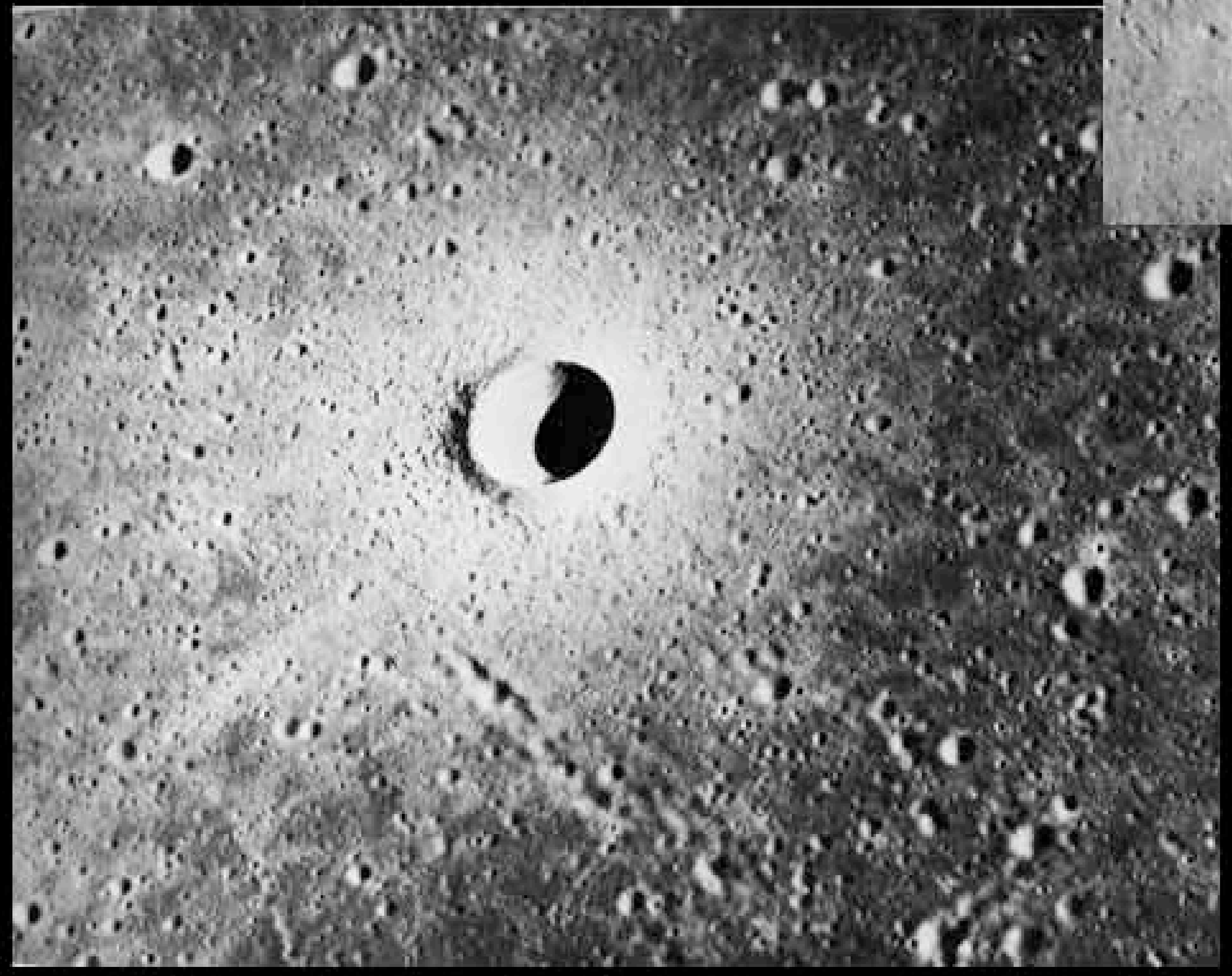
# Simple craters

- Bowl shaped features, d/D ~ 1:3
- Transient crater, apparent crater, “true” crater
- Ejecta and subsurface brecciation
- Impact melting
- Secondary impact craters

North Ray ~ 1 km



Mösting C ~ 4 km



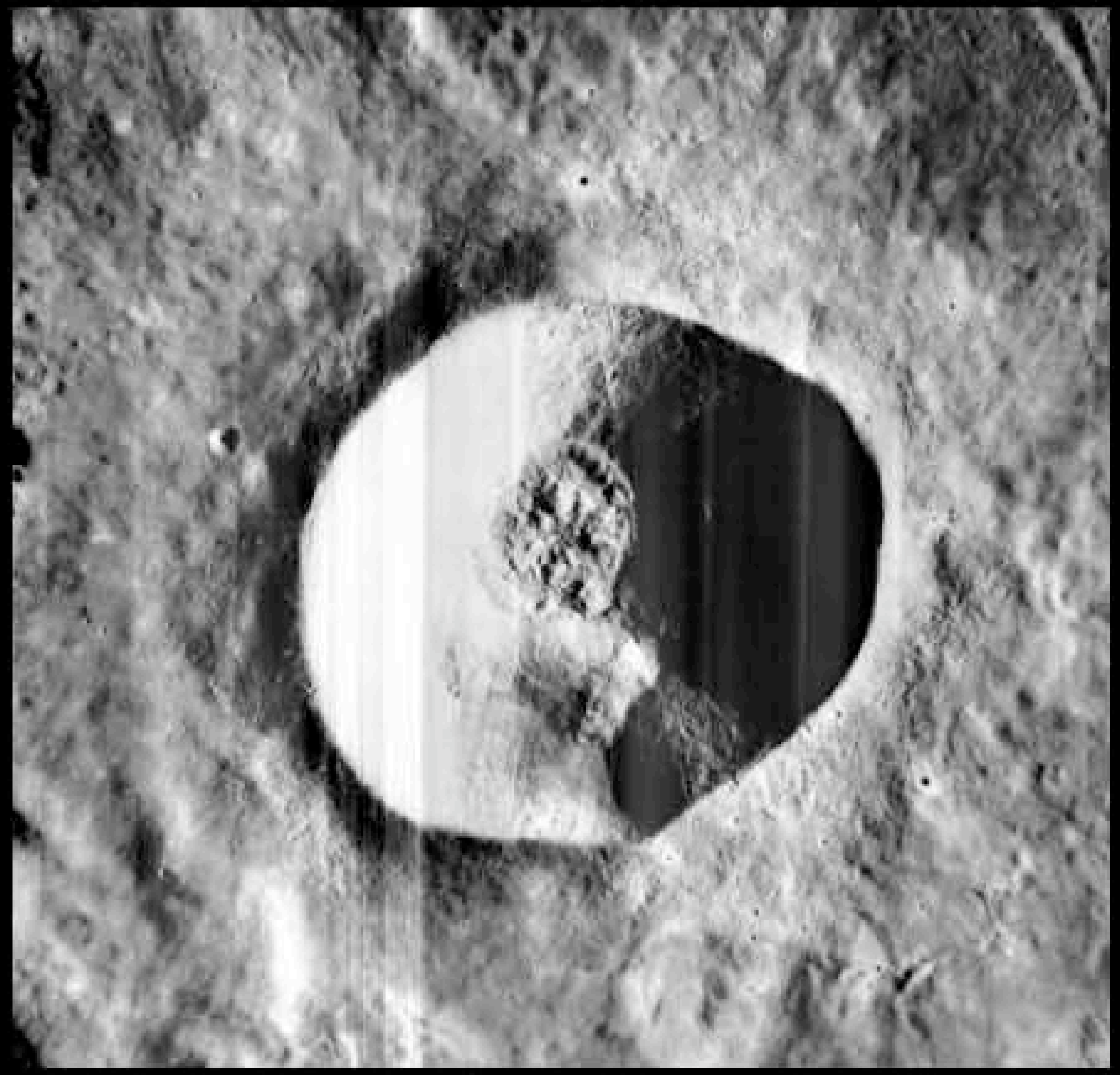
Moltke ~ 6 km

# Simple to Complex Transition

- Simple crater d/D relation
- Wall slumps, floor debris
- Rim scalloping
- Incipient terracing
- Melt sheet
- Central mounds

Sulpicius Gallus ~ 12 km

Bessel ~ 15 km



Dionysius ~ 18 km

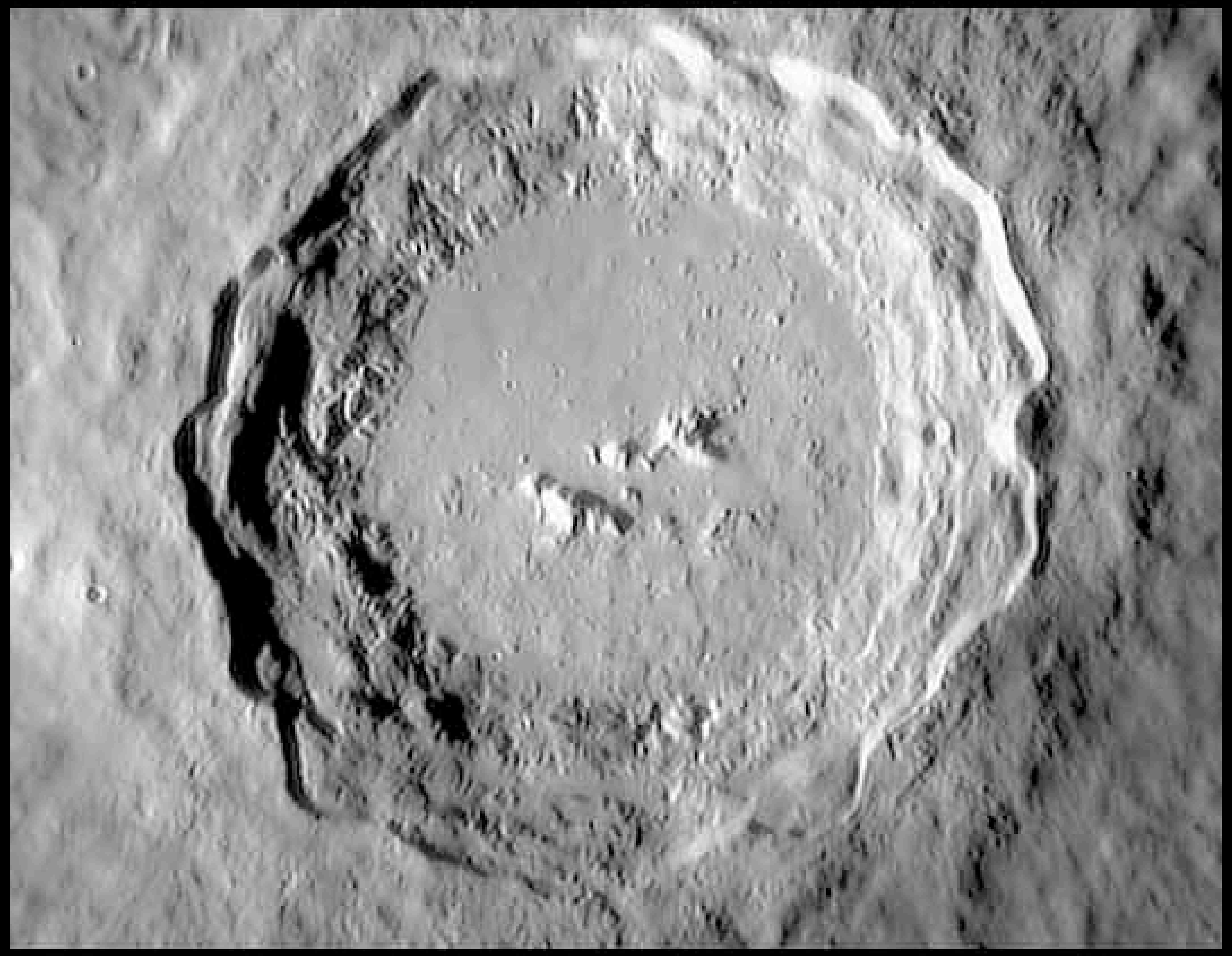
Triesnecker ~ 26 km

# Complex Craters

- Crater morphology
- Wall terraces
- Flat floors
- Central Peaks
- Impact melt deposits
- Ejecta and secondaries
- Rays

King D~77 km

Tycho D~85 km

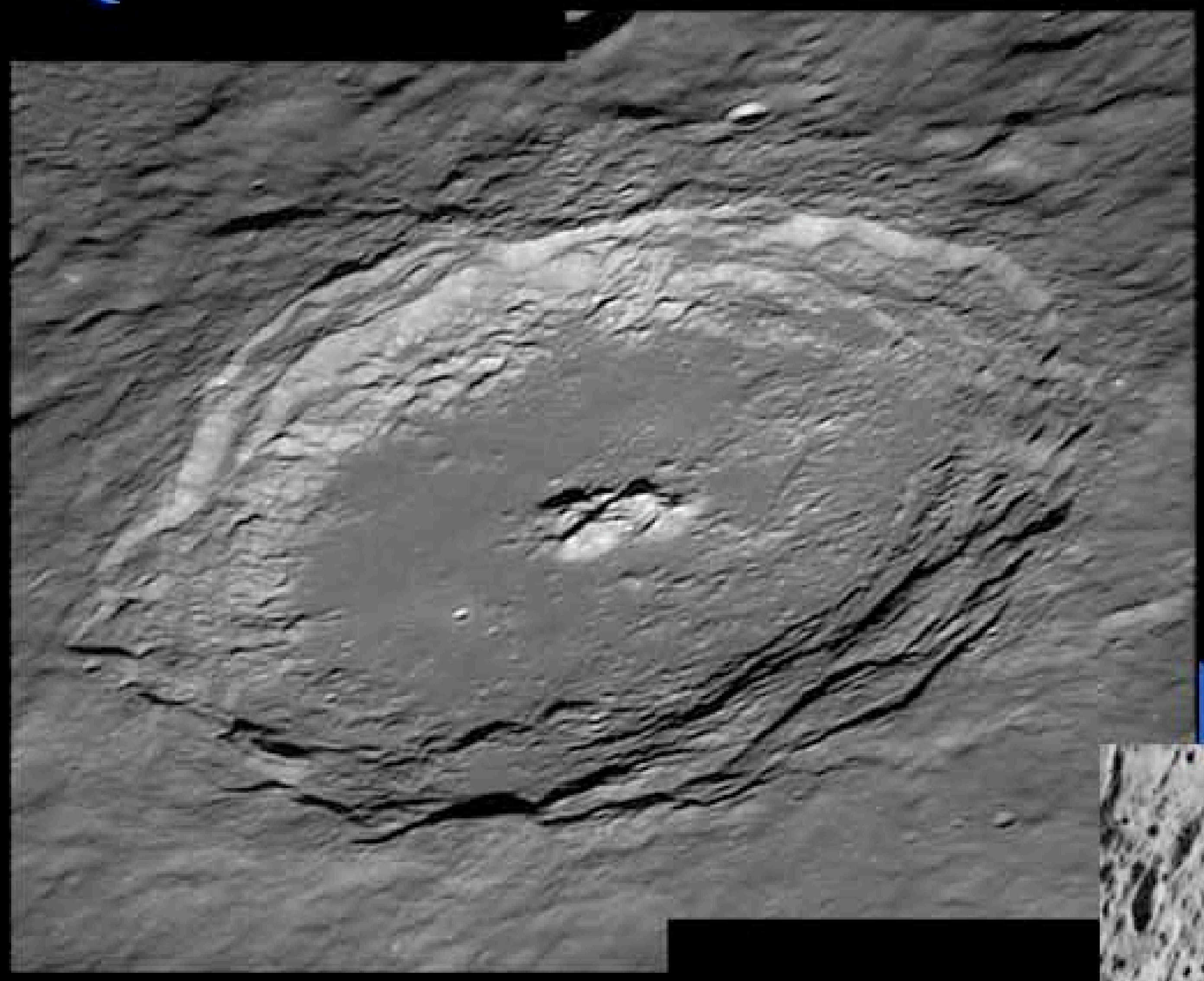


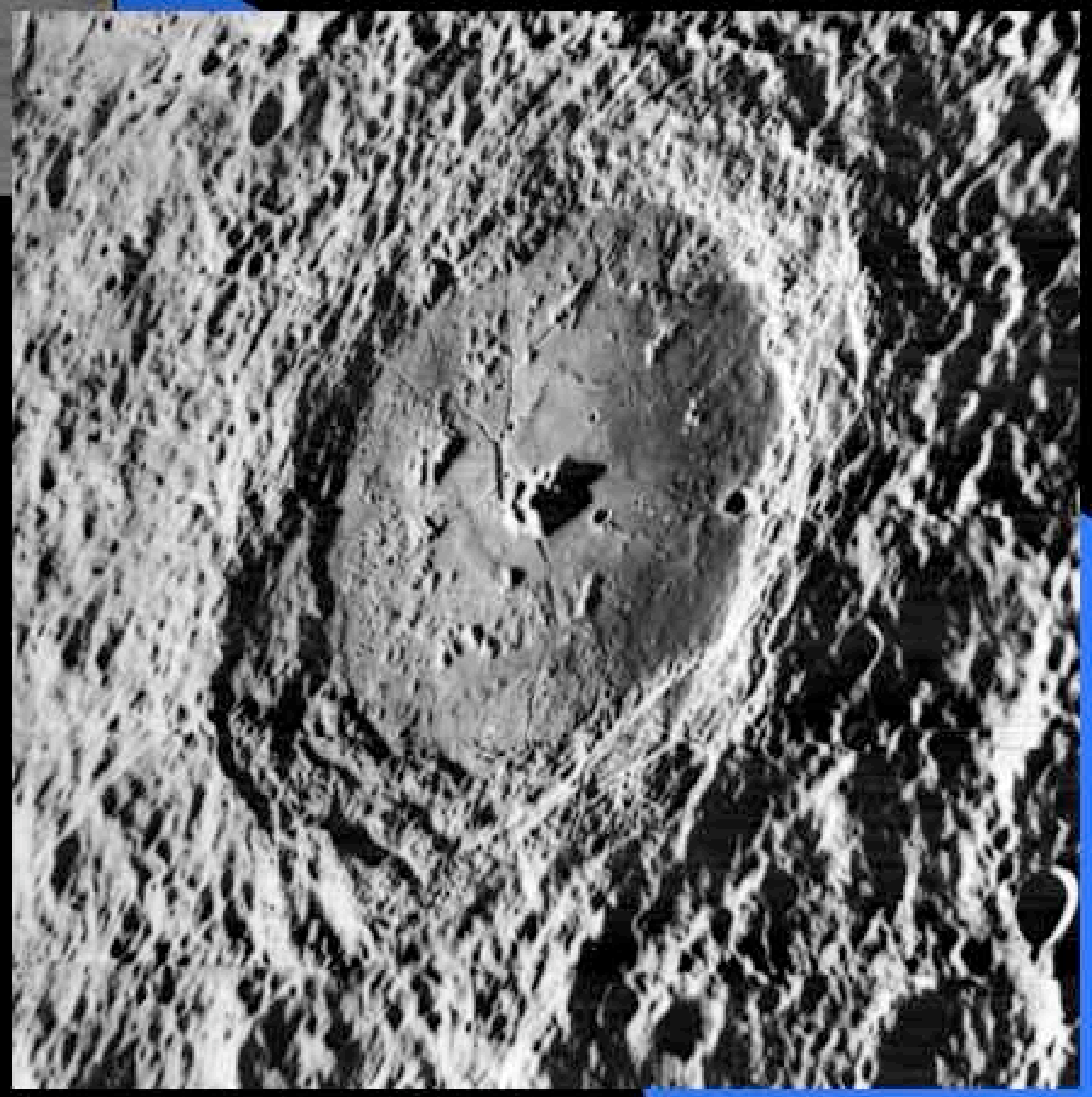
Copernicus D~96 km

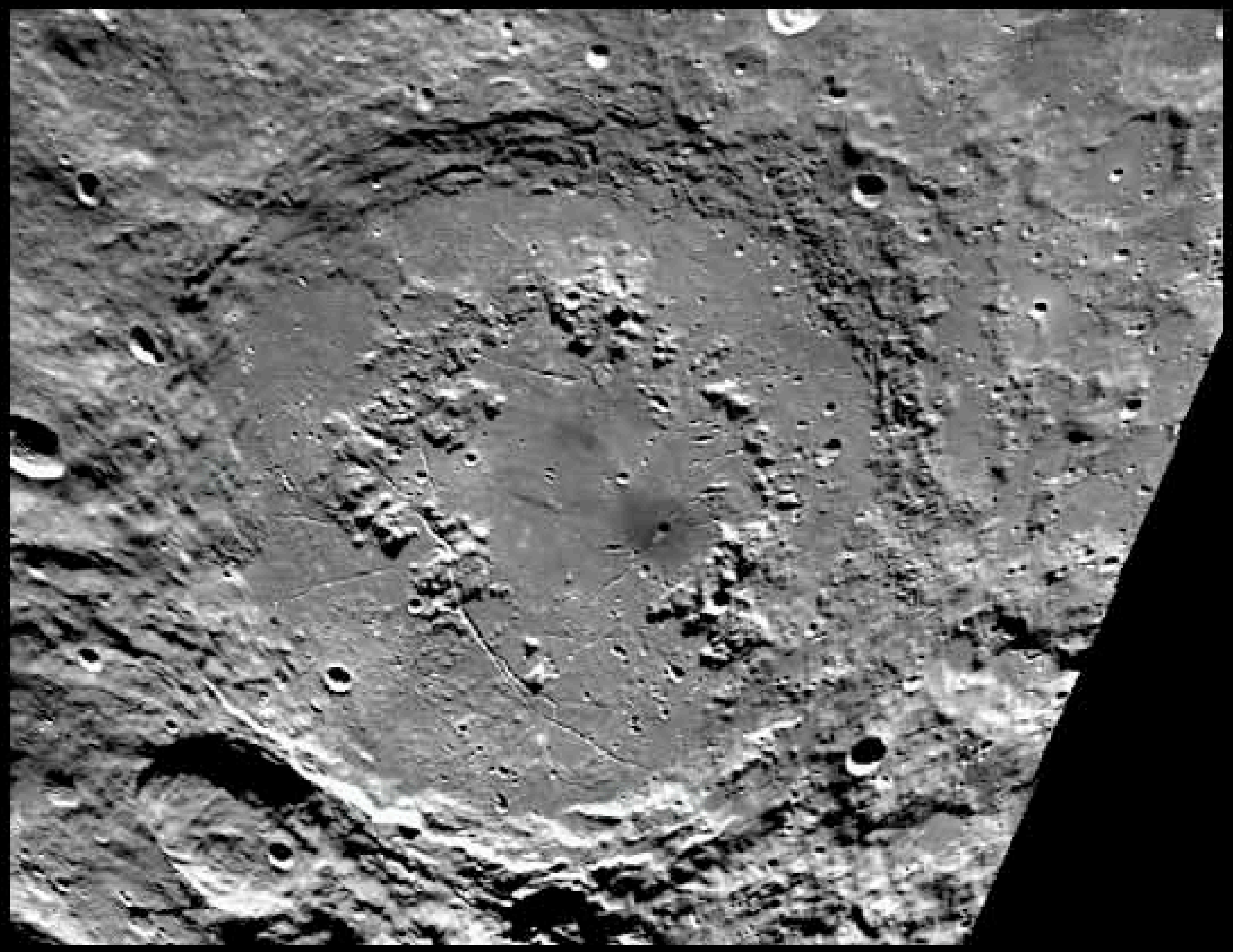
Theophilus D~110 km

# Crater to Basin Transition

- Floor roughening
- Central peak complexes and rings
- Peak rings (Compton)
- Two-ring basins (Schrödinger)
- Ejecta and central peaks

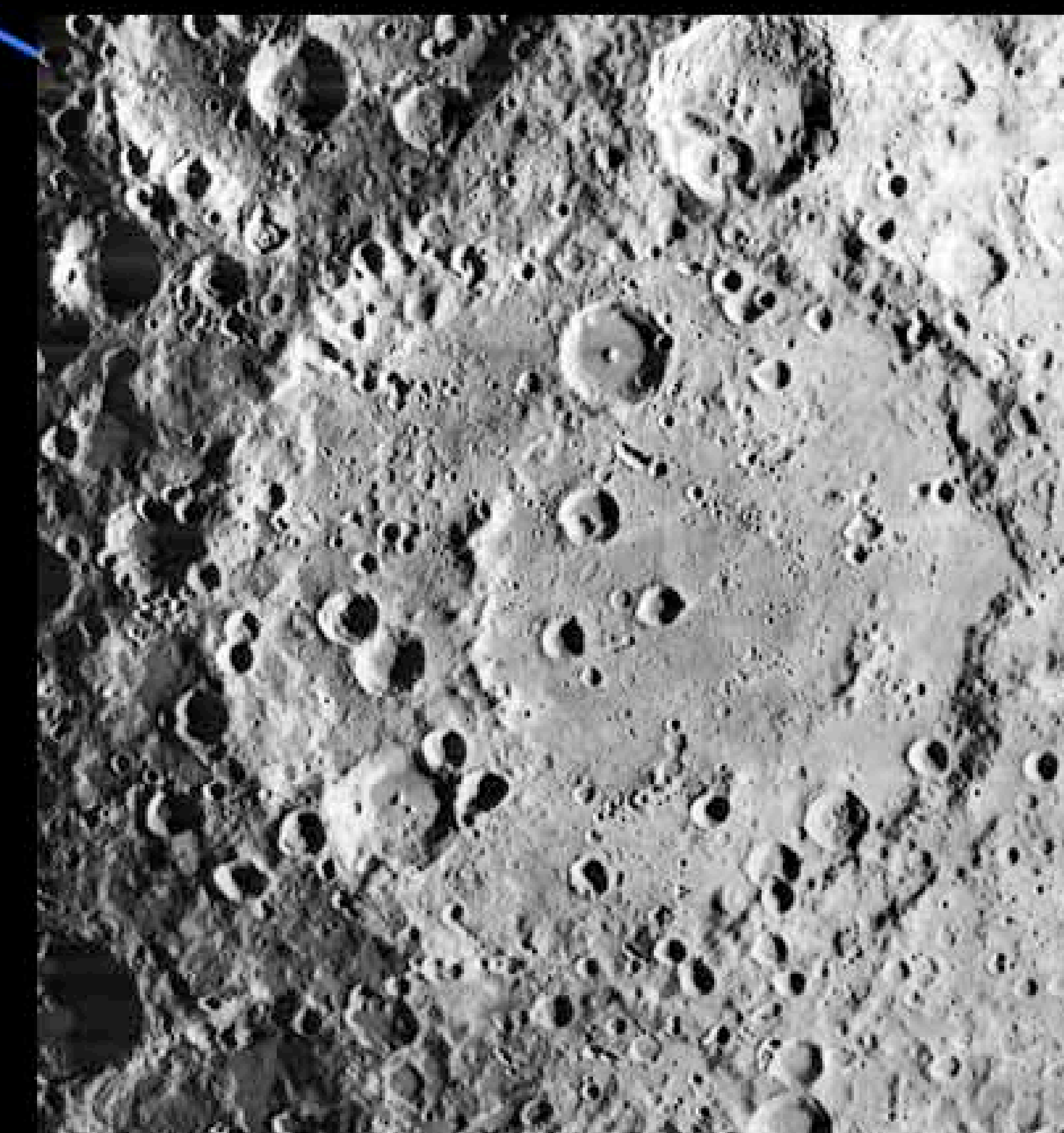

Langrenus ~127 km


Compton ~162 km

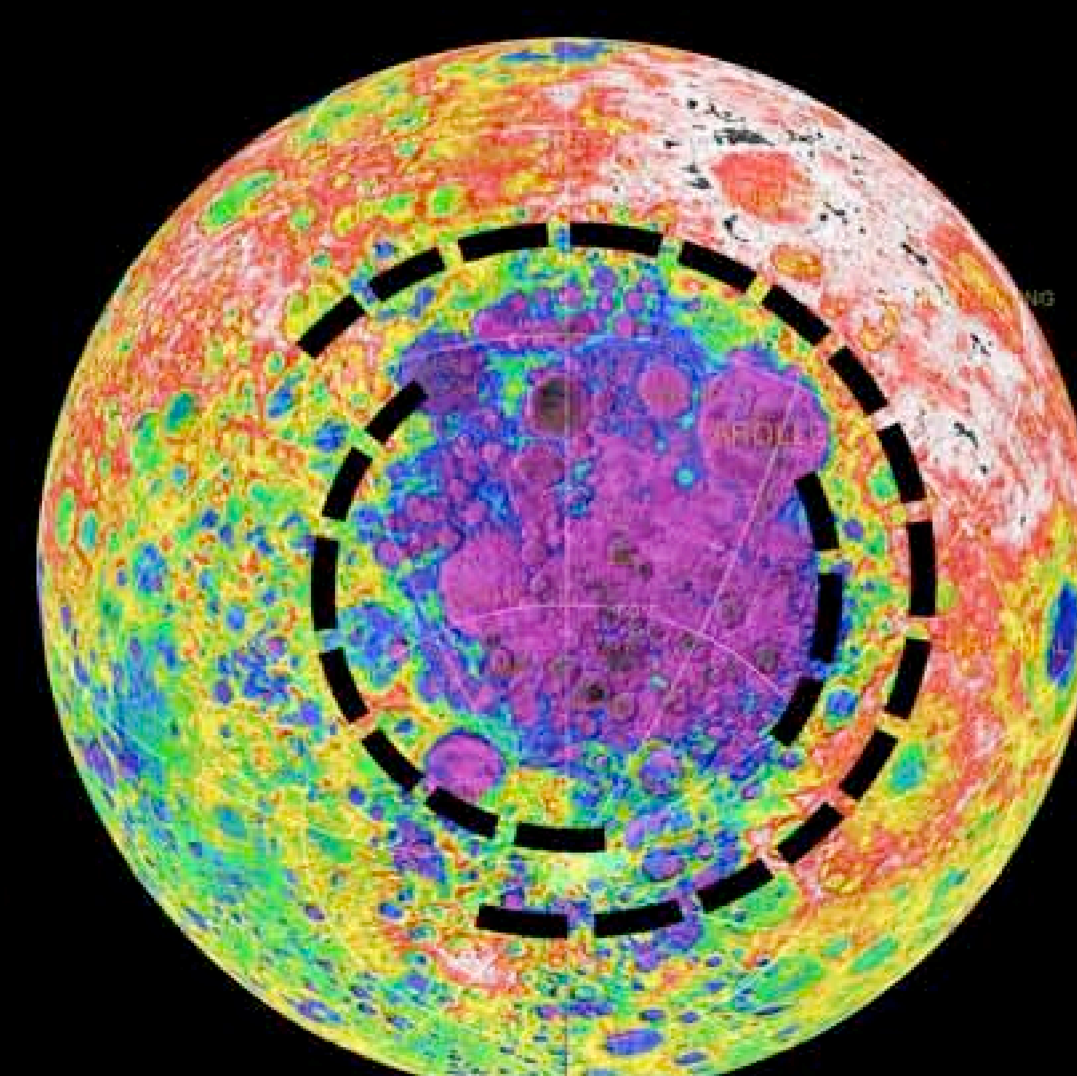

Schrödinger ~320 km

# Multi-ring Basins

- Two-ring basins; massifs appear between inner ring and rim
- True MR basins: Orientale
- Older MR basins: mapping ancient rings
- Largest basins: SPA



Korolev ~440 km

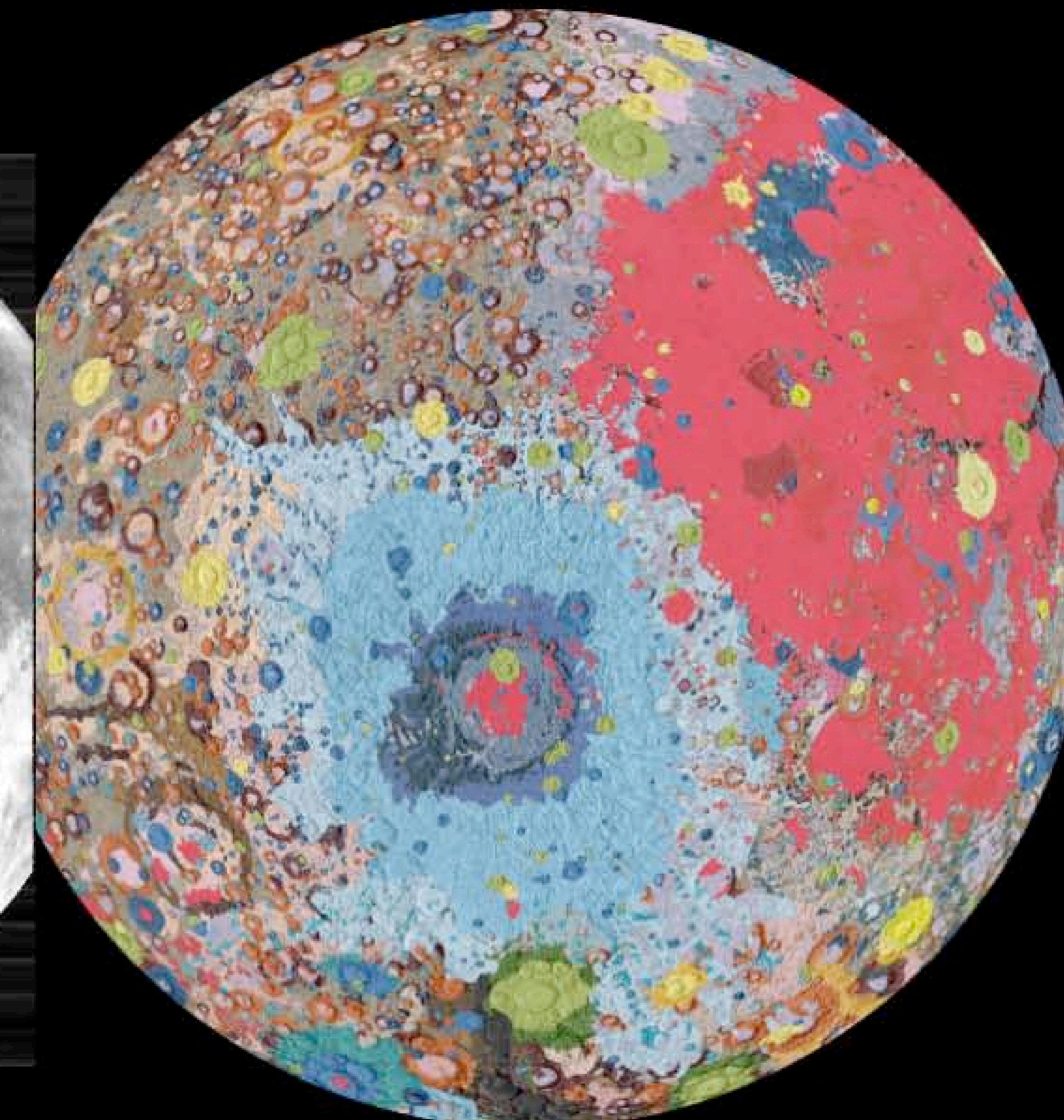


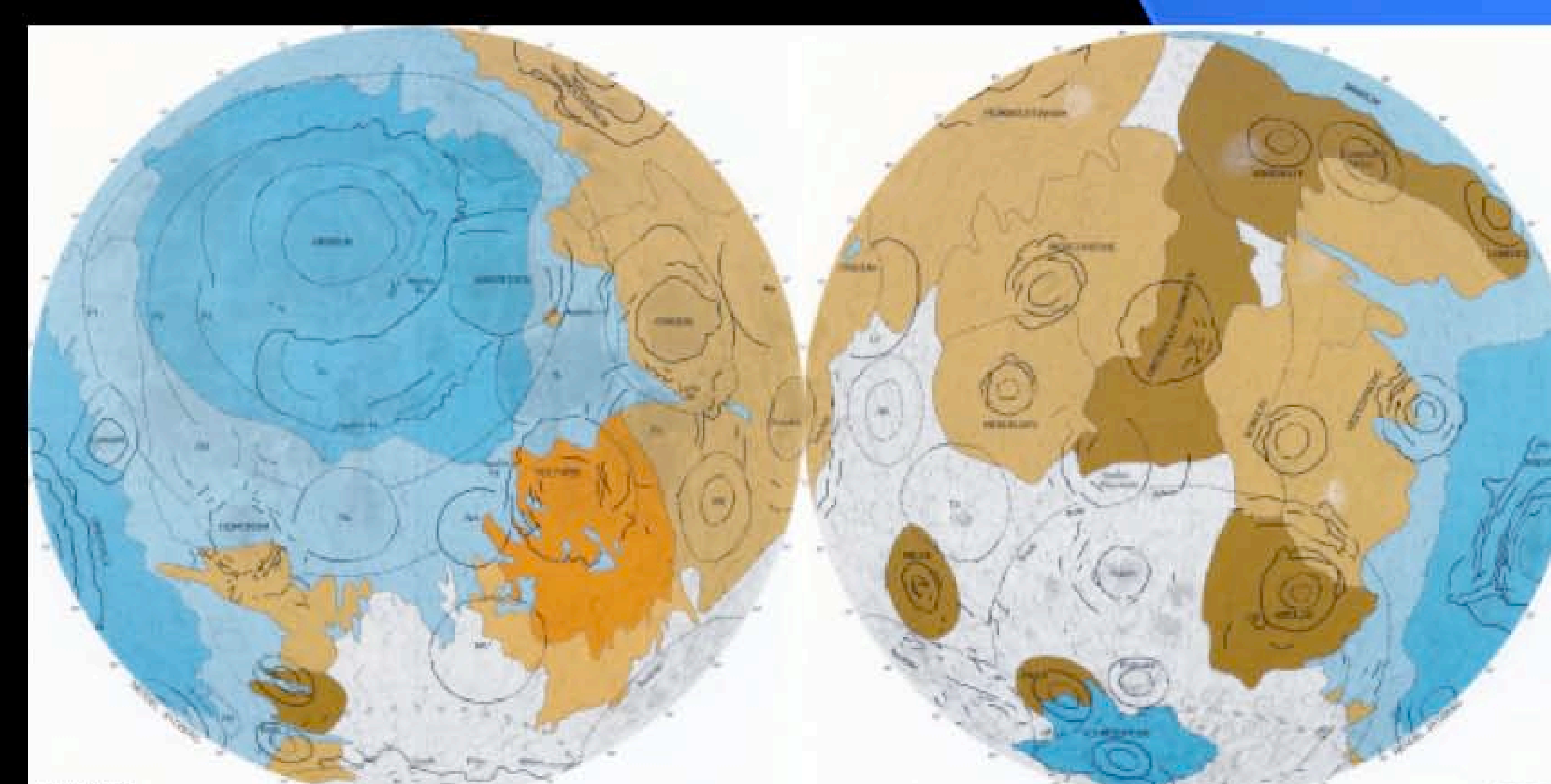
South Pole-Aitken ~2600 km

Orientale ~920 km

# Multi-ring Basin Geology

- Impact melt sheet
- Continuous Ejecta facies
- Secondary craters
- Basin ejecta asymmetry and "rays"
- Local mixing; Cayley plains
- Antipodal ejecta and deposits





# Apollo sites and Basins

Apollo 14 (#2) Imbrium

- Fra Mauro Fm., continuous ejecta

Apollo 15 (#3) Imbrium

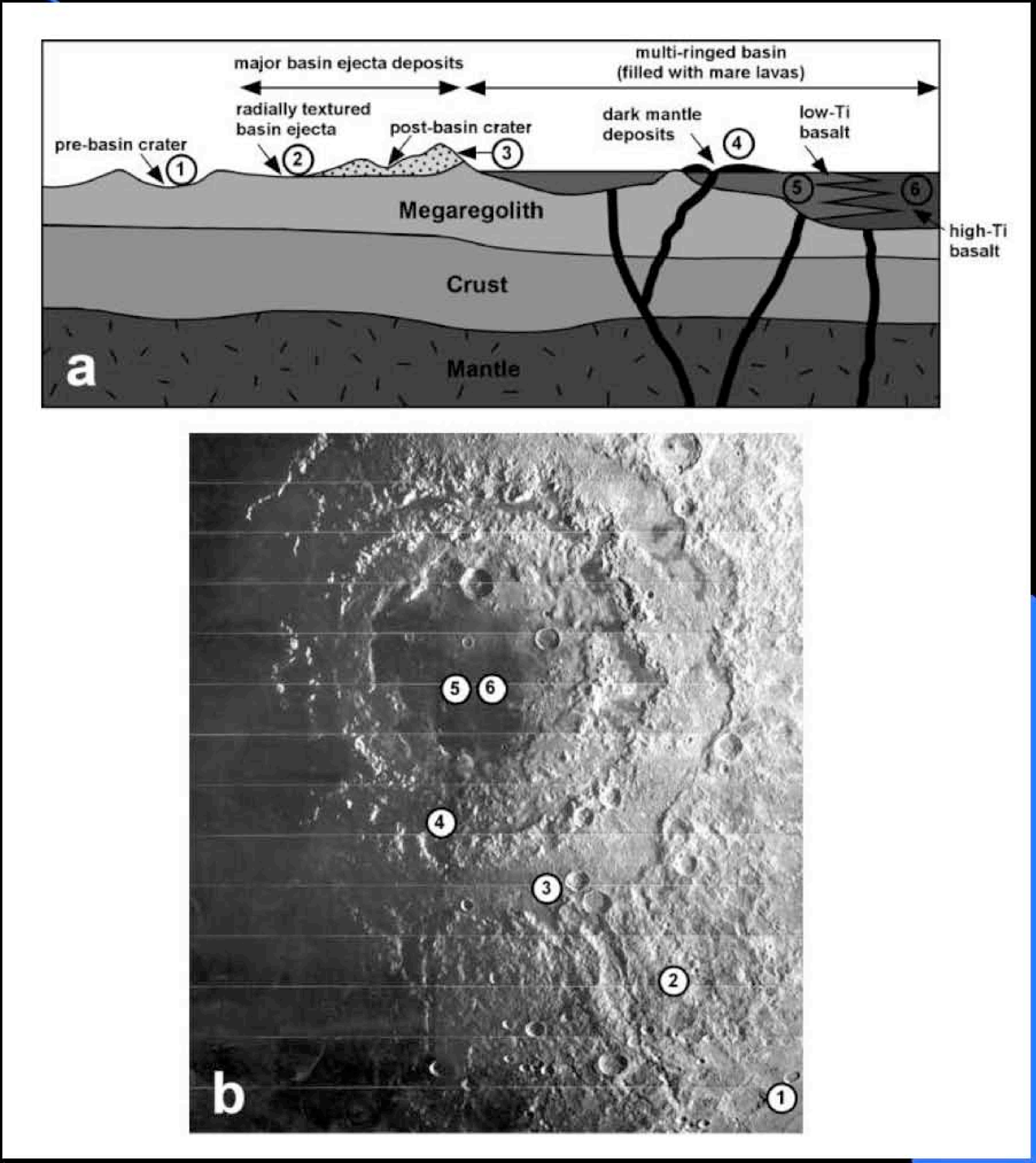
- Apenninus material; continuous deposits plus pre-Imbrium bedrock?

Apollo 16 (#2) Nectaris, (#1) Imbrium

- Descartes material (continuous Nectaris deposits); Cayley plains (Imbrium distal deposits)

Apollo 17 (#4) Serenitatis

- Taurus Massifs (Serenitatis ring); Imbrium distal (Sculptured Hills?)



# Off the main sequence

## Oddball craters

**Crater chains**

- Secondary impacts
- Simultaneous impacts

**'Delta-rim" craters**

- Not clearly impact; volcanic?

**Crater clusters**

- Crater and basin secondaries

**Irregular features**

- Volcanic vent craters

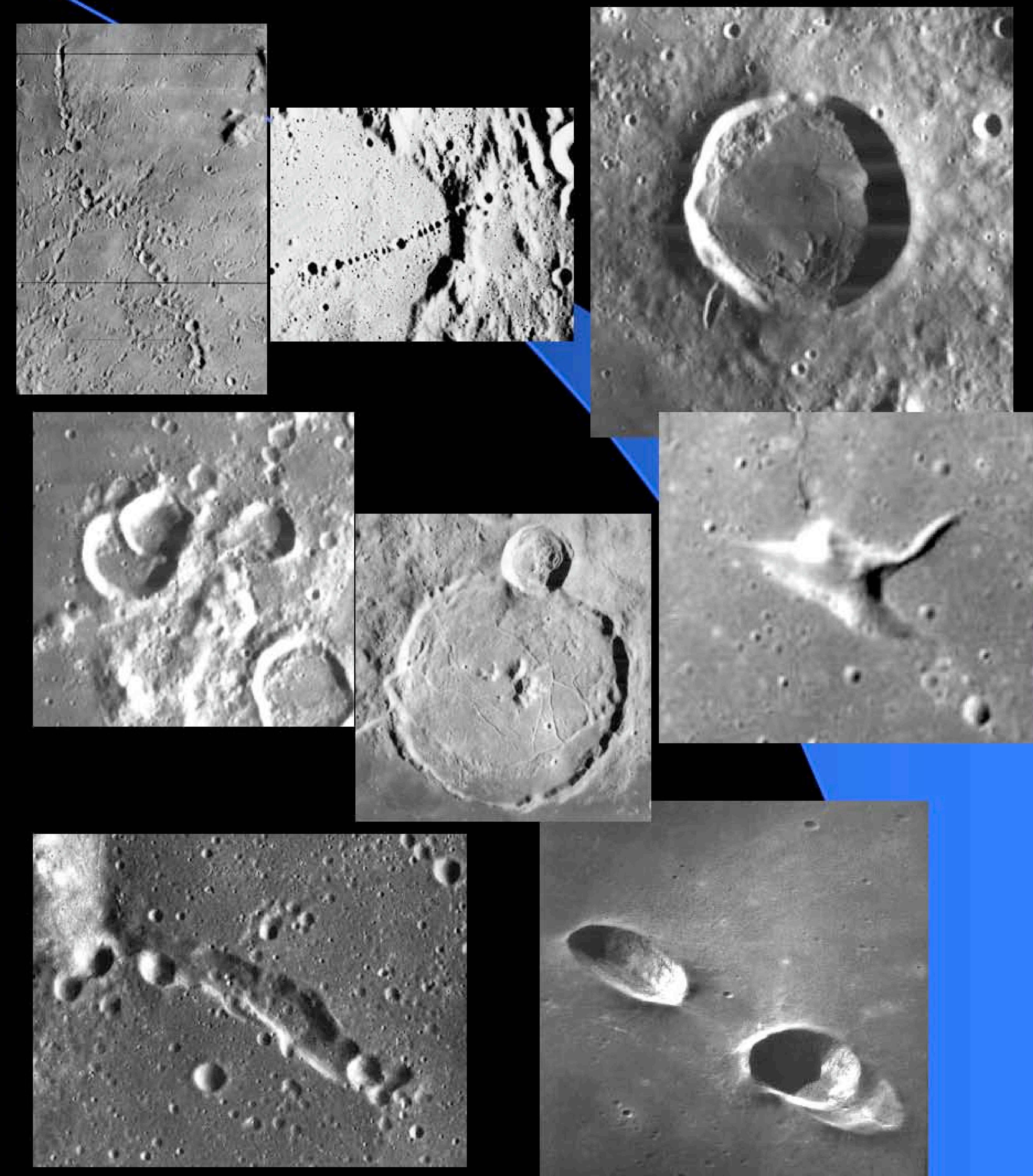
**Floor-fractured craters**

**Rimless pits**

- Collapse craters

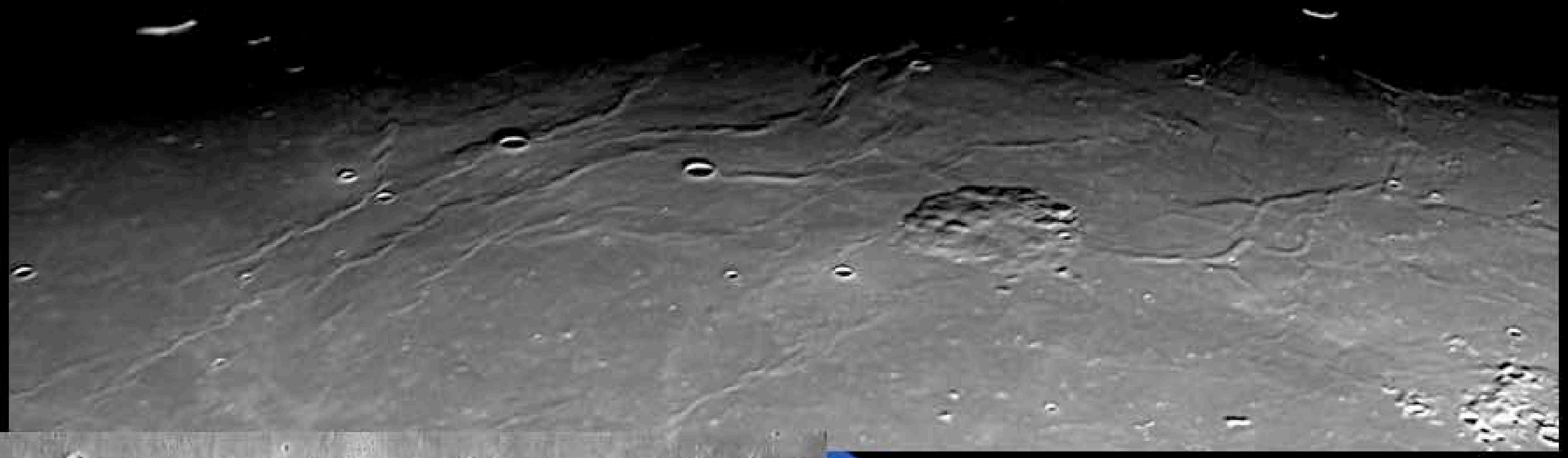
**Elliptical craters**

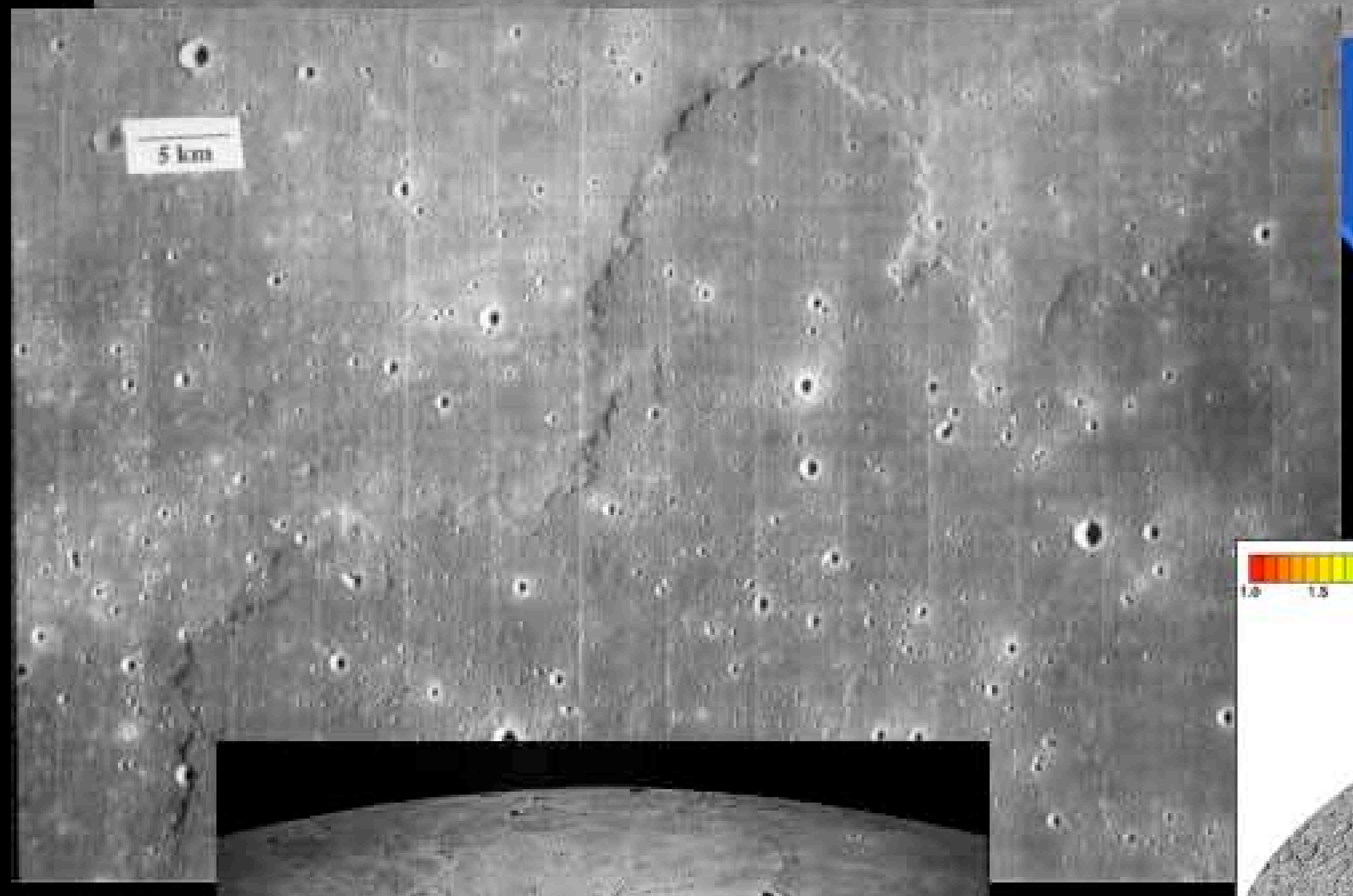
- Oblique impact features

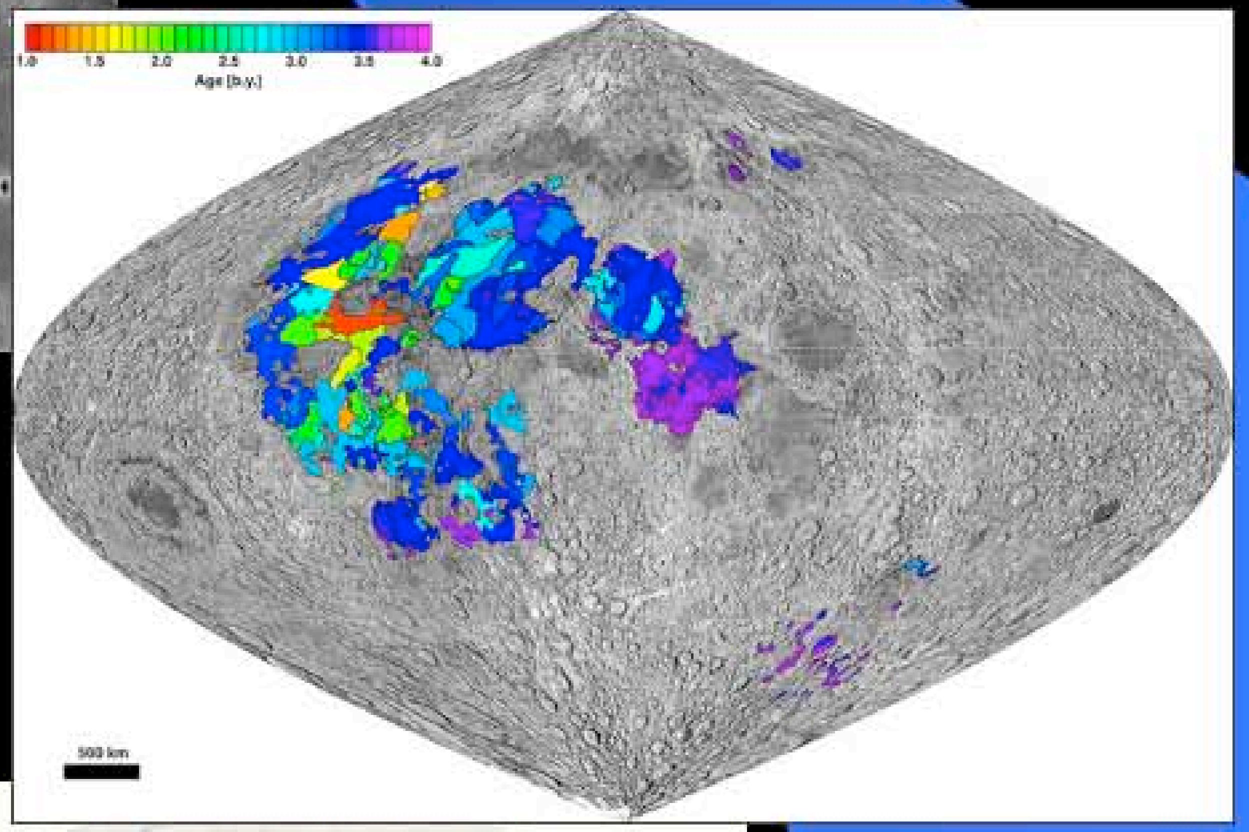


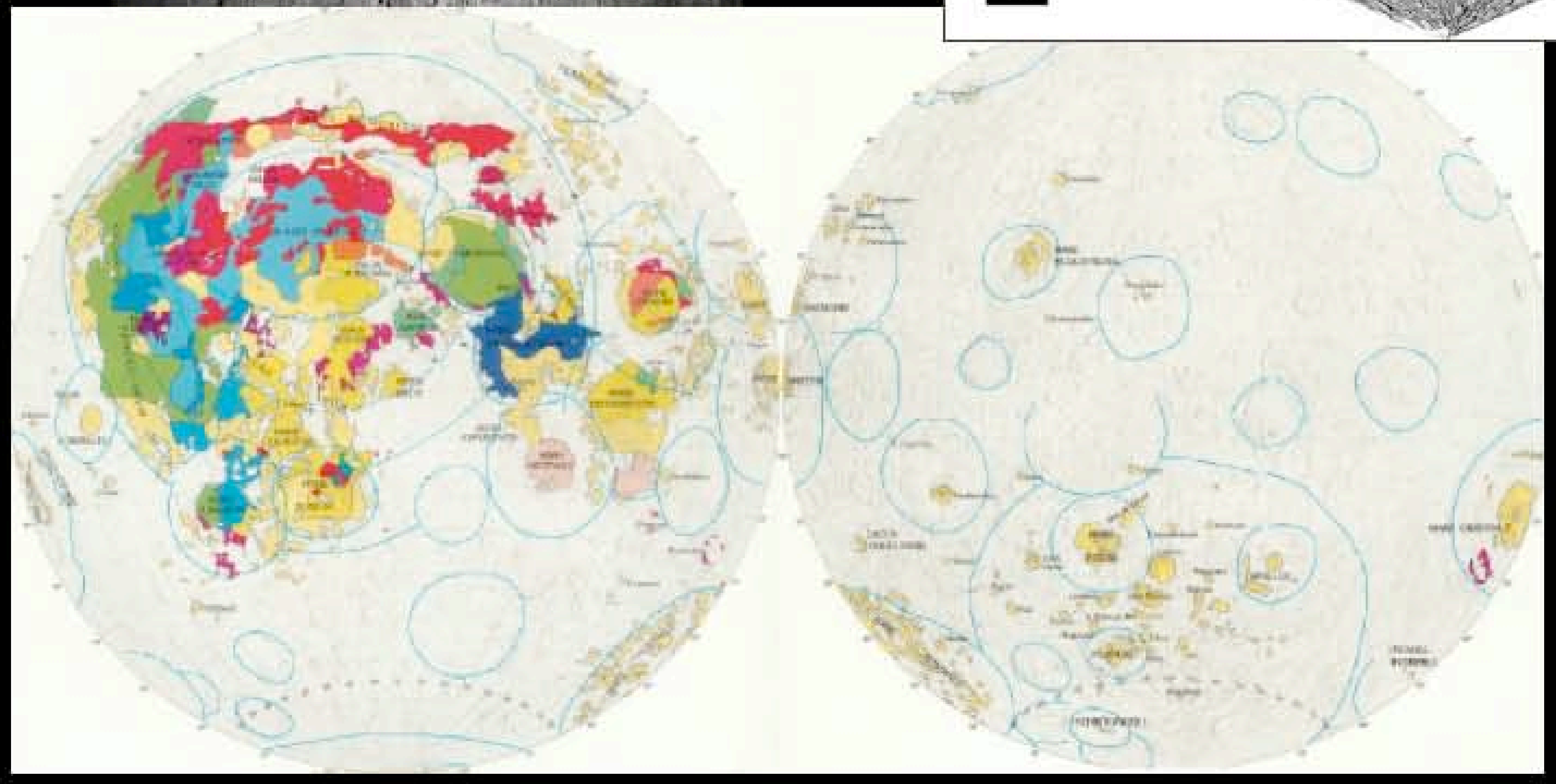
# Maria

- Dark, smooth plains
- Concentrated on near side
- Flood lavas; central vent volcanism minor
- Individual flows may be hundreds km long, tens of m thick
- Most maria relatively thin (< 100 m)
- Sinuous rilles - lava channels/tubes
- Pyroclastic (dark mantling) deposits; lunar ash







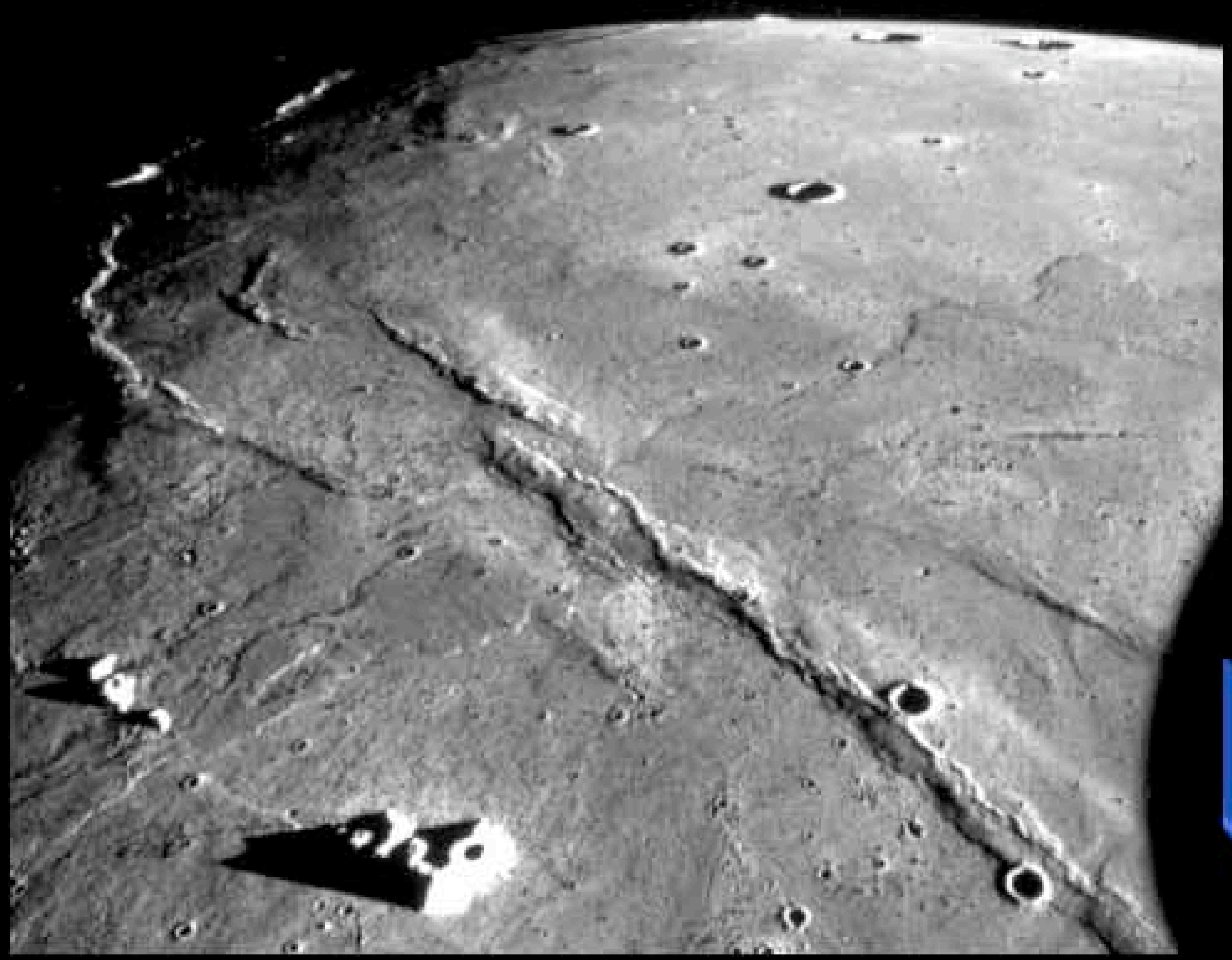
# Types of Mare Volcanism

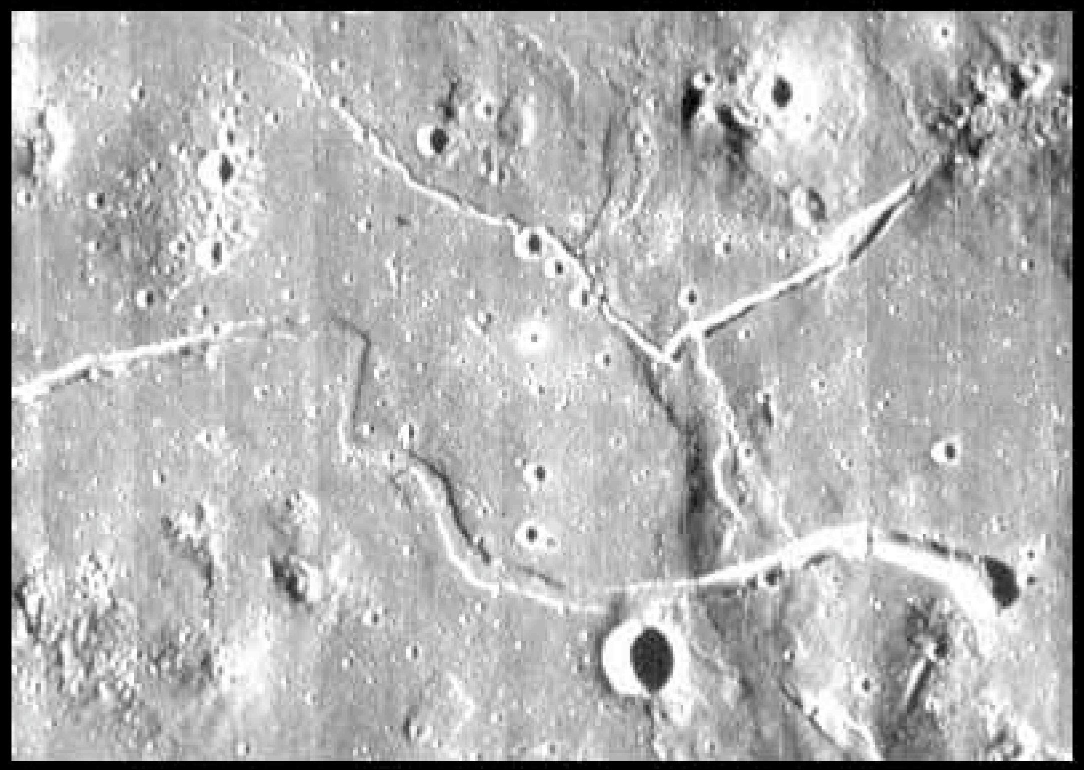
**Basaltic lava effusions**

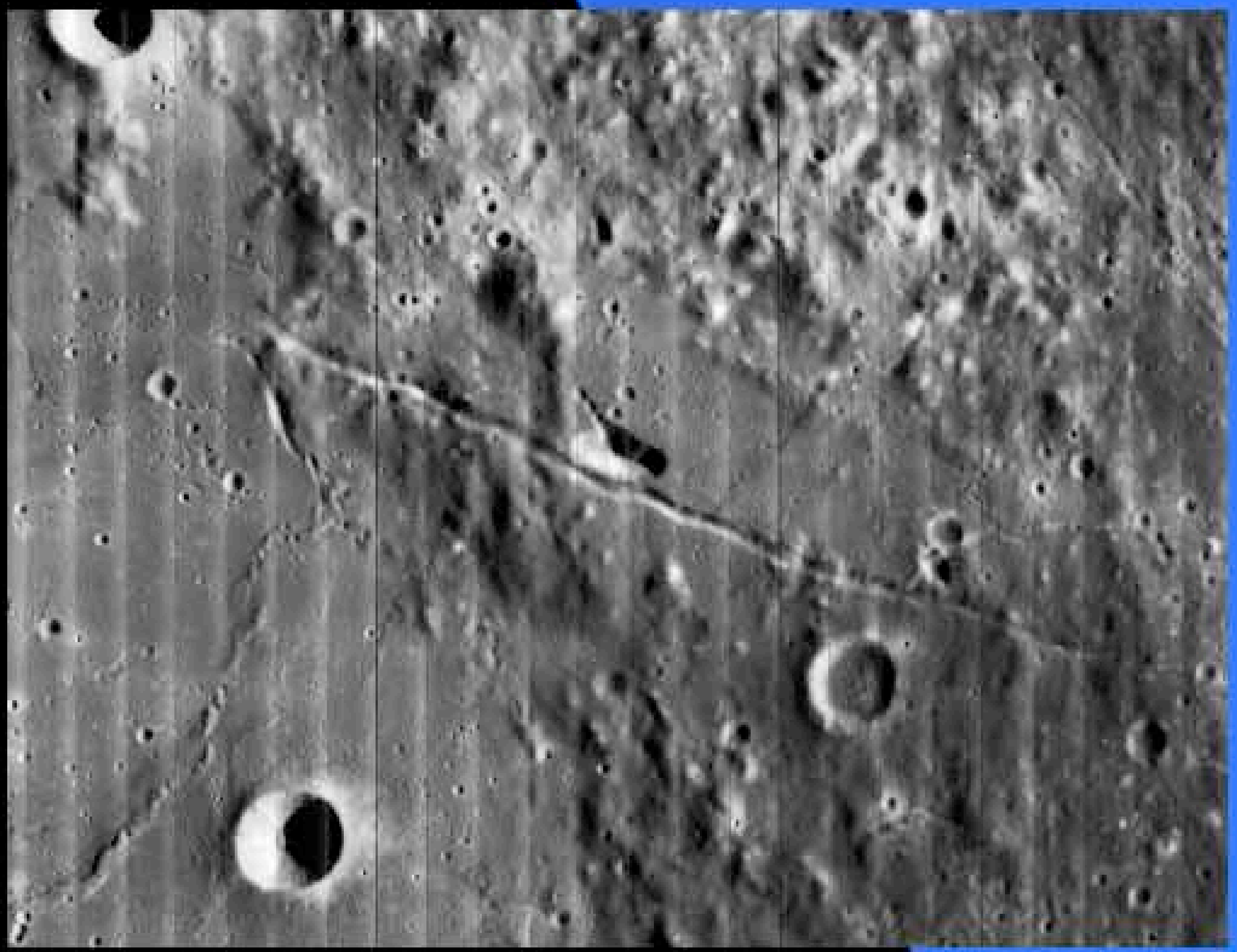
- Flood lava eruptions
- Central vent volcanoes
- Sinuous rilles (lava channels and tubes)

**Pyroclastic eruptions**

- Regional ash blankets
- Dark halo craters (vents)



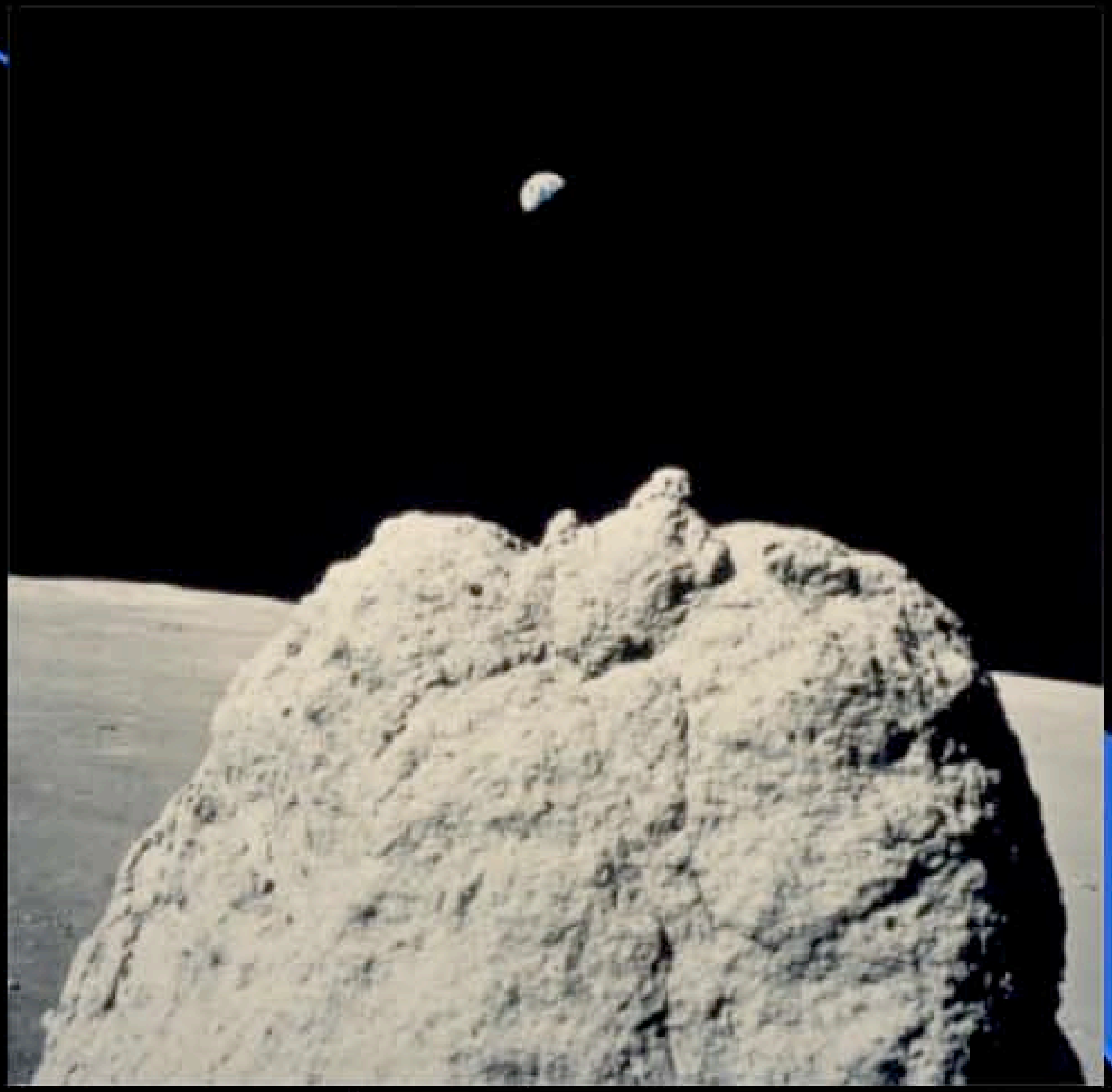


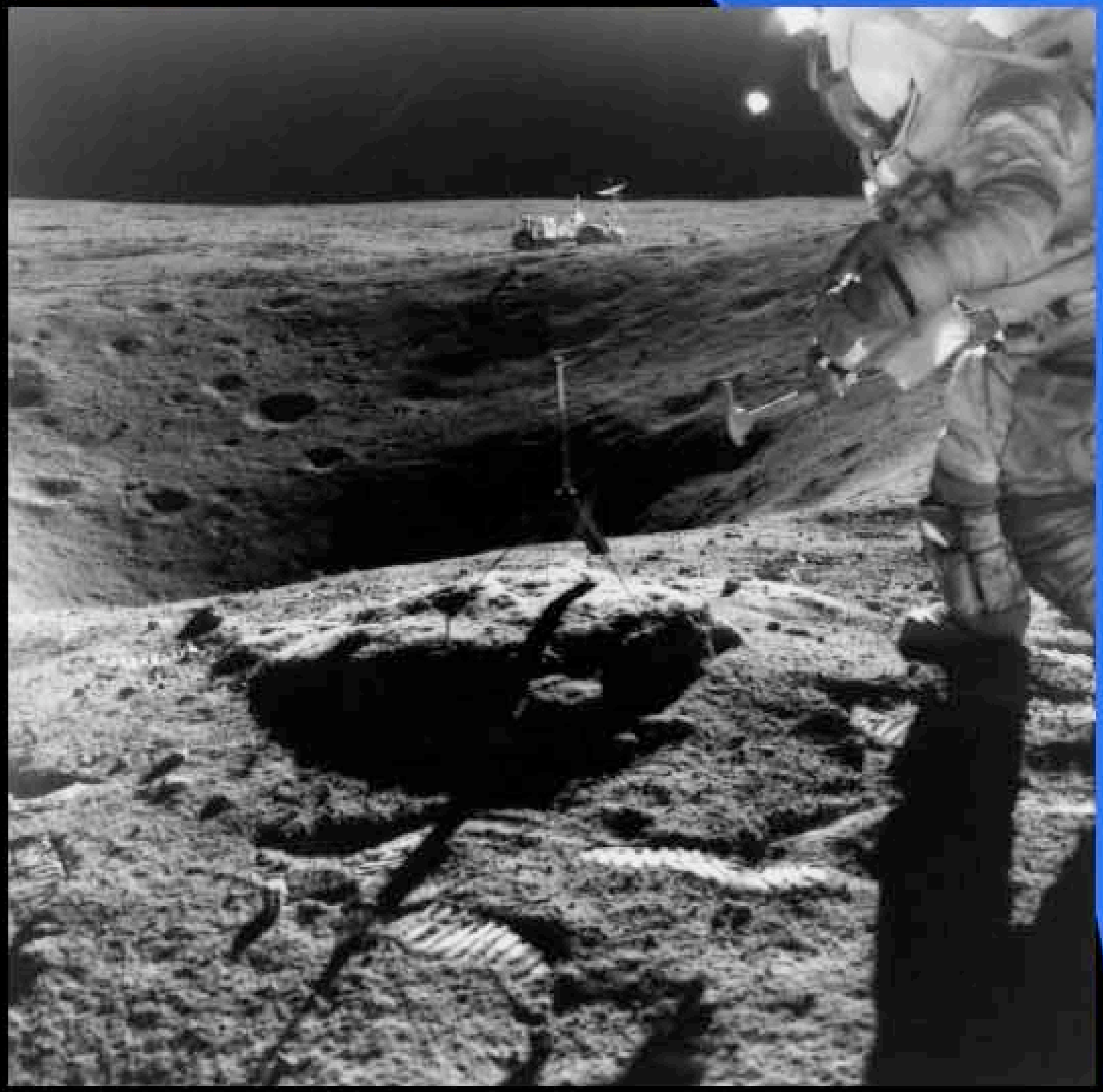


# Geology

**Describes processes and history of solid rocky bodies**

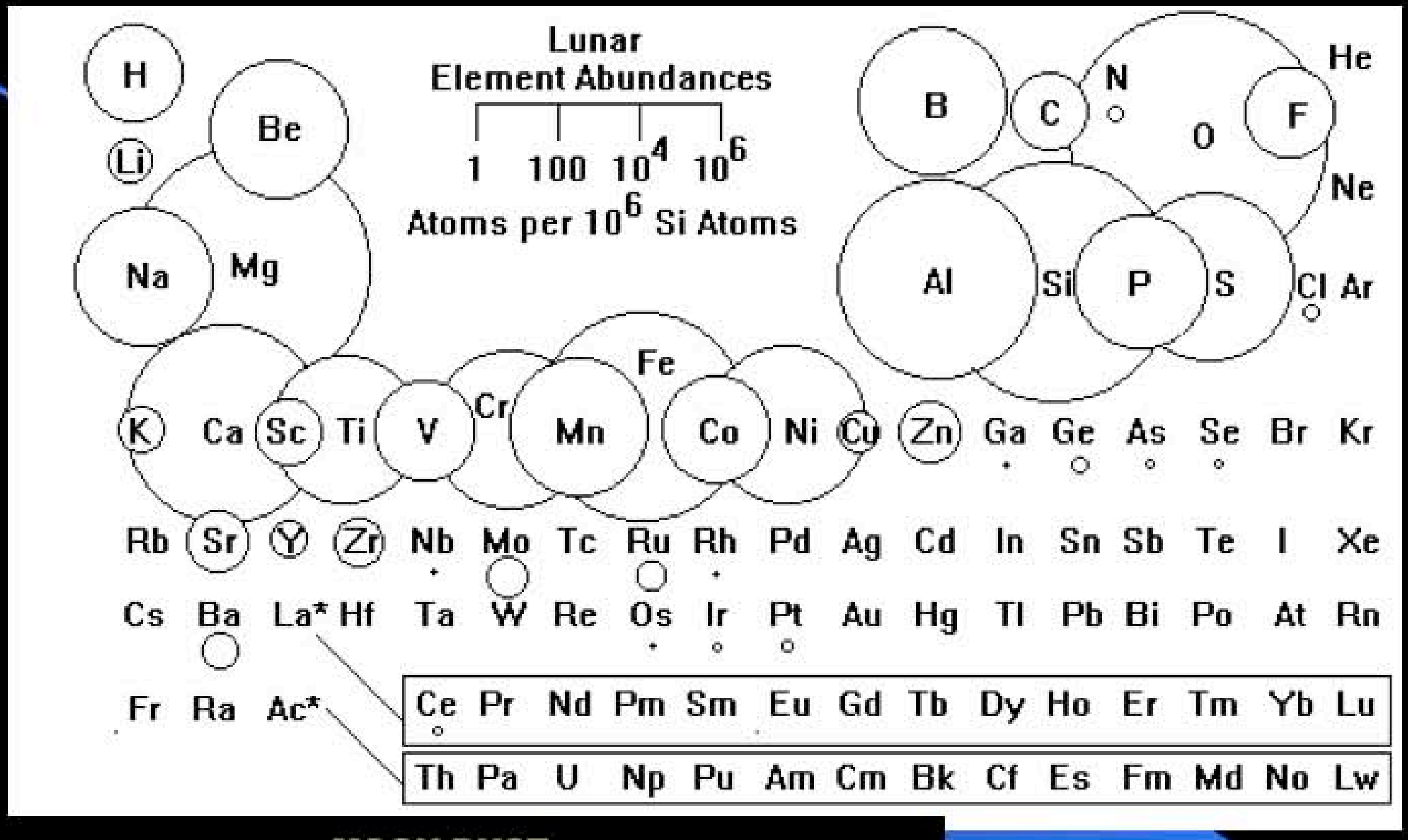
- Geochemistry - elemental composition of the Moon and its materials
- Mineralogy/Petrology - minerals and rocks that make up the Moon
- Structural geology - mechanical deformation of the outer portion of the Moon
- Geophysics - properties and state of the Moon's interior
- Stratigraphy - sequence of rock units and their history

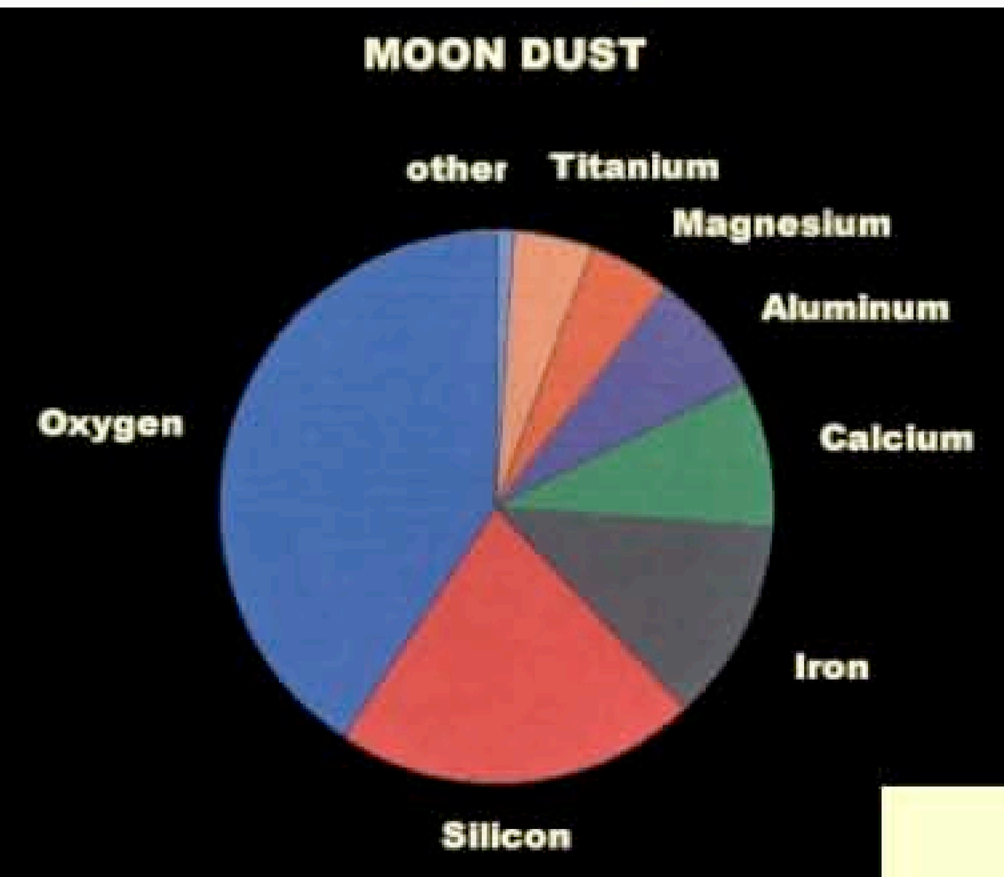


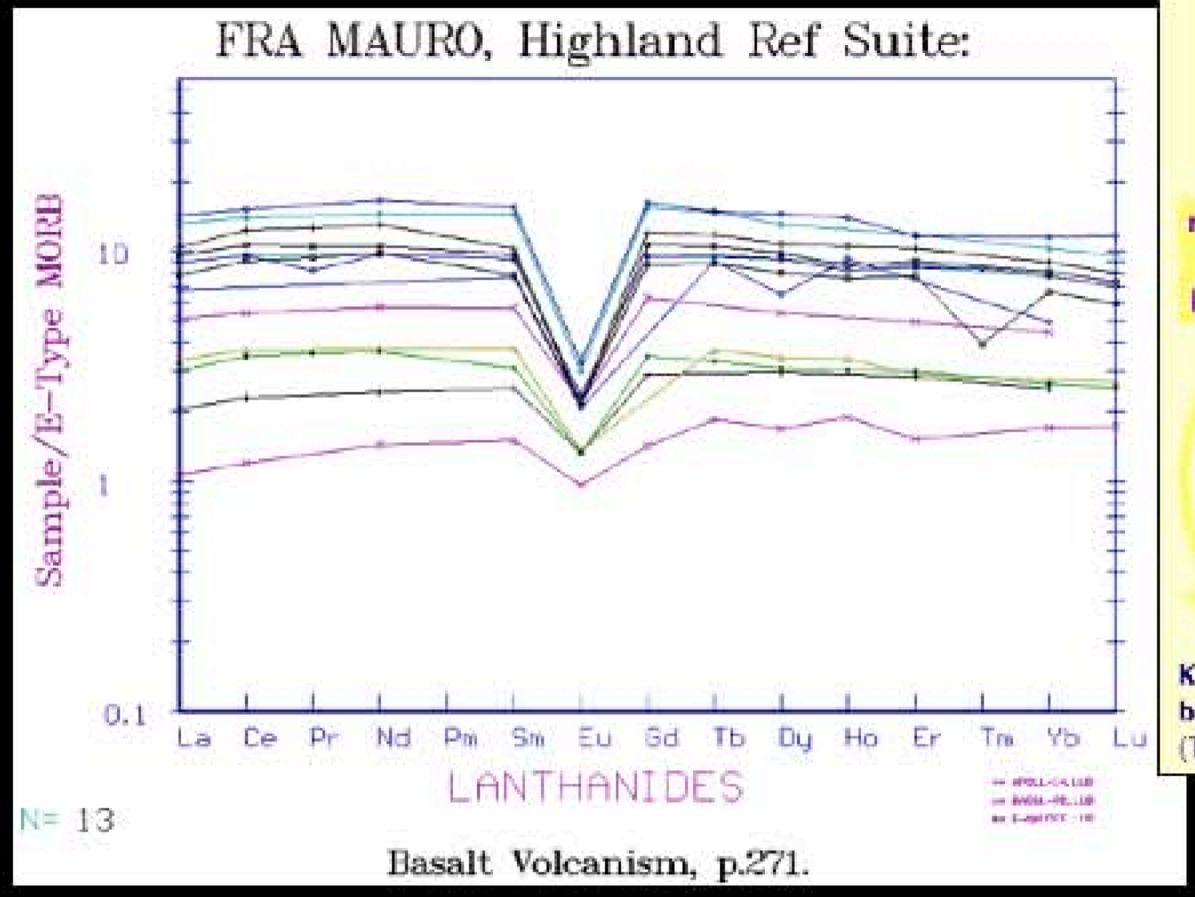


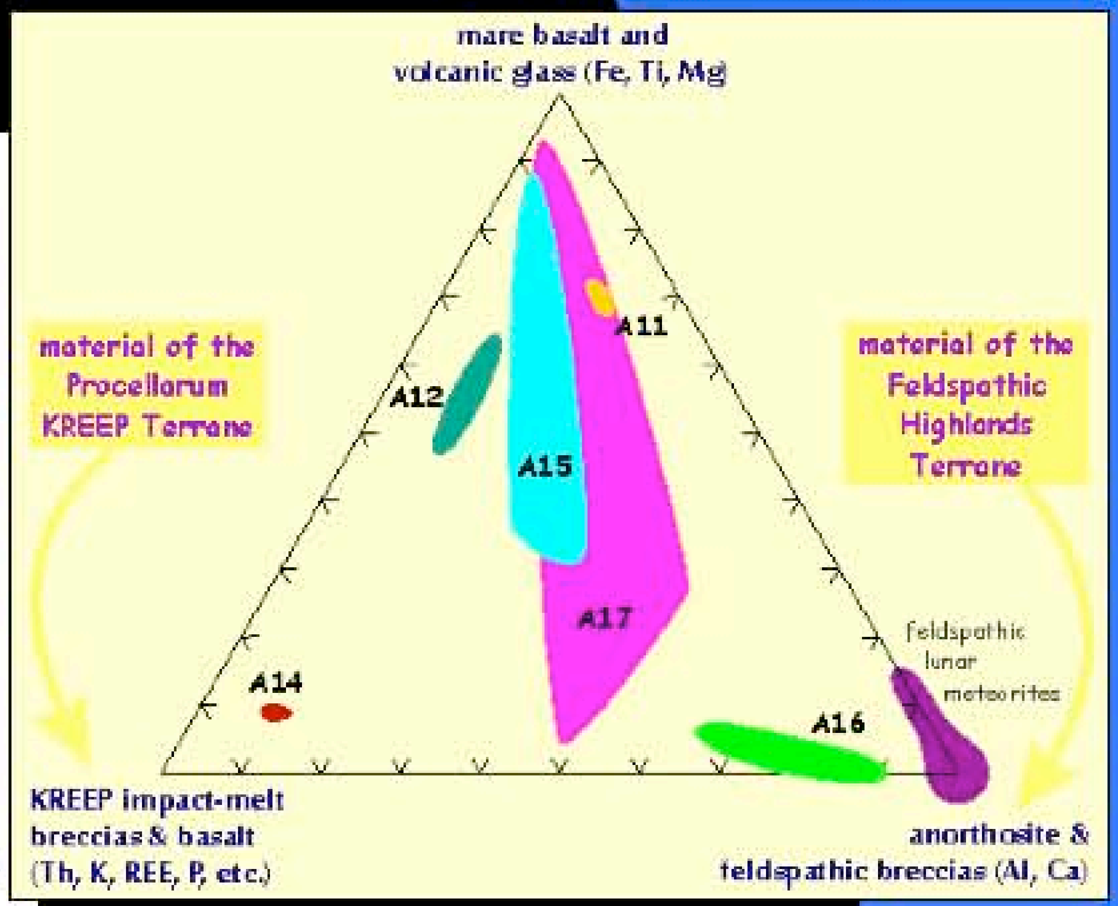
# Geochemistry

- Depleted in volatile and light elements (e.g., H, N, C)
- Enriched in refractory elements (e.g., Al, Ca, Ti)
- Depleted in iron (Fe) compared to bulk Earth (no core)
- Depleted in siderophile (Fe-loving) elements (e.g., Ni, Co)
- Bulk composition similar to *silicate* Earth mantle



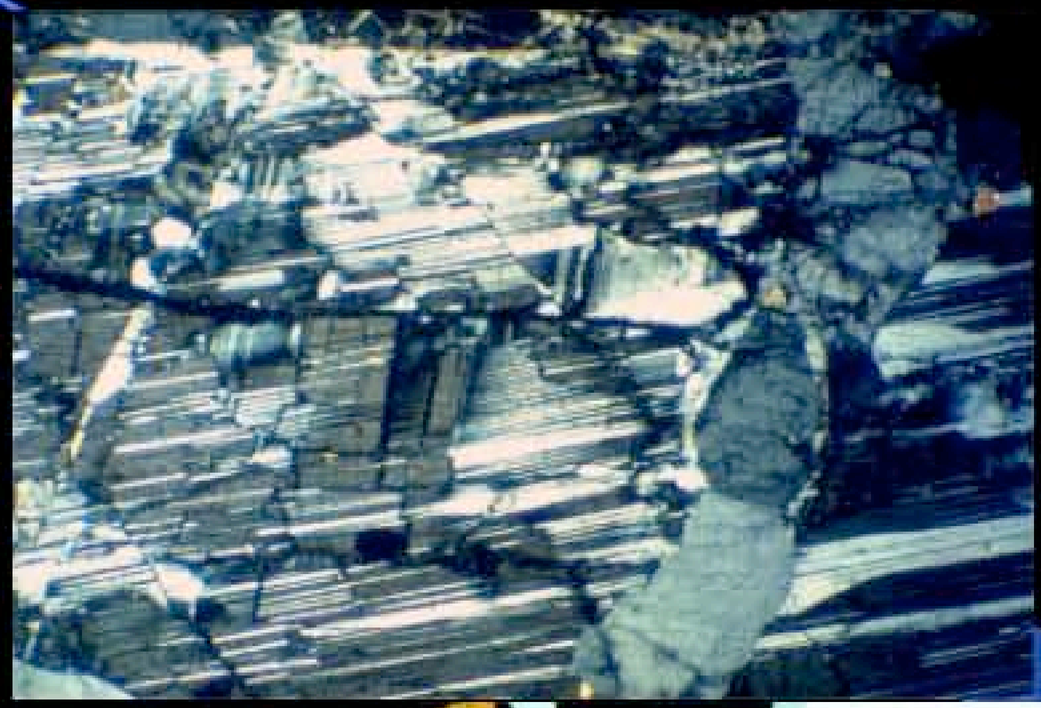



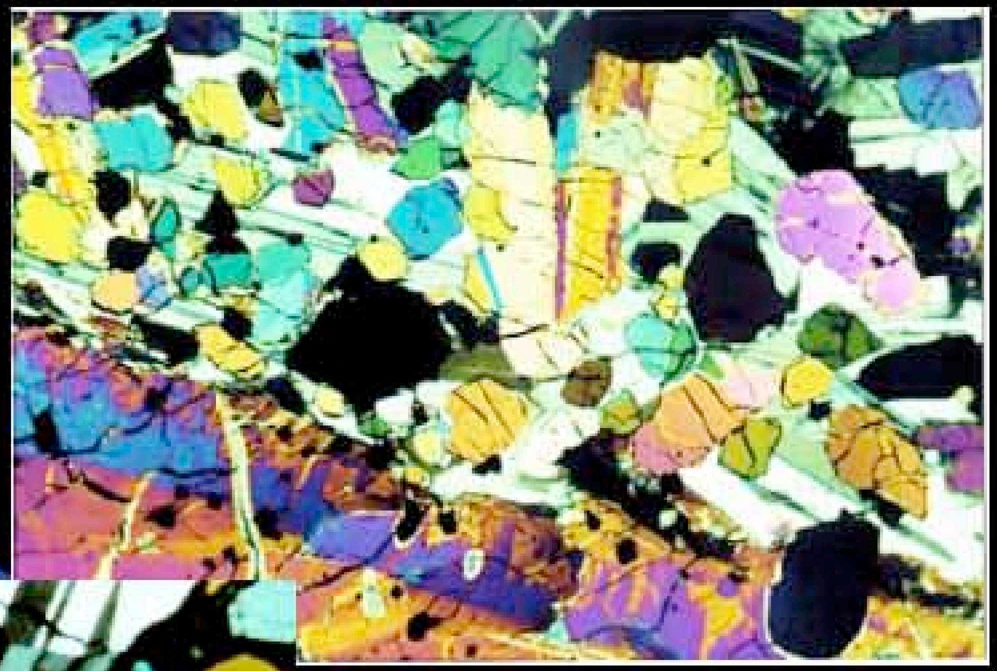



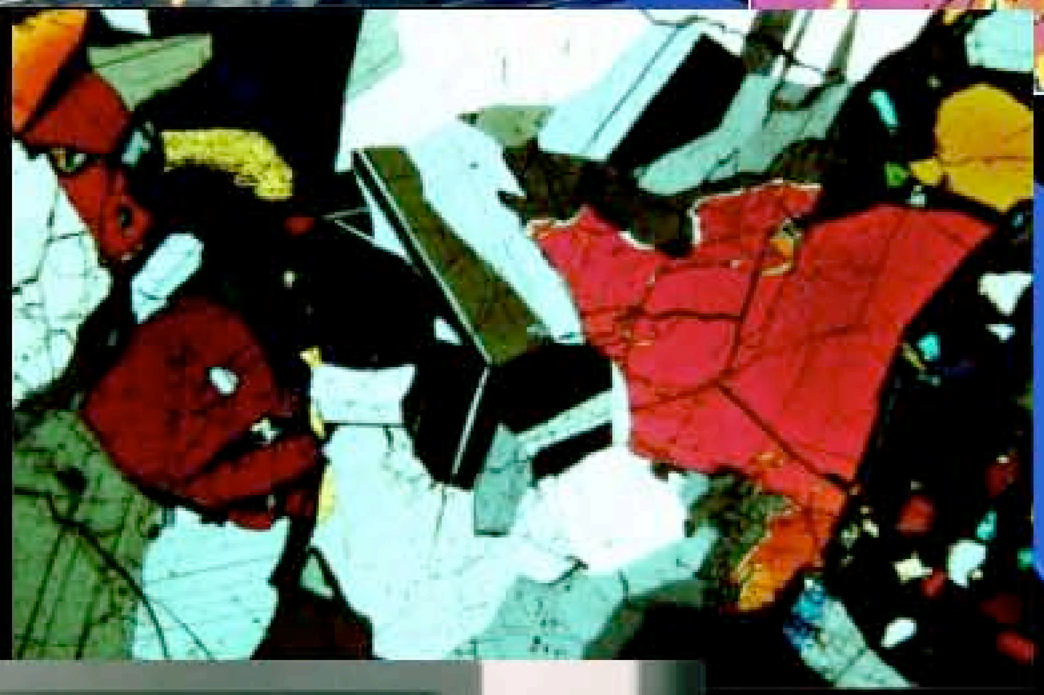
# Mineralogy and Petrology

## Minerals

- Plagioclase (Al, Ca)
- Pyroxene (Mg, Fe)
- Olivine (Mg, Fe)
- Oxides (e.g., ilmenite - Fe/Ti oxide)

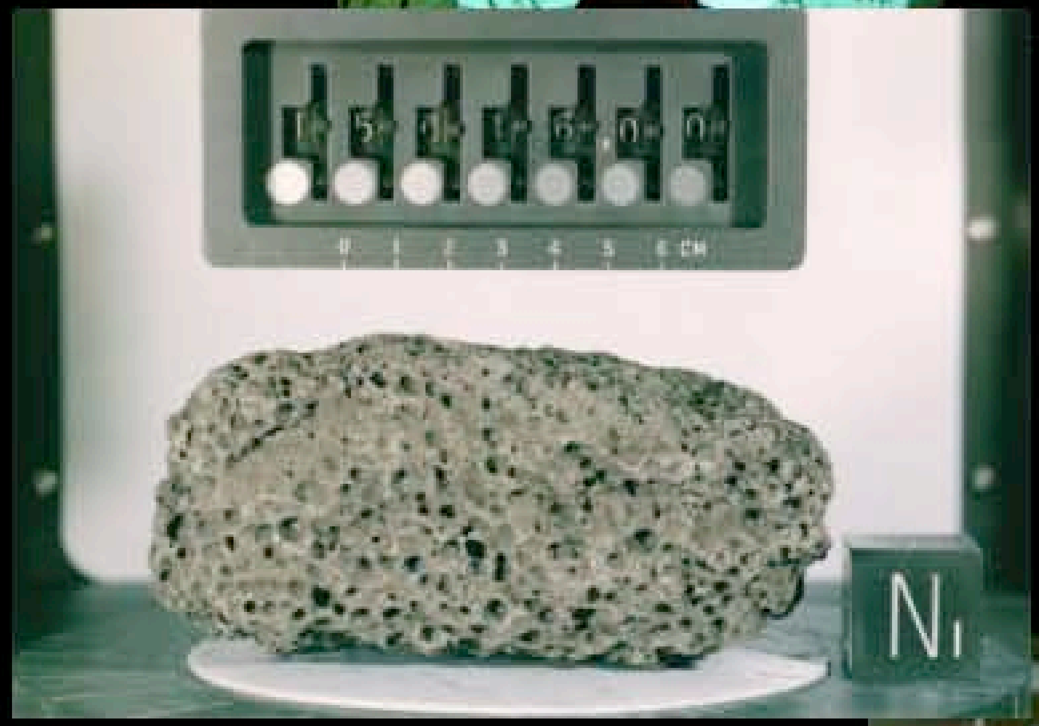


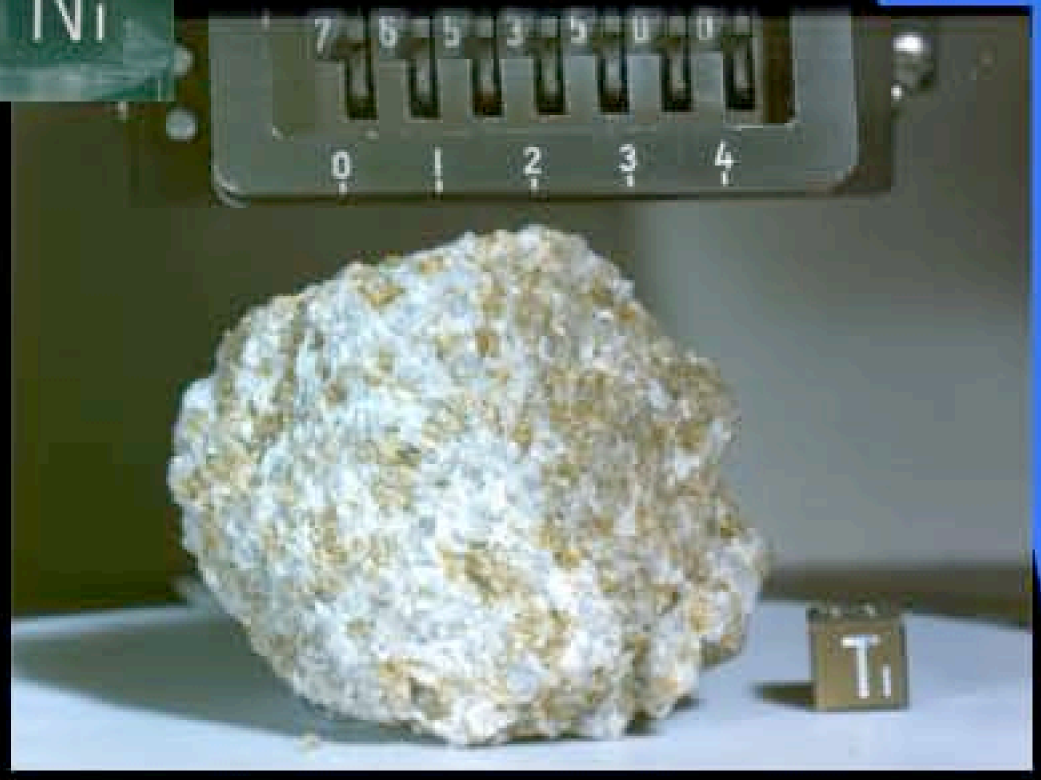




## Petrology

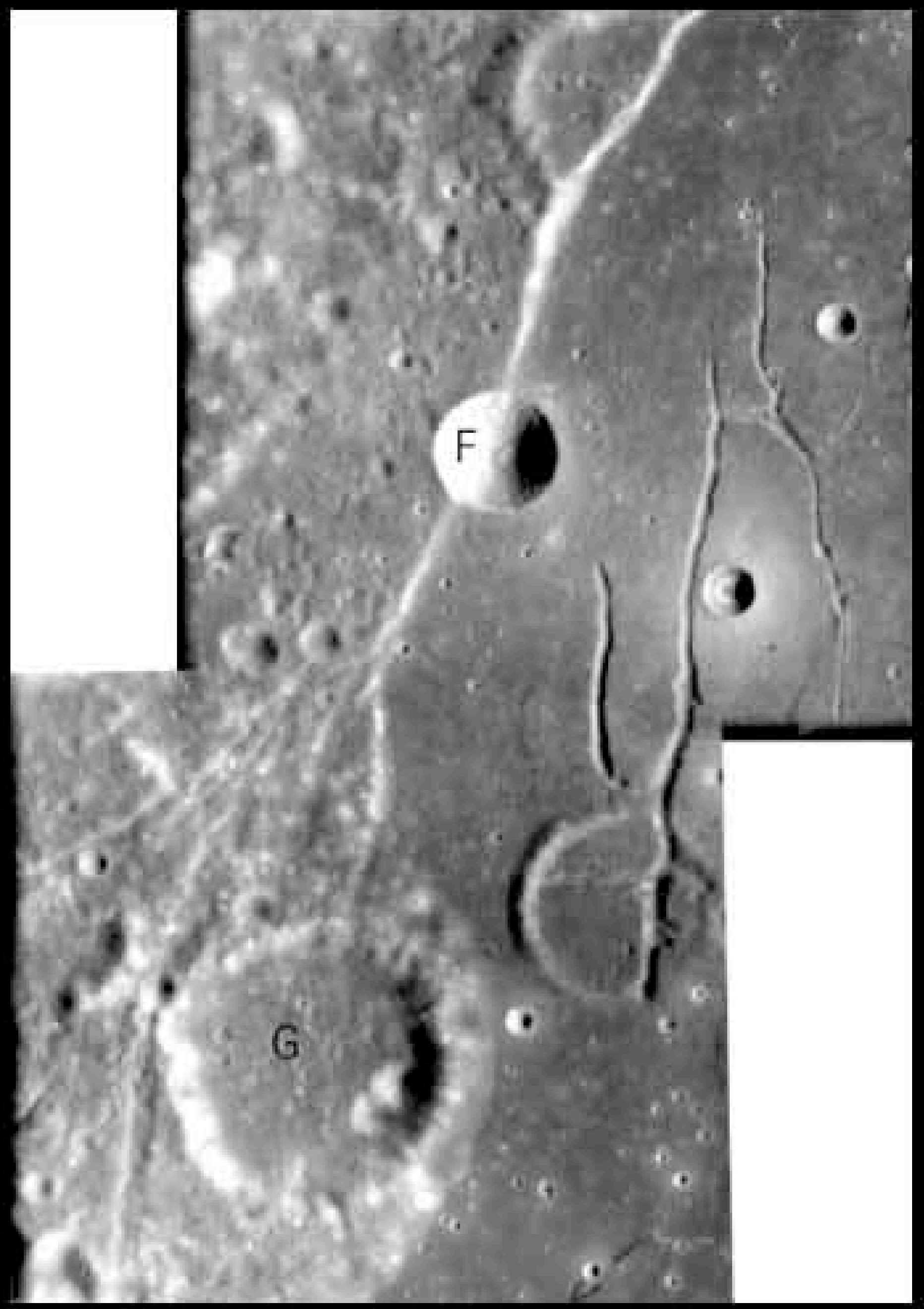
- Maria = basalt (Fe-rich pyroxenes, ilmenite)
- Highlands = anorthositic (Al-rich, plagioclase (up to ~100%); Mg-rich rock types (norite, troctolite)

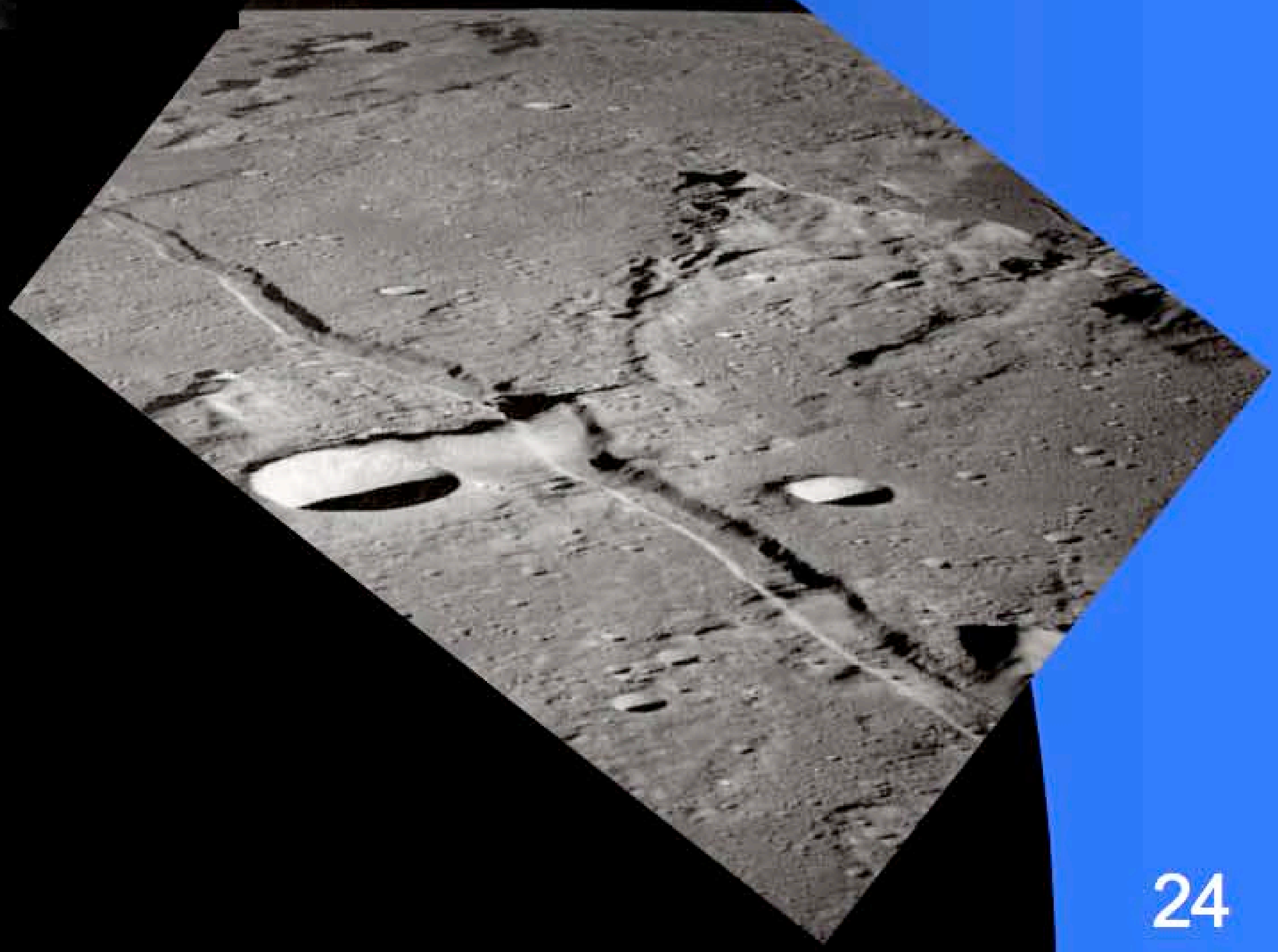




# Structural Geology

- Deformation and failure of crust
- Compression
  - Wrinkle ridges
  - Highland scarps
- Extension
  - Normal faults and graben
- No strike-slip faults seen on Moon



# Geophysics

Inferring the nature of the lunar interior

**Crust**

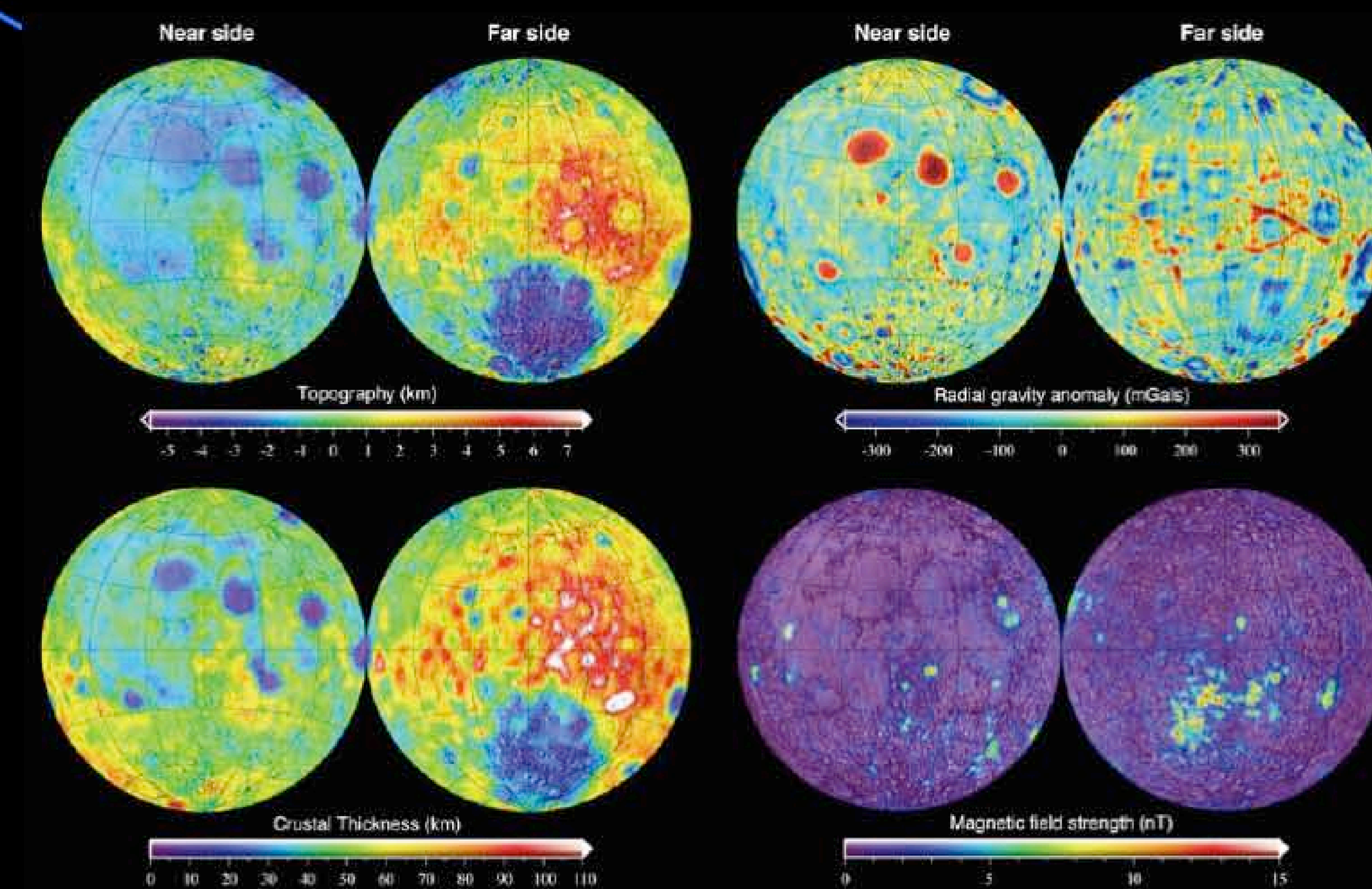
- About 50 km thick on near side; 80 km on far side
- May be layered (mafic at base)

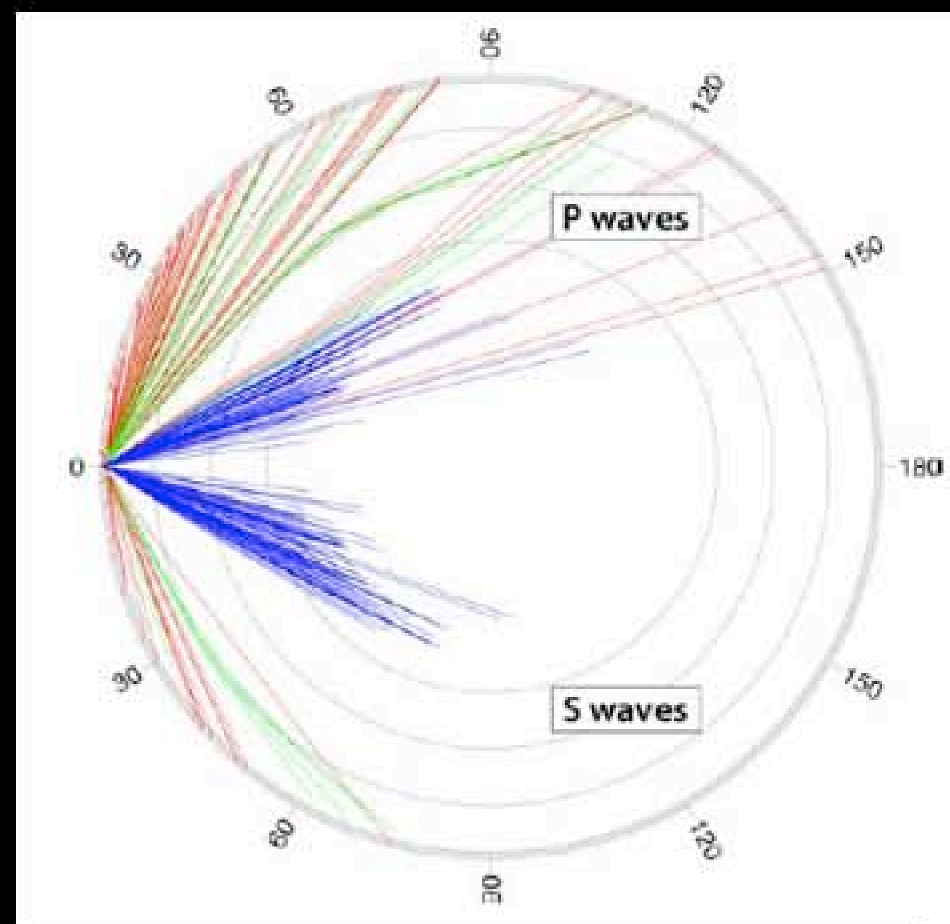
**Mantle**

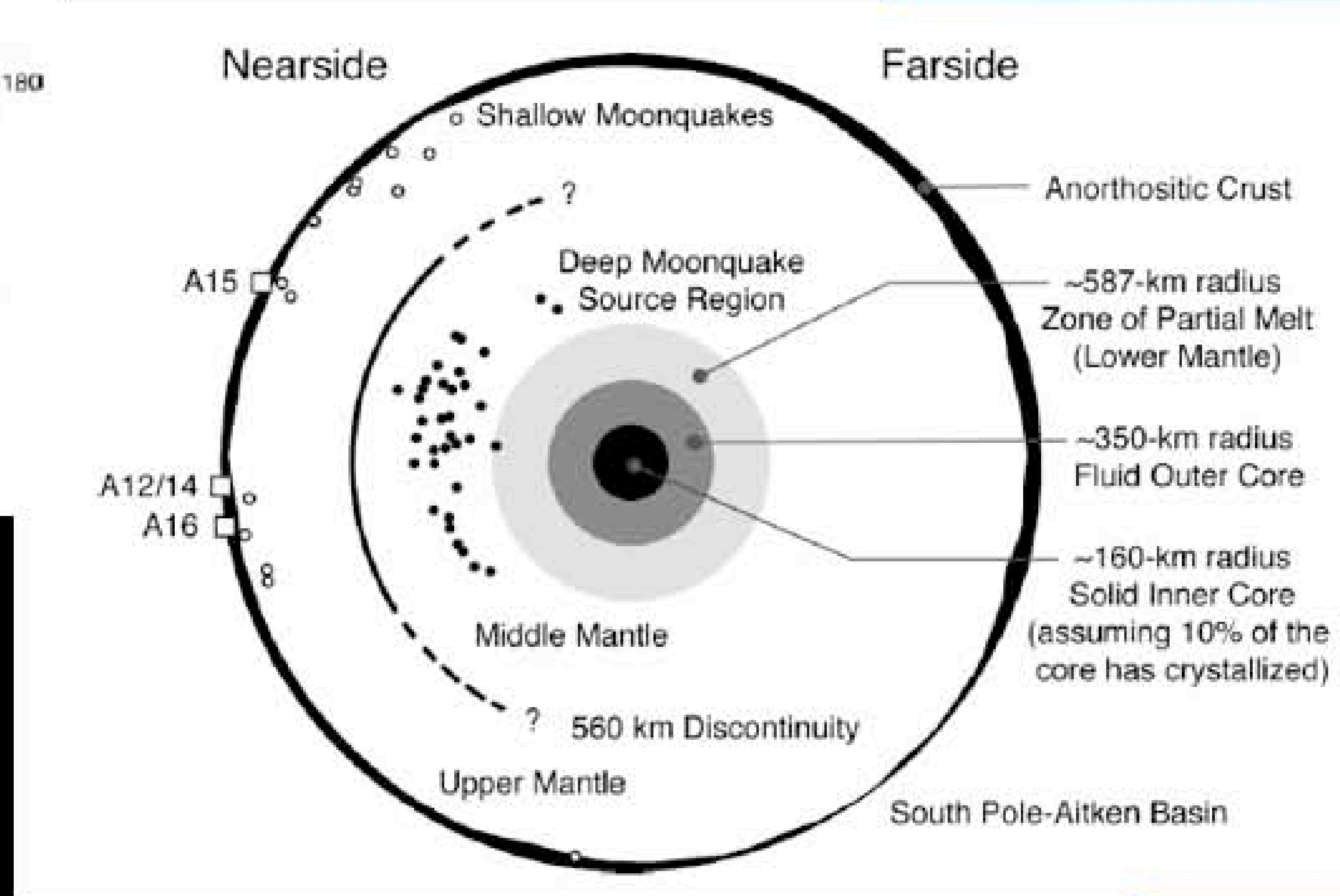
- Base of crust down to 1300 km
- Source for mare basalts

**Core**

- Small; max radius ~400 km; FeS (?)

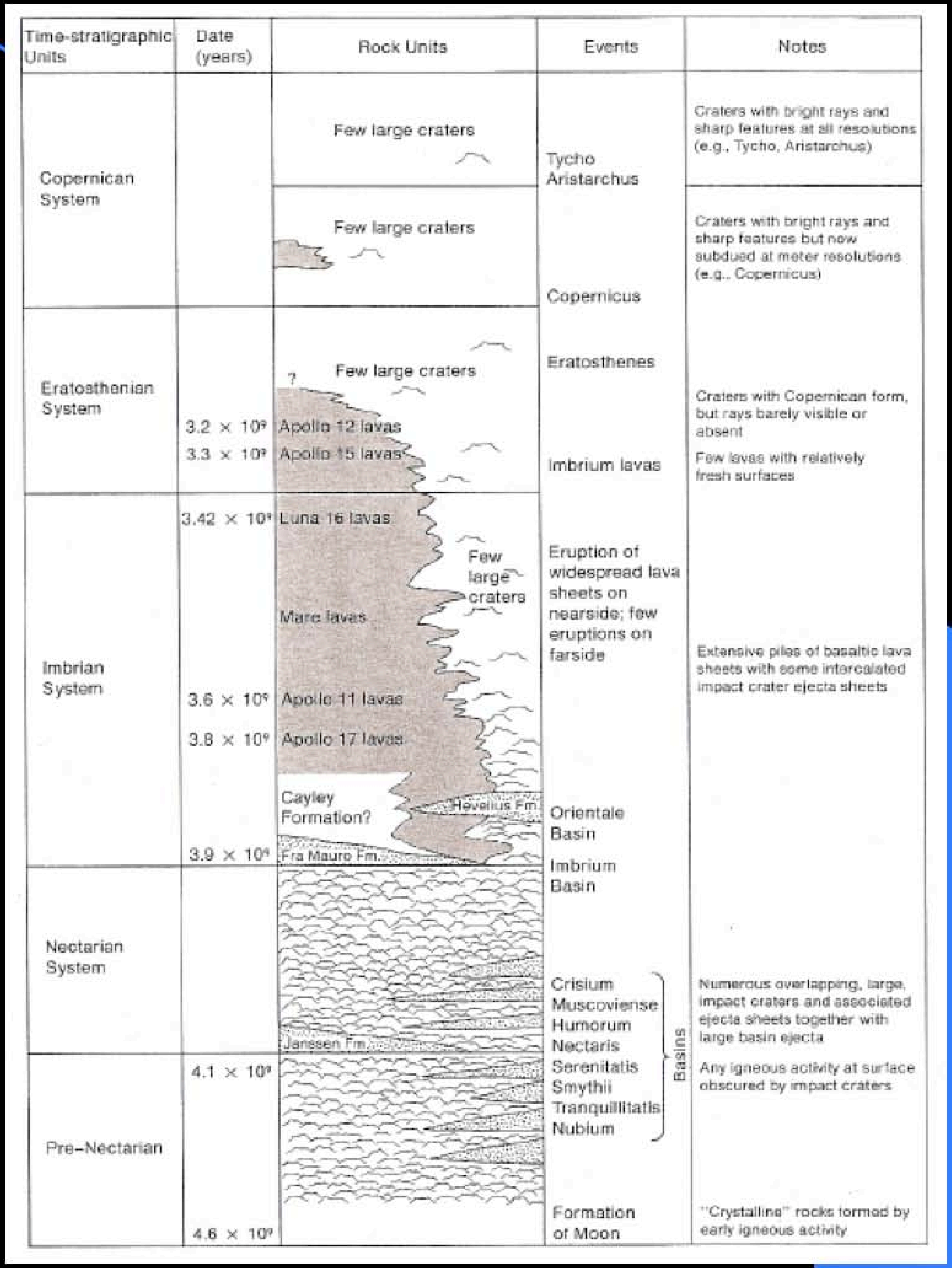


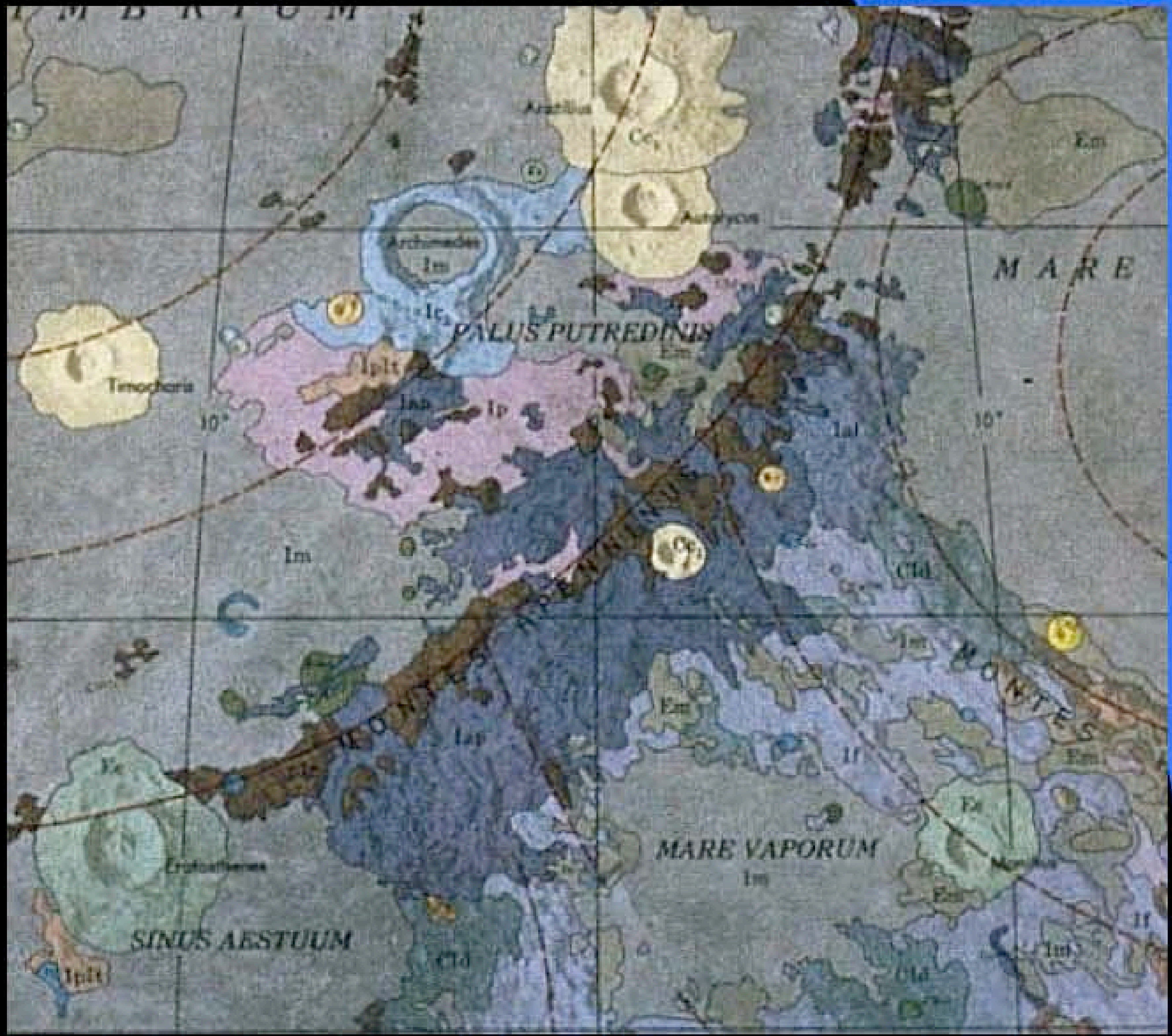
# Stratigraphy

- Study of layered rocks or rock sequences
- On Moon, relative ages determined by overlap, superposition, crater density, degradation state
- Keyed to events on central near side:
  - Copernican (< 1 Ga)
  - Eratosthenian (3.3 to 1 Ga)
  - Imbrian (3.85 to 3.3 Ga)
  - Nectarian (3.92 to 3.85 Ga)
  - pre-Nectarian (> 3.92 Ga)
- Rock or time units
  - Formation - genetically related rock unit
  - System - age-related; includes variety of rock units



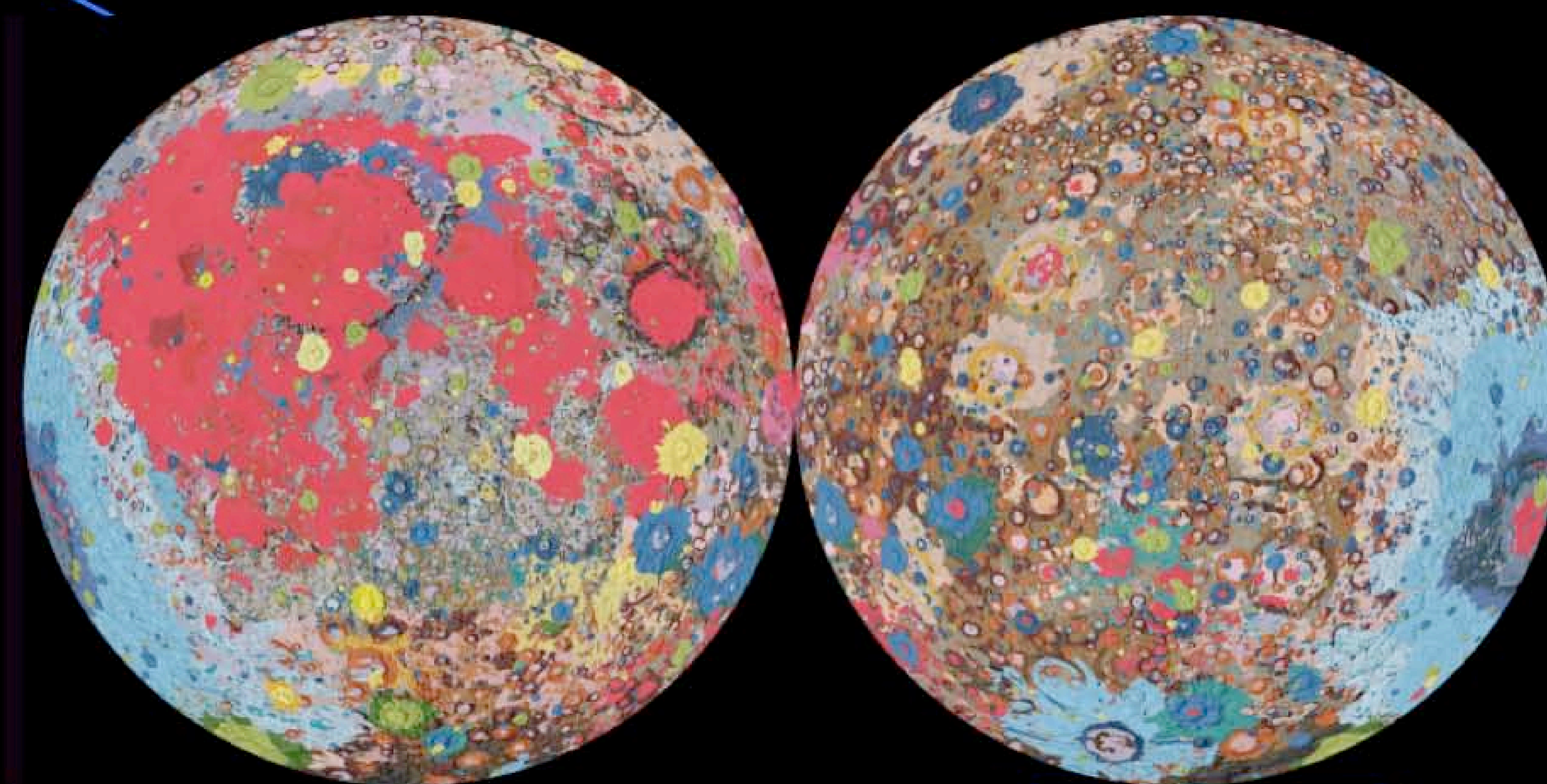
# Geological Mapping

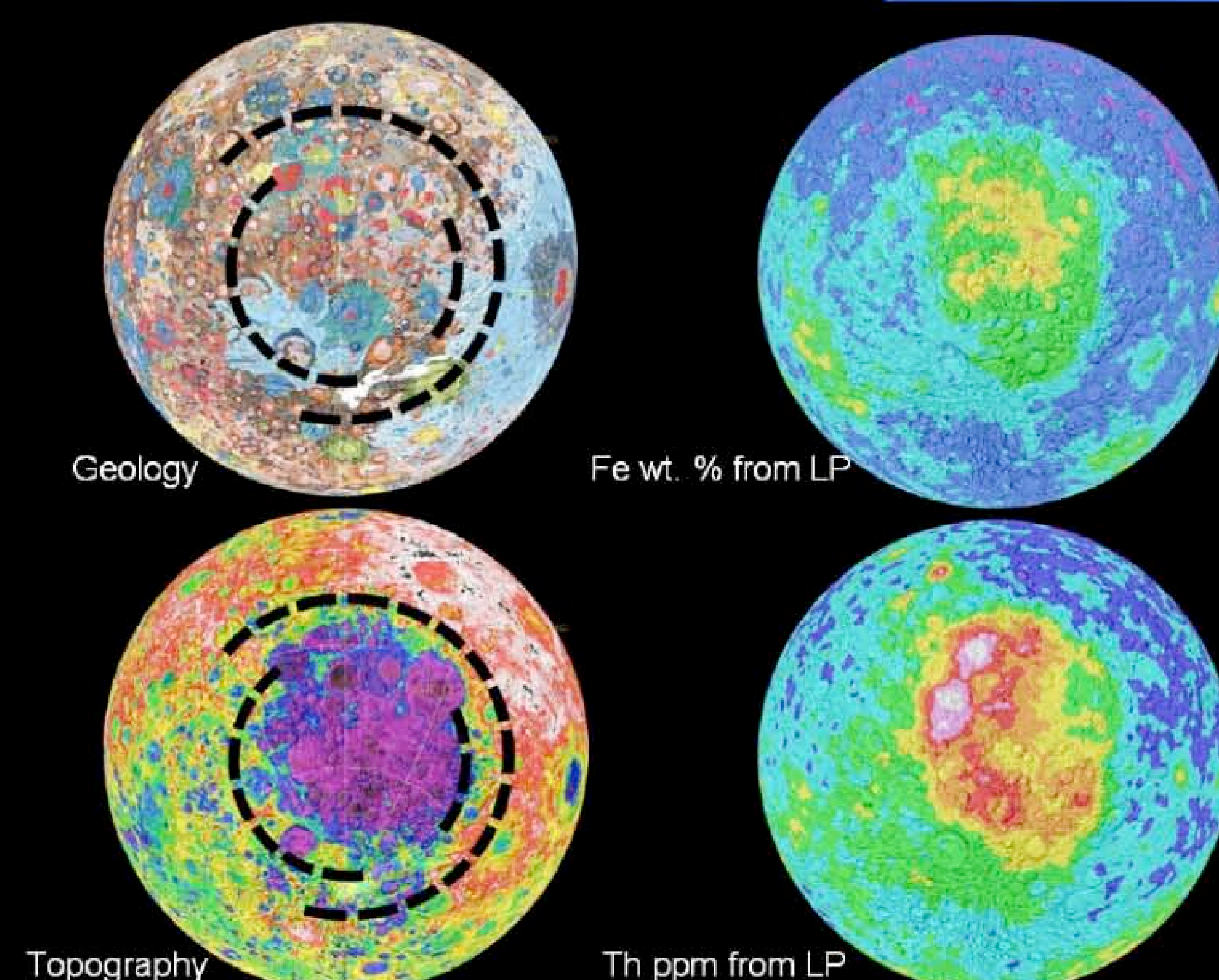
- Define laterally and vertically contiguous rock units, laid down at a single time and as a result of one process
- Sequence of rock units can be defined from images of surface
- Groups of rock units can be created during one event (e.g., basin impact)
- Subsequent events bury or modify previous units
- Unit sequence and type define geological history



# Global Geology

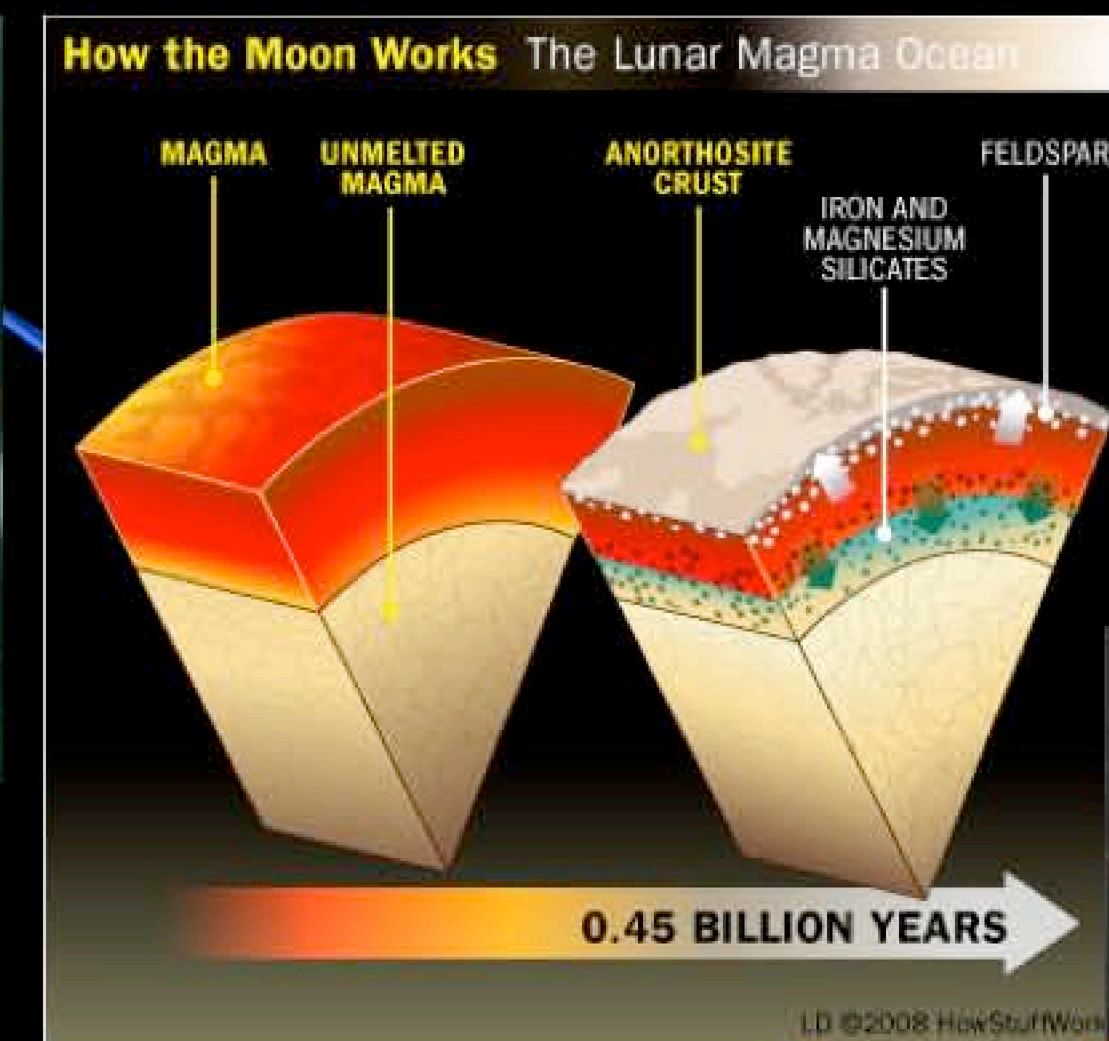
- Most maria occur on near side (16% 0f Moon)
- Near side highlands dominated by youngest basins, Imbrium and Nectaris
- West side dominated by Orientale basin
- Far side dominated by South Pole-Aitken basin in south, ancient cratered terrain in north
- More than 97% of Moon’s surface older than 3 Ga

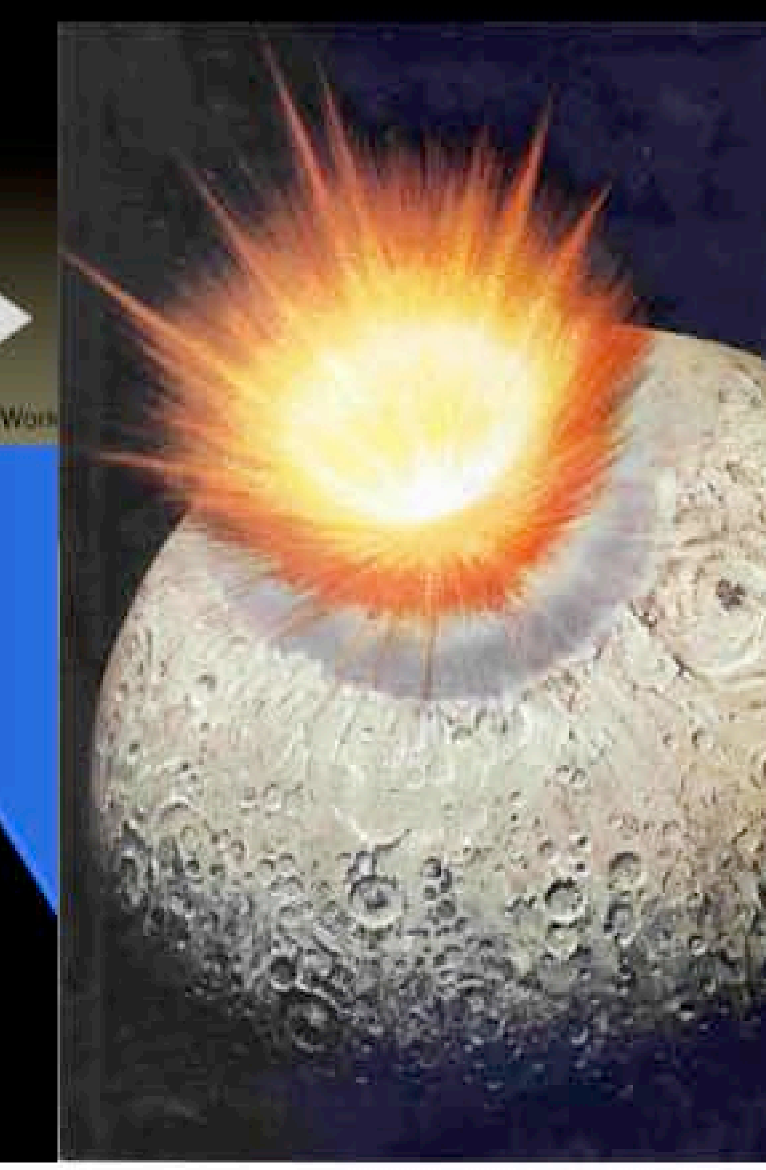


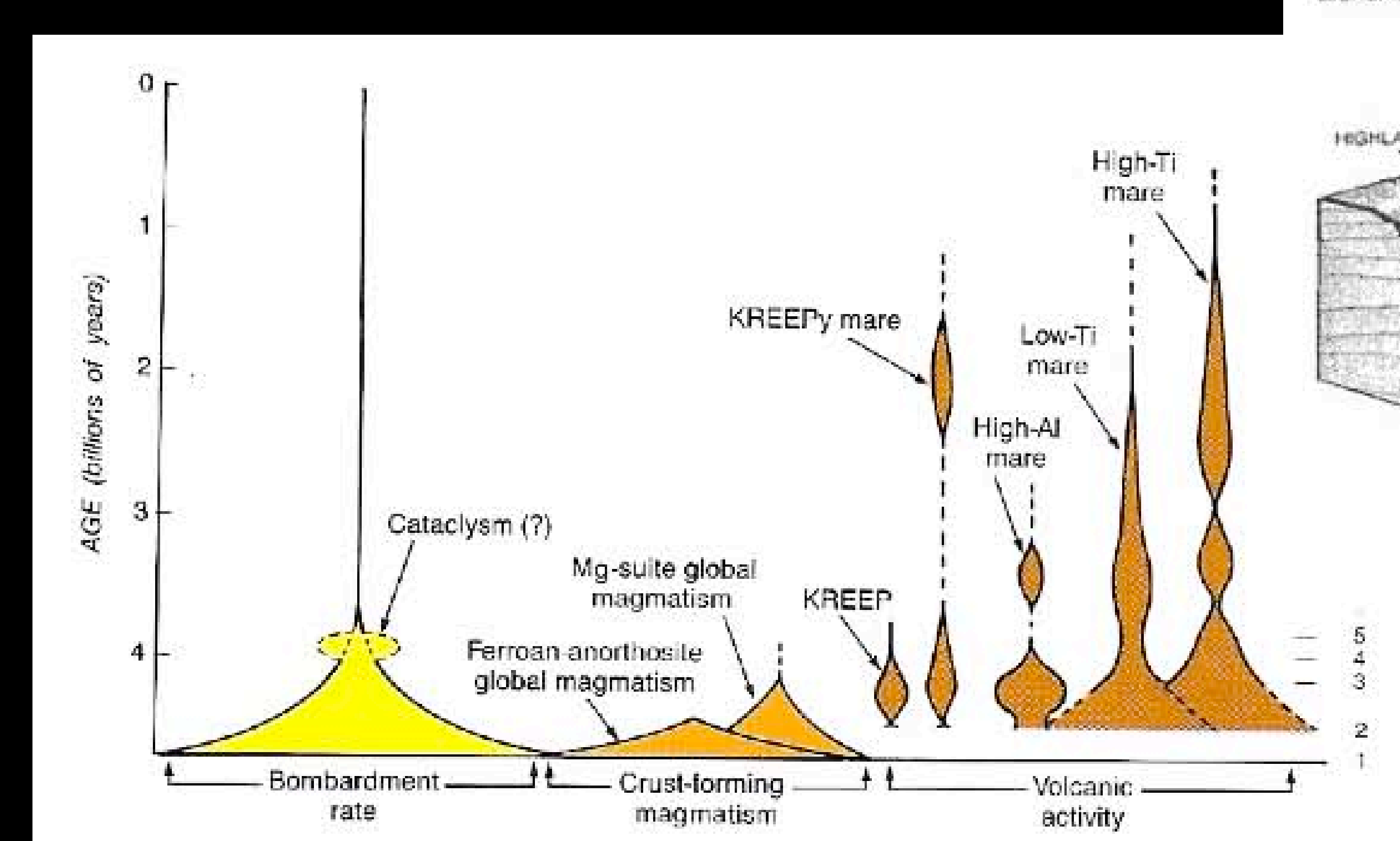


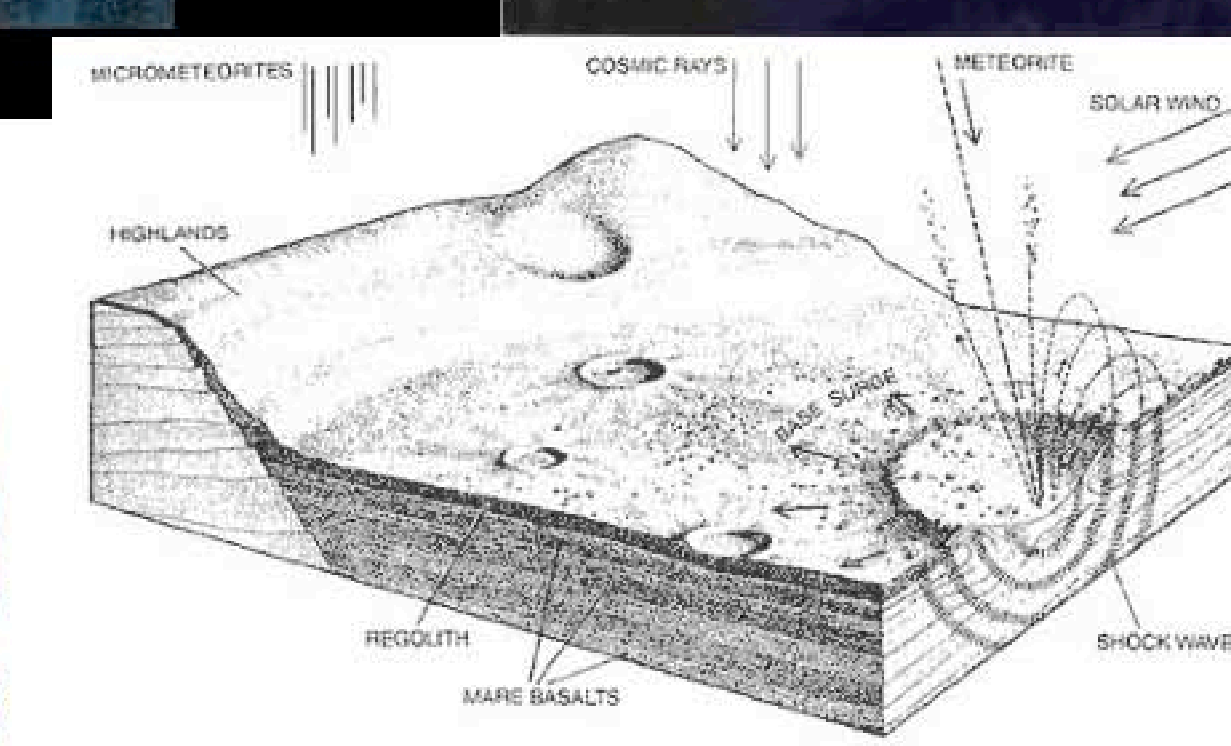
# Geological History

- Accretion and global melting
- Heavy bombardment
- Basins and cataclysm
- Mare volcanism
- Impact and regolith growth
- Most of evolution of the Moon occurs in first 1000 Ma of its 4600 Ma history



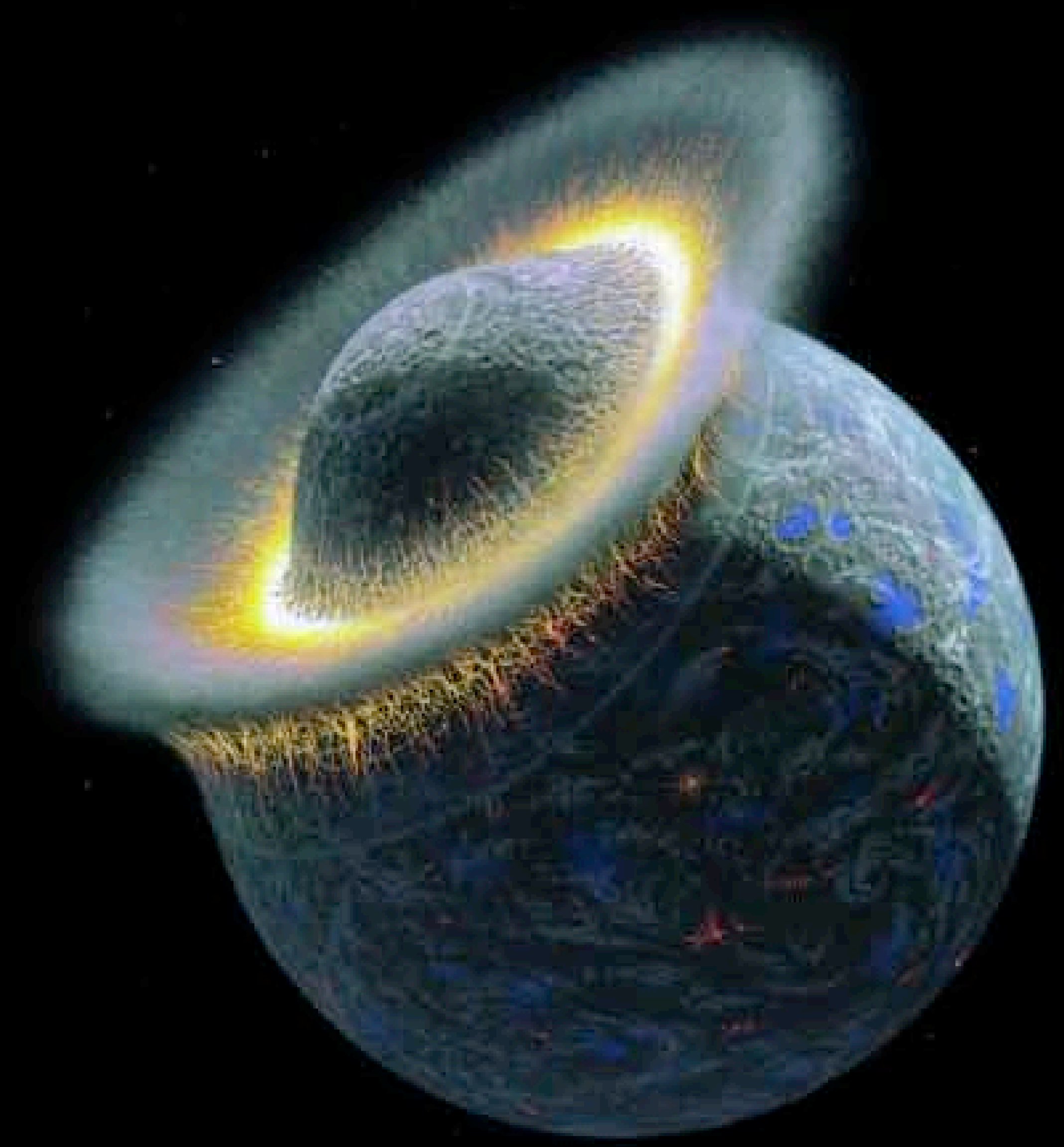



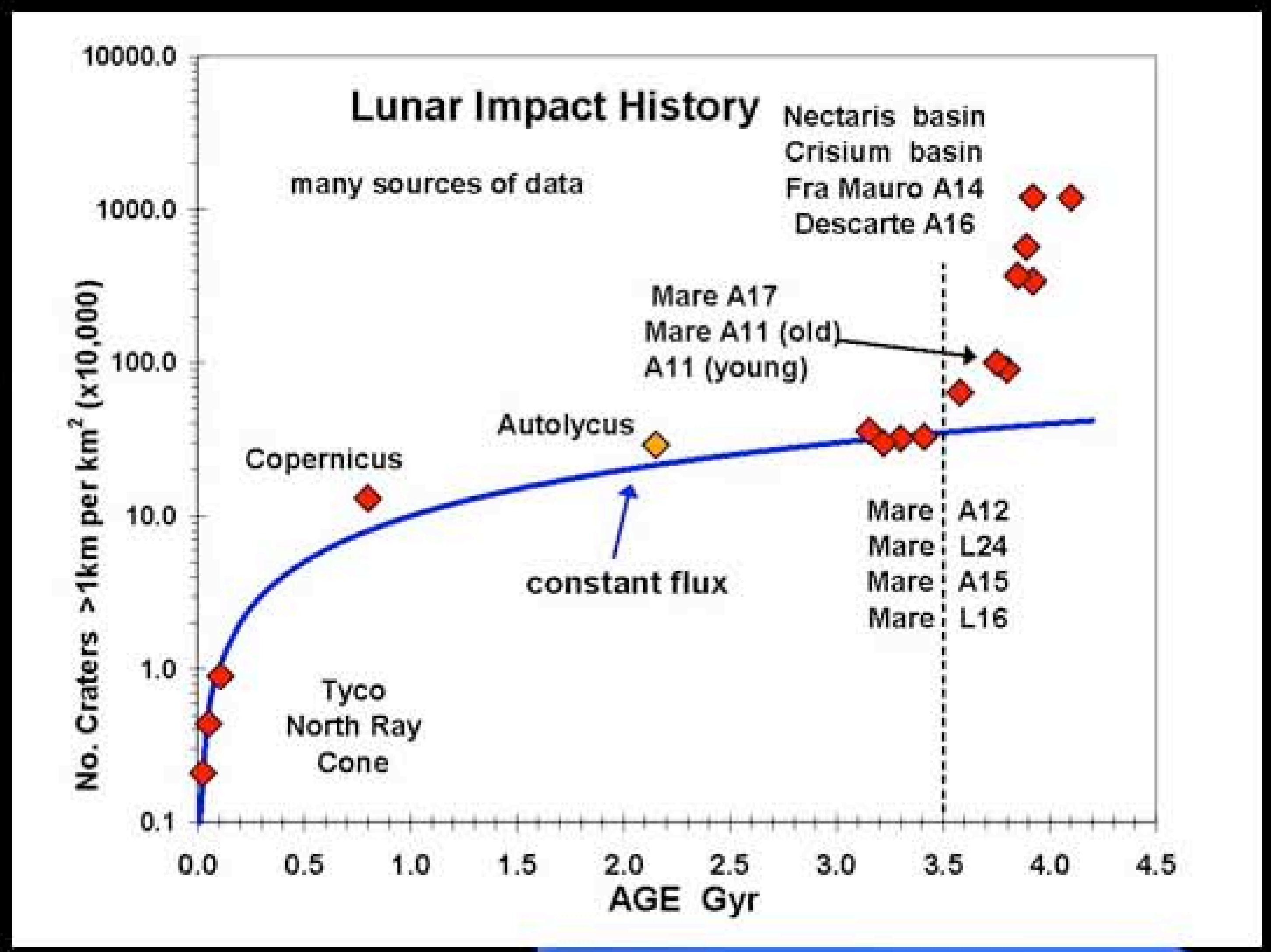


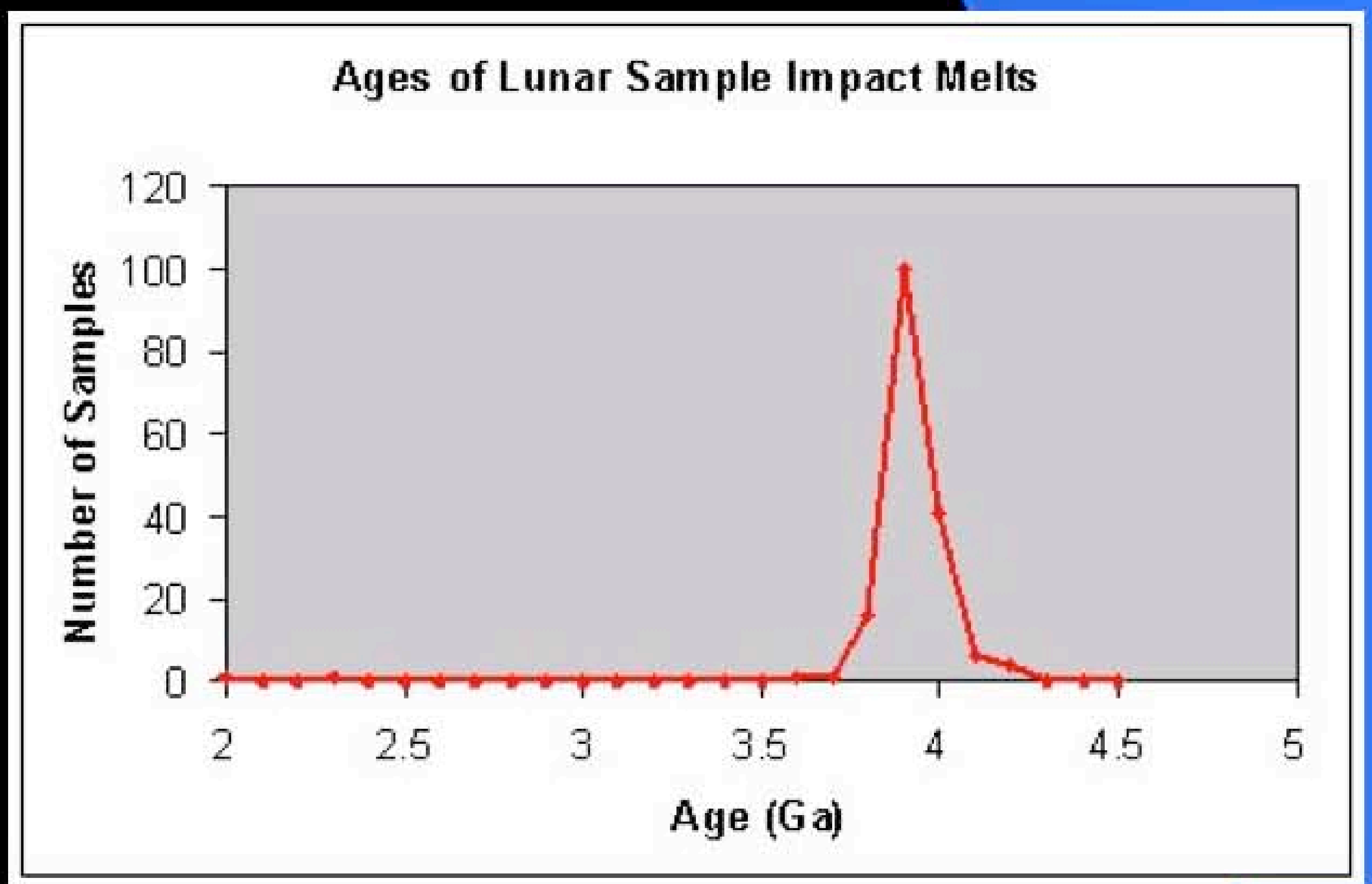



# The impact history of the Earth-Moon system

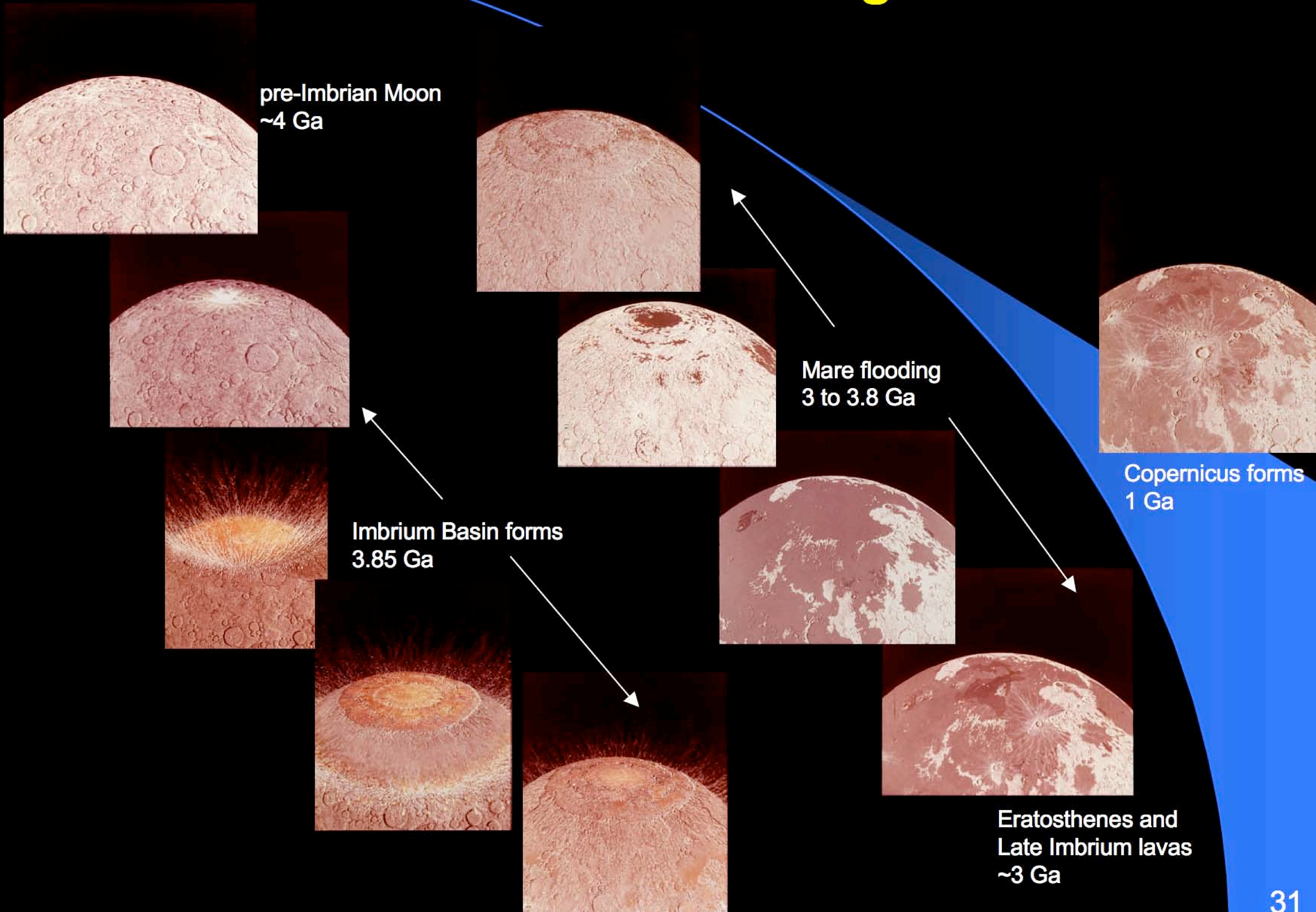
- Craters are erased on the dynamic, eroded surface of Earth
- The Moon retains this record
- Both bodies reside at 1 AU, recording the impact flux in this part of the solar system
- The Moon's impact record can be recovered and interpreted in terms of Earth-Moon history
- Was there an impact cataclysm 3.9 Ga ago and if so, how did it affect Earth's evolution?





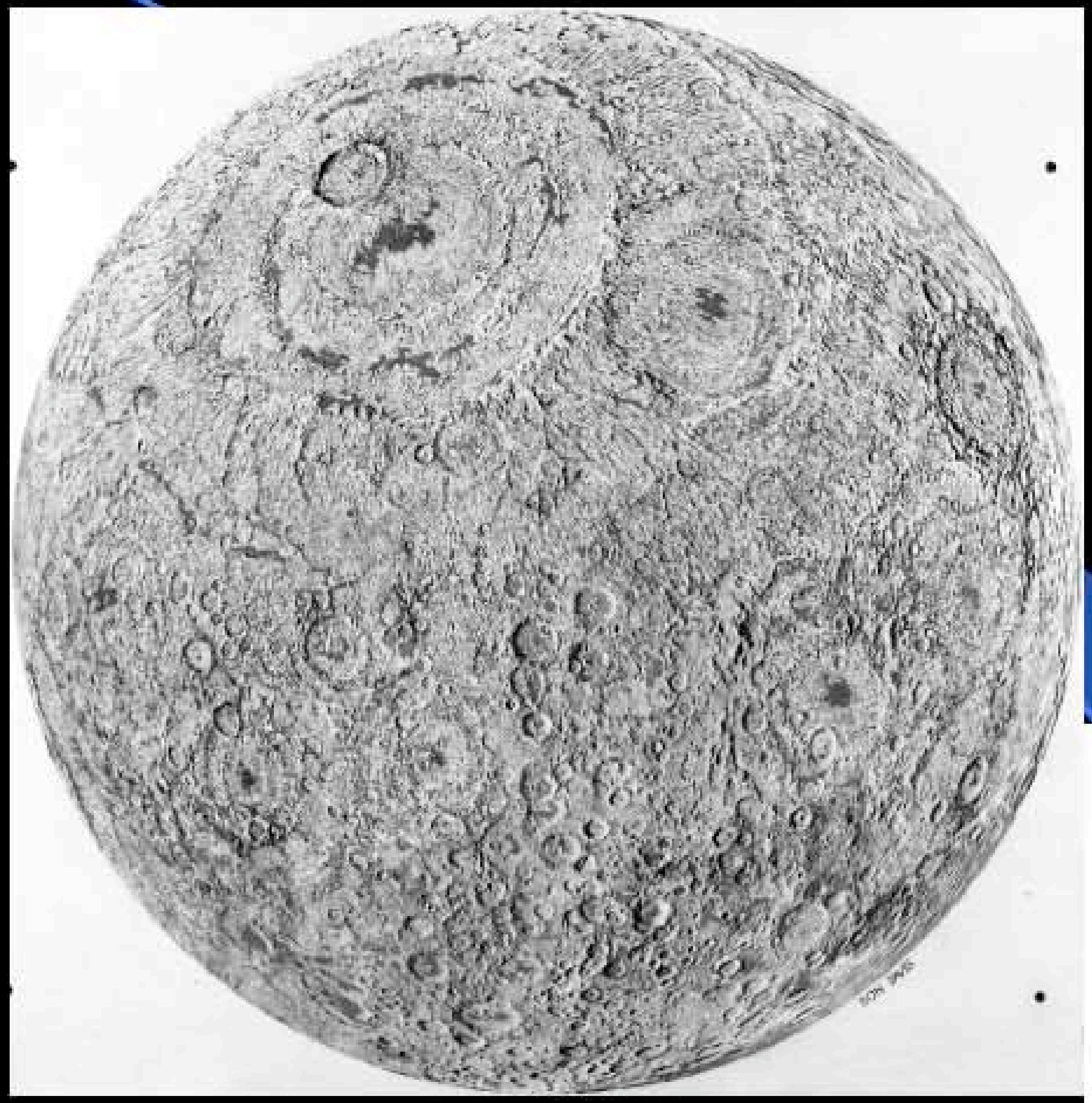



# The Moon's Face Through Time

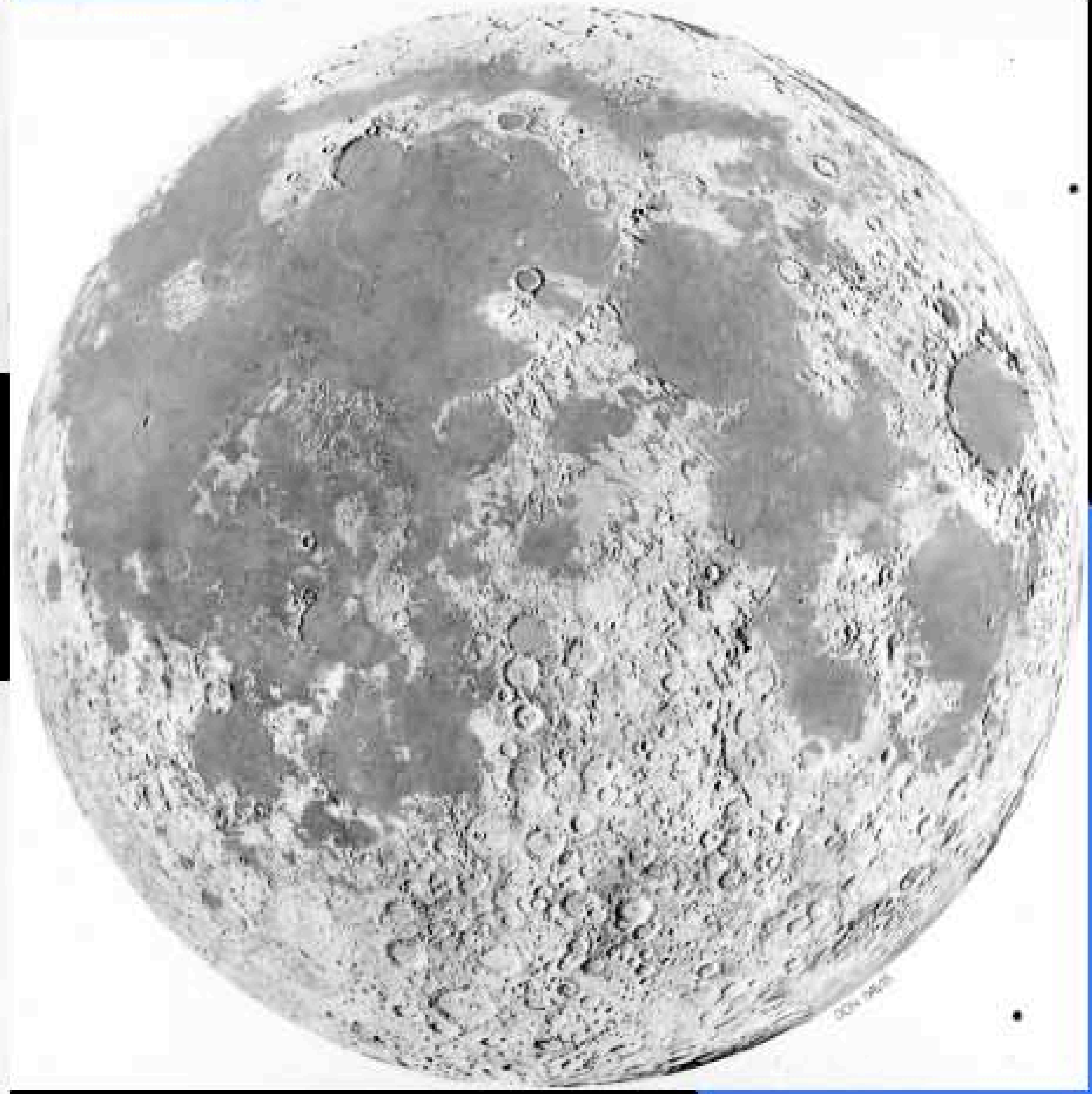


# Former Faces of the Moon

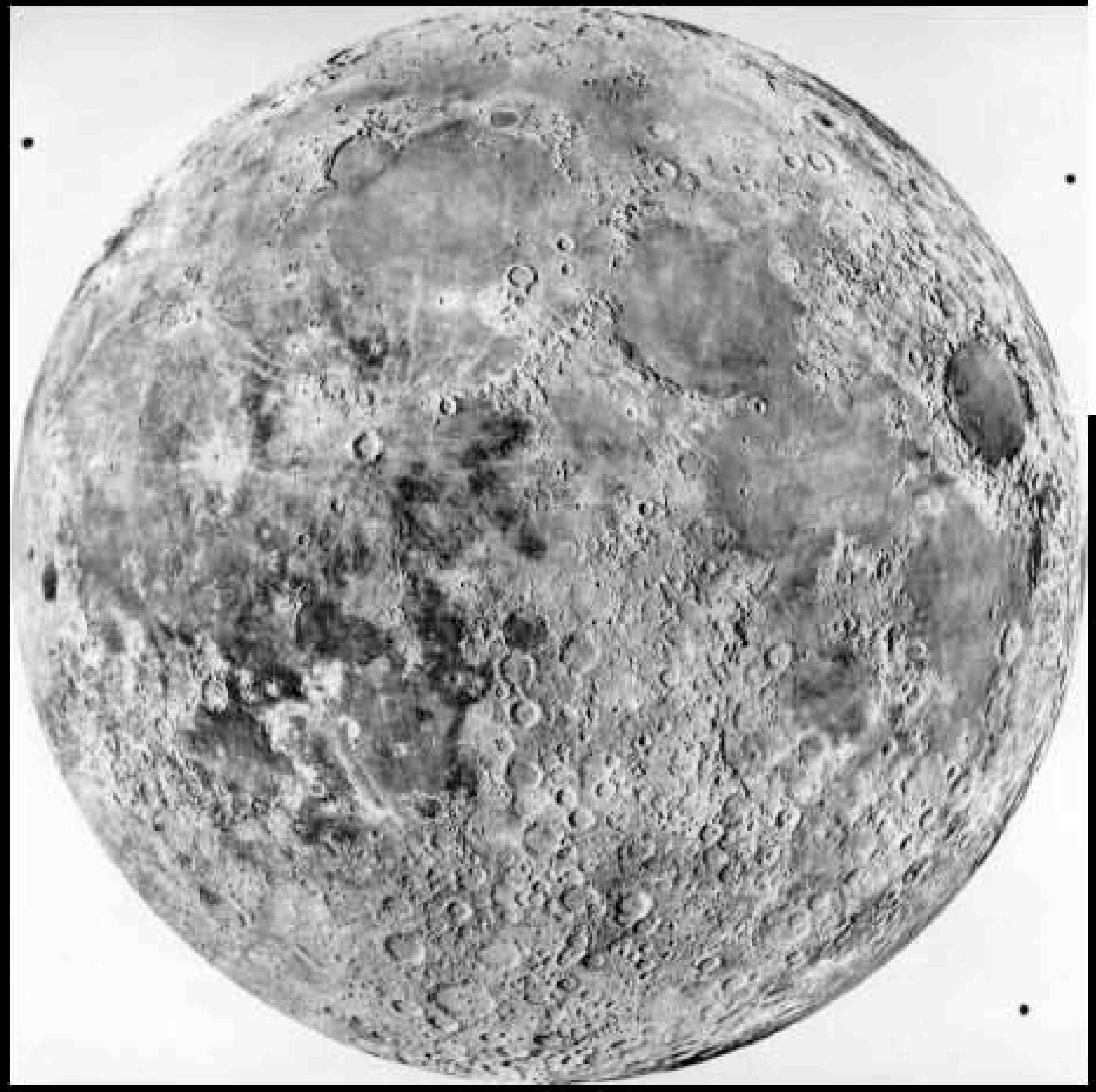
- Geologic maps permit us to "strip off" younger units progressively
- Don Davis drew the Moon at two different times in its past:
  - Immediately after the formation of the Imbrium basin
  - Just after the eruption of most mare basalts



Imbrian Moon
~3.8 Ga



Eratosthenian Moon
~3.0 Ga



Present Moon

# Paleogeological Maps of the Moon

Moon's geology as it was in the distant past

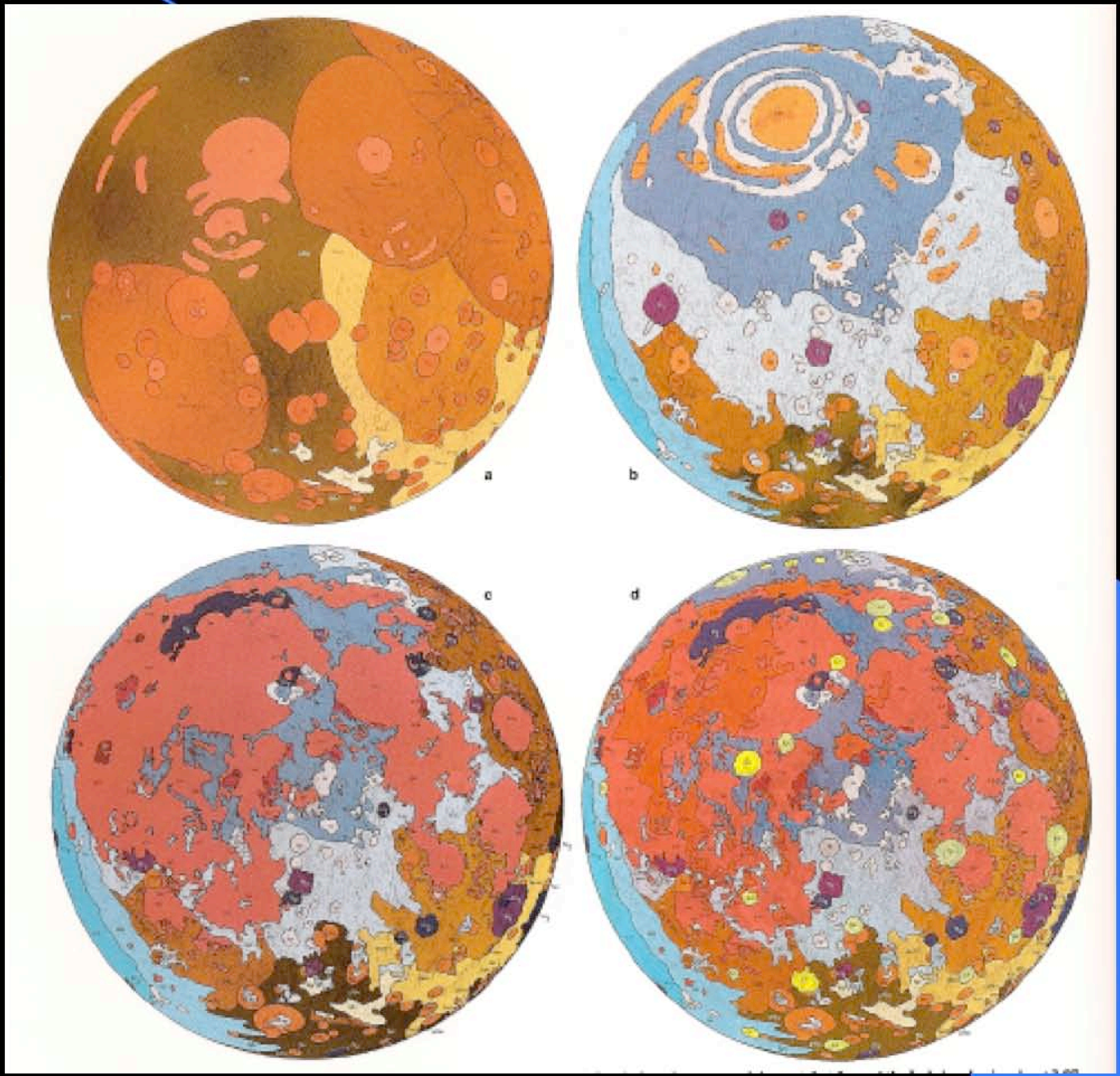
Four times portrayed:

a. Before Imbrium basin ~3.9 Ga

b. Just after Imbrium impact ~3.85 Ga

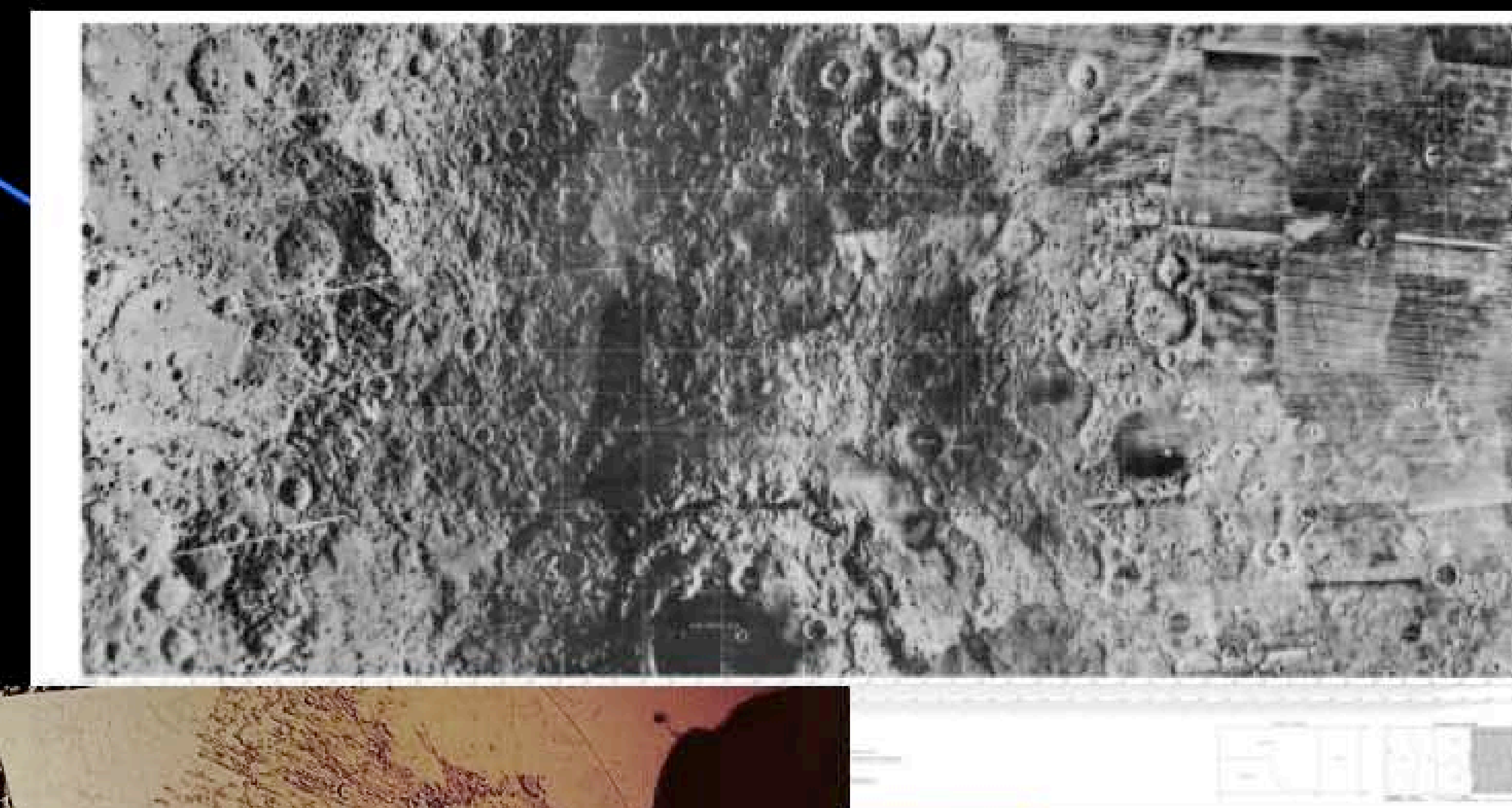
c. Just after most mare flooding ~3 Ga

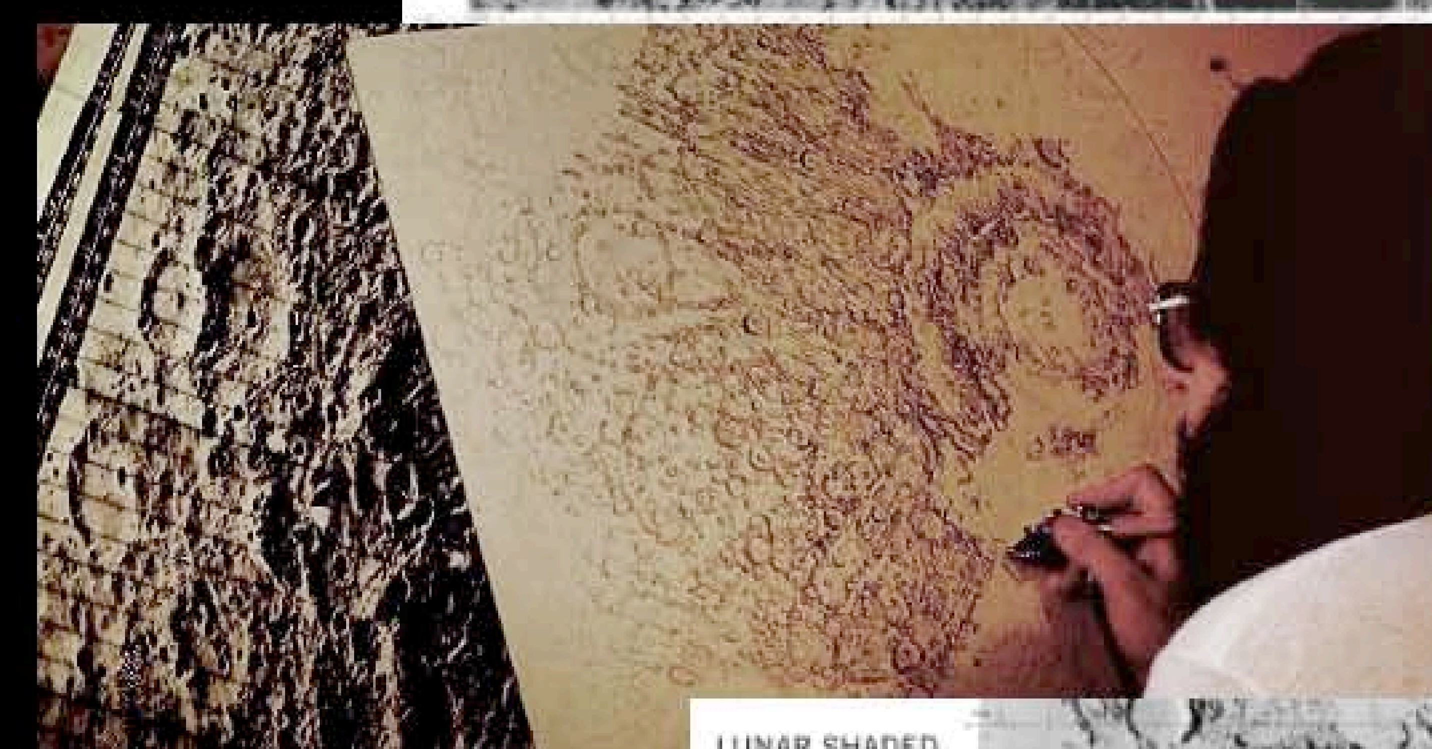
d. Present Moon



# Cartography

- Most mapping done with spacecraft images
- Photomosaics as base maps
- Shaded relief drawing synthesize observations
- Variety of scales serve different purposes
- Geodetic control an issue for poles, parts of far side

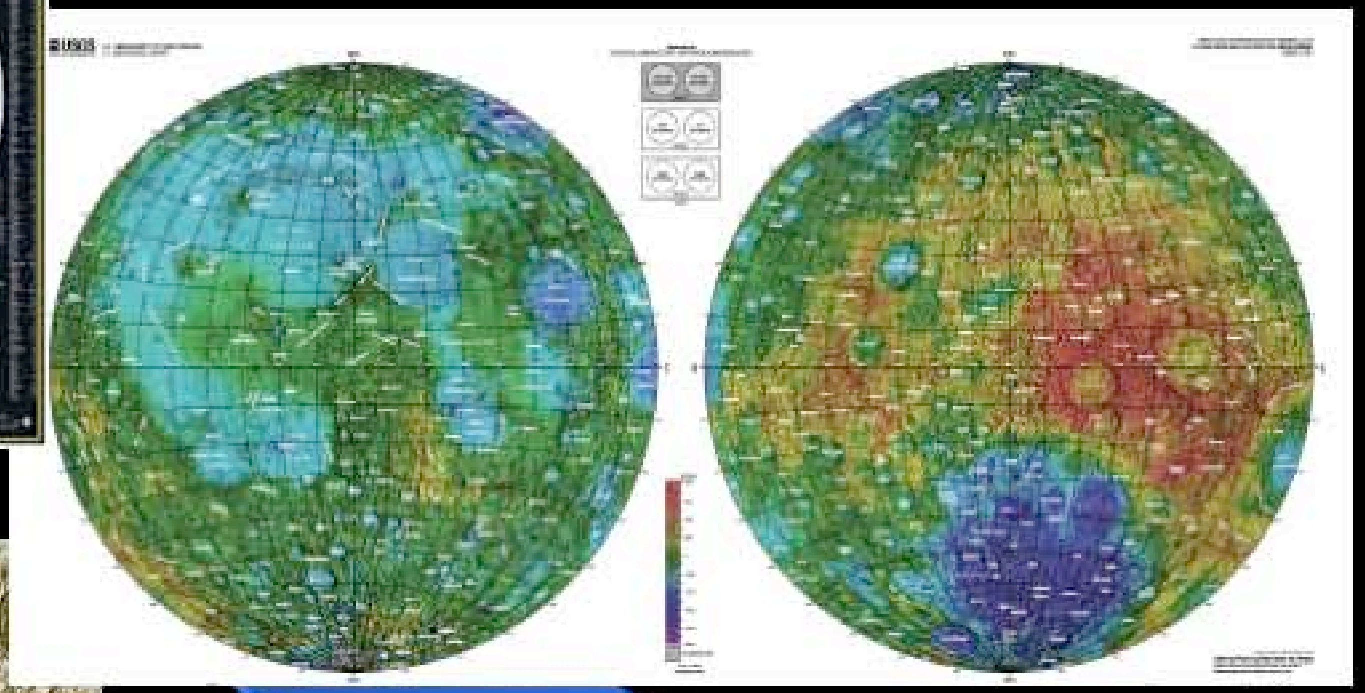


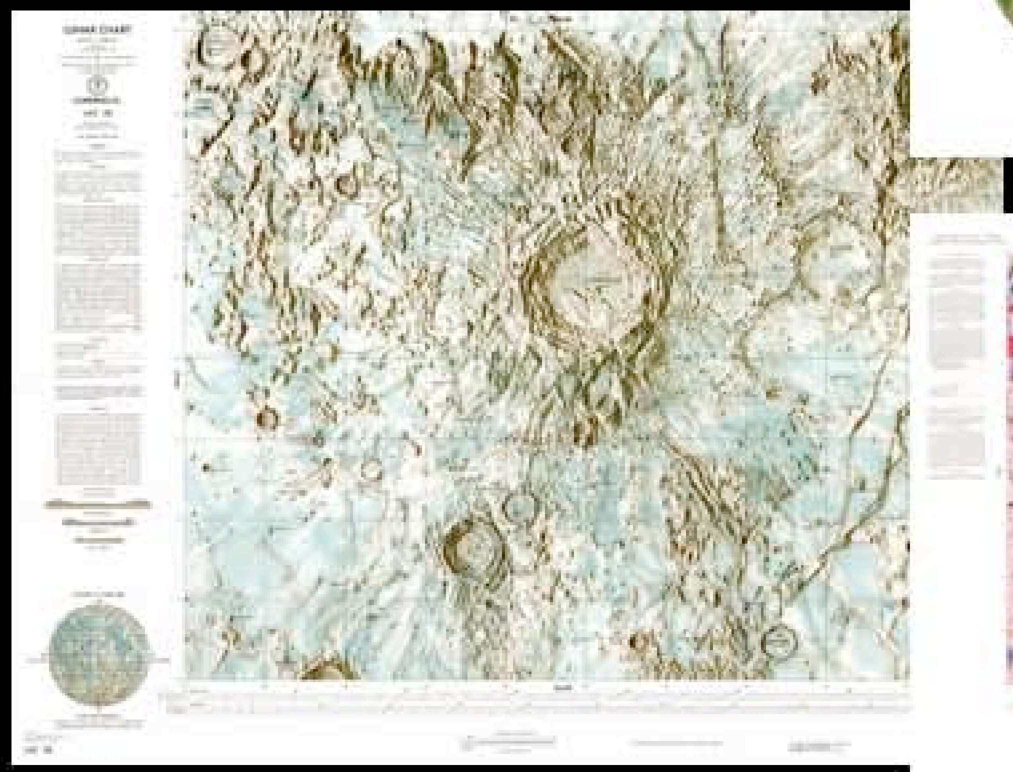


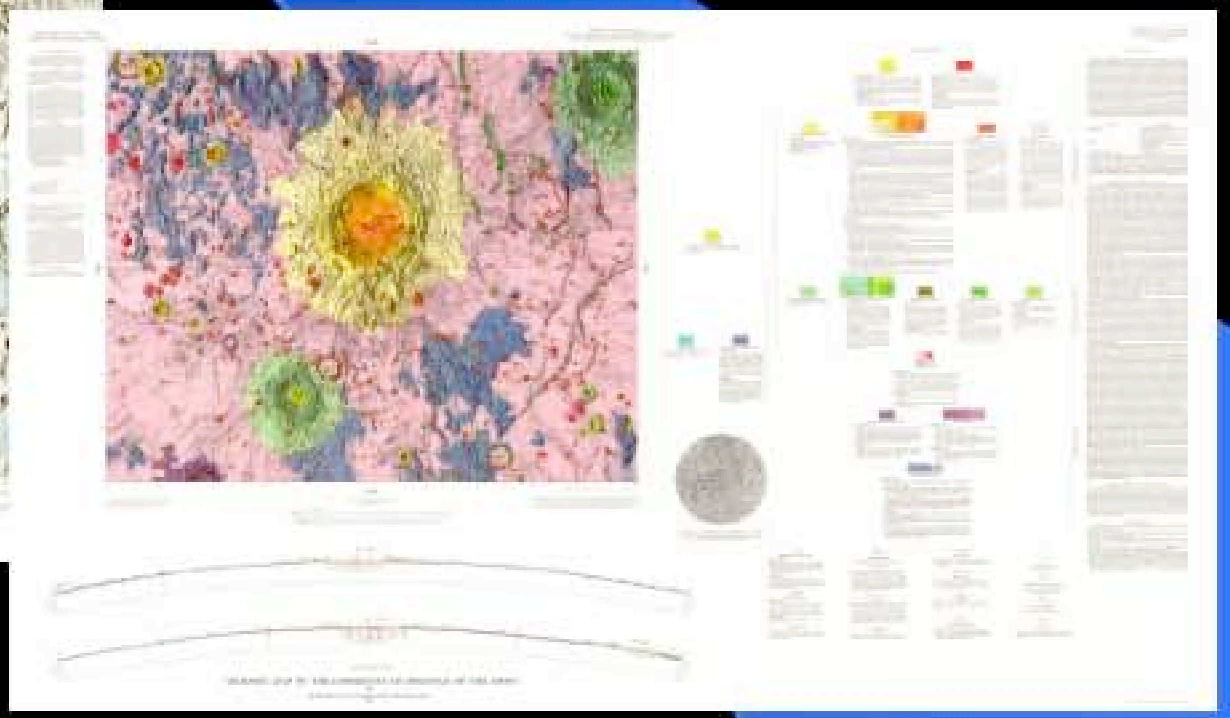
# Maps of the Moon

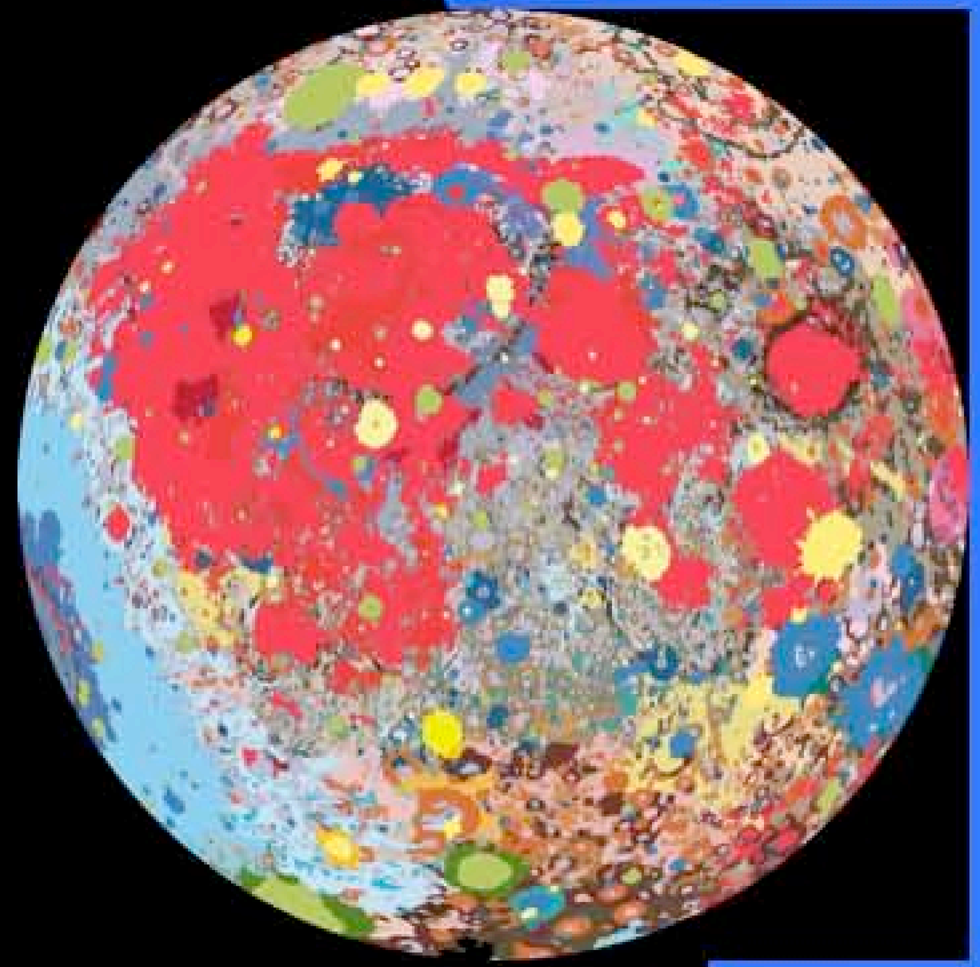
*"All we need is a map…." Michael D. Griffin, 2005*

- Available in a variety of formats and scales
- Most useful general map: Lambert Equal Area 1:10M, published by National Geographic Society
- Six hemispheres in this projection have been published with topography by USGS
- LAC (LM) series at 1:1M show better surface detail
  - 44 LAC charts cover lunar near side; 144 cover whole Moon (Clementine Atlas)
- Global geological maps at 1:5M; 44 LAC geology quads at 1:1M
- Small scale special purpose maps of scientific sites, Apollo sites
- Almost all available at LPI web site: http://www.lpi.usra.edu/resources/mapcatalog/







# Suggested Reading and Reference


Masursky H., Colton G. and El-Baz F. (1978) *Apollo Over the Moon: The View from Orbit*. NASA SP-362, 266 pp. Available at: http://www.lpi.usra.edu/lunar/documents/NASA%20SP-362.pdf

Wilhelms D.E. (1984) Moon In *The Geology of the Terrestrial Planets* (M.H. Carr, ed.), NASA SP-469, 106-205. Available at: http://hdl.handle.net/2060/19850010579

Wilhelms D.E. (1987) *Geologic History of the Moon*. USGS Prof. Paper 1348, 302 pp. Available at: http://ser.sese.asu.edu/GHM/

French B.M. (1998) *Traces of Catastrophe*, Chapter 3, Lunar and Planetary Institute Contr. 954, p. 17-30. Available at: http://www.lpi.usra.edu/publications/books/CB-954/chapter3.pdf

National Geographic Society (1976) *Earth's Moon*. Map, Lambert Equal-Area projection, 1:10M scale. http://shop.nationalgeographic.com/product/179/47/123.html

Bussey B. and Spudis P.D. (2004) *The Clementine Atlas of the Moon*, Cambridge Univ. Press, Cambridge UK, 376 pp. http://www.amazon.com/Clementine-Atlas-Moon-Ben-Bussey/dp/0521815282/ref=pd_sim_b_title_3

# Moon 101 - A Look Ahead

**June 4, 2008 Introduction (Spudis)** – motions, history of orbit/axis tilt, surface conditions, general properties, proposed origin.

**June 18, 2008 Environment (Mendell)** – thermal, radiation, plasma, electrical (including interactions with Earth's magnetosphere), exosphere

**July 2, 2008 Physiography and geology (Spudis)** – terrains, landforms, topography (photogeology). Impact crater formation, excavation, ejecta emplacement, secondaries, impact melting and shock metamorphism, lunar meteorites. Flux through time; cataclysm, periodicity, correlation with terrestrial record and other planets

**July 16, 2008 Surface (Plescia)** – dust, rocks, slopes, trafficability (geotechnical properties). Formation and evolution of regolith, interface with bedrock. Crater size-frequency distributions, exotic components, highland/mare mixing, vertical and lateral transport of material. Chemical and mineral composition, physical state, properties, characteristics

**July 30, 2008 Crust (Lofgren)** – formation and evolution, highland rocks types and magmatism, rock provinces and terranes; Volcanism: magma types, flood v. central vent eruptions, pyroclastics, number of flows, thicknesses, changes in composition with time, history; deformation and tectonic history

**August 13, 2008 Interior (Plescia)** – megaregolith, crustal thickness and variation, near side/far side dichotomy, mantle/core size, composition, heat flow, lunar magnetism, bulk composition

**August 27, 2008 Poles (Bussey)** – environment, sunlight and shadow, volatiles, opportunities and difficulties of living and working at the poles

**September 10, 2008 The Apollo Program (Eppler)** - architecture, capabilities, evolution, surface exploration, rover experience, advanced Apollo (cancelled missions)

**September 24, 2008 Exploration and Station Emplacement (Eppler/Spudis)**– geological reconnaissance and field work, surveys, traverses, transects, stratigraphy and the third dimension, bedrock on the Moon, site selections and surveys, networks, emplacement, construction, alignment, maintenance

**October 8, 2008 Lunar Meteorites (Righter)** – What we've learned from meteorites from the Moon.

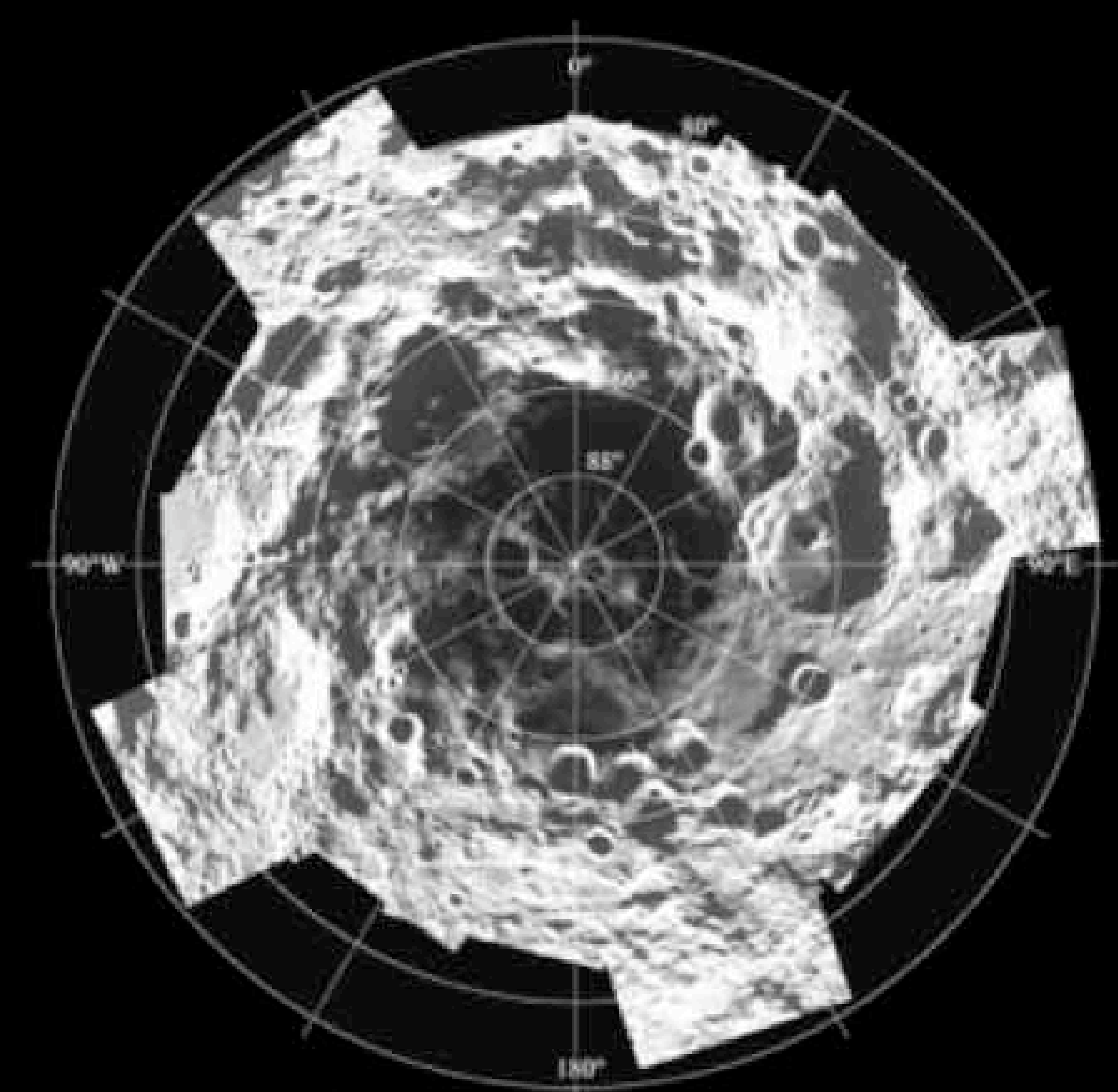
# For more information, go to:

http://www.spudislunarresources.com

## *Spudis Lunar Resources*

Using the Moon to learn how to live and work productively in space

**What's this web site all about?**



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